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How much noise is too much? Methods for identifying thresholds for soundscape quality and ecosystem services

L.A. Ferguson [a,*], P. Newman [b], M.F. McKenna [c,1], D.H. Betchkal [c,d], Z.D. Miller [b,2], R. Keller [e], K.M. Fristrup [c], B.D. Taff [b]

[a] Recreation Management and Policy Department, University of New Hampshire, Hewitt Hall, Durham, New Hampshire 03824, USA
[b] Recreation, Parks and Tourism Management Department, The Pennsylvania State University, 801 Ford Building, University Park, PA 16802, USA
[c] Natural Sounds and Night Skies Division, National Park Service, 1201 Oakridge Drive, Fort Collins, CO 8525, USA
[d] Natural Sounds and Night Skies Division, Denali National Park and Preserve, PO Box 9, Denali Park, AK 99755, USA
[e] Norwegian Institute for Nature Research, Human-Dimensions Dept, Vormstuguvegen 42, 2618 Lillehammer, Norway

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ABSTRACT

The United States National Park Service mandate is to conserve park resources and provide superlative visitor experience. In the context of acoustic resources, Denali National Park and Preserve provides an advantageous opportunity to understand the effect of aircraft noise on visitor experience because it possesses high levels of air tour traffic in a park renowned for its remote, wilderness character. Park visitors in four different settings were asked to rate the acceptability of recordings of aircraft noise, presented in randomized order relative to noise level. A cumulative link mixed model fitted visitor assessments to acoustic and nonacoustic factors. In addition to noise level, interest in an air tour was an important predictor of sound clip acceptability. For visitors uninterested in an air tour, the probability of rating aircraft noise as unacceptable at 54 dB LAeq,30 s or higher was 26%. For reference, this aligns with federal guidance that identified 55 dB as a threshold for interference with outdoor activities at rural residences and schools. Predictions of visitor response were joined to a spatial model of aircraft noise propagation to map visitor acceptability of aircraft noise in Denali's entrance area (frontcountry). This map can be used to assess the condition of park management zones, to inform hiking recommendations for visitors, and to predict the range of soundscape conditions experienced by park visitors.
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1. Introduction

The Organic Act [25] established a system of national parks whose purpose was to conserve park resources unimpaired for the enjoyment of future generations. For most park visitors, hearing natural sounds is an important motivation for their park visit [9,20,21]. They also provide numerous ecosystem services to park visitors: aesthetic pleasure, sensory cues that alert them to wildlife viewing opportunities and potential hazards, and health benefits arising from immersive experience and stress reduction [7,14]. Yet every means of moving people near and within parks generates noise [26], p. 56. In parks like Denali National Park and Preserve (DENA), noise is often the most pervasive and noticeable intrusion of human activities in remote and wilderness settings [6,16]. Transportation and park visitation are likely to increase, so quantitative predictions of the adverse effects of noise on park visitors are important for informing future decisions regarding noise reduction or mitigation options.

Aircraft broadcast noise across more area in Denali National Park than any other source [5,33]. Part of this aircraft traffic arises from commercial scenic air tours and transportation to sites in the park's interior. Over 100 national park units experience commercial air tour flights. Air tours offer opportunities for the public to experience portions of parks that might otherwise be inaccessible to them. Air tours also offer distinctive landscape perspectives. Yet air tours often concentrate noise in scenic portions of the park that are esteemed by visitors on the ground. Air tour noise is generally more noticeable than high altitude jet noise (commercial passengers and freight) because air tour aircraft are more visually

* Corresponding author at: Recreation Management and Policy Department, University of New Hampshire, Hewitt Hall, Durham, New Hampshire 03824, USA.
E-mail addresses: lauren.ferguson@unh.edu (L.A. Ferguson), pbn3@psu.edu (P. Newman).
[1] Current affiliation: NOAA National Centers for Environmental Information, Boulder, CO, USA.
[2] Current affiliation: National Park Service, Intermountain Regional Office.

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obvious and their noise level changes more rapidly. Also, the structure of propeller aircraft sound is more salient to human listeners due to prominent tonal components (versus the smoother, broadband spectrum of jets). Though all aircraft noise has effects in national parks, air tours are of special interest because there are specific procedures available to park managers to help reduce their impacts (49 USC 40128).

What is the effect of aircraft noise on outdoor recreation in the park? In residential communities there have been decades of research documenting relationships between aircraft noise exposure and public response (e. g. [11,13,31]). Community studies found that air traffic noise diminishes human cognition, induces stress, and impacts other measures of health [2,3,8,14]. In national parks, higher expectations for environmental quality are likely to yield greater sensitivity to aircraft noise. This has been confirmed by visitor evaluations of noise obtained after the completion of recreational activities in national parks [1,22,28]. These studies corroborated more rapid increases in annoyance than comparable community studies [11,12].

Field studies of noise effects over the course of a visitor activity are limited by the range of exposures that happen to occur during those observations. Accordingly, laboratory studies were pursued that simulated noise exposures by playing back recordings of noise. For example, an audio-visual simulation of a seaplane takeoff was used to elicit visitor assessments of the cumulative impact of multiple seaplane departures [15]. Even when simulated noise exposures were shorter than the actual noise events, the resulting dose–response curves were congruent with results from more intensive field methods [28]. The viability of noise playback studies empowered laboratory studies with university students that revealed other effects of noise exposure. For example, laboratory simulations of Grand Canyon National Park soundscapes found that helicopter noise degraded the perceived scenic quality of landscapes [18].

Recent extensions of laboratory research replicated the capacity of noise to degrade nonauditory experience and showed that noise sources differ substantially in their effect even when noise level is held the same [17]; [34]. Air tour aircraft noise had greater effects than high altitude jets [17], showing that observed differences in responses to different aircraft types in parks were evoked by short segments of sound played back in laboratory contexts. Noise playback studies within park and protected area sites have enabled researchers to study visitors' responses while exploring a wider range of soundscape conditions than they could sample during observational studies. This approach has been applied to visitor sounds [20,27], military aircraft noise [32], energy development noise, and quiet paving options for roads [24]. This small, yet growing body of research informed the methods used in our study.

Studies of noise effects in national parks have often been rendered in the context of normative theory to inform thresholds for quality [19]; norms are cultural rules that guide behavior. However, the concept that park visitors converge on a norm for noise exposure is at odds with one of the most striking results from community noise studies: individuals and communities differ greatly in their evaluations of noise [12,30]. Accordingly, it seems essential that representations of park noise effects emphasize this variability, offering park managers insights into the probabilities of their visitors that will experience different degrees of response for each level of noise exposure. Mapping noise effects at a landscape scale better reflects the implications in the extent of aircraft's noise footprint. Spatially explicit representations of noise effects on visitors show the interactions of time, space, and intensity, to help integrate with management plans that utilize zoning. Further, these maps may guide visitors to the conditions they would like to experience during their visit.

