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Developing visitor thresholds of sound from shale natural gas compressors for motorized and non-motorized recreation users in Pennsylvania State Forests

Zachary D. Miller [a,*], Lauren A. Ferguson [b], Peter Newman [c], Michael Ferguson [b], Nathan Tipton [d], Victor Sparrow [d], B. Derrick Taff [c]

[a] Department of Environment and Society, Institute of Outdoor Recreation and Tourism, Utah State University, Logan, UT, USA
[b] Department of Recreation Management and Policy, University of New Hampshire, Durham, NH, USA
[c] Department of Recreation, Park, and Tourism Management, The Pennsylvania State University, University Park, PA, USA
[d] Graduate Program in Acoustics, The Pennsylvania State University, University Park, PA, USA

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ABSTRACT

Understanding visitor evaluations of human-caused sounds is an essential component to managing recreation experiences in parks and protected areas. In this study, the impact of sounds from natural gas compressors in Pennsylvania State Forests is explored. Using data collected from over 400 onsite visitors, researchers developed a threshold model that shows how visitor experiences change with sounds from natural gas compressors. The threshold model shows that increased sound levels (dBA) from natural gas compressors have a negative impact on visitor experiences. Further segmentation by activity type shows that there is a negligible impact on motorized users and a negative impact on non-motorized visitors. The threshold model shows that sounds from natural gas compressors become unacceptable to non-motorized users at about 55 dBA. The results from this study can be used to help managers of forests plan for high-quality recreational experiences in an era of expanding natural gas extraction.

1. Introduction

Sounds are a critical component of the visitor experience in many parks and protected areas around the globe [17,30,32]. In most park and protected areas, the management of sounds focuses on reducing anthropogenic sounds as they often degrade the visitor experience [11,32,48]. However, even the most remote wilderness areas experience sound pollution from anthropogenic sources [3,16]. Given the importance of natural quiet and its increasing scarcity [3,9,16], it is essential that managers of parks and protected areas have science-based information to understand and address the impacts of anthropogenic sounds on visitor experiences in parks and protected areas.

In Pennsylvania, State Forests provide a diversity of motorized and non-motorized recreational opportunities that rely on naturalistic settings. However, Pennsylvania State Forests (PSF) are also a globally important area for the extraction of natural gas from the subsurface Marcellus Shale formation. This extraction occurs through unconventional hydraulic fracturing methods. Unconventional hydraulic fracturing (commonly referred to as 'fracking') utilizes the high-pressure injection of water, sand, and chemicals into a wellbore to create cracks and fissures in deep-rock formations where natural gas and oil can flow more freely to the surface for collection [34,35]. As part of this process, natural gas compressor stations are used to transport natural gas via pipelines from one location to another [45]. During this industrialized process, compressor stations generate noise [15]. As natural gas extraction expands in PSF [5], it is unknown how associated natural gas compressor sounds will impact recreational users. The purpose of this study is to assess how sounds from natural gas compressors may be impacting the visitor experience in PSF through normative threshold concepts. Additionally, there are numerous recreational user groups (e.g. hikers, kayakers, hunters, off-highway vehicle users) across PSF with diverse motivations, which may further influence visitor perceptions of sounds [23,28,48]. This includes both motorized and non-motorized recreational users. To address this purpose, a single broad research question was developed: *How do sounds from natural gas compressors impact the visitor experience of diverse user groups in PSF?*

* Corresponding author at: 5215 Old Main Hill, Logan, UT 84322, USA.
E-mail address: zachary.miller@usu.edu (Z.D. Miller).

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2. Conceptual framework

2.1. Threshold approaches for understanding visitor experiences in protected areas

Providing quality visitor experiences is an essential component to park and protected area management [21]. Rigorous social science methods developed over the past few decades allowing managers and scientists to understand how visitor experiences change over a range of resource conditions. These methods generally fall under a broad framework referred to as Management-By-Objectives (MBO) [21,27]. MBO is inclusive of a diversity of agency-tailored approaches for understanding changes in visitor experience, including Limits of Acceptable Change (LAC) [24,40,39], Visitor Experience and Resource Protection (VERP) [51,20,22], and the Interagency Visitor Use Management Framework (IVUMF) [13].

