Advancing geographic information systems (GIS) and econometric analyses for monitoring natural resources and visitors' preferences in national parks and forests

by

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AN ABSTRACT OF A DISSERTATION

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DOCTOR OF PHILOSOPHY

Department of Horticulture and Natural Resources
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Abstract

The U.S. National Park Service (NPS) and the U.S. National Forest System conserve vast areas of public land in the U.S., including diverse ecological landscapes, and provide space and opportunities for outdoor recreational activities. The NPS and the U.S. Forest Service have been conducting inventory, monitoring, and research to assess specific natural resource conditions and visitor use experiences through direct and indirect monitoring methods. Some key monitoring activities include acoustic monitoring in national parks, low-level overflight monitoring in parks popular for air tours, lightscape pollution monitoring, land use and land cover analysis, vegetation monitoring, endangered species and habitat monitoring, climate change vulnerability assessments, and visitor usage monitoring. Monitoring is an important component of evidence-based decision-making in parks and forests. However, monitoring has been more opportunistic than systematic, and it is challenging to maintain long-term, systematic monitoring of natural resources in parks and forests. Meanwhile, monitoring tools and techniques are constantly evolving through the application of satellite and communication technology, powerful computers, smartphones, and cloud services. New monitoring tools and techniques have made data collection more efficient and effective, often capturing information from remote areas of the landscape using satellite and radio signals.

This dissertation comprised three discrete studies on monitoring natural resources and visitors' preferences in national parks and forests. The first study estimated the acoustic active space from two aircraft categories in the Cades Cove site of the Great Smoky Mountains National Park (GRSM) using newer technology. The NPS-ActiveSpace toolkit, an open-source software developed by the NPS, was employed to pair overflight and acoustic data of aircraft recorded by the Automatic Dependent Surveillance-Broadcast (ADS-B) data logger and a sound

level meter (SLM), respectively, in 2023. The jet aircraft (fixed-wing multi-engine) were parsed into two categories based on their maximum takeoff weight: “Light” with a takeoff weight less than 20,000 pounds, and “Heavy” with a takeoff weight more than 20,000 pounds. “Heavy” aircraft generated a larger active space than “Light” aircraft. The second study investigated low-level aircraft data recorded by two flight monitoring systems—the ADS-B data logger and onboard GPS—in Denali National Park and Preserve (DENA) from 2021 to 2023. DENA is popular for air tours and air taxi services for tourists, mountaineers, and backcountry users. The two systems were compared by analyzing their geospatial data characteristics, specifically their waypoint locations across *x*, *y*, and *z* dimensions. The ADS-B and onboard GPS datasets were compared based on the length of the overflights, spatial coverage of waypoints, and altitude discrepancies. The results demonstrated that onboard GPS was more effective for overflight monitoring in the rugged, mountainous terrain of DENA. The third study examined visitors’ preferences for alternative recreation sites during wildfire- and drought-induced displacement using a discrete choice experiment in the national forests of Southern California. The questionnaire survey was conducted in the summer of 2024 at eight priority sites across four national forests. Conditional logit models were applied to analyze respondents’ preferences for site attributes. The models showed preferences for “wildland-urban” views and “wildlands” views compared to “city” views in the wildfire-induced displacement scenario, whereas “1–2 hours” and “>2 hours” of travel time compared to “less than 1 hour” travel time in the drought-induced displacement scenario. Additionally, variations in preferences across socio-demographic groups were analyzed to understand preference heterogeneity within the population. The findings of these three discrete studies will assist park and forest managers in several ways, including mapping aircraft routes and noise, determining the most effective technologies for aircraft

tracking over national parks, and identifying the preferences for site attributes and environmental factors during recreation displacement in Southern California national forests. These efforts will advance monitoring tools and techniques while supporting natural resource conservation and meeting the recreational and educational needs of a growing population.
Keywords: aircraft noise, active space, automatic dependent surveillance-broadcast (ADS-B), onboard GPS, discrete choice experiment, forest recreation, displacement

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Abstract

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tracking over national parks, and identifying the preferences for site attributes and environmental factors during recreation displacement in Southern California national forests. These efforts will advance monitoring tools and techniques while supporting natural resource conservation and meeting the recreational and educational needs of a growing population.
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Dedication

I dedicate this work to my parents, Ms. Dhan Kumari Gurung and Mr. Krishna Bahadur Gurung, and my siblings, Bikram Gurung, Binita Gurung, and Bikash Gurung, as well as to all custodians of natural resources across this biosphere.

Chapter 1 - Introduction

Parks and forest resources

The U.S. National Park Service (NPS) incorporates 433 units (or parks) covering more than 85 million acres of land in all 50 states, and these units include national parks, monuments, preserves, lakeshores, seashores, wild and scenic rivers, trails, historic sites, military parks, battlefields, historical parks, recreation areas, memorials, and parkways. Similarly, the National Forest System includes 154 national forests and 20 grasslands, covering 193 million acres of public land. The forest biome encompasses a wide range of ecological landscapes, such as Warm Continental, Hot Continental, Subtropical, Marine, Prairie, Mediterranean, Tropical and Subtropical Steppe, Tropical and Subtropical Desert, Temperate Steppe, Temperate Desert, and Savanna. Parks and national forests provide ample space and opportunities for various outdoor recreational activities while also helping people connect with their natural and cultural heritage. Millions of people visit public lands and waters to engage in a variety of visitor experiences. In a recent report, 325.49 million people visited 394 NPS units in 2023 alone (National Park Service, 2023c). An estimated 159 million people visited national forests from 2018 to 2022. In FY2021, recreation visitors spent approximately USD 11 billion in areas near national forests and grasslands, thereby contributing to the GDP and local economy (U.S. Forest Service, 2023). Managing vast resources across difficult terrains and diverse topography presents significant challenges for these agencies. They must cater to the growing needs of various user groups by expanding services and outreach to broader communities while also protecting the resources.

