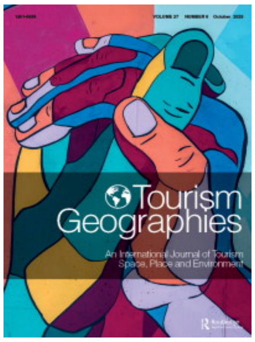

Tourism Geographies

An International Journal of Tourism Space, Place and Environment

ISSN: 1461-6688 (Print) 1470-1340 (Online) Journal homepage: www.tandfonline.com/journals/rtxg20

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TOURISM GEOGRAPHIES
https://doi.org/10.1080/14616688.2025.2591832

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Integrating aircraft tracking, acoustic data, and surveys to evaluate park aircraft noise

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ABSTRACT

Noise from low-flying aircraft has negative impacts on nature-based tourist experiences, wildlife, and communities in tourist destinations worldwide. Within the United States, some national parks, such as Denali National Park and Preserve (DENA), experience a high volume of low-flying overflights, including from tourism activities like flightseeing tours. We utilized flight tracking data to identify overflight patterns, acoustic monitoring to estimate noise exposure, and visitor surveys to measure visitor thresholds for noise from overflights. Low-flying propeller aircraft flight patterns were identified using Automatic Dependent Surveillance-Broadcast data. A mean of 21 flights per day occurred in DENA's frontcountry, the developed area of the park, during the study period (23 June 2023 to 29 July 2023), when visitation is at its peak. Visitor survey data were separated by interest in taking a flightseeing tour. For visitors interested in a flightseeing tour and those not interested, 25 flights or more per day were rated as unacceptable on a Likert scale for acceptability. The maximum sound level visitors may experience while in DENA's southern frontcountry area is 56 dBA_{1s}, which we predict will be rated as unacceptable based on previously published data from DENA. These results highlight the impact of low-flying propeller aircraft on visitor experiences. Finally, these methods can be applied in other tourism contexts where overflights are a concern for tourism managers and local communities.

ARTICLE HISTORY
Received 17 June 2025
Accepted 13 November 2025

HANDLING EDITOR
Rose Keller, Norwegian Institute for Nature Research

KEYWORDS
Soundscapes; thresholds; ADS-B; overflights; acoustic monitoring; parks; protected areas; visitors

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Introduction

Conserving natural soundscapes is essential to high-quality nature-based tourism, as the acoustic environment enhances positive visitor experiences while noise diminishes them (Dávid et al., 2024). Noise, defined as unwanted, human-made sounds, can disrupt tourism encounters in and with places, especially in destinations where visitors are likely seeking quiet or escape from the noise disturbances of daily life (Molz & Buda, 2022). Countries have enacted laws or policies to limit noise, including in areas such as national parks (Barborak et al., 2018). For example, the United States (U.S.) National Park Service (NPS) has specific laws, regulations, and policies that limit noise within national parks (49 USC 40128; 36 CFR § 2.12; NPS, 2006).

Aircraft overflights are one of the most prevalent sources of noise in parks within the U.S. (Buxton et al., 2019) and likely the world. Specifically, low-flying aircraft, like flightseeing tours, are a significant and multifaceted management challenge (Beeco & Joyce, 2019). These types of overflights have adverse effects on visitor experiences (Rapoza et al., 2015), wildlife (Kunc & Schmidt, 2019), and residents living near tourist destinations (Drage, 2021). The negative impacts of low-flying overflights (Taff et al., 2014) are not unique to the U.S.; tourist areas worldwide have noted concern. Air tours of tourist destinations range from Israel (Beeco & Joyce, 2019) to New Zealand (Watts et al., 2020). Effective management and measurement of low-flying aircraft traffic are crucial for ensuring positive tourism experiences and minimizing environmental disturbances.

Our paper examines how low-flying propeller aircraft affect visitors to Denali National Park and Preserve (DENA) by triangulating data from flight patterns using Automatic Dependent Surveillance-Broadcast (ADS-B) data, acoustic monitoring, and visitor survey data. We examine the impacts of low-flying propeller overflights on visitor experiences, which can inform decision-making regarding noise mitigation and soundscape management. Beyond the borders of national parks, our research broadly highlights the effects of low-flying aircraft, which may occur in cities, above popular flightseeing destinations, or tourism gateway communities.

Overflight noise impacts on nature-based tourism

Overflights in residential communities have been extensively studied, with evidence showing that consistent exposure to aircraft noise negatively affects both the mental and physical health of residents (Basner et al., 2014; Francis et al., 2017). Nature-based tourism researchers have been interested in how low-flying overflight noise influences visitor experiences (Miller, Taff, et al., 2018; Taff et al., 2015). Laboratory studies simulating park experiences have demonstrated that aircraft noise diminishes respondents' perceptions of scenic beauty, naturalness, and solitude (Benfield et al., 2010; Mace et al., 1999; Weinzimmer et al., 2014). Evidence from these community and lab-based studies emphasize the adverse effects of aircraft noise.

Research outside the U.S. further indicates that visitor sensitivity to noise in parks and protected areas is a consistent finding across cultures, as demonstrated in studies involving both Chinese and U.S. visitors (Miller, Huang, et al., 2018). In New Zealand, flightseeing tours to glaciers on the South Island negatively affected tourist experiences (Watts et al., 2020). A soundscape study from a Spanish national park found overflights were the second most common source of human-caused noise (Merchan et al., 2014). However, a full understanding of the distribution of noise over a landscape is generally lacking because until recently, it has been challenging to collect overflight travel pattern data, and their effects often span large geographic areas (Betchkal et al., 2023).