A critical concept all MBO frameworks share is the development of visitor thresholds [21,13] (Fig. 1). These thresholds are derived from normative concepts about what is and is not acceptable in park and protected area settings by collecting visitor evaluation data over a range of resource conditions [21,47]. Threshold concepts and associated statistical models allow managers to understand how indicators of related resource conditions (i.e. dBA for soundscapes) are related to visitor evaluations, and thus how changes in resource conditions may impact the visitor experience. Statistical threshold models also identify the quantitative point where resource conditions are no longer acceptable for maintaining quality experiences [21,47]. Fig. 1 provides a conceptual model of thresholds with acceptability on the y-axis and decibel level on the x-axis. As shown, as decibel level increases, the acceptability of the condition decreases until it finally crosses over the neutral line. This indicates that any sounds louder than the decibels at this point would be unacceptable for this setting. Managers can then monitor conditions and apply management actions to maintain quality visitor experiences as informed by the threshold [21,38].

Although thresholds were used to understand a variety of diverse resource conditions in parks and protected areas [1,22,29,49,52], several studies specifically focused on visitor thresholds related to sounds in parks and protected areas. In Muir Woods National Monument, CA, Pilcher et al. [32] developed thresholds for visitor-caused sounds. These visitor caused sounds included people talking, crying, and making other forms of vocalization. The threshold model showed that at 37 dBA the visitor experience became unacceptable due to these visitor-caused sounds. In Denali National Park and Preserve, Alaska, Ferguson [8] examined thresholds for aircraft noise in developed areas of the park. This research found that aircraft noise louder than about 53 dBA exceeded visitor thresholds and thus would no longer be acceptable conditions. Although some ecological studies explore the role of natural gas compressor sounds on avian communities [10], this current study is the first that the authors are aware of that examines visitor experiences through a thresholds approach in relation to natural gas compressor sounds.

2.2. Recreation experience preferences

Although objective levels of sound certainly influence visitor evaluations [32,48], psychological concepts may also impact visitor evaluations of sounds. One psychological consideration is visitor motivations [2,43,23,48]. The working definition of motivation is a psychological concept that influences the directionality and strength of human behavior [14,23]. In research investigating visitor experiences, motivations are measured through the concept of recreation experience preferences (REPs) [6,7,18] (Manfredo et al., 1996).

A large body of work shows that individual visitor motivations often group to form REPs [19]. For instance, "viewing scenery" and "experiencing natural quiet" may be both related to a REP about "nature appreciation." These REPs help managers and scientist understand why visitors are coming to a certain area and engaging in specific activities [18]. Although visitors participating in the same activity often share similar REPs, REPs can also help explain variation in attitudes, quality, outcomes, and other visitor experience concepts among visitors participating in the same activity (Manfredo et al., 1996) [35]. For instance, if two people were engaging in hiking as an activity, one may choose a certain trail because they are motivated by fitness REPs, and the other may choose a different trail because they are motivated by escape or solitude REPs. Incorporating REPs into statistical models that develop thresholds allows us to better understand visitor evaluations of sound levels [23].

3. Methods

3.1. Site selection

Study sites were selected in collaboration with managers from the Pennsylvania Department of Conservation and Natural Resources (DCNR). To maximize efficiency, sites needed to have

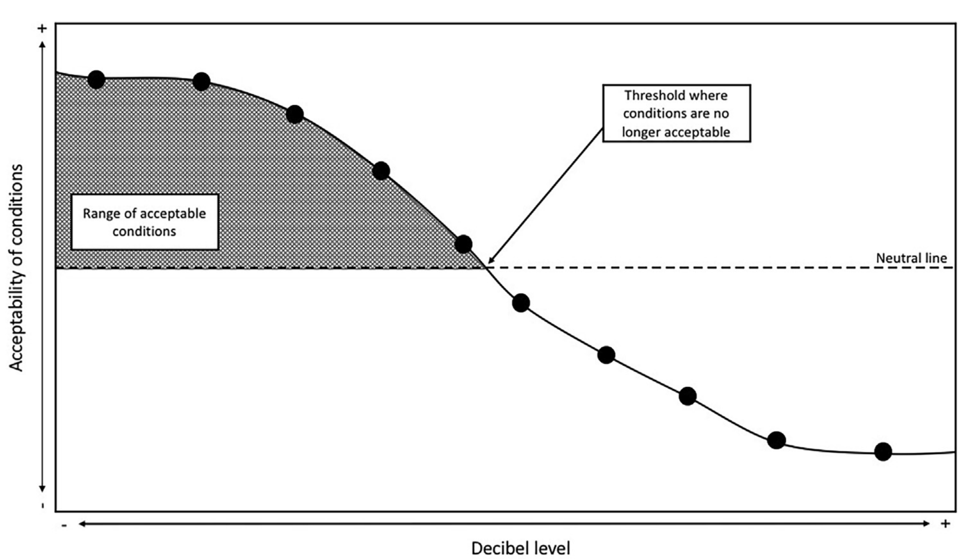

Fig. 1. Conceptual model of a normative approach to developing visitor thresholds [21].