2. Materials and methods

2.1. Survey location

Visitors in the large entrance area of Denali National Park and Preserve (DENA), which encompasses campgrounds, visitor centers and trails (hereafter frontcountry), were intercepted at four different survey locations. This sampled different types of frontcountry visitors (day-use, overnight campers, etc.). These locations were: the Denali Visitor Center (DVC), Horseshoe Lake Trail (HS), Healy Overlook Trail (HO) trails, and the Murie Science and Learning Center (MSLC). DENA's frontcountry supports numerous activities: hiking, visiting the Denali Visitor Center, camping and picnicking, and attending educational programs. In contrast, DENA's backcountry provides visitors with primitive wilderness experiences and activities such as cross-country hiking and backcountry camping [26]. Facilities in DENA's frontcountry are proximal to noise sources that are integral to the function of the park, including an aircraft landing strip, roads, and a train depot, which are sources of potentially unwanted sounds heard by visitors.

2.2. Survey logistics

Surveys were administered from June 23rd to July 29th, 2017, at four different locations within Denali's frontcountry. Surveys were collected at the MSLC on days when inclement weather made sampling at the HO Trail difficult. During the sampling period, trained surveyors used a random number generator to choose a number between 0 and 30 to determine the minute when sampling effort would begin. Surveyors intercepted every 3rd group they encountered at the DVC, or the next group encountered after completing the previous survey at other locations that experienced lower traffic.

Groups were asked if they were willing to participate. If they declined, two questions were asked to enable analysis of participation bias. If they agreed, the person with a birthday closest to the survey date was selected to complete the survey. This randomizing procedure sought to minimize selection bias within the group. The surveyor then handed the visitor a laminated (re-usable) copy of the questionnaire and instructed the visitor to provide verbal responses that were recorded by the surveyor using a tablet computer.

Our goal was to assess visitors' perception of propeller aircraft sounds in DENA's frontcountry. After answering several demographic questions, visitors were provided noise canceling headphones (BOSE Quietcomfort 15 Headphones) and asked to listen to a series of "five short recordings of sounds that are typically heard in Denali's frontcountry". Five 30-second audio recordings selected at random from a larger pool were played. At the conclusion of each recording, visitors rated the audio clip on a 9-point acceptability scale [20,32]. Audio clips were played through the iPad tablet computer and amplified through the JDS Labs C5D Headphone Amplifier + DAC. After the five audio clips were played and rated, the survey administrator then replayed the clip (6th clip) that was rated as the most acceptable or most pleasing (if more than one audio clip had the highest rating for acceptability or interpretation, the first audio clip played was chosen). This was done manually by the researcher. Visitors listened to the most pleasing or most acceptable audio clip, which could have possibly been the quietest audio clip. After the 6th audio clip was played, they rated how acceptable it would be to hear that sound at varying minutes per hour and number of times per day. Visitors listened to the audio clip with the highest acceptability rating so that we can assess temporal thresholds based on lower noise levels. This method is consistent with Newman et al. (2014) and it provides an upper bound for acceptable levels of cumulative exposure.

2.3. Audio clip development

We developed a pool of 36 audio clips (.wav files) previously recorded by park staff at several sites in DENA's frontcountry. The recorded sound levels were measured with a Larson Davis 831 Sound Level meter, and clips were selected to span the range of noise levels observed at frontcountry locations frequented by visitors. The playback levels of these clips were adjusted to match the recorded levels by measuring the output of the BOSE Quiet Comfort 15 headphones using a G.R.A.S. Ear Simulator Type RA0039 and a Larson Davis 831. The calibrated settings were full volume on the iPad and 23 "steps" or volume toggles on the JDS Labs C5D Headphone Amplifier + DAC.

Each clip was thirty seconds in length, with aircraft noise present for approximately 25 seconds. The length of these clips expresses a balance between economizing on a visitor's time spent in our survey and presenting a realistic simulation of noise exposure [29]. Additionally, our study took place in the field setting and interrupted a visitor's planned activity, so longer audio clips could have caused visitor annoyance or survey fatigue. SPL was measured over the duration of the clip as a 30 s average sound level ($LA_{eq\ 30s}$) expressed in decibels weighted to reflect human hearing (A-weighting, [10]). The amplitude of each audio clip was adjusted to realize $LA_{eq\ 30s}$ values ranging from 50.6 to 78.3 dB (dB).

Because the order in which stimuli are presented to visitors can impact ratings, we chose to randomize the order in which visitors heard audio clips [35]. The first audio clip was chosen randomly from the pool of 36 different audio clips with varying SPL. Successive audio clips differed from the preceding clip by at least six decibels (higher or lower); each clip meeting this criterion had an equal chance of being chosen. During data analysis, we realized that these sequences of audio clips created an unintended trend. The second and fourth audio clips had lower sound levels, on average.

2.4. Survey questions

2.4.1. Assessing individual noise events

Visitor assessments of noise exposure were elicited as the acceptability of each sound clip [20]. Expressed differently, acceptability could mean tolerance of aircraft noise. After each audio clip was played visitors were asked: "How acceptable or unacceptable would the aircraft sounds in the recording have been if you had heard them during this visit to Denali while in the frontcountry?" Acceptability of each clip was indicated by selecting one of nine response options (-4 = extremely unacceptable, −3 = very unacceptable, −2 = moderately unacceptable, −1 = slightly unacceptable, 0 = nuetral, +1 = slightly acceptable, +2-moderately acceptable, +3 = very acceptable, +4 = extremely acceptable Response measures for audio clips were developed based on those previously used in other dose response studies [20,29,32,36].

2.4.2. Assessing cumulative noise exposures

To evaluate visitors' tolerance and threshold for the number of aircraft events heard during their visit to DENA, the most acceptable audio clip was re-played as the final (6th) audio clip, which measures the upper bounds for acceptable levels of cumulative exposure. Visitors rated the acceptability of hearing the aircraft in the final recording 3, 9, 15, and 30 min per hour. Subsequently, they were then asked: "How frequently would you prefer to hear small airplanes as you heard in recording #6 while in Denali's front country?" Visitors chose to either provide a number of airplanes they would prefer to hear in an hour or check a box, "I would prefer to never hear small airplanes". They were then asked to rate the acceptability of final recording in terms of times per day: 1, 10, 25, 50, and 100 times per day. The next questions asked, "How frequently could you hear small airplanes as you heard in recording #6 before you would no longer visit Denali's frontcountry?" Respondents could provide a number for the statement, "No more than ______ overflights in a day" or check a box for the statement, "I would visit Denali's front-country regardless of how frequently small airplanes or helicopters are heard".

2.4.3. Air tour flight interest

Trip motivations and interests are important mediators of visitor experience [23]. To better contextualize visitors' responses regarding aircraft we asked visitors, "Are you interested in taking a commercial flightseeing tour over Denali?" They had the choice to choose, "yes", "no", or "don't know/not sure". For those who answered "no", their response was coded as "0". For those who answered "yes", they were coded as "1". Visitors who marked "don't know/not sure" their data was coded as "3".