Over the past two decades, Denali National Park and Preserve (DENA) has been a focal point for soundscape research, monitoring, and management within protected areas. Moreover, aircraft noise is the most pervasive and noticeable intrusion of human activities in remote wilderness settings like DENA (Ferguson et al., 2023; Miller, Taff, et al., 2018). Commercial flightseeing tours and transportation to sites within the park contribute to high flight activity, specifically, 86% of aircraft overflights in DENA are fixed-wing aircraft, with the rest being commercial jets or helicopters (Peterson et al., 2025). This leads to a concentration of aircraft noise in portions of the park that are also occupied by visitors on the ground (Betchkal et al., 2023; Ferguson et al., 2023). Low-flying aircraft, specifically propeller noise, are generally more noticeable than other aircraft because their noise level changes more rapidly, and the structure of propeller aircraft sound is more salient to human listeners due to forward tonal components (Ferguson et al., 2023).

Spatiotemporal methods

Overflights can be tracked by collecting ADS-B data, which determines location using the satellite navigation system and then broadcasts its position to other aircraft (Peterson, Shively, et al., 2022). These data, which are unencrypted and publicly accessible, can be passively and automatically collected by a terrestrial logger with an expansive skyward exposure. Since 2020, the U.S. Federal Aviation Administration (FAA) requires all aircraft that enter designated airspace to be equipped with ADS-B technology (see 14 CFR § 91.225 and 14 CFR § 91.227; FAA, 2023). However, at DENA, ADS-B technology is only required when flying at or above 18,000 feet MSL (FAA, 2025). Regardless of airspace designation, prior studies suggest a rather ubiquitous adoption of ADS-B technology (Peterson, Shively, et al., 2022).

Few peer-reviewed studies have used ADS-B data to track overflights in Parks and Protected areas (PPAs). Early papers explored the feasibility and utility of ADS-B data to examine flight patterns over national parks (Beeco et al., 2020; Beeco & Joyce, 2019) with a later paper focusing more specifically on the analysis of altitudes (Peterson, Shively, et al., 2022). Peterson, Brownlee, et al. (2022) used ADS-B data to identify terrestrial visitor attraction sites affected by overflights. Betchkal et al. (2023) synthesized ADS-B and acoustic data to estimate the geographic scope of noise from low-level overflights and found that speech interference is possible when air tours are within a mile and that overflight noise is audible within five miles. Although these studies advanced the understanding of overflight travel patterns and associated noise effects, they did not triangulate ADS-B data, acoustic data, and visitor perception data to more fully explore overflight noise disturbances.

Thresholds for noise

Visitor thresholds for noise have been developed utilizing Normative Theory, which is guided by the premise that individuals share standards or rules that guide behavior (Manning, 2010). The normative approach guides the Interagency Visitor Use Management Framework (IVUMF), which is widely used by outdoor recreation managers throughout the U.S. to identify thresholds for impacts like noise or crowding (IVUMC, 2016). The IVUMF identifies indicators of quality experiences (e.g. soundscape) and thresholds for impacts that guide management decisions for maintaining desired conditions within parks. This approach has been used to identify thresholds for gas compressor noise in Pennsylvania State Forests (Miller et al., 2020) and visitor noise in Muir Woods (Marin et al., 2011; Stack et al., 2011).

Ferguson et al. (2023) used a cumulative link mixed model (CLMM) to examine sound level thresholds for propeller aircraft noise in DENA and predict areas where visitors would be negatively affected. Visitor interest in a flightseeing tour was a significant factor, so the model separated interested from non-interested groups. It predicted, with 0.26 probability, that non-interested visitors would rate aircraft noise at 54 decibels (dB) or louder as unacceptable. Combined with propagation maps, results suggested that most of DENA's frontcountry has aircraft noise levels likely to be rated as unacceptable. The paper also examined thresholds for daily overflights: 45% said they would visit regardless of the number of overflights heard, while 55% gave limits averaging 40.2 flights per day (median = 25). Responses varied widely, and prior literature suggests choosing an arbitrary number of flights is difficult (Manning, 2010; Roggenbuck et al., 1991). Accordingly, our study asked visitors to listen to an audio clip of propeller aircraft noise and rate the acceptability (on a Likert scale) of hearing that clip in terms of times per day (10, 5, 50).

Summary and research questions

Analyzing the effects of noise from low-flying aircraft within tourism destinations, such as PPAs, requires a nuanced approach that considers both the physical characteristics of the soundscape and sound pressure levels, as well as wildlife and human responses and tolerance thresholds. Previous research has examined overflight patterns, aircraft noise impacts, and human response to aircraft noise, but to our knowledge, no study has triangulated these data. We present an innovative method for combining data sources that best informs how noise from low-flying aircraft impacts tourist destinations. We use DENA's frontcountry as a case study due to frequent low-flying overflights, focusing on propeller aircraft as the most common and most disturbing to visitors.

RQ1: What are the spatial patterns of low-flying propeller overflights? How many low-flying propeller flights per day are visitors experiencing?

RQ2: What sound levels are visitors experiencing?

RQ3: How do current conditions align with visitor thresholds for low-flying propeller overflights?

Materials and methods

Study location

DENA is located in south-central Alaska and spans over six million acres of diverse terrain. Visitors travel to DENA to experience natural beauty, wildlife, and the sounds of nature (Miller, Taff, et al., 2018). DENA is a vast wilderness park with limited roads. In DENA, and more generally, Alaska, reliance on aircraft for both tourism and transportation is significant, regularly being used to access remote communities, recreation areas, and essential services. Consequently, DENA visitors are likely to experience aircraft noise. Past research in DENA identified the sounds of propeller aircraft as an indicator of soundscape quality that negatively affects visitor experiences (Fix & Hatcher, 2011; Miller, Taff, et al., 2018). Our research for this project focused on the DENA frontcountry, which includes popular visitor attractions such as hiking trails and visitor centers (Figure 1).