high levels of recreational use, as well as visitors participating in a diverse array of recreational activities. Additional consideration was given for selecting sites with active natural gas extraction as well as sites that did not have active natural gas extraction as visitors recreating in areas with active natural gas extraction may have different experiences with natural gas compressors sounds during their visit. Using these criteria, two Pennsylvania State Forests (PSF) were selected: the Tiadaghton State Forest (TSF) and the Michaux State Forest (MSF). At TSF, sampling was conducted at the Whitetail/Ramsey Parking Area and the Mid-State Trail Overlooks. At MSF, sampling was conducted at the Long Pine Run Reservoir and the Michaux All-Terrain Vehicle (ATV) Trail. Natural gas extraction is active in TSF, but not in MSF. These locations represent the sampling frame for this study.

3.2. Development of natural gas compressor sound clips

Sound clips of natural gas compressors were constructed from a single natural gas compressor site in TSF (Compressor Station 289). Any sound clips that contained wind and/or rain events were removed from consideration due to the masking of other sounds in the recordings. From the remaining recordings, 15 sound clips were constructed and ranged from 40 dBA to 60 dBA. dBA was used to represent the range of human hearing. Following previous research [32], each sound clip was 30 s long with a 5 s fade in and a 5 s fade out.

3.3. Data instrument

A survey-based questionnaire was developed to collect quantitative responses from visitors. The instrument contained three main sections relative to this study: Recreation Experience Preferences (REPs), dose-response measures from the sound clips, and visitor characteristics. One question measured five statements to assess a limited selection of visitor motivations (Table 1). The question read, "We would like to know what motivated you to recreate today. Please indicate how important each of the experiences below was to you as a reason to recreate on this State Forest today." The five statements were: 1) appreciate the history or cultural significance of the site, 2) view the natural scenery, 3) experience a sense of calmness, peace, or tranquility, 4) experience a sense of adventure, and 5) enjoy the natural quiet or sounds of nature. Responses were recorded on a 5-point unidirectional scale where 1 = not at all important and 5 = extremely important to reduce skewness and increase variance [26].

Dose-response methods were used to collect evaluative responses of sound clips from visitors. Dose-response methods draw from laboratory-based studies and allow for a controlled exposure to a variety of fixed conditions that would otherwise be difficult to obtain in a field-based setting [25,32]. In dose-response studies, research participants are exposed to a precise "dose" of a condition (e.g. an exact amount of sound) that is controlled by the researcher. People are then asked to respond to the different conditions using an evaluative scale (e.g. people rate how acceptable to condition is). In this way, researchers obtain respondent evaluations over a range of conditions. Dose-response methods are particularly valuable for estimating thresholds in statistical models for sounds in visitor use management [32].

Table 1
Principal component analysis[1] and descriptive statistics from recreation experience preferences.

Component	Variables	Factor loading	Mean (*sd*)[2]
Calmness and quiet $\alpha = 0.95$			3.86 (*1.22*)
	Experience a sense of calmness, peace, or tranquility	0.933	3.91 (*1.23*)
	Enjoy the natural quiet or sounds of nature	0.944	3.80 (*1.27*)
Single item measures			–
	View the natural scenery	–	4.47 (0.68)
	Experience a sense of adventure or challenge	–	4.51 (0.83)
	Appreciate the history or cultural significance of the area	–	1.67 (*1.13*)

[1] KMO = 0.621; Bartlett's test of sphericity, $p < .001$.
[2] Measured on a scale where 1 = not at all important and 5 = extremely important.

For the dose-response portion of the study, the 15 sound clips were placed in 5 different blocks, with 3 sound clips in each block (Table 2). The pool of 15 sound clips provides a wide range of resource conditions, while the blocking ensures visitors did not get two sound clips that were too similar. Participants were assigned a random starting block, and the administration of the remaining blocks was presented in a random order to avoid bias [12]. The sound clips from each block were also randomly assigned. This approach ensured that visitors received 5 random sound clips in a random order from the overall pool of sound clips. Providing 5 sound clips from the overall pool reduces visitor burden while also providing a more diverse assortment of resource conditions. Respondents listened to the sound clips using noise-cancelling headphones (Bose Quietcomfort 15 headphones). All sound clips were calibrated with the headphones to ensure proper sound level before administering the dose-response component to respondents. Sound clips contained ambient natural sounds, such as birds and insects, with natural gas compressor sounds as the only discernable anthrophonic component.