2.5. Statistical framework for predicting probability of visitor response

To understand the factors that affect visitor response to aircraft noise, we fit survey data using a cumulative link mixed model (CLMM), using the clmm2 function in the ordinal package (R Statistical Software, version 3.2.6). CLMMs are designed to fit discrete, ordered, dependent variables. Additionally, this approach allowed for integrated modeling of responses at all levels of the dependent variable in response to changes in the independent variables. We fit thirteen candidate models based on factors that might influence respondents' ratings of the audio clips. The fixed effects or variables included: noise level ($LA_{eq,\ 30s}$), clip sequence number, location of the intercept survey; and air tour flight interest. Variability in visitor sensitivities to noise were modeled as a random effect, with a Gaussian distribution. Maximum likelihood estimates of parameters were approximated using the adaptive Gauss-Hermite quadrature method with 10 quadrature nodes (Christensen, 2019).

A "best" model was selected using Akaike Information Criterion (AIC). If the (AIC) was reduced by >2 from a similar candidate model, it was considered different and better at predicting visitor acceptability of audio clips. The following CLMM (acceptability) was used:

$$\begin{aligned}\mathrm{logit}(P(Y_i \le j)) = {} & \theta_j - \beta_1(LA_{eq,\ 30s}) - \beta_2(\text{flight interest}) \\ & - \beta_3(\text{clip sequence}) - u(\text{visitor})\ i \\ = {} & 1..2405,\ j = -4 \text{ to } 4\end{aligned}$$

The model explained the cumulative probability that of the i th rating falling in or below the j th integer value, where i indexes all observations (n = 2405) and j indexes acceptability categories (−4 = very unacceptable to +4 = very acceptable). θ_j are known as threshold coefficients or cut points. Individual variability in responses was assessed by analyzing the influence of the random variable on model predictions.

2.6. Spatial predictions of visitor response

The results of the survey and predictive models of visitor response were combined with models of aircraft noise across the region to understand spatial variation in predicted visitor response (Fig. 1). To model noise from aircraft departing the airstrip, acoustical modelling software (NMSim version 1.0.0.5, Blue Ridge Research and Consulting 2014) was used. The model accounts for attenuation effects of terrain, ground cover, and atmospheric conditions. Model inputs include noise properties of the aircraft (a

Cessna 207) and a typical route through the airspace. Because takeoffs from the airstrip were bi-directional, the route we used represents takeoffs in both direction.

Results of the model were computed as a raster with spatial resolution of 150 × 150 m. Each pixel represents the average amount of takeoff noise over a 30-second period ($LA_{eq,\ 30s}$). To check the results of the acoustic model we relied on measurements made at NPS acoustic monitoring sites deployed within the study area. Some of these monitoring data were explicitly collected for this study; other data came from the park's legacy database [4]. To compile acoustic metrics for observed takeoff events, we used NPS Sound Pressure Level Annotation Tool (SPLAT) software. We then implemented a gradient descent algorithm in Python to minimize the root-mean-square error between observed $LA_{eq,\ 30s}$ values at sites and the modelled $LA_{eq,\ 30s}$ values for pixels containing those sites. The resulting model was used to transform raw NMSIM output into more accurate predictions of noise exposure:

$$LA_{eq,\ 30s\ FIELD\ OBS} = 1.27\,LA_{eq,\ 30s\ NMSIM} - 23.6$$

The final step in creating the spatial map of predicted visitor response was to use CLMM model equations to map predicted visitor responses onto the sound levels from the noise model. Assuming conditions of other variables in the predictive model (e.g. interest in air tour flight), the $LA_{eq,\ 30s}$ from the noise model can be used to predict visitor response at all cells. This premise can be represented spatially by taking every pixel $LA_{eq,\ 30s}$ value and transforming it using the Raster Calculator tool in ArcMap for input into the CLMM equation.

3. Results

A total of 566 visitors were contacted and 85% chose to participate. This yielded 481 completed surveys and 2405 audio clip assessments. We did not identify a response bias, participants were not statistically different from non-participants. The spatial distribution of completed surveys was Denali Visitor Center (DVC; N = 160), Horseshoe Lake Trail (HS; N = 185), Healy Overlook Trail (HO; N = 115) and Murie Science and Learning Center (MSLC; N = 24). The mean age for respondents was 48 years old. The majority (82%) of respondents were first-time visitors to the park. Regarding air tours, 36% were interested, 48% were disinterested, and 16% were unsure. Thirteen percent of respondents provided home zip codes for the Alaskan region. For ethnicity, 74% identified as white, 9% as Asian, 4% as Hispanic or Latino, 1% as American Indian or Native Alaskan, and 0.5% as black.

3.1. Predicting probability of sound clip acceptability

We aggregated the data and included survey location as a categorical variable in the candidate models given the different sample sizes at each location. In the top performing model, based on a comparison of AIC, location was not included (Table 1). We chose to focus our summary of acceptability based on the top performing model, even though the delta AIC was less than two when location was included in the model (Table 1). Further, while all coefficients for the locations in the second-best model were positive, they were not deemed significant using p-values.

Table 1
Hypothesized candidate models. Acceptability rating (−4 to 4) is modeled as an ordered factor in cumulative link mixed modeling framework (CLMM). Clip sound level (LAeq30s) is continuous variable ranging from 50 to 78 dB; clip sequence is a numerical variable (1–5); flight interest is a categorical variable (0 = no interest, 1 = interest, 3 = unsure); location is a categorical variable (site 1–3). All models include visitor as random effect.

Model structure	AIC	ΔAIC
LAeq30s + Clip Sequence + Flight interest	8219.4	–
LAeq30s + Clip Sequence + Flight interest + Location	8220.3	0.9
LAeq30s + Clip Sequence	8235.3	15.9
LAeq30s + Clip Sequence + Location	8235.5	16.1
LAeq30s + Flight interest	8261.2	41.9
LAeq30s + Flight interest + Location	8262.2	42.9
LAeq30s	8276.9	57.5
LAeq30s + Location	8277.1	57.8
Clip Sequence + Flight interest	9720.1	1500.7
Clip Sequence + Flight _interest + Location	9720.5	1501.1
Clip Sequence + Location	9733.9	1514.5
Clip Sequence	9734.3	1514.9
Flight interest	9754.1	1534.7
Flight interest + Location	9754.4	1535.1
Location	9768.1	1548.7