Monitoring natural resources

Monitoring is a regular and systematic collection of information or observations to assess specific natural resource conditions and visitor experiences (Interagency Visitor Use Management Council, 2019). Natural resource conditions include trail conditions, cultural

resources, landscape fragmentation, wilderness conditions, and wildlife viability, while visitor experiences include types of activities, visitor numbers, crowding, use conflicts, displacement, and soundscapes. Monitoring not only helps identify threshold and trigger levels for particular ecosystem indicators but also contributes to adaptive management and planning by agencies (Interagency Visitor Use Management Council, 2019). The Visitor Use Management framework consists of four key stages: clarifying the project purpose and need; defining the desired conditions to be achieved or maintained; identifying visitor use management strategies; and implementing monitoring to evaluate the effectiveness of management actions in achieving those conditions (Interagency Visitor Use Management Council, 2019). The National Park Service and the Forest Service have long been conducting monitoring, inventory, and assessment of natural resources, particularly research and studies on biotic components and ecological processes. The U.S. Forest Service employs the National Visitor Use Monitoring Program to estimate the volume and characteristics of recreational visitation during each five-year cycle (U.S. Forest Service, 2023).

Techniques for monitoring visitors in outdoor recreation are broadly categorized as direct and indirect methods. Direct methods include interviews, direct and indirect observation, access permit counts, counting devices, and self-registration, whereas indirect methods include mapping “traces of use” and other “digital traces” in recreation areas (Muhar et al., 2002). Similarly, citizen science and social media data have recently been used to collect data describing wilderness characteristics and visitor use (U.S. Forest Service, 2019). Local stakeholders and volunteer groups apply monitoring protocols and use ESRI products (Collector, Survey123) for visitor use monitoring. Social media users frequently share their locations using place-name tags in their posts. This information can be gathered and analyzed to understand

recreational uses and user behaviors. Users share photographs on Flickr that contain the timestamp geolocated data and the text. An assessment of Flickr posts identified the most visited sites and peak tourist seasons in Nepal, yielding results consistent with official tourism statistics (Bhatt & Pickering, 2023). For air tour monitoring in parks, the NPS requires air tour operators to submit semi-annual reports and flight monitoring data in the prescribed format (National Park Service, 2022). The adoption of a particular method or approach depends on the objectives of the monitoring program, as well as practical, legal, and organizational considerations. The ethical aspects of monitoring are equally important, and visitor privacy must be respected. A mixed-method approach is recommended for monitoring, as different methods vary in coverage, precision, and accuracy, with one method compensating for the limitations of another (Muhar et al., 2002). Monitoring systems are continually evolving with technologies such as automatic detection counters, privacy-enhanced mobile device data, QR codes for questionnaire surveys, and geographic information system (GIS) tools. This evolution in monitoring tools and techniques has presented both opportunities and challenges for park management for decades (Cessford & Muhar, 2003).

GIS for monitoring

The early application of GIS can be traced back to 1969 in a survey of recreational boaters' spatial behaviors on inland lakes in Ohio (Lee & Graefe, 2004). Researchers employed geospatial tools to test the distance decay function, in which the spatial distribution and use of recreational sites depended on distance and associated costs. Since then, the use of GIS technology has increased significantly in outdoor recreation management, as well as in urban park and recreation management. In one study, GIS was used to analyze the behavior of on-water recreational users, including their clustering patterns, as they dispersed throughout an area to avoid conflict at a research site (Confer & Graefe, 1992). The global positioning system (GPS)

tracking technique was applied to identify visitor locations and use densities along trail corridors in the Tuolumne Meadows trail system of Yosemite National Park (D'Antonio et al., 2010). Similarly, GPS Visitor Tracking (GVT) was used in combination with Recreation Suitability Mapping (RSM) to spatially map visitor use preferences in a multi-use public forest facing high spatial demand and space utility in western South Carolina (Beeco et al., 2014).

Air tours are another widely used mode of visiting natural and cultural sites. Thus, the National Park Service (NPS) and the Federal Aviation Administration (FAA) have established protocols and recommendations for the use of airspace and designated flight paths or corridors over parks and cultural areas. As of January 1, 2020, the FAA requires all aircraft flying in designated airspace to be equipped with Automatic Dependent Surveillance-Broadcast (ADS-B) Out avionics. Aircraft equipped with ADS-B Out transmit signals to satellites (Global Navigation Satellite System or GNSS), other aircraft, and air traffic controllers (ATC) to provide real-time position and identification data. These unencrypted and publicly accessible signals are also received by terrestrial dataloggers mounted in locations with minimal shielding from terrain and buildings. ADS-B data have been successfully used to analyze low-level overflights, including air tours in parks, since their initial testing at Haleakalā National Park (HALE) and Hawai‘i Volcanoes National Park (HAVO) in 2018 (Beeco & Joyce, 2019). The NPS has used an automated toolbox designed with an `ArcPy` module to specifically analyze ADS-B data collected from numerous parks.

Aircraft and road vehicles are the most common sources of anthropogenic noise in parks (Buxton et al., 2019). These noises can degrade wilderness quality and visitors' experiences in parks and forests while also disrupting the behavioral ecology and physiology of wildlife, including avifauna. Natural sound is a protected resource in national parks, and one of the

primary objectives of national park management is to protect, maintain, or restore the acoustic environment throughout their park systems (National Park Service, 2006). Since the establishment of the Natural Sounds Program in 2000, the NPS has been monitoring noise in parks using standard sound level meters (SLMs). These instruments record sound as 1/3-octave band data in A-weighted decibels (dBA) every second. Sound exceedance levels in an area are estimated based on acoustic recordings. Researchers have also conducted dose-response experiments to assess the threshold at which aircraft noise is considered unacceptable and interferes with visitors' experiences in parks (Ferguson et al., 2023). Understanding anthropogenic noise, including aircraft noise, helps park managers devise strategies to restore "natural quiet" or the "park soundscape" and improve both visitor experiences and wildlife ecology. Noise monitoring has become an essential component of park management, particularly in parks requiring air tour management plans. The NPS ActiveSpace toolkit has been used to quantitatively estimate active space from aircraft noise and, in turn, to estimate detection distances relative to the listener's position in two parks (Betchkal et al., 2023).