ADS-B data collection

ADS-B data were collected by two ADS-B data loggers positioned at Healy Radio Repeater (63.73855, −148.98126) and K'esugi Ken Ranger Station (62.59215, −150.23111). Automated data processing and cleaning were accomplished using a custom ArcGIS

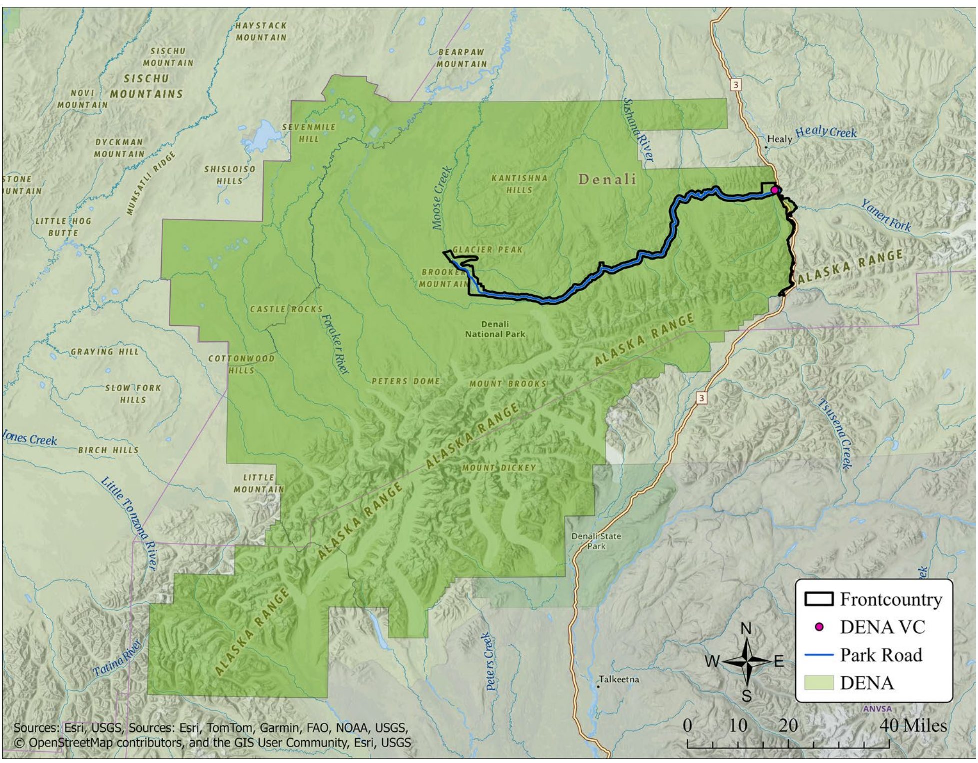

Figure 1. DENA overview map.

Pro toolbox (https://github.com/GISSAL/ads-b). The toolbox removed duplicate flight data collected by more than one logger and created a geodatabase of feature classes. Flight metadata, such as aircraft type, were retrieved from the FAA Releasable Database using aircraft tail numbers. Flights identified as government flights, major airlines, or survey flights were removed from analysis. Analysis focused on propeller overflights from 23 June 2023 to 29 July 2023 that flew below 2,500 feet above ground level (AGL) and within five miles of the DENA visitor center. These low-level overflights produce more intense noise disturbances than higher-level flights. While some prior studies have examined flights below 2,000 ft (Peterson, Shively, et al., 2022), more recent research suggests noise impacts of aircraft on visitors can occur at greater altitudes (Betchkal et al., 2023). Our study used a conservative criterion of 2,500 feet AGL.

The five-mile distance was estimated to be the detection distance of propeller aircraft by listeners (Betchkal et al., 2023). To estimate a contextually appropriate geographic detection distance between listeners and aircraft, we relied on predictions following the active space theory of spatial audibility (Hubbard & Maglieri, 1958; Marten & Marler, 1977). Quantitative polygonal predictions from three proximal acoustic monitoring sites (Mount Healy Overlook Trail, 63.73597, −148.94116; North Triple Lakes Trail, 63.72395, −148.91730; Triple Lakes Trail, 63.66258, −148.87505) were calculated using NPS-ActiveSpace software v2.0.0 (Betchkal et al., 2023). Conceptually, the vertices of each active space polygon predict detection distance from the listener to the aircraft at many irregularly spaced azimuths. We generalized azimuthal effects by resampling the vertices of each polygon such that they were spaced equally along the perimeter. The median detection distance at each site was between 4 and 5 miles (6.5–8.5 kilometers). We used the 5 mile (8.5 km) detection distance to select aircraft potentially audible to listeners in the DENA frontcountry. These methods define a three-dimensional volume surrounding the DENA frontcountry within which low-level propeller aircraft were selected.

Analysis of overflight spatial patterns was conducted using ArcGIS Pro v3.4.0. All propeller aircraft, including fixed-wing single-engine and fixed-wing multi-engine, within the detection volume were analyzed. Next, the number of flights per day between 23 June 2023 and 29 July 2023 were counted and used to determine the average and median number of daily flights.

Sound pressure level data collection

A Larson Davis 831 sound level meter and digital audio recorder were co-deployed to collect continuous acoustic data and meteorological data at Triple Lakes Trail (TRLA; 63.66256, −148.87488, 650 meters) from June to September 2023. Only data collected from June to July 2023 were analyzed. Additionally, hours in the sampling period with wind speeds exceeding 5 m/s or partial days of data due to equipment error were excluded from the dataset. The system continuously recorded A-weighted Sound Pressure Level (dBA) and 1/3 octave band data ranging from 12.5 to 20,000 Hz at 1-s intervals, as well as digital audio and wind speed and direction measurements throughout the ADS-B data collection period. Sound pressure level files were created using protocols described in Lynch et al. (2011) and provided the necessary data for subsequent calculations of acoustical metrics. Acoustic metrics are separated into daytime (07:00:00–18:59:59) and nighttime (19:00:00–06:59:59) periods.