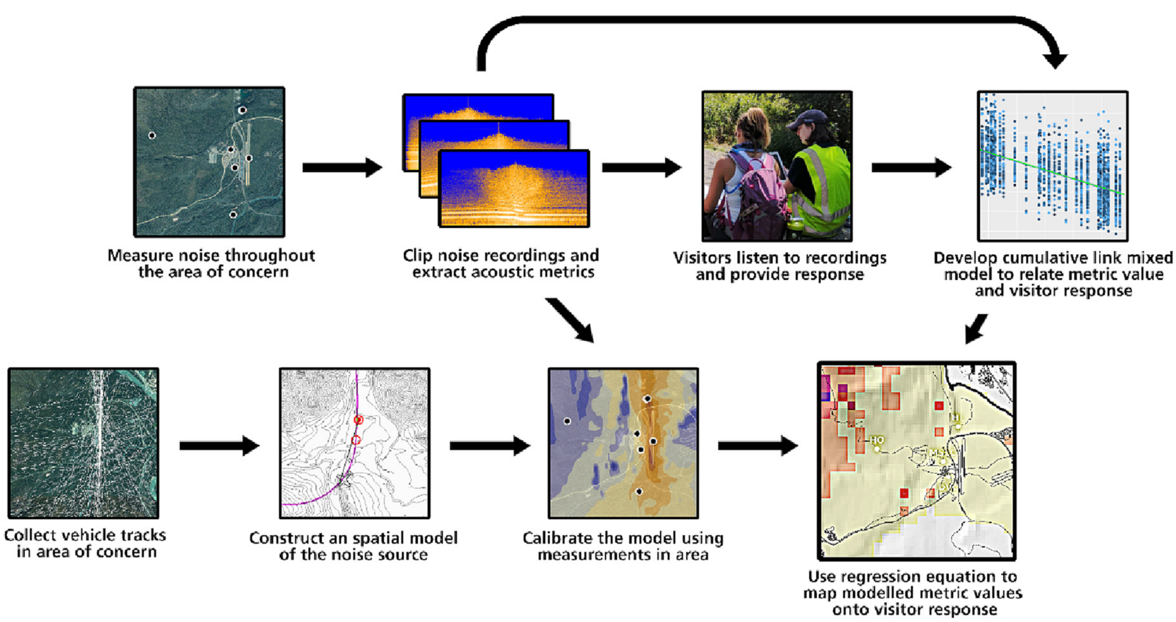

Fig. 1. Overview of method for developing spatial maps representing visitor response to aircraft noise.

Table 2
Summary of final model: Acceptability ~ LAeq30s + Clip sequence + Flight interest + (random = visitor).

Variables	Estimate	Std. Error	z value	Pr(>|z|)
LAeq30s	−0.17	0.01	−33.66	<2.22E-16
Clip sequence	−0.18	0.03	−6.60	4.07E-11
Flight interest (Yes)	1.06	0.24	4.47	7.71E-06
Flight interest (Unsure)	0.35	0.31	1.13	2.58E-01
Threshold coefficients	**Estimate**	**Std. Error**	**z value**	
−4|-3	−14.55	0.42	−34.60	
−3|-2	−12.89	0.40	−32.50	
−2|-1	−11.30	0.37	−30.47	
−1|0	−9.96	0.35	−28.36	
0|1	−8.92	0.34	−26.25	
1|2	−8.00	0.33	−24.08	
2|3	−6.30	0.32	−19.49	
3|4	−4.28	0.34	−12.69	
Random effect	**Variance**	**Std. dev**		
Visitor ID	4.79	2.19		

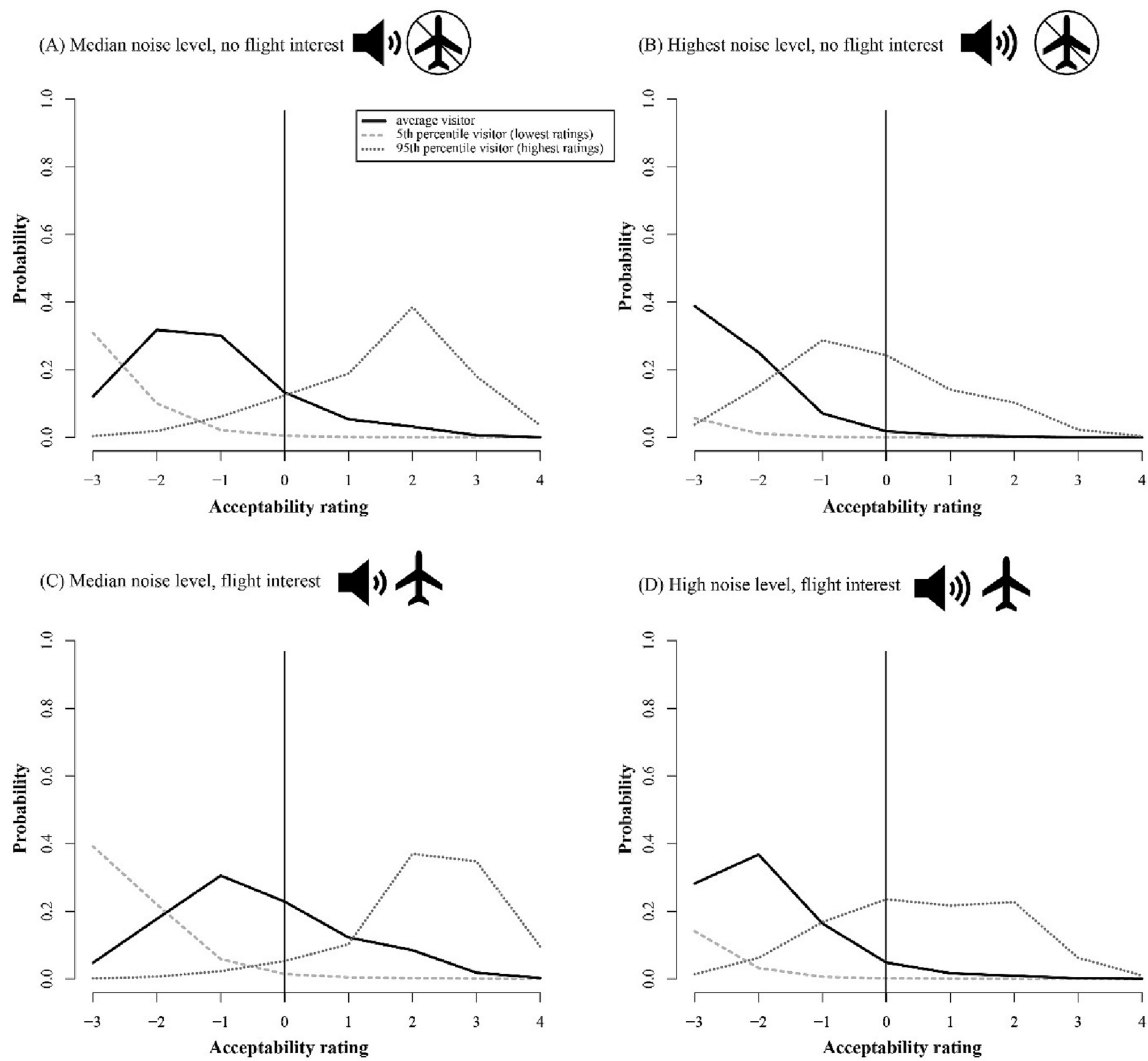

Fig. 2. Comparison of predicted acceptability rating probabilities under different conditions. Four experimental conditions are shown for the average (solid line), lowest response ratings, most sensitive (95th percentile visitor, dashed line), and highest response rating, least sensitive (95th percentile visitor, dotted line). (A) Median noise level (64 dB $LA_{eq,\ 30s}$) and visitor with no interest in taking an air tour flight; (B) 95th percentile noise level (78 dB $LA_{eq,\ 30s}$) and visitor with no interest in taking an air tour flight; (C) Median noise level (64 dB $LA_{eq,\ 30s}$) and visitor with interest in taking an air tour flight; and (D) 95th percentile noise level (78 dB $LA_{eq,\ 30s}$) and visitor with interest in taking an air tour flight.