Visitor preference monitoring

Forest and park managers regularly assess visitor preferences to optimize resource use and visitor experience, while ensuring compliance with regulations and protocols. Similar to ADS-B data, mobile device data is used to analyze geo-positioning, human mobility, and visitation patterns in parks and forests. Similarly, understanding visitor preferences and choices in park and forest recreation is an important aspect of public policy and resource management. Visitor preferences for recreation are assessed using Likert scaling, contingent valuation, and discrete choice experiments (Holmes et al., 2017). Forest managers and researchers use questionnaire surveys, a direct monitoring method, to apply these valuation and preference identification techniques in forests and parks. This is particularly important in displacement

scenarios, where visitors must alter their recreation behavior due to crowding, environmental stressors (e.g., wildfires and drought), or site degradation. Researchers have applied these monitoring techniques to assess public participation in fire mitigation programs, the effects of past fires on visit frequency, trade-offs in transportation modes in parks, and willingness to pay (WTP) for environmental attributes.

Analyzing monitoring data

The monitoring system and methods encompass many tools and techniques, including state-of-the-art geospatial and communication technologies, continually evolving with advancements in satellite technology, computing technology, smartphones, and cloud computing. Researchers use a mix of monitoring methods based on the management objectives, costs, capacity, legal frameworks, and accessibility for data collection in recreational sites in parks and forests. ADS-B, onboard GPS, and noise monitoring are relatively novel methods for assessing natural resources and visitor use, whereas survey questionnaires have long been in use. This dissertation employs various monitoring tools and techniques across three ecologically important areas and analyzes the resulting data to assess the condition of natural resources and the quality of visitor experience within those ecosystems. The overarching research question is: How can different monitoring and assessment tools be applied to assess the condition of natural resources and visitor experience in ecologically important areas? The dissertation consists of three distinct studies. In the first two studies, GIS analytics are integrated with emerging technologies to monitor low-level aircraft activity and associated noise in two parks. The third study employs an econometric model to analyze visitor experience in national forests in Southern California.

Study 1 investigated aircraft noise in the Great Smoky Mountains National Park (GRSM). The natural acoustic environment is a protected resource in national parks and includes all natural sounds within the park environment. However, it is often interrupted or masked by

anthropogenic noise, primarily from aircraft and road vehicles, which are the most common sources of human-generated noise in parks. These disturbances can degrade the visitor experience and disrupt wildlife behavior and ecology. Terrestrial wildlife responses have been reported at noise levels of approximately 40 dBA (A-weighted decibel) (Shannon et al., 2016), and detrimental effects on behavior and physiology become more pronounced as ambient noise increases. This study analyzed acoustic data recorded by standard sound level meters (SLMs) and overflight data by ADS-B data loggers at the Cades Cove site. The NPS ActiveSpace toolkit was used for ground truthing and generating active space from the listener's point. NPS Active Space is an open-source software program that uses Noise Map or Noise Model Simulation (NMSIM). Acoustic data were paired with georeferenced overflight data using timestamps, a process known as ground-truthing, in which the audibility section of waypoints was selected based on spectrogram displays. Ground-truthing was conducted for two jet aircraft weight classes: "Light" aircraft with a takeoff weight of less than 20,000 pounds, and "Heavy" aircraft with a takeoff weight of more than 20,000 pounds. The active space module generated the listener-to-aircraft distance at various sound level thresholds and the quantitative estimates of active space for the two aircraft weight classes. The active space model uses a digital elevation model (DEM) of the study area, geometric divergence, diffractions, and atmospheric absorption to estimate detection distances to the active space boundary.

Study 2 analyzed and compared two different types of overflight data in Denali National Park and Preserve (DENA), Alaska: ADS-B and onboard GPS. Aircraft equipped with ADS-B Out transmit signals containing information about their position and identification to ground controllers and other aircraft. Additionally, some aircraft use lightweight, low-cost GPS equipment for navigation in certain airspace, including DENA. These two technologies differ in

terms of cost for operators and performance for use as a monitoring tool, but have not been directly and quantitatively compared. The two sets of geospatial data were recorded separately. The datasets were parsed into multiple feature classes based on unique registration numbers (aircraft) identified in the onboard GPS dataset. Parsed datasets with matching registration numbers were selected from ADS-B and onboard GPS datasets. Subsequently, timestamps (departure and landing times) from onboard GPS were used to filter the ADS-B datasets (waypoints) within the same time range. This procedure identified flights recorded simultaneously by the ADS-B datalogger and onboard GPS equipment. Flights, or their associated waypoints, were then compared in terms of flight length or spatial extent, spatial coverage, and altitudinal discrepancies between the two geospatial datasets collected in the mountainous terrain of DENA. The signal update rate (ping rate) of onboard GPS was also analyzed.

Study 3 analyzed visitor preferences for recreational site attributes and environmental factors in wildfire- and drought-induced displacement scenarios across four Southern California national forests. These forests represent a Mediterranean-type climate and a chaparral biome. They offer numerous urban-proximate day-use sites that attract millions of visitors annually. The two large metropolitan areas—Los Angeles and San Diego—are located near these forests, and the majority of visitors come from ten surrounding counties. However, California is frequently affected by environmental stressors, such as wildfires and droughts, which cause recreational displacement. Numerous studies and surveys have examined visitor responses and displacement patterns during such crises. A discrete choice experiment (DCE) was conducted to assess the utility based on visitors' responses to site attributes and environmental conditions in wildfire- and drought-induced displacement scenarios. This stated-choice model estimates the probability

of selecting one site with a given set of attributes over another site with a different set of attributes. The study identified statistically significant site attributes preferred by survey respondents in response to displacement from wildfires and drought. It also revealed heterogeneous preferences across socio-demographic groups.