The acoustic environment was characterized over the entire study period using broadband equivalent sound levels, $L_{Aeq,1s\ [12.5–20,000\,Hz]}$, as weighted for human hearing (dBA). From these, exceedance levels (L_x) were determined, representing the sound level exceeded x percent of the time. For example, L_{90} is the sound level that has been exceeded 90% of the time, with only 10% of the measurements quieter. Conversely, the L_{10} is the sound level that has been exceeded 10% of the time, and 90% of the measurements are quieter. The existing ambient sound level (L_{50}) is a key descriptor, representing the median sound level. Additionally, the maximum and ambient sound level (L_0 or L_{max}) was determined for the site.

Social science data

Face-to-face surveys with DENA visitors were conducted from 23rd June to 29th July 2017 (85% response rate, $n = 481$). For this project, visitor data from 2017 were compared to flight data from 2023. This study was approved by the Institutional Review Board of Penn State University (IRB# 00005067) and informed consent was obtained verbally from visitors before participation. Participants were handed a copy of the survey and provided verbal responses to a surveyor using a tablet computer. Missing data were limited, and no deletion methods were used. Surveys took place at four locations: the Denali Visitor Center, Horseshoe Lake Trail, Healy Overlook Trail, and the Murie Science and Learning Center. Ferguson et al. (2023) highlight visitor thresholds for flights per day when visitors were asked to name an arbitrary number ('how many flights per day could you hear before you would no longer visit DENA?'). There was high variation in response to the question, so for this paper, we wanted to examine visitor thresholds for flights per day based on an interval scale question.

Visitors who participated in the survey listened to and rated five audio clips of propeller aircraft overflights (Ferguson et al., 2023; Marin et al., 2011). Visitors then re-listened to the audio clip rated as the most acceptable or pleasing. This was usually the quietest audio clip. To assess temporal thresholds for lower noise levels, they rated how acceptable it would be to hear aircraft from that clip 10, 25, and 50 times per day on a nine-point acceptability scale (extremely unacceptable-extremely acceptable). This approach aligns with the methodology used by Miller, Taff, et al. (2018) and establishes an upper limit for thresholds.

We used the Potential for Conflict Index (PCI_2), a graphing strategy to help researchers and managers evaluate norm consensus, and to visualize a norm curve for the acceptability of noise events per day (Marin et al., 2011; Vaske et al., 2010). This approach allowed us to evaluate consensus and the strength of agreement regarding the number of events per day. Additionally, based on the results from Ferguson et al. (2023), visitors were analyzed separately into three categories: those interested in a flightseeing tour, those not interested, and those who were possibly interested. We used one-way ANOVAs to determine differences between the flightseeing motivation group's acceptability for events per day. For the PCI_2 graph, we only examined visitors who were interested in flightseeing and those who were uninterested because the sample size of visitors who were uncertain about a flightseeing tour was low ($n = 77$).

The PCI_2 values and differences between values were tested using SPSS (Statistical Package for the Social Sciences; IBM Corp, 2021) code and software available from https://sites.warnercnr.colostate.edu/jerryv/.

Results

Flight patterns

Spatial patterns of low-level propeller overflights that flew within 5 miles of the DENA visitor center show flight corridors above the frontcountry, which extend into the backcountry (Figure 2). Also, low-level propeller overflights traversed above frontcountry trails and most occurred to the south and west of the visitor center (Figure 3). The daily average number of low-level propeller overflights was 21.4, and the median was 19.0 during daylight hours when air tours are active.

To understand overflight activity for a single day with 20 flights, Figure 4 displays spatial patterns and timing of flights for 10th July 2023. The time of day for these flights spans the hours that air tours are active (Table 1). This means that visitors who are at the visitor center in the morning could hear 8 flights instead of the total 20. However, by evidence of the loop *via* the Denali Private (AK06) airstrip southeast of the park, a visitor could hear a single flight on two or more different occasions.