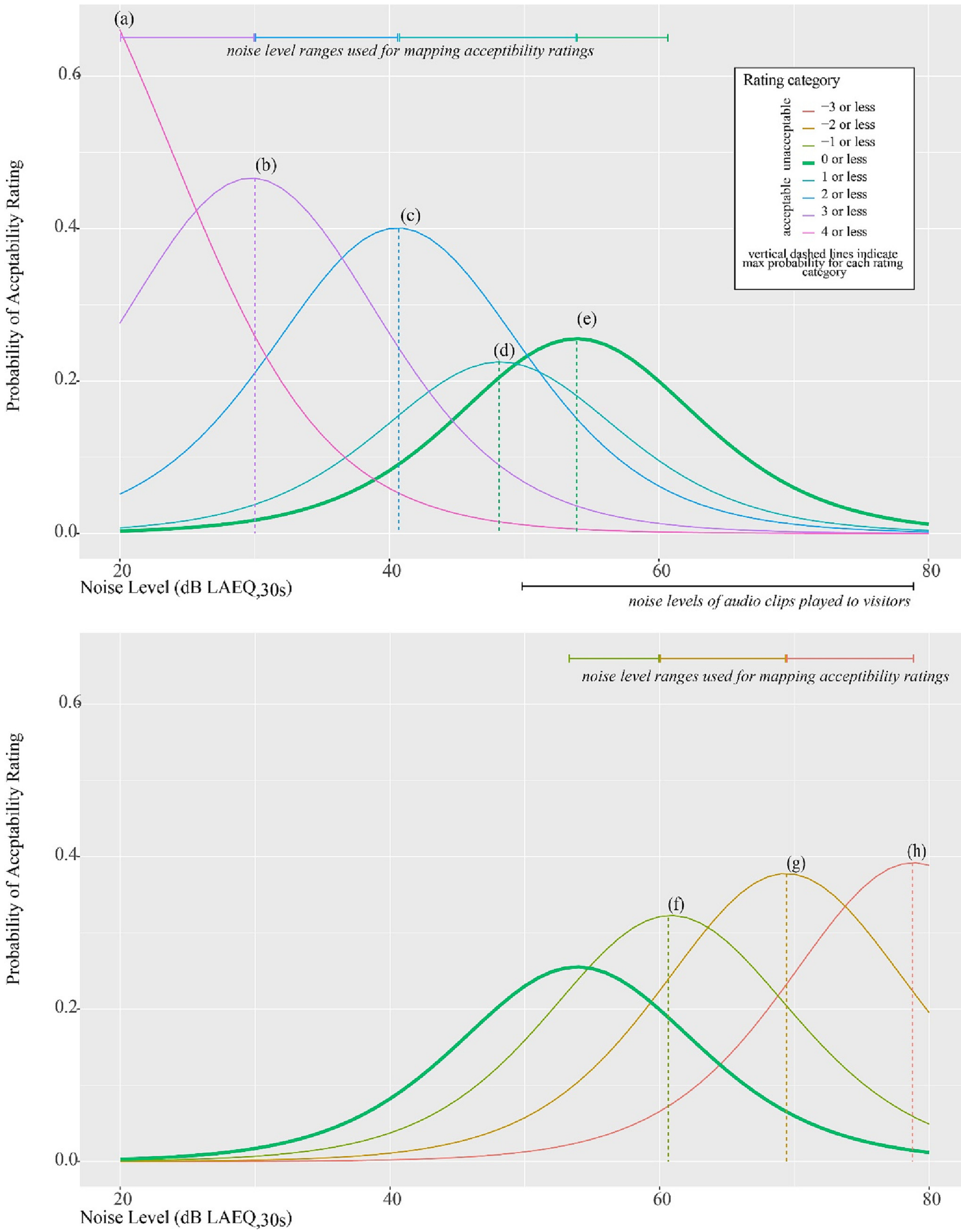

Fig. 3. Predicted probabilities for acceptability rating categories for range of noise levels. Model assumes average visitor with no interest in an air tour flight and predicted results are for noise levels between 20 and 80 dB LAeq,30 s. Noise levels of audio clips played to visitors ranged between 50.6 and 78.3 dB LAeq,30 s. Peaks of each curve represent the noise level with the highest probability for that rating category. (a) Acceptability rating of 4 or less (best rating) has maximum probability of 0.66 for noise level of <20 dB LAeq,30 s. (b) Acceptability rating of 3 or less has maximum probability of 0.47 at 30 dB LAeq,30 s. (c) Acceptability rating of 2 or less has maximum probability of 0.40 at 41 dB LAeq,30 s. (d) Acceptability rating of 1 or less has maximum probability of 0.22 at 48 dB LAeq,30 s. (e) Acceptability rating of 0 or less has maximum probability of 0.26 at 54 dB LAeq,30 s. (f) Acceptability rating of −1 or less has maximum probability of 0.32 at 61 dB LAeq,30 s.(g) Acceptability rating of −2 or less has maximum probability of 0.38 at 69 dB LAeq,30 s. (h) Acceptability rating of −3 or less (worst rating) has maximum probability of 0.39 at 79 dB LAeq,30 s.

The results for all locations combined, using the fitted CLMM (Table 2) showed that $LA_{eq,30s}$, clip sequence, and flight interest, were key explanatory variables in predicting visitor rating of acceptability (Table 2). For this model, the condition number of the Hessian, which measures the curvature in the log-likelihood function in the parameter space, was high (4E-5), which indicates the model structure is adequate, but optimization was difficult. The coefficient for noise level ($LA_{eq,30s}$) was negative, indicating that higher noise levels decrease acceptability ratings of the audio clips. The coefficient for clip sequence was also negative (-0.18), demonstrating that as the number of audio clips visitors heard increased, acceptability decreased. The coefficient for flight interest was positive, indicating that interest in an air tour or being unsure increased both increased acceptability ratings of the audio clip, with those interested in a flight had higher effect. The likelihood ratio test for the random effect in the best model was statistically significant, which indicated that visitors differed significantly in their perceptions of noise. The standard deviation for visitor as the random effect was 2.19. This means the median absolute difference between any two visitors is 2 ($\sqrt{2} \times 2.19/1.4826 = 2.09$), which is nearly twice the effect of affirmative interest in taking an air tour, and nominally equivalent to more than a 12 dB change in noise exposure.