Participants were told, "For the following questions, we would like you to listen to short recordings of sounds in Pennsylvania State Forests (PSFs). Please place the headphones on your head. As you listen to each recording, imagine how you would have felt if you heard the sounds in the recording during your visit to this State Forest. Please listen to each recording in its entirety. After each recording is finished playing, you can respond to the question below." After listening to each clip, a single question asked, "How acceptable or unacceptable would the sounds in this recording be if you heard them during this visit to this State Forest?" Responses were collected on a 7-point Likert-scale, where 1 = completely unacceptable and 7 = completely acceptable. Four was considered the neutral point on the scale.

The last portion of the survey collected several demographic questions, including recreational user group, visitation history, and residence description. User group was a categorical variable that asked visitors "Which of the following activities was the primary activity for you or your group today?" Visitation history was a dichotomous "no" or "yes" question that asked visitors, "Is this your first visit to this State Forest?" Residence description was a categorical variable that asked people, "How would you describe the area in which you live?" Responses were "urban", "suburban", or "rural."

3.4. Survey administration

Trained university researchers collected data using onsite intercept surveys from June 18th to August 31st of 2018 during daylight hours. Sampling times were distributed evenly throughout daylight hours and represented both weekends and weekdays. Groups were systematically intercepted using an *n*th technique (e.g. every second group). If a group of more than 1 person was intercepted, the person with the most recent birthday (not date of birth) was asked to participate to randomize the selection process. From the 430 groups contacted during the sampling period, 392 visitors agreed to participate in the research resulting in a response rate

Table 2
Descriptive statistics[1] for sound clips of natural gas compressor stations.

Block number	Sound clip	Mean	Std. dev.	Min.	Max.	Median	*n*
Block 1	dBA 40.00	6.95	0.22	6	7	7	138
	dBA 41.47	6.77	0.65	3	7	7	135
	dBA 42.35	6.91	0.29	6	7	7	116
Block 2	dBA 44.71	6.64	0.60	3	7	7	143
	dBA 46.1	6.12	0.92	1	7	6	136
	dBA 47.06	5.81	0.93	1	7	6	113
Block 3	dBA 48.24	5.87	0.84	3	7	6	142
	dBA 49.41	5.57	1.12	1	7	6	120
	dBA 50.59	5.63	1.21	1	7	6	130
Block 4	dBA 51.76	5.26	1.16	1	7	5	118
	dBA 52.94	5.30	1.21	1	7	5	142
	dBA 55.29	4.27	1.50	1	7	5	131
Block 5	dBA 56.47	4.44	1.45	1	7	5	133
	dBA 58.82	4.70	1.35	2	7	5	138
	dBA 60.00	3.60	1.70	1	7	3	119

[1] Responses were recorded on a 7-point scale where 1 = completely unacceptable and 7 = completely acceptable.

of 91.2%. A non-response bias check was conducted and there were no significant differences ($p < .05$) detected between respondents and non-respondents.

3.5. Data analysis

To analyze Recreation Experience Preferences (REPs), a principal component analysis (PCA) was used. PCA identifies underlying relationships among related variables and forms a set of "latent" components from a larger data set. Two assumptions must be met for PCA to be a valid technique: Bartlett's test of sphericity should be significant ($p < .05$) and the Kaiser-Meyer-Olkin (KMO) statistics should be >0.50. All component with Eigenvalues >1.0 were extracted, and a minimum loading of.40 was used to identify which motivation items belong to which REP component [44]. Identified components must also show sufficient reliability, with Cronbach's $\alpha > 0.65$ [46]. Lastly, items in each component must show "face" validity, meaning that they make intuitive sense together.

Mixed linear models were used to develop thresholds of sound conditions. In these models, the acceptability of sound clips is the dependent variable. The individual is considered a random effect, and therefore the models control for any unique variation associated with a single respondent. All other variables are considered fixed effects in the models. The Statistical Package for the Social Sciences (SPSS, Version 25) was used to develop the threshold models, and the ggplot2 package in R was used to graph the results [50].