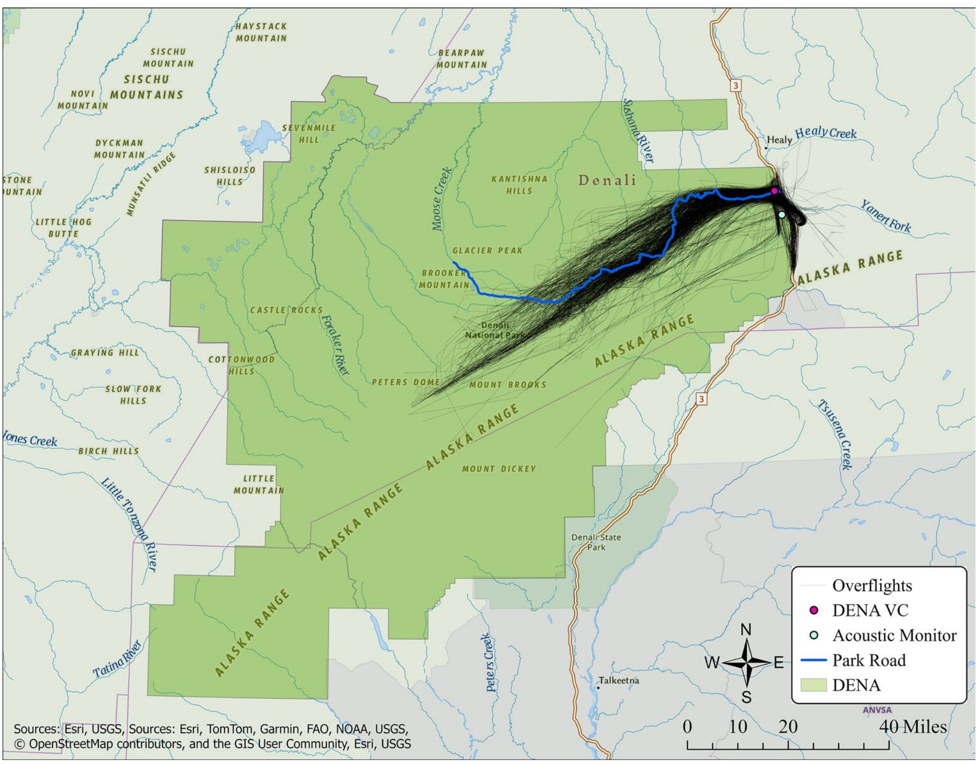

Figure 2. Spatial patterns of low-level propeller overflights that flew within 5 miles of the DENA visitor center.

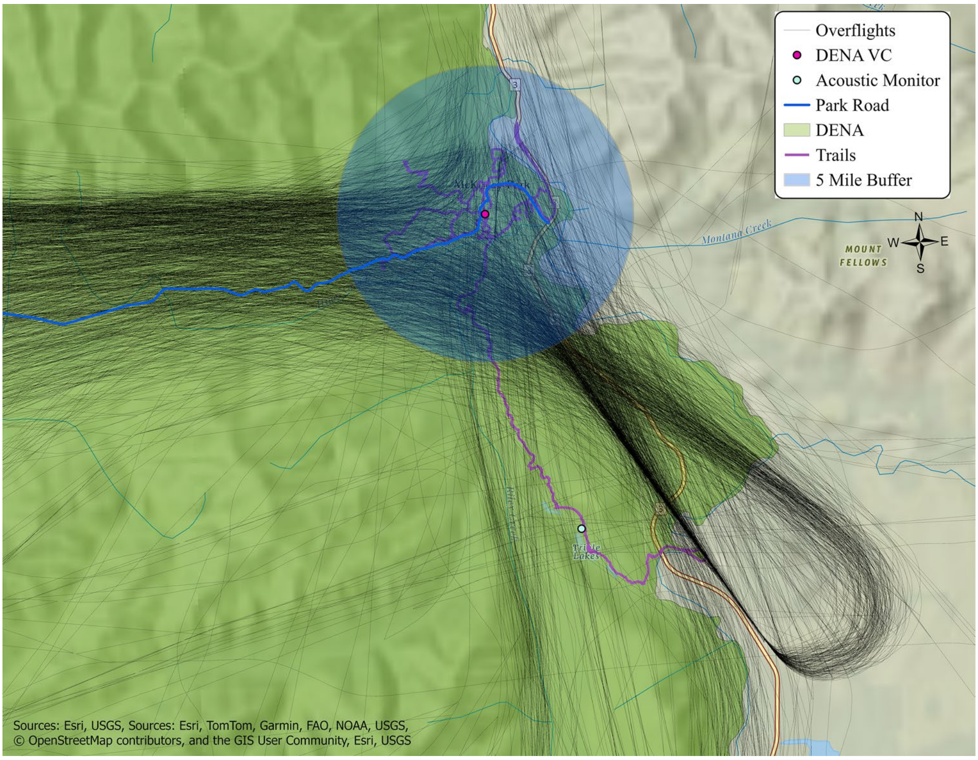

Figure 3. Spatial patterns above the DENA visitor center of low-level propeller overflights.

Sound levels

The acoustic environment at TRLA was characterized from June through July 2023 using metrics that captured spectral measurements, durations, and overall sound levels over 600 h of observation. The mean hourly L_{max} observed in the 07:00–19:00 h—coinciding with peak visitation and aircraft events—was 56.0 dBA (Table 2). The median sound pressure level (L_{50}) during daytime hours at TRLA was 30.1 dBA.

The percentage of time that sound levels were above critical functional thresholds was calculated (Table 3). Here, thresholds refer to sound levels associated with potential impacts on visitor experience and communication. Results reveal significant differences in sound level between day and night across all thresholds. During the day, sound level exceeded 35 dB ($L_{Aeq,1s}$) for 25.62% of the time, and at night only 5.27% of the time. Sound levels exceeded 52 dB ($L_{Aeq,1s}$) 0.57% and 60 dB ($L_{Aeq,1s}$) 0.12% of the day. These thresholds are particularly relevant, as 60 dBA is known to disrupt general conversation, whereas 52 dBA can interfere with interpretive programs and safety for travelers in bear country.

Current conditions and visitor thresholds

Research question three examined visitor thresholds for overflights and how they align with conditions within DENA. Visitors were asked to rate how acceptable it would be to hear propeller aircraft (like what they heard in the final audio clip) 10,