Chapter 2 - Estimating active space noise extent from two aircraft weight classes over Great Smoky Mountains National Park (GRSM)

Abstract

The natural and cultural components of the acoustic environment are a resource intrinsic to parks and protected areas and are critical to wildlife and the visitor experience. However, noise degrades the natural acoustic environment, and aircraft introduce spatially extensive noise into such environments. This study examined aircraft noise events at Great Smoky Mountains National Park, U.S., for different jet aircraft types categorized as "Light" (<20,000 pounds) and "Heavy" (>20,000 pounds). Detection distances were determined for these aircraft types by examining the active space of each aircraft's noise events by pairing acoustic and flight monitoring data. The results of this study determined mean detection distances of 15.2 km for "Light" aircraft and 18.3 km for "Heavy" aircraft to the active space boundaries. Increased thrust or jet velocity from the higher mean altitude resulted in a larger active space. From a practical management perspective, to minimize the noise impacts on the natural and cultural resources of the park, efforts should focus on "Heavy" aircraft because they produce greater thrust and frequently operate above GRSM. Using detection distances, managers could work with these aircraft operators or airports to reduce thrust and velocity when flying above protected areas and to discuss routing around noise-sensitive areas, especially with low-level overflights.

Keywords: acoustic environment, active space, automatic dependent surveillance-broadcast (ADS-B), transportation geography, parks and protected areas

Introduction

Acoustic environments consist of all sounds and the physical capacity to transmit sound throughout an area (Maher et al., 2005). They may consist solely of natural sounds or a combination of natural and human-made sounds (Ambrose & Burson, 2004). In parks and protected areas (PPAs), acoustic resources enhance visitors' experiences and foster tranquility (Watts et al., 2020). Further, organisms in the animal kingdom possess auditory capabilities that guide their behavioral ecology (Zeller et al., 2024). When noise is introduced to a natural acoustic environment, it reduces the 3-dimensional 'active space' humans and other organisms can hear (Betchkal et al., 2023). Active space is the sensory area surrounding an individual within which information is perceived or exchanged (Burnham & Duffus, 2023).

The natural acoustic environment in PPAs is increasingly threatened by transportation networks that generate extensive noise footprints (Lynch et al., 2011). Terrestrial animals exhibit responses to noise stimuli as low as 40 dBA, with noticeable impacts occurring at noise levels below 50 dBA (Shannon et al., 2016). Noise also disrupts and degrades visitors' experiences at PPAs. Since the passage of the U.S. NPS Organic Act of 1916, natural sounds have been recognized as essential park resources and contribute to quality visitor experiences. Consequently, various strategies have been implemented to preserve or restore natural soundscapes (National Park Service, 2006).

Aircraft and road vehicles were found to be the most common sources of anthropogenic noise in an assessment of sound pressure data from 66 parks in the United States (Buxton et al., 2021). In particular, low-level overflights are one of the most pervasive sources of noise in PPAs (Peterson et al., 2022). As a result, protected area managers have begun monitoring aircraft in the

airspace above to better understand possible impacts on the acoustic environment in terrestrial settings.

Monitoring

The Natural Sounds and Night Skies Division (NSNSD) of the NPS has been conducting acoustic monitoring since the 2000s, collecting long-term data on acoustical conditions in PPAs and providing important metrics such as existing and natural ambient sound levels (Lynch et al., 2011; National Park Service, 2025). The NPS's acoustic monitoring equipment can be categorized into three distinct generations or phases, all of which use ANSI Type 1 sound level meters (SLMs) with ½" microphones. These meters record 33 one-third octave sound pressure levels (SPLs) in decibels per second across a frequency range of 12.5 to 20,000 Hz (Lynch et al., 2011). At the time of this analysis, the SLM model in use was the Larson Davis 831, which features a solid-state audio recorder and is also capable of simultaneously recording wind speed, wind direction, temperature, and humidity.

Acoustic monitoring data have a wide variety of management applications in protected areas, such as establishing baseline existing and natural ambient, identifying noise sources, identifying species present/absence and abundance, and quantifying the effects of management actions. A combination of aircraft tracking and sound level monitors has been used for aircraft noise monitoring and detection (Betchkal et al., 2023). Noise modeling demonstrates the spatial extent of noise and the varying areas of audibility of noise from sources such as low-level overflights. Subsequently, noise mitigation strategies can be developed based on findings from noise monitoring, spatial modeling, and quantitative estimates of active space.

Numerous technologies have been used to track aircraft across time and space; however, most recent research has focused on Automatic Dependent Surveillance–Broadcast (ADS-B).

ADS-B is used in aircraft to facilitate routing, enhance air traffic surveillance, and improve situational awareness (Giladi, 2020). ADS-B signals are broadcast at approximately 0.5-second intervals at a frequency of 1,090 MHz (Zha et al., 2020). These unencrypted and publicly accessible signals relay the aircraft's geographical position and unique identification code, which can be collected by a terrestrial data logger (Beeco et al., 2020). In the U.S., the Federal Aviation Administration (FAA) has mandated that all aircraft must be equipped with ADS-B Out Avionics to fly in its controlled airspace as of January 1, 2020 (14 CFR § 91.225 and 14 CFR § 91.227).

Research purpose

Aircraft noise poses a significant issue in national parks. Aircraft operating in PPAs include various types such as single-engine fixed-wing, multi-engine fixed-wing, and rotorcraft. Each aircraft type has a specific engine configuration that determines thrust and noise emissions (Zellmann et al., 2018). Betchkal et al. (2023) demonstrated optimal active space estimates for aircraft noise for only a single aircraft type. However, the active space has yet to be constructed for other aircraft types, which will help identify the variations in the noise exposure model based on source types in the park. Further, factors such as varying topography and background ambient also play a role in active space estimations. Thus, our objective is to expand on the work of Betchkal et al. (2023) by considering different aircraft types based on maximum takeoff weight classes in a different location.

The key research question is:

How does aircraft weight affect the active space of fixed wing aircraft perceived by a terrestrial listener?