To understand the variability in rating by visitor, we computed the probability of acceptability ratings for the average visitor and extreme visitors, those in the 5th or 95th percentiles (Fig. 3). These different visitors, average and extreme, are based on the random effect of the visitor in the best performing model (Table 2). We fitted and examined acceptability probabilities while holding four different conditions as constants: median noise level (64 $LA_{eq,30s}$) and no flight interest (Fig. 3A); 95th noise level (78 $LA_{eq,30s}$) and no flight interest (Fig. 2B); median noise level (64 $LA_{eq,30s}$) and yes flight interest (Fig. 2C); and 95th noise level (78 $LA_{eq,30s}$) and yes flight interest (Fig. 2D). Based on results for the average visitor, ratings of acceptability were lower for the 95th percentile (higher) noise level (black lines, Fig. 2). Ratings of acceptability decreased for visitors who were not interested in taking an air tour flight (Fig. 2A,B). For visitors in the 5th percentile (lowest ratings, most sensitive), we observed no change in acceptability ratings between the median and the higher sound level, both had unacceptable ratings (Fig. 2, dashed lines). The probability that the acceptability rating would be marked as -3 or less was lower for the visitor interested in a flight seeing tour. For visitors in the 95th percentile (highest ratings, least sensitive), acceptability ratings decreased with the higher sound level (Fig. 2, dotted line), however interest in air tour flight did not change the rating for median noise levels (Fig. 2A,C).

To help interpret these findings in a management context, we examined the predicted probabilities for all acceptability rating categories for noise levels between 20 and 80 dBA. For simplicity, we used the average visitor with no interest in taking an air tour flight (Fig. 2A,B, solid lines). These predicted probabilities are relevant for determining a potential noise level threshold or the point at which the noise level from aircraft shifts from acceptable to unacceptable. For the acceptability of 0 or less (unacceptable), the maximum probability is 0.26 at 54 dB $LA_{eq,30s}$ (Fig. 3(e)). Twenty six percent of visitors with no interest in taking an air tour will rate noise exposure of 54 dB $LA_{eq,30s}$ as neutral or worse acceptability (Fig. 3A, green line). This noise level closely aligns with U. S. Environmental Protection Agency guidance, which states that the noise level threshold for interference with outdoor activities a rural homes and schools is 55 dB (Table 4, [10]).

Noise levels for the maximum probability of rating for acceptable (>0) decreased with higher acceptability rating category (Fig. 3A). For unacceptable ratings (<0), the noise level for the maximum probability also shifted to lower values as rating category increased (Fig. 3B). In other words, the higher the acceptability rating the lower the predicted the noise level (Fig. 3).

3.2. Spatial predictions of visitor response

During takeoff events, most of the Denali frontcountry is predicted to have unacceptable levels of aircraft noise (Figs. 4 and 5). Only along the northwest corner of DENA's frontcountry, are visitors predicted to find takeoff events acceptable. Importantly, noise impacts to the visitor's center campus, campground, and the most popular hiking trails in the area are all predicted to provoke moderate-to-extremely unacceptable responses from visitors. For visitors with interest in an air tour flight (Fig. 5), most of the frontcountry area is predicted to be mostly unacceptable.

3.3. Threshold for number of aircraft noise events

Respondents were asked follow-up questions regarding their response to the 6th audio clip (the clip rate as the most acceptable). Seventy-six percent of respondents indicated that it would be OK to hear some aircraft noise as they heard in audio clip six (Table 3). Of those who indicated it would be OK to hear some air-

Table 3
Acceptability of hearing small aircraft sounds from recording #6 (flights per hour).

	Percent of respondents	Preference of flights per hour			
		Mean[1]	Minimum	Maximum	SD
OK to hear some	76	3.1	1	20	2.3
Prefer to never hear	24	–	–	–	–

Extreme Outliers were eliminated 2000, 100.
[1] Median = 3.

Table 4
Acceptability of hearing aircraft sounds from recording #6 (times per day) before respondent would no longer visit Denali.

	Percent of respondents	Flights per day			
		Mean[1]	Minimum	Maximum	SD
No more than...	55	40.2	1	200	41.7
I would visit regardless of how many aircraft heard	45	–	–	–	–

Extreme Outliers were eliminated (250, 300, 1000).
[1] Median = 25.

craft sounds, 18% indicated they would prefer to hear no more than one flight per hour, 27% indicated they would prefer to hear no more than 2 flights per hour, and 27% indicated they would prefer to hear no more than 3 propeller aircraft noise events per hour.

Over half of the sample (55%) specified a number of overflights they could hear before they would no longer visit DENA (Table 4). Of the 55% who specified a number of propeller aircraft, the median number was 25 overflights flights per day. Forty-five percent of respondents indicated that they would visit DENA frontcountry regardless of the number of overflights heard.

4. Discussion

This study provides a predictive framework to evaluate the effects of aircraft noise exposures in the frontcountry of Denali. Our results show that interest in an air tour was an important variable, so we assessed acceptability of aircraft noise for visitors with and without interest in air tours. This expands on Miller et al.'s (2020) approach to developing noise thresholds for separate visitor groups and not treating the population as one homogenous group. Based on the model of visitor responses we predict with 0.26 probability that visitors who are not interested in an air tour flight will rate aircraft noise as unacceptable at 54 dB $LA_{eq,\,30s}$ or higher. For context, 55 dB is associated with 95% sentence comprehension [10]. These findings indicate that most visitors find even low levels of aircraft noise to be unacceptable.

4.1. Informing thresholds for aircraft noise

The methods we used to analyze visitor responses to audio clips advance the identification of thresholds for acceptability of aircraft noise by including probability of response based on visitor differences. Specifically, we used CLMM to calculate probabilities of response to aircraft noise across a variation of visitors (i.e., visitor responses that are average or fall into the 5th or 95th percentiles extremes (Fig. 2)). Additionally, this multimodel analysis allowed us to better understand the variables that contribute to visitor evaluation of audio clips and soundscape quality.

We found that air tour flight interest had a large effect size, indicating that visitor preference for an air tour flight has an important impact on visitor rating of aircraft noise acceptability. On average, visitors who had no interest in an air tour flight had lower ratings of acceptability for aircraft noise at the same noise level. This finding is intuitive, perhaps visitors that intend on taking an air tour flight or have interest in the activity find aircraft noise to be more acceptable because they might be on a plane themselves, creating aircraft noise. This is similar to how motivation to hear natural sound [27] and for adventure [23] can predict soundscape response. While incorporating visitor differences creates more options for threshold setting, it allows managers to be explicit about motivations for thresholds and clear approaches to evaluate effectiveness of noise reduction efforts.