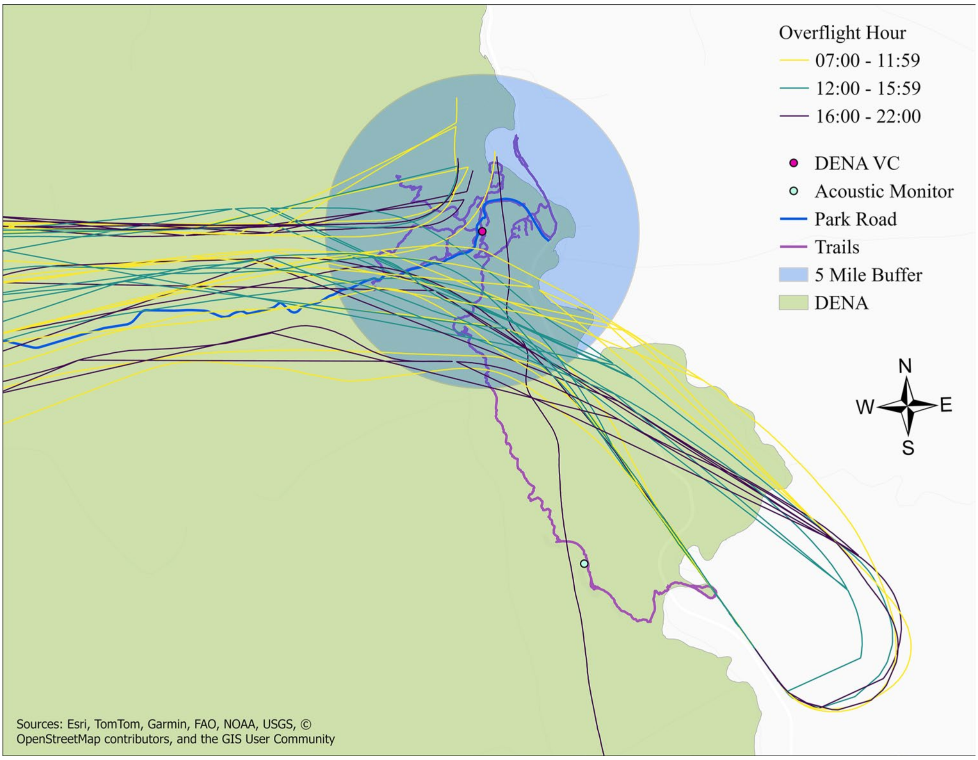

Figure 4. Low-level overflights on 10th July 2023, by hour of the day ($n = 20$).

Table 1. Number of flights across a single day (10th July 2023; $n = 20$).

Hour	Number of overflights
07:00–11:59	8
12:00–15:59	6
16:00–22:00	6

Table 2. Sound levels (dBA) at Triple Lakes Trail ($n = 600$).

	L_{min}	L_{99}	L_{90}	L_{50}	L_{10}	L_{001}	L_{max}	L_{eq}
Day	21.7	22.9	25.0	30.1	35.6	47.4	56.0	40.0
Night	17.9	18.9	20.5	24.4	31.4	37.1	43.7	34.7

Table 3. Percent time above dB ($L_{Aeq,1s}$) ($n = 600$).

	35 dBA	45 dBA	52 dBA	60 dBA
Day	25.62	2.12	0.57	0.12
Night	5.27	0.42	0.11	0.01

25, and 50 times per day (Table 4). Most visitors rated hearing propeller aircraft 10 times per day as acceptable (mean = 1.7 on a scale from −4 = extremely unacceptable to 4 = extremely acceptable). At 25 times per day or more, most visitors indicated an unacceptable level of propeller aircraft overflights.

Results from the one-way ANOVAs (Table 5) indicate mean ratings for events per day vary significantly between visitors based on interest in taking a flightseeing tour.

Table 4. Overall acceptability of hearing propeller aircraft (events per day).

Events per day	Frequency (%) Unacceptable					Acceptable						
	−4	−3	−2	−1	0	1	2	3	4	*M*	Median	*SD*
10	0	2	6	8	10	14	20	22	18	1.7	2	1.9
25	16	8	16	19	6	13	10	9	3	−0.7	−1	2.3
50	40	19	11	11	4	5	5	3	2	−2.2	−3	2.2

Table 5. Comparison of acceptability ratings based on visitors' flight interest.

Events per day	Interest in a flightseeing tour: Interested ($n = 177$)	Not interested ($n = 233$)	Maybe interested ($n = 76$)	*F*-value	*p*-Value	Eta (η)
10	1.40[a]	0.50[b]	0.82	8.812	<.001	0.19
25	−0.31[a]	−1.03[b]	−0.64	5.58	.004	0.15
50	−1.90[a]	−2.41[b]	−2.10	3.92	.020	0.13

Notes. Means in a row sharing superscript are significant at the $p < 0.05$ level, using the Tukey Honestly Significant Difference post hoc test. Response code: −4 = extremely unacceptable through 4 = extremely acceptable.

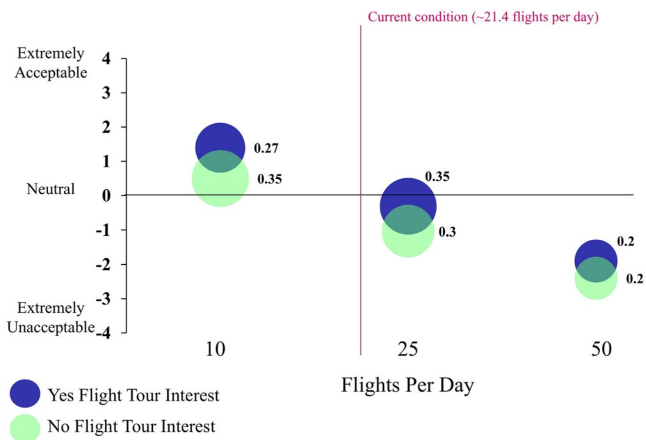

Figure 5. Visitor acceptability of noise events per day (10, 25, and 50) by interest in a flightseeing tour.

Visitors who indicated that they were maybe interested in a flightseeing tour did not have mean scores for acceptability that differed significantly from the visitors who did and did not have an interest in a flightseeing tour. However, the effect sizes were low ($\eta = 0.19$ for 10 events per day; $\eta = 0.15$ for 25 events per day; $\eta = 0.13$ for 50 events per day), suggesting a meaningful but modest difference in acceptability based on flight interest. The minimally acceptable condition on the norm curve (Figure 5) was ≤25 events per day for both visitors interested in a flightseeing tour and uninterested. Overall, those who were not interested in a flightseeing tour rated the same number of events per day as less acceptable.