Literature Review

Acoustic environment

Semantically, a national park's soundscape may be separated into three primary components: biophony (animal sounds), geophony (geological, hydrological, or meteorological sounds), and anthrophony (human-induced sounds) (Maher et al., 2005). Natural ambient sound is typically the presence of natural sounds that vary with ecological and natural processes (Maher et al., 2005). Anthropogenic noise originates from human activities, such as noise from vehicular, aircraft, watercraft, and heavy equipment operations. A park's natural acoustic environment consists of all natural sounds present within the park, the physical capacity to transmit those sounds, and the interrelationships among natural sounds of varying frequencies and amplitudes (National Park Service, 2006). The NPS is responsible for maintaining and restoring natural soundscapes by mitigating noise—an unwanted sound or sounds that interfere with a signal of interest.

Noise pollution

Noise masks natural sounds and interrupts important signals for wildlife (Buxton et al., 2021). Noise alters animal behavior, response mechanisms, physiology, individual fitness, agility, foraging behavior, and the structure of wildlife communities (Shannon et al., 2016). For humans, noise reduces the benefits of experiencing natural acoustics, which has been shown to increase relaxation, restore attention (Abbott et al., 2016), improve mood and focus (Benfield et al., 2014), and reduce stress and annoyance (Buxton et al., 2021). Hearing the sounds of nature and experiencing natural quiet is also an important reason visitors list for visiting national parks (Resource Systems Group (RSG) and Wyoming Survey and Analysis Center (WYSAC), 2019).

Noise not only degrades visitors' experiences in parks and their health but also alters wildlife behavior, structure, and diversity.

Noise pollution is an issue in PPAs, and aircraft, especially low-level overflights, are a primary source of noise. Acoustic recordings collected from 251 sites in 66 park units in the U.S. showed that 37% of the samples contained anthropogenic noise, with aircraft and vehicle sounds being the most common noise sources (Buxton et al., 2019). Surveys in Denali National Park and Preserve (DENA) found aircraft noise to be annoying and unacceptable, as evaluated by visitors, and thus recommended that managers focus on aircraft noise as a potential indicator for assessing the wilderness soundscape experience (Miller et al., 2018). In a laboratory simulation experiment with three aircraft noise conditions, rotorcraft noise was found to be the most disruptive to the national park experience, followed by propeller plane noise and then jetliner noise (Mace et al., 2013). A study was conducted with park visitors in four different front country settings in DENA to identify the threshold of acceptability for noise, and the probability of rating aircraft noise as unacceptable at 54 dB $L_{Aeq,\ 30s}$, or higher was 26% for the visitors uninterested in air tours, which suggests that visitors not interested in air tours are even more sensitive to aircraft noise impacts (Ferguson et al., 2023). Apart from sound pressure level as a predictor of acceptability and threshold in visitor experience, sound qualities entailing roughness (sound irregularities) influence visitors' experience and acceptability in protected areas (Miller et al., 2021).

Executive Order 10092, issued in 1949, marks the first ban on aircraft flights to establish an airspace reservation over areas of the Superior National Forest in Minnesota, prohibiting any flights below 4,000 feet mean sea level (McKenna et al., 2016). The Grand Canyon National Park Enlargement Act of 1975 paved the way for studies on noise pollution caused by aircraft in the canyon (Schmidt, n.d.). This was followed by the National Parks Overflights Act of 1987,

and a Congressional assessment study was drafted in 1995 to evaluate the need for air tour management at all NPS units. To mitigate noise and maintain the safety and aesthetics of national parks and tribal lands, Congress passed the National Park Air Tour Management Act of 2000, which requires the FAA to cooperate with the NPS in developing and implementing an air tour management plan (National Park Service, 2022). Aircraft are considered an extrinsic sound in parks because they do not form an essential part of the establishing purpose or originate from outside the park boundary (Betchkal, 2015).

Noise Monitoring

The natural acoustic environment in PPAs is preserved by restoring natural conditions and reducing noise to an acceptable level for both visitor experience and wildlife conservation (National Park Service, 2006). Human-induced noise, including that from air traffic routes, disrupts an area's natural "acoustic zones" and, in turn, creates altered, non-natural acoustical conditions (Ambrose & Burson, 2004). Assessing the spatial distribution of noise pollution, especially in protected lands, is important (Buxton et al., 2017). Management actions, such as designating a permanent "quiet zone" in Muir Woods National Monument (Lynch et al., 2011) and limiting noise levels above 35 dBA to ≤20% of a 12-hour day in Glen Canyon National Recreation Area, have been implemented to restore or protect the acoustic environment in parks (FAA & NPS, n.d).

Typically, normal human hearing ranges from 20 Hz to 20 kHz (Carpenter & Beeco, 2021; ISO 226, 2023). Sound measurements are often weighted for differential human hearing sensitivity over this range by using adjustments such as the A-weighting network (ISO 226, 2023). In a sound assessment setting, sound pressure levels were categorized as existing (median) and natural ambient sound levels, which were presented as exceedance levels (L_x).

Exceedance level shows the sound level (measured in dBA, dBC, dBT, or dBZ) exceeded *x* percent of the time during the measurement period (Betchkal, 2015). Existing ambient sound is represented by the median sound pressure level (L_{50}). L_{50} shows the sound level exceeded 50% of the time or the median sound level in the measurement period. Existing ambient sound estimates the energy within an acoustic environment from both natural and extrinsic sounds (Betchkal, 2015). The existing (median) ambient sound level (L_{50}) is an average background level consisting of both natural and anthropogenic sound sources, and NPS uses the term existing ambient sound level (Lynch et al., 2011). Exceedance metrics L_{10} and L_{90} (also 90^{th} percentile and 10^{th} percentile of sound pressure level, respectively) estimate the sound level exceeded 10% and 90% of the measurement observation period. These metrics are convenient estimates of the upper and lower energy bounds of a given acoustic environment as it varies over the observation period (Betchkal, 2015). The natural ambient (L_{nat}) sound level of an environment is an estimate of the sound level energy from natural sound sources alone, without any human-caused noise.