Several different models were proposed in an iterative process to identify variables that contribute to acceptability of sounds and to evaluate model fit. Fixed effects were considered contributing if they have a p-value <.05. A model was considered improved if the Bayesian Information Criterion (BIC; an index of model fit) difference between two models was >2, with lower BIC indicating better fit [33]. Models were only accepted over previous models if fixed effects were significant predictors of acceptability and BIC was improved (e.g. difference >2, and BIC is lower). Once a final model was identified, the results were plotted for interpretation and regression equations were produced that allow for the prediction of visitor evaluations of sound conditions at any level.

4. Results

4.1. Sample characteristics

The majority (53.8%) of respondents lived in rural settings, with only 4.8% of the sample stating they lived in urban settings. About 88% of all respondents were repeat visitors to the state forest they were visiting. The top five most popular primary recreation activities were: 1) canoeing/kayaking (31%), 2) Hiking/walking (24%), 3) Bicycling/mountain biking (23%), 4) All-Terrain Vehicle (ATV)/Off-Highway Vehicle (OHV) use (11%), and 5) Hunting/fishing (3%). Overall, 52% of respondents were MSF users, and 48% were TSF users.

4.2. Recreation experience preferences

The assumptions of using Principal Component Analysis (PCA) were satisfied (Kaiser-Meyer-Olkin = 0.621; Bartlett's test of sphericity, $p < .001$). Overall, the PCA extracted two different components (Table 1). Two items (experience a sense of calmness, peace, or tranquility; enjoy the natural quiet or sounds of nature) loaded onto one component. This component was called *Calmness and quiet* (Table 1). The second component had two other items load on it (view the natural scenery; experience a sense of adventure or challenge), but failed to show sufficient reliability and face validity. Therefore, all other items except those identified in the Recreation Experience Preferences (REP) component (*Calmness and quiet*) were treated as single item measures of motivations.

4.3. Mixed linear models evaluating the impact of sounds from natural gas compressors on visitor experience

Descriptive statistics for responses to sound clips can be found in Table 2. From these data, we tested several different mixed-linear models to select a model that best predicted sound clip acceptability using maximum likelihood estimation (Table 3). These models started with the simplest relationships and became increasingly complex.

Model 1 (M_1) was the simplest. M_1 used a random effect of the individual (subject) and a fixed effect of decibel level (dBA) to predict visitor acceptability (Table 3). This model showed a statistically significant effect for decibel level. As decibel level increased, there was a negative response in acceptability. Model 2 (M_2), was the same as M_1, but added an additional fixed effect for the site where the data was collected (MSF or TSF). The Bayesian Information Criterion (BIC) was not improved. Based on these data, we do not accept M_2 over M_1. Model 3 (M_3) was the same as M_1, but added an additional fixed effect for user type. User type was defined as motorized or non-motorized users. Primary activity type was used to identify whether users were motorized or non-motorized users. There was a significant effect for user type as well as a significant interaction between user type and decibel level. Additionally, the BIC was improved by 331.25. Based on these data,

Table 3
Model selection for thresholds.

Model	Model equation[1]	BIC
M_1	Acceptability ~ Decibel level + [subject]	5239.77
M_2	Acceptability ~ Decibel level + sampling location + [subject]	5246.42
M_3	Acceptability ~ Decibel level + user group (motorized or non-motorized) + user group * decibel level + [subject]	4908.52
M_4	Acceptability ~ Decibel level + user group (motorized or non-motorized) + user group * decibel level + residence description + [subject]	4917.32
M_5	Acceptability ~ Decibel level + user group (motorized or non-motorized) + user group * decibel level + first time or repeat visitor + [subject]	4915.59
M_6	Acceptability ~ Decibel level + user group (motorized or non-motorized) + user group * decibel level + Calmness and quiet REP + [subject]	4910.83
M_7	Acceptability ~ Decibel level + user group (motorized or non-motorized) + user group * decibel level + Natural Scenery REP + [subject]	4905.07
M_8	Acceptability ~ Decibel level + user group (motorized or non-motorized) + user group * decibel level + Appreciate culture REP + [subject]	4912.25
M_9	Acceptability ~ Decibel level + user group (motorized or non-motorized) + user group * decibel level + Sense of adventure REP + [subject]	4898.99

[1] [bracketed] items are random effects.

we accept M_3 over M_1. Models 4 through 9 (M_4 to M_9) were the same as M_3, but each model added additional variables, including REPs (see Table 1). Overall, only M_9 showed the REP "Experience a sense of adventure or challenge" to be a significant predictor of acceptability and improved the BIC score by a difference of >2. Using the criteria of significant prediction and improved BIC, M_9 was selected as the best model for interpreting the data. M_9 explained 70.5% of the variance in acceptability ratings ($R^2 = 0.7045$) [36].