The calculated PCI_2 values for each group indicate agreement among visitors for ratings of flights per day, as all the values were at or below 0.35 on a scale ranging from 0.0 (indicating consensus) to 1.0, indicating total polarization and a high potential for conflict (Vaske, 2010). Ratings for 50 noise events per day had the greatest agreement (PCI_2 values for both groups were 0.2). There were no statistical differences between PCI_2 values for visitors who were interested in a flightseeing tour and those who were not interested (Vaske et al., 2010; PCI_2 difference test: $d \geq 2.24$, $p < 0.05$).

Discussion

Aircraft noise, especially from low-flying, propeller aircraft, can negatively influence visitor experiences at tourist destinations, especially PPAs. This study examined the effects of aircraft overflights on visitors to DENA, utilizing the geographic distribution of aircraft travel patterns, related acoustic characteristics, and how these align with visitor thresholds for such overflights. We utilized ADS-B and acoustic monitoring data collected in the summer of 2023 and visitor survey data from the summer of 2017 to investigate current conditions related to overflights and how they align with visitor thresholds for flight events per day. The methods and results in this paper provide tourism managers with information about how to evaluate the impact of overflights on the soundscape, along with visitors' perceptions of overflight noise and at what point the number of overflights becomes unacceptable.

Overflight conditions and thresholds

The first research question explored spatial patterns of low-flying propeller aircraft and the number of flights experienced by visitors. Flight patterns (Figures 2 and 3) indicate low-level propeller overflight corridors from Healy and the Denali Private airstrip (AK06) converge over the frontcountry. The latter airstrip produces a notable approach/departure flight pattern to the southeast of the Visitor Center. Altogether, overflight traffic is occurring at high enough rates over hiking trails to influence the hiking experience (Mace et al., 2013; Newman et al., 2018). The daily average number of low-level propeller overflights that flew within 5 miles of the DENA visitor center was 21.4 flights, and the median number of flights per day was 19.0. Time is also an important component of understanding the number of overflights a visitor might experience. Figure 4 displays the times of flights across a single day (10th July 2023) with 20 flights. The timing of these flights is spread across the hours in which air tours are active (7:00–22:00). Therefore, it's unlikely that all visitors would experience all 20 of those overflights, yet visitors also could have heard a single flight multiple times. Further, visitors are mobile too. Visitors could spend time indoors, in a vehicle, or travel to other areas of the park. Conversely, there is a campground within this area, thus visitors who camp, hike, and stay in this area may experience all the flights.

Our analysis only accounted for low-flying propeller aircraft traffic. Visitors are also likely to experience helicopters, commercial airliners, and other higher-flying propeller aircraft traffic. These results help to justify the need for monitoring overflight traffic within popular tourist destinations. Finally, these results also add to the small but growing number of studies that apply ADS-B data for visualizing overflight travel patterns within popular tourist destinations to estimate the impacts of overflights on visitor experiences (Betchkal et al., 2023; Peterson, Brownlee, et al., 2022).

The second research question examined the sound levels visitors experience while in DENA. The 2023 acoustic record from TRLA had a mean hourly L_{max} of 56 dB. For context, 52 dBA can interfere with interpretative park programming and 60 dBA can disrupt conversations (US EPA, 1978). Daily sound levels exceeded 45 dBA ($L_{\text{Aeq, 1s}}$) 2.12% of the time. Therefore, visitors experience higher sound level events that can interfere with interpretive programming during their visit, but the interference is not temporally extensive. It is important to note that acoustic data were collected in an area 4.9 miles south of the DENA Visitor Center. The sound levels presented here are a rough estimate of what visitors may experience in the area surrounding the Visitor Center. Additionally, the acoustic monitoring device was in an area that experienced a smaller number of overflights (Figure 3) when compared to other areas. Visitors hiking trails near the Denali Visitor Center are likely to experience more noise events over 45 dBA ($L_{\text{Aeq, 1s}}$) than what is represented in these data. Finally, visitors are generally annoyed by aircraft at both low and high sound levels (Benfield et al., 2010; Ferguson et al., 2023; Rapoza et al., 2015).

Both the ADS-B and acoustic data were collected in the summer of 2023; however, we utilized data from a 2017 summer survey that asked visitors about their thresholds for flights per day. Visitors rated 10 propeller aircraft overflights per day as acceptable, and there was agreement and consensus amongst visitors (PCI_2 values were <0.40). Acceptability of 25 or more propeller aircraft overflights per day fell below the minimally acceptable threshold for most visitors, both those interested in a flightseeing tour and those who were not interested. Mean scores for acceptability were significantly lower for visitors who did not have an interest in a flightseeing tour, suggesting that they have a lower tolerance for the number of propeller overflights per day. Yet, PCI_2 values indicate consensus amongst visitors regarding the lack of acceptability of 25 or more flights per day. This suggests that there is a low level of conflict between visitors in how they perceive the acceptability of flights per day.

During the ADS-B study period, the frontcountry experienced a mean of 21.4 flights per day. The current condition does not exceed visitor thresholds for overflight noise; however, a slight increase in flights could exceed visitor preferences. Moreover, the mean L_{max} during the 07:00–19:00 h was 56.0 dB ($L_{\text{Aeq,1s}}$). Given the norm curve established by Ferguson et al. (2023), we predict that visitors would rate overflight noise at that sound level to be unacceptable. Comparing current conditions with visitor thresholds is valuable because it can help inform decisions regarding increasing or decreasing the number of flights the park permits.