A total of 270,000 hours of acoustic measurements were collected from 190 NPS unit sites to analyze sound pressure levels and corresponding geospatial features using a Random Forest algorithm (Mennitt et al., 2014). The importance scores of explanatory variables indicated that anthropogenic sources were among the most common in the soundscape, accounting for about one-third of the most influential explanatory variables over the frequency range from 12.5–20,000 Hz, particularly at lower frequencies.

Tracking overflights using ADS-B

ADS-B Out receives information from satellites and aircraft avionics and then broadcasts it as signals comprising real-time data on geographical position, altitude, velocity, heading, barometric altitude, and a unique identification code to other aircraft and air traffic controllers.

Aircraft are registered with the FAA with unique codes (hex-code), and other metadata are stored in the publicly available FAA Releasable Database (Beeco & Joyce, 2019). ADS-B signals can be collected by terrestrial ADS-B data loggers deployed at suitable locations with unobstructed skyward exposure and no terrain shielding. ADS-B data loggers were piloted in Haleakalā National Park (HALE), Hawai‘i Volcanoes National Park (HAVO), and Mount Rushmore National Memorial (MORU) in 2018, which showed that overflights can be successfully tracked over PPAs using ADS-B data (Beeco & Joyce, 2019).

Active Space

The concept of active space is widely used in animal ecology, where it describes an area within which sensory information is received or relayed by an individual organism, guiding navigation, prey and predator detection, and social interactions (Burnham & Duffus, 2023; Gabriele et al., 2018; Marten & Marler, 1977). Active space defines the distance between an emitter and a receiver and is influenced by background or ambient sound levels, which can often lead to acoustic masking of the desired sound or signal. The active space concept was applied to define a causal geometric relationship (i.e., the spatial intersection) of a listener (a visitor or wildlife) and a specific sound source (Betchkal et al., 2023).

In an assessment conducted by NASA Langley Research Center, a single-engine de Havilland DHC-3 airplane flying at 1,000 feet above ground level (AGL) was estimated to have a planar detection distance exceeding 10 km (6.2 miles) for a listener at a sound level of approximately $L_{Aeq,\,[20\text{-}10k\ Hz]}$ of 40 dB (Hubbard & Maglieri, 1958).

In another real-time noise measurement near an airport, an ADS-B logger was coupled with an NTi XL2 sound level meter (collectively denoted as the “ADS-B monitor”) and set up within the “square of interest,” along with the airport authority’s radar-driven remote sound

monitor (Giladi, 2020). Aircraft noise identification using ADS-B triggers was comparable to the radar-driven noise monitoring system, achieving a high accuracy of up to a 95% true positive rate (Giladi, 2020).

Various soundscape modeling software have been used to understand the spatial extent of noise impacts. The NODSS (National Overflight Decision Support System) model was previously used by the NPS to analyze air tour data for the Grand Canyon (Reddingius, 1994; Schmidt, n.d.). The acoustic condition of HALE was modeled using an Integrated Noise Model Analysis tool (INMA), where the input parameters included nominal air tour routes, hours of operation, the average number of flights per day, and the types of aircraft flown, as collected from air tour operator reports (McKenna et al., 2016). The Integrated Noise Model generated acoustic metrics and audibility contours for an area based on percent time audible [% T_{Aud}] or equivalent continuous sound level [L_{Aeq}]. The algorithm accounted for noise-power-distance relationships, source-receiver geometry, acoustic directivity, and atmospheric absorption. The tool is Windows-based and was developed by the U.S. Department of Transportation. Similarly, the NMSIM model, which includes the NORD2000 sound propagation algorithm, is Windows-based, more user-friendly, and features an expanded noise library (Schmidt, n.d.). NMSIM was developed based on the fundamental physics of noise transmission to incorporate range-dependent models of sound propagation, which allow it to consider effects such as terrain shadowing.

The NMSIM model was used in the development of the NPS Active Space Toolkit (Betchkal et al., 2023). The NPS Active Space Toolkit was applied to estimate the optimal active space for aircraft noise at two sites—one in Hawai‘i Volcanoes National Park (HAVO) and another in Denali National Park and Preserve (DENA) (Betchkal et al., 2023). Both sites

experience a high volume of low-altitude overflights, including air tours, with mean detection distances of 7.9 km (4.9 mi) at HAVO and 13.1 km (8.2 mi) at DENA. Each of these sites experienced little noise other than aircraft. The optimal active space in that study was computed using a single aircraft type.

The ultimate goal of this line of research is to broadly and specifically understand how aircraft travel patterns influence the acoustic environment across the landscape of noise-sensitive protected areas (Betchkal et al., 2023). However, multiple aircraft types traverse airspace at varying altitudes, each producing distinct sound pressure levels in different frequency bands and exerting varying impacts on people and wildlife, thereby posing challenges in land use planning (Schäffer et al., 2014). Further, the noise exposure model varies according to aircraft type and operational phase (e.g., ascending, descending, or cruising). Therefore, it is important to estimate optimal active spaces and detection distances separately for various aircraft types. To date, no comparative analysis of observer-based modeling has been conducted concurrently across multiple aircraft types. Betchkal et al. (2023) also recommended incorporating additional sources (aircraft) in the active space toolkit in future analysis. The current study applied the NPS Active Space Toolkit separately to two different types of jets, classified by maximum takeoff weight (light and heavy), using data recorded over Great Smoky Mountains National Park (GRSM) during the study period.

Study Objectives

Previously, an optimal active space was generated for a single aircraft type by integrating overflight data, associated noise measurements, and landscape attributes into the noise exposure model using the NPS ActiveSpace toolkit (Betchkal et al., 2023). Here, we expanded on the prior

approach by integrating aircraft type into active space development at a different location. Specifically, we focus on jet aircraft (fixed wing multi-engine), which can be categorized into different types based on their maximum takeoff weight. Zellmann et al. (2018) also classified aircraft types according to maximum takeoff weight in their noise emission model. This study aims to estimate active space from the listener's point to the aircraft noise source for the two jet types, classified based on their weight classes—one with a takeoff weight of less than 20,000 pounds (Weight Class 1 & 2 and denoted as "Light") and the other with a takeoff weight of more than 20,000 pounds (Weight Class 3 and denoted as "Heavy"). The following research questions guide the methodology and analysis.