Table 4 shows the tests of fixed effects in M_9. The significant interaction term between decibel level and user group indicates that the slopes of the lines that predict acceptability from decibel level are significantly different between the two groups (Table 4). This means that motorized and non-motorized users have significantly different levels of acceptability for sounds from natural gas compressor stations when controlling for the REP "Experience a sense of adventure or challenge".

Table 6
Equations by user group for acceptability when controlling for the motivation "Experiencing a sense of adventure or challenge".

User group	Regression equation
Motorized users	Acceptability = 7.669 + (−0.0297) * Decibel level
Non-motorized users	Acceptability = 13.382 + (−0.1708) * Decibel level

The results in Table 5 are the estimated fixed effects for M_9. These fixed effects estimates are used to describe the differences between motorized and non-motorized users in regards to the acceptability of natural gas compressor sounds by computing two separate regression equations when controlling for the motivation "Experience a sense of adventure or challenge". Table 6 below displays the regression equations for each group. These data are further interpreted in Fig. 2 below.

In Fig. 2, the turquoise colors represent motorized users and the red colors represent non-motorized users. The transparency of the dots in the scatter plot in Fig. 2 indicates the density of data in those areas, with darker dots indicating more data. The dashed line is the neutral point in the acceptability scale, and any sound conditions below this line are interpreted as unacceptable to visitors. Regression lines (see Table 6) are graphed onto the scatter plot to display differences in acceptability between motorized and non-motorized users when controlling for the motivation "Experience a sense of adventure or challenge".

The results from the mixed linear models are further displayed in Fig. 2. As shown on Fig. 2, dBA has a fairly flat relationship with acceptability for motorized users. Using the regression equation in Table 6, the point at which sounds from natural gas compressors become unacceptable (acceptability = 3.99) is at 123.87 dBA. In Fig. 2, this threshold cannot be displayed as it is far beyond anything measured. In contrast with the results for motorized users, decibel level has negative relationship with acceptability for non-motorized users. Using the regression equation in Table 6, the point at which sounds from natural gas compressors become unacceptable (acceptability = 3.99) is at 54.99 dBA. This threshold is displayed on Fig. 2 by the red "X", which is the point where the red regression line for non-motorized users crosses over the dashed neutral line for acceptability. For non-motorized users, any natural gas compressor sounds louder than 54.99 dBA is considered unacceptable.

Table 4
Statistical testing of fixed effects.

Source	Numerator df	Denominator df	*F*	*p*-value
Intercept	1	1196.89	1183.97	<.001
Decibel level	1	1566.12	545.85	<.001
User group	1	1787.78	166.03	<.001
Decibel level * user types	1	1566.11	269.85	<.001
REP: Experience a sense of adventure or challenge	1	391.14	7.413	.007

Table 5
Estimates of fixed effects.

Fixed effect	Estimate	Std. error	*p*-value	Lower bound	Upper bound
Intercept	7.669	0.4710	<.001	6.745	8.593
Decibel level	−0.0297	0.0081	<.001	−0.0457	−0.0139
Non-motorized users	5.715	0.4435	<.001	4.845	6.585
Motorized users	–	–	–	–	–
Decibel level * Non-motorized users	−0.1411	0.0086	<.001	−0.1580	−0.1242
Decibel level * Motorized users	–	–	–	–	–
REP: Experience a sense of adventure of challenge	0.1243	0.0460	.007	0.0348	0.2158

Random effect: Individual (Residual = 0.4953, $p < .001$; Intercept variance = 0.4727; $p < .001$).