Results from CLMM showed that visitors' response to aircraft noise depends largely on the level of noise played in the audio clip. Specifically, our results also show that visitors were annoyed with propeller aircraft noise, even at low sound levels (30–40 dB $LA_{eq,\,30s}$). These findings are congruent with other studies that found park visitors report annoyance with aircraft at both low and high levels [18,37,29,12].

Another important result from the predictive modeling approach is the significance of the random effect, the visitor, on predicting acceptability of aircraft noise. The standard deviation of the random effect term for visitors was 2.19, which would equate to 3.1 for the standard deviation of the difference between any two visitors ($\sqrt{2} * 2.19 = 3.1$). This is sizeable variation, especially in comparison to the smaller effect size of sound level (0.17). Therefore, the average difference between two visitors would be nominally equivalent to a $\sqrt{2} * \frac{2.19}{0.17} = 18$ dB change in noise expo-

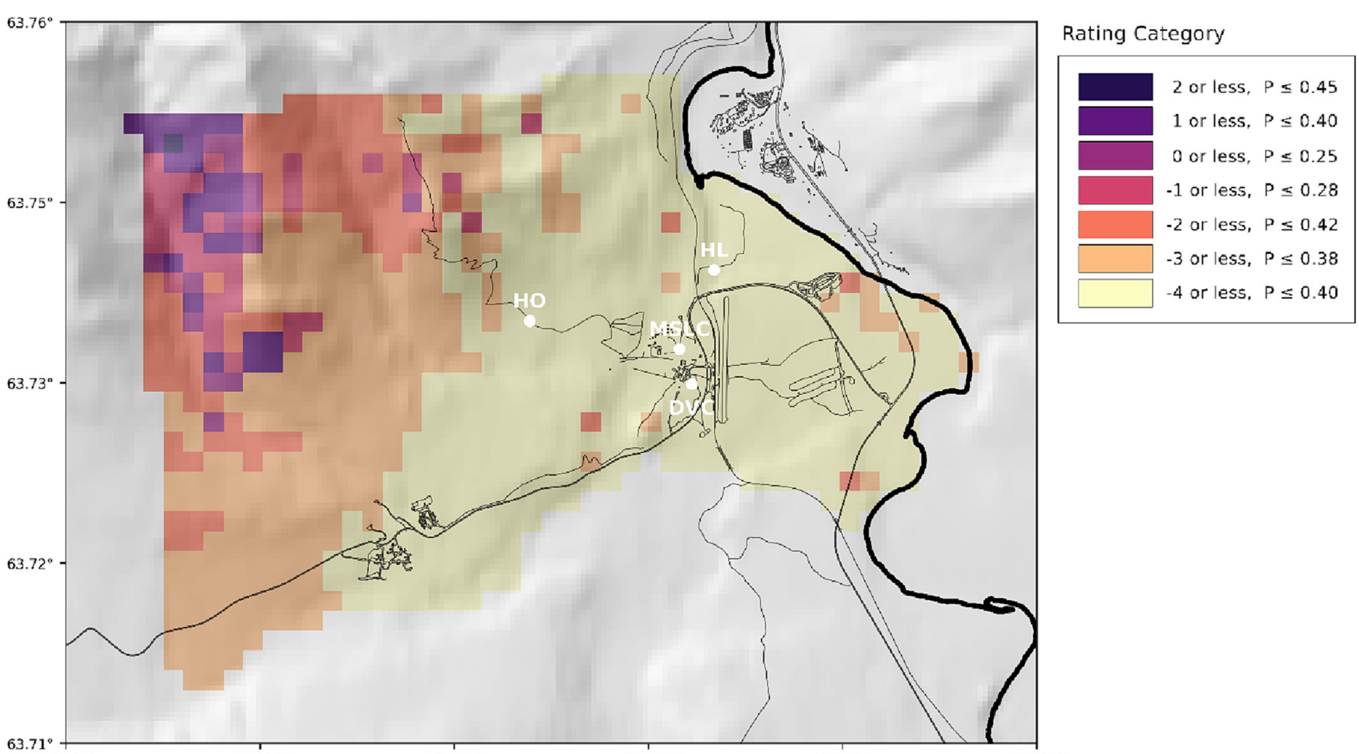

Fig. 4. Map predicting acceptability of aircraft noise for visitors with no air tour flight interest. Model assumes average visitor with no interest in an air tour flight (the Denali Visitor Center (DVC), Horseshoe Lake Trail (HS), Healy Overlook Trail (HO) trails, and the Murie Science and Learning Center (MSLC)).

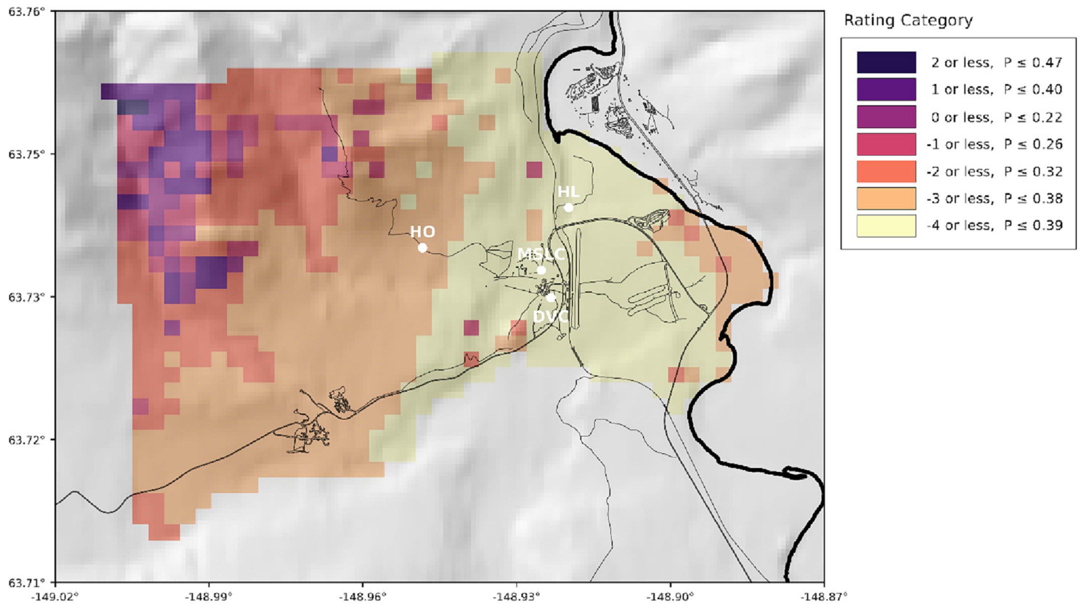

Fig. 5. Map predicting acceptability of aircraft noise for visitors with air tour flight interest. Model assumes average visitor with interest in an air tour flight (the Denali Visitor Center (DVC), Horseshoe Lake Trail (HS), Healy Overlook Trail (HO) trails, and the Murie Science and Learning Center (MSLC)).

sure. Physically, this means the two visitors would render the same ratings if the more sensitive visitor were more than eight times farther away from the source. This large variation among visitors is contrary to the assumptions of normative theory. It does not seem that visitors have shared beliefs about acceptable conditions and suggests visitors experience of noise is contingent on other individual-level (e.g. interests and motivations) and social (e.g. expectations) factors. Our results align with findings in airport noise studies, which found a substantial amount of variability between individual responses to identical noise exposures [12,30].