RQ1: What are the microphone-to-aircraft distances for various sound level categories (i.e., exceedance levels) for the two aircraft types?

RQ2: What are the detection distances (i.e., when a noise source becomes audible) for the two aircraft weight types based on their quantitative estimate of active spaces?

Methods

The key steps for separating the aircraft types and generating active spaces are outlined below.

1. Record acoustic data using a sound level meter and aircraft tracking data using an ADS-B data logger for the same timeframe in the same geographic location.
2. Temporally join the acoustic data with the overflight data. Identify the audible segment of aircraft noise events using a spectrogram.
3. Retrieve aircraft metadata using the FAA Releasable Database to identify "Light" and "Heavy" aircraft.

4. Parse the geospatial file into two: one for aircraft weight class “Light” and another for aircraft weight class “Heavy.”
5. Estimate the exceedance levels, audible distance, and generate quantitative estimates of active space for two aircraft types.

Study site

The study site is GRSM, which lies on the border between Tennessee and North Carolina and has elevations ranging from 875 ft at Abrams Creek to 6,643 ft on top of Clingmans Dome (Fig. 2.1). The park covers 522,000 acres, of which 464,544 acres—nearly 89% of the park area—are recommended or proposed wilderness (National Park Service, 2022). The park has diverse flora and fauna, including threatened and endangered species such as the Carolina northern flying squirrel, gray bat, northern long-eared bat, Indiana bat, bald eagle, and peregrine falcon. GRSM is the most visited national park in the U.S., attracting over 12 million visitors per year, and was classified as “extremely concerned” regarding the effects of overflights on the national park system in an NPS report to Congress in 1994. In 2020, 1,404 air tours were reported over GRSM (Sheilds & Ward, 2023). Jet aircraft were the most common aircraft noise source above GRSM, and the area near the Cades Cove site (Parson Branch) lies beneath a common flight path for high-altitude commercial jets (Carpenter & Beeco, 2021). The Cades Cove site was selected for analysis because it is highly visited by terrestrial visitors, receives numerous overflights of different aircraft types, and protecting the acoustic environment is a park management objective. A study area boundary measuring 80 km × 80 km was delineated around Cades Cove to incorporate a sufficient sample of acoustic and overflight data that could result in active space development.

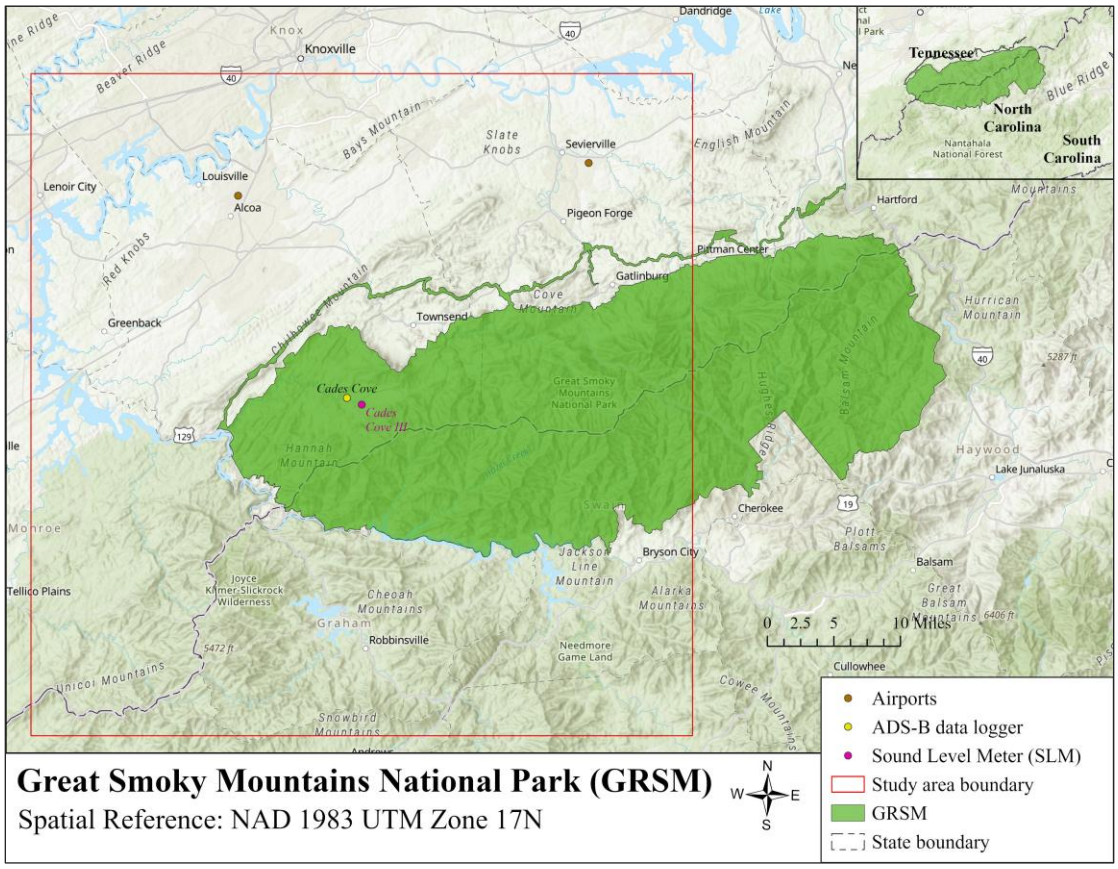

Figure 2.1 *ADS-B data logger and Sound Level Meter (SLM) site in Great Smoky Mountains National Park (GRSM); a red square displays an 80 km × 80 km study area boundary for the Cades Cove site.*

Data collection

Overflight and acoustic data collected from the Cades Cove site were used for the analysis. ADS-B data were collected using a data logger deployed at Cades Cove (35.594922, -83.841762; 521.9 meters mean sea level [MSL]). The Cades Cove record contained ADS-B data from March 3, 2023, to September 18, 2023. The data were saved and transferred in TSV format. The ADS-B data logger included a uAvionix PingRX ADS-B receiver, an Arduino-based microcontroller, an RTC and microSD card logging shield, a DC-DC regulator, and PVC housing (Betchkal et al., 2023). The uAvionix PingRX receiver is dual-band, collecting both 978

MHz and 1,090 MHz radio signals. Acoustic data were collected from Cades Cove (35.58801, -83.82158; 536 meters MSL). The Cades Cove record contained usable audio data from June 6, 2023, to June 17, 2023. The data were collected using an omnidirectional ANSI Type 1 sound level meter and following NPS protocols for deployment (Lynch et al., 2011, as mentioned in Betchkal et al., 2023).