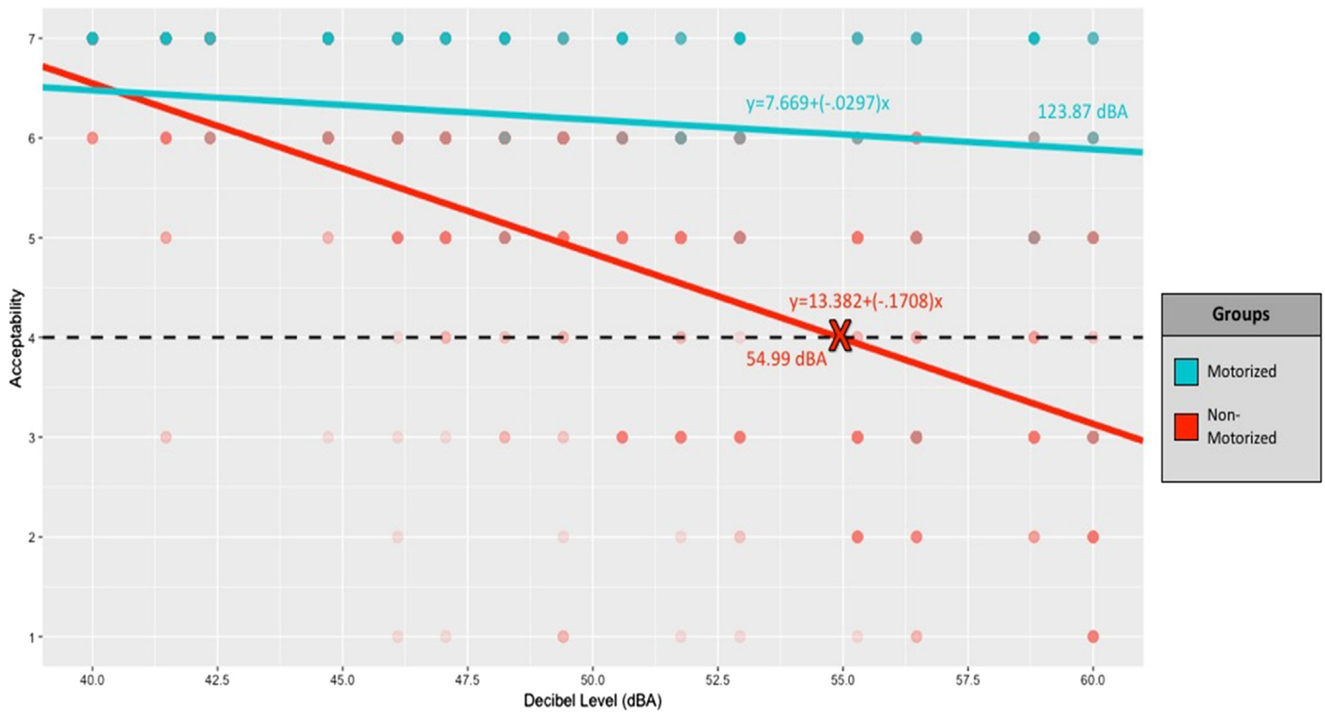

Fig. 2. Evaluative model of gas compressor sound thresholds. 1 = Completely unacceptable, 7 = Completely acceptable.

5. Discussion

The purpose of this study was to explore the potential impacts of sounds from natural gas compressors on diverse recreation users in Pennsylvania State Forests (PSF). We found that acceptability of sound was predicted by decibel level (dBA), user group (motorized or non-motorized), and the motivation "Experience a sense of adventure of challenge". Overall, the model explained about 70% of the variation in acceptability ratings. When controlling for the motivation "Experience a sense of adventure or challenge", motorized users found louder sound levels from natural gas compressors more acceptable than non-motorized users. These results have several important implications for the management of soundscapes and future research.

From the mixed linear model, two different regression equations were identified to understand visitor evaluations at any sound level. For motorized users, sound conditions from natural gas compressors crossed over the threshold point (Acceptability = 3.99) at an extremely high decibel level (dBA = 123.87). This is not a realistic level, as any sound above 120 dBA causes immediate harm [4]. Instead, it likely reflects that sound levels from natural gas compressors likely have no impact on the experience of motorized users. The reason for this tolerance of natural gas compressor sounds is likely due to the loud sounds that are unavoidably generated from their activity. In contrast, non-motorized user evaluations of sound conditions from natural gas compressors crossed over the threshold point (Acceptability = 3.99) at dBA = 54.99. For non-motorized users, sound conditions from natural gas compressors louder than 54.99 dBA are considered unacceptable. However, it must be noted that sound conditions quieter than 54.99 dBA are still having an impact on some non-motorized recreation users.