Our study also assessed thresholds for the number of aircraft noise events heard by visitors by hour and by day. After rating the first five audio clips, respondents listened to a 6th audio clip, which was the clip they rated the most acceptable, or the most pleasing. This was a conservative method to identifying temporal thresholds because respondents were rating audio clips that were typically quieter and less annoying. When asked to identify the number of flights it would be okay to hear per hour, 24% of the sample said they would prefer to never hear aircraft sounds. For the remaining sample, the average number of acceptable flights per hour was 3.1. This number closely matches the average number of propeller aircraft heard by visitors in the frontcountry (3 per hour).

Visitors were also asked, how many overflights they could hear, as they heard in audio clip #6, before they would no longer visit the park. Fifty-five percent of the sample indicated a specific number of flights they could hear before they would no longer visit the park. On average this number was 40.2 flights per day, but the median response was 25 flights per day. Forty-five percent of visitors indicated they would visit the park regardless of the number of overflights heard. There was a high amount of variation in response to this question. Previous research that uses norm theory suggests this is one of the issues associated with asking respondents to choose an arbitrary number [38,39]. It is difficult for respondents to identify a number of overflights they could hear before they would no longer visit the park. Future research should aim to better understand what might lead to displacement from noise, perhaps through qualitative approaches in order to develop nuanced or non-numerical measures that can be taken up in surveys. In general, these results can help frame the discussion for park managers regarding how much more aircraft noise could be allowed in the park before it negatively impacts the majority of visitor experiences.

Clip sequence, or the order in which audio clips were played was an important factor in predictive models for acceptability. Part of this effect may have been caused by the unintended patterning in our randomized presentation of noise levels: the second and fourth clips had lower than average sound levels. Yet it seems likely that some of this modeled effect expressed decreasing tolerance of the experimental noise upon repeated exposure.

4.2. Spatial predictions of visitor response

The purpose of the spatial prediction maps (Figs. 4 and 5) was to interpret the impact of current aircraft noise in the frontcountry area of the park. This mapping technique would not have been possible if we had determined acceptability using average ratings of audio clips or interpolation. The CLMM equation allows prediction of acceptability within a range of potential sound levels. Pairing results from the audio clip assessments with noise modeling layers assist park managers in identifying specific geographic regions where propeller aircraft noise more likely impacts visitor experiences. Our results show that the majority of the frontcountry, specifically areas near the DENA landing strip - where visitors participate in park activities like hiking - have noise levels that are predicted to be rated as very unacceptable. In the abstract, noise levels and decibel values can be difficult to relate to park management objectives. Mapping acceptability – or other visitor evaluations – provides a tool that can be immediately compared with park management zones and desired conditions for visitor experience.

4.3. Utility of results for park management

Two features of the cumulative link mixed effect model provide useful measures of variation in visitor responses. The random effect coefficient estimates the magnitude of variation in visitor sensitivity to noise. In this study the average difference between two visitors was equivalent to an eight-fold change in distance to the noise source. Secondly, the unequal intervals between the threshold coefficients – θ– show that some changes in acceptability responses reflected a greater change in conditions than others (Table 2). In this survey, the extreme acceptability responses were more distant from adjacent ratings than any of the interior assessments were from each other. This indicates transitions to or from these extreme assessments represent larger changes in visitor experience than one might infer from the regularity of the associated integer values.

We converted the descriptive social science results to the landscape interpretations by combining probability of response with spatial understanding of aircraft noise. Managers could predict, based on visitors' location on the map, their assessment of acceptability: or rather, the probability of how acceptable or unacceptable they would interpret the aircraft noise. This could eventually be taken a step further to provide managers with a higher level of detail and understanding of variability. If we can estimate the number of visitors who use a certain area or trail in the park, it would be possible to calculate the number of visitors that are negatively impacted by overflights at a specific sound level. Ultimately, park managers, visitors and other stakeholders can easily visualize the location and degree of impacts of noise on park experience, providing a more detailed view of visitor response and more explicit justifications for setting thresholds.

5. Conclusion

This study broadens the application of indicators of quality and thresholds that are used in managing park resources by applying statistical framework to predict probabilities of thresholds for soundscape quality and spatial integration to understand extent of impact. Specifically, we predicted that 26% of visitors with no interest in an air tour would rate aircraft noise as unacceptable at 54 dB $LA_{eq,\ 30s}$ and this encompasses a large area of the frontcountry. Together these results can inform how managers mitigate aircraft noise in protected areas. DENA management can use these tools and outcomes to determine areas where aircraft noise is a concern because it exceeds visitors' threshold for acceptability. More specifically, DENA manages an aircraft landing strip. Takeoff and landing events within the park could be scheduled to mitigate adverse effects on visitors.

While the results from this study are specific to aircraft noise in frontcountry use in DENA, methods can be adapted to other use areas where commercial aircraft tours operate. Additionally, these methods could be adapted to understand acceptability of other noise sources including, vehicles, shuttles, motorcycles, and generators. Further, a statistical framework that includes a probability along with a threshold may prove useful in to determine indicators for other factors that influence visitor experience (e.g. visitor density, light pollution). Our CLMM revealed that visitor responses to aircraft noise were diverse. One divergent factor was interest in taking an air tour. Accordingly, it seems unrealistic to conceptualize this population as sharing a unifying, normative level for acceptable noise exposure. It is possible that this is true for other dimensions of park visitor experience. Therefore, park leadership and future research should contemplate alternative justifications for formulating thresholds that inform park management.

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CRediT authorship contribution statement

L.A. Ferguson: Conceptualization, Methodology, Project administration, Writing – original draft, Writing – review & editing. **P.B. Newman:** Conceptualization, Methodology, Supervision, Writing – review & editing. **M.F. McKenna:** Data curation, Formal analysis, Writing – review & editing. **D. Betchkal:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – review & editing. **Z.D. Miller:** Conceptualization, Writing – review & editing. **R. Keller:** Conceptualization, Methodology, Writing – review & editing. **K.M. Fristrup:** Formal analysis, Writing – review & editing. **B.D. Taff:** Conceptualization, Methodology, Writing – review & editing.

Data availability

The saved code for the stats models can be found in the link below https://github.com/mfmckenna/LF_DENAvisitorAircraft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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