There was a total of 12 days of overlap between ADS-B and acoustic data for the Cades Cove site, which contained a sufficient number of jet aircraft acoustic data for our analysis.

NPS-ActiveSpace modules

An aircraft noise exposure model in the lower half-sphere of the aircraft is demonstrated with an overflight offset from a listener (mic) with longitudinal (θ) and lateral (φ) sound emission angles from the noise source (Fig. 2.2).

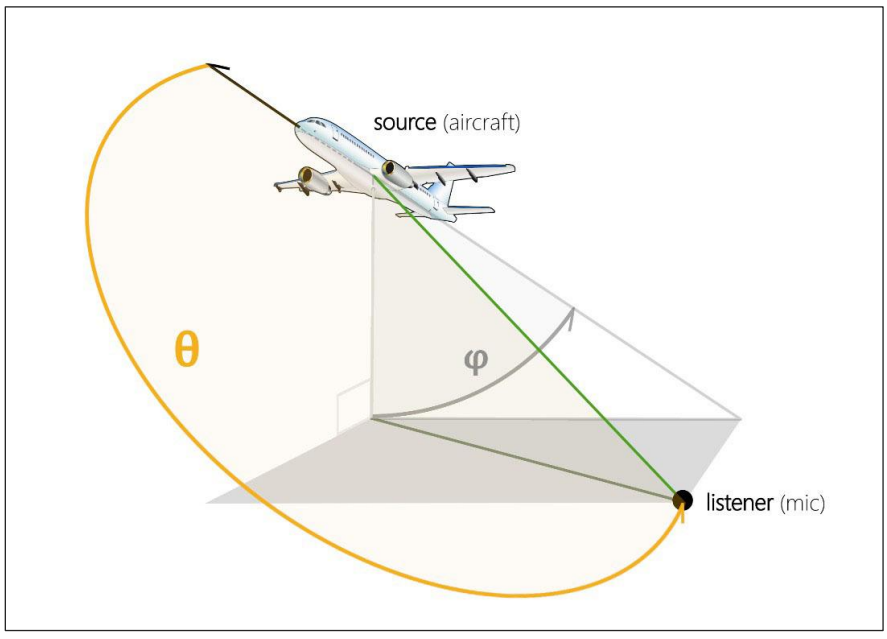

Figure 2.2 *A schematic representation of a noise exposure model based on flight path and SLM on the Ground (Zellmann et al., 2016)*

NPS-ActiveSpace is an open-source geoprocessing toolkit that provides a quantitative estimate of active space using NMSIM. The tool analyzes acoustic data and georeferenced overflight data. In its ground truthing module, the toolkit identifies the closest point from the sound receiver to the flight path as the temporal reference for determining the noise event window in the acoustic data. The selected flight track points are spatiotemporally interpolated using a cubic spline function to achieve a one-second temporal resolution, consistent with the acoustic data (Betchkal et al., 2023). The toolkit delimits audible and inaudible sections of overflight within the study area. The acoustic data and flight track data are manually matched. Records are manually inspected to verify whether the sound data corresponds to the selected flight record. The timestamp is applied as a primary key to track aircraft data alongside its corresponding noise data in a spectrogram. Interpolated flight track points are classified as audible or inaudible based on sound pressure level from the aircraft. A map is generated to visualize the aircraft track (line) and its overlapping noise data (Fig. 2.4).

In the active space module, a polygon representing a quantitative estimate of active space is generated by sound propagation modeling. The active space module is a synthesis of five inputs: the sound receiver location (listener's position), the spectral residual sound level at the listener's position, the study area around the receiver point, a 30-meter Digital Elevation Model (DEM) spanning the study area, and the spatiotemporally joined overflight trajectory segments created as outputs of the ground truthing module (Betchkal et al., 2023). The active space module then uses optimization to fit the active space from the listener's point. The mean altitude of aircraft flights was considered for estimating the active space. The toolkit generates a planar, polygonal estimate of active space for a given geographic setting based on the gain in dB in the back-propagation sound model. For a specific aircraft position, iterative audibility testing is

performed, retaining audible points while adding new points to the updated test set. A Cartesian grid is used to generate the estimated polygon or interior rings for different aircraft headings (e.g., 0^o, 120^o, and 240^o). The polygons or interior rings define the final active space. NMSIM models sound propagation from the aircraft, incorporating geometric divergence, atmospheric absorption, diffraction, and ground reflection. The residual sound level for the area under investigation is set at the 10^{th} percentile or the exceedance metric L_{90}, $L_{Aeq,\ 1s\ [20–1{,}250\ Hz]}$, which represents the sound level exceeded 90% of the time. This represents the background sound pressure level for parks, which excludes anthropogenic sources commonly associated with ambient noise, and is therefore used to characterize the detection properties of the acoustic environment (ANSI/ASA, 2014). Aircraft noise is detected if ambient sound exceeds the residual sound level in any one-third octave band at the receiver location. An aircraft noise event was marked as audible when the measured $L_{Aeq,\ 1s}$ in one-third octave band exceeded both the threshold of human hearing and the concurrent residual sound level in the same band by $\geq$ 4dB (Betchkal et al., 2023). The F-measure, incorporating recall and precision, is applied to select the optimal active space using ground truth points (