Managers can use this information to plan when managing multi-use sites, such as those providing both recreation and natural gas extraction. For instance, because sounds from natural gas compressors are unlikely to impact motorized recreation users, placing these natural gas compressors in close proximity to motorized recreation trails is likely an appropriate action when considering new motorized recreation trails or new natural gas compressor sites. Conversely, placing natural gas compressor stations in close proximity to non-motorized recreation users in PSF is likely to negatively impact the visitor experience of these users, and managers should use caution when planning either new non-motorized user access locations (e.g. trails, boating areas) or new natural gas compressor sites in these areas. Similar to previous studies [8], spatial models of sound propagation could be merged with threshold models to determine where either non-motorized user trails or natural gas compressor stations could be placed that would still maintain high quality visitor experiences.

The results from this research also provide a variety of insights related to future inquiries about visitor experiences and sounds. For instance, previous research found that motivations for experiencing sound were predictive of sound level acceptability [23]. However, in this current research, we show that motivations to experience natural sounds (e.g. *Calmness and quiet*) are not predictive of sound level acceptability. Instead, the motivation "Experience a sense of adventure or challenge" was predictive of sound level acceptability. Managers should be mindful that recreation users with higher adventure or challenge motivations may hold different perceptions about sounds. For instance, sounds that are generally considered to detract from the visitor experience, such as anthropogenic sounds (i.e. motor sounds, vehicle sounds, etc.) may actually add to the visitor experience for some recreation groups, like motorized users. Although the reason for this is currently unknown, it may be that these anthropogenic sounds help increase visitor perceptions of safety and awareness [42]. As an example, hearing the sounds of other ATV users may help them become more aware of where other riders are. Additionally, this research is some of the first to develop sound thresholds in Management-By-Objectives MBO approach for separate user groups. Most threshold studies consider populations of recreation users to be fairly homogenous, resulting in thresholds that reflect "the average camper that does not exist" [37]. Detailing and developing thresholds for diverse user groups in the same locations can help managers better identify the types of experience that align with the management goals of the area.

5.1. Limitations and future research

Several limitations should be noted from this research. The soundclips used were only from one natural gas compressor station. It is possible that other stations have different sound characteristics, like roughness, that may influence visitor perceptions of sounds. The effects of these sound characteristics on visitor acceptability rating of soundclips is unknown. Additionally, the sound clips were from a limited range (40 dBA–60 dBA). Although these conditions are fairly representative of conditions recreation users would experience in PSF, expanding this model at the very high and very low ends of conditions (e.g. <40 dBA or >60 dBA) may provide further understanding of visitor thresholds. Some survey variables could be improved upon in the future. For instance, residence description could be improved by using census as opposed to self-reported data, and REP scales could be greatly expanded on as well. Visitors were also provided sound clips in a fixed environment via the dose-response methods, not while they were actually participating in their activity. Further research that explores the *in situ* effects of sounds is warranted. Lastly, for practical reasons sampling was restricted to the summer months in two PSF. Expanding these sampling efforts to be more inclusive of other times of year and PSF may produce additional insights.

Additional research could expand upon and further apply these findings. For instance, recent developments are merging spatial modeling of sounds with social science concepts like thresholds [8]. Developing a similar model to this would allow managers to precisely place natural gas compressors in a modeled spatial context to examine where natural gas compressors would have an impact on the visitor experience. This could also include methods for sound attenuation, such as vegetation and concrete barriers. Additionally, some research shows that messaging can change visitor evaluations of sounds [41]. The role of messaging in the acceptability of sounds from natural gas compressors is unknown, but may present an additional management strategy to mitigate any impacts. Specifically for motorized users, future explorations about whether this group is innately tolerant of anthropogenic sounds, or if other sounds are masked by their own activities, is needed. Lastly, research on the social impacts of sounds from natural gas compressors should move beyond the concept of visitor experience. Recreation is closely linked with human health and well-being [9,30], and explorations of how natural gas compressors stations influence concepts like perceived restorativeness [31] and attention restoration [53] are also needed.

6. Conclusion

The study shows have sounds from natural gas compressor stations impact the visitor experience of recreation users in Pennsylvania State Forests (PSF). Using a mixed linear model, we discovered that non-motorized users found increasing sound levels from natural gas compressors much less acceptable than motorized users when controlling for "Experience a sense of adventure or excitement." The model shows at 54.99 dBA, natural gas compressor sounds become unacceptable to non-motorized users. Using the findings from this research, managers of PSF can make informed decisions about energy development in recreation areas.

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Declaration of Competing Interest

There is no conflict of interest known to the authors.

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Appendix A. Supplementary data

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