Theoretical implications

We used the norm curve (Manning, 2010) and PCI_2 (Vaske et al., 2010) to visualize thresholds and norm crystallization for low-flying propeller overflights in terms of events per day. We found standard deviations for the mean scores for flights per day to be high (Table 4). On a nine-point Likert scale, a standard deviation of 2 shows high variation in how visitors rate events per day. Ferguson et al. (2023) also found a high variation in how visitors responded to propeller overflight noise, which suggests norms for aircraft noise at DENA are not fully crystallized about acceptable conditions. However, we found values for PCI_2 to be low, indicating higher levels of consensus and lower levels of disagreement. The value of PCI_2 accounts for the distribution of responses on either side of the scale (acceptable v. unacceptable). It also accounts for the distance between responses (Vaske et al., 2010). For example, a visitor who marked +1 on the acceptability scale for 10 flights per day will likely conflict with someone who marked −3 on the acceptability and less conflicted with someone who marked −1. Differences between values on the scale are considered in the PCI_2. Finally, the PCI_2 figure is a clear way to convey threshold results to a wide range of audiences, which enhances the usability of results (Vaske et al., 2010). Because standard deviations for mean scores were high, future research in the field should continue to examine the degree of norm crystallization related to noise exposure.

Spatial and temporal considerations within normative-based management frameworks are generally lacking (Beeco & Brown, 2013). Here, we show the value of including spatial and temporal patterns in normative-based research by connecting the spatial patterns of noise sources to levels of acceptability. However, we also show how this gap still exists. Specifically, while we have a better understanding of aircraft travel patterns, there is a lack of knowledge about how terrestrial visitors are impacted by overflights in terms of where, when, and how many times, because visitors on the ground are also mobile. More research is needed to consider both mobile sources of noise and mobile visitors. Thus, normative-based management frameworks could be advanced to include spatial *and* temporal considerations for both source and receiver.

Management implications for low-level overflights

Low-level overflights typically produce more intense noise than higher-level flights, making them more noticeable and a greater disturbance to visitors and wildlife. These results can be applied to IVUMF and guide management decisions that are proactive, so that visitor thresholds are not exceeded. At DENA, most low-level overflights occur during the summer, while other seasons, such as winter, receive significantly fewer overflights (Peterson et al., 2025). With added spatial context, DENA managers can effectively communicate with local aircraft operators about the potential for flight practices that minimize noise introduced into specific areas of the park. Additionally, research has shown that educational messaging can positively affect visitor acceptability of aircraft noise (Taff et al., 2014). These approaches can lead to immediate benefits for DENA visitors.

Our analysis demonstrated the number of flights per day and the general spatial patterns of flights around the DENA Visitor Center. However, determining the exact number of flights heard by a visitor is exceedingly difficult to calculate because of human mobility throughout a park like DENA. It is unlikely that a visitor would experience every single propeller aircraft. Thus, when setting specific thresholds or limiting flights to specific numbers should consider the space-time likelihood of interactions between aircraft and visitors. Also, low-level overflight spatial patterns typically vary across space and time. Even if managers are unable to objectively track overflights, this can be accomplished using an observational approach. This information can help identify when minimal acceptable levels are reached, indicating the need for management intervention to ensure that terrestrial visitor experiences remain acceptable.

Beyond DENA, locations that experience high levels of flightseeing tours or other low-flying overflights can use a similar approach to understand the effects of overflight noise and when to implement management strategies. Overflight noise in popular tourist destinations may have negative influences on environmental quality, wildlife, tourist experiences and satisfaction, and the local community. Sustainable tourism practices should involve the consideration of noise. Utilizing data to measure noise events and visitor responses to noise can inform soundscapes management plans.

Limitations

For this current project, we compare visitor norm data from 2017 with flight patterns and acoustic data from 2023. Although findings on norm stability are mixed (Manning, 2010; Nettles et al., 2023), research shows that soundscape norms have remained stable. Specifically related to soundscapes, across surveys from the 1990s to 2018, large majorities of the public and park visitors consistently valued natural quiet and the sounds of nature as important reasons for visiting national parks (Haas & Wakefield, 1998; McDonald et al., 1995; RSG & WYSAC, 2019). Future studies should triangulate physical overflight data with norm data that are collected in the same time frame. Additionally, future studies should concurrently assess the ecological effects of overflights on wildlife and the associated impacts on visitor experiences within an integrated social–ecological systems framework.

Conclusion

This study advances the application of physical measures of the soundscape, spatial extent of flight patterns, and how they compare with visitor perceptions or thresholds for noise. While these data were collected in DENA, the methods can be used in tourist destinations that attract a high volume of low-flying aircraft. We used data from two different summer field seasons to compare current conditions with visitor thresholds. DENA managers suggest that flight patterns and trips per day have not varied much in recent years. In DENA and other locations, transportation systems evolve, and the assumption of consistency in flights from year to year may not as always be valid. Finally, these methods could be applied to other noise impacts, such as vehicles. Tracking the causes of noise, like vehicles, measuring the effects across the landscape, and considering human perception provides researchers and managers with a holistic understanding of noise disturbances on tourism experiences.

Acknowledgments

The authors extend their gratitude to the research technicians, especially Heather Costigan and Alex Graf, for their valuable support with this study. They also thank Denali National Park and Preserve management, with particular appreciation for David Schirokauer. Thank you to the National Park Service Natural Sounds and Night Skies Division and specifically to Damon Joyce and Warren Deeds for their support of designing and building ADS-B logging units. Additionally, they acknowledge that the data for this study were gathered on ancestral lands. We want to honor and acknowledge the original stewards of Denali National Park, the Hwtsaay Hwt'aene, Dichinanek' Hwt'ana, Denaakk'e, Benhti Kenaga', and Dena'ina peoples.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Cooperative agreements with the National Park Service, CESU # P14AC00921, # P21AC10586, and P21AS00320. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE1255832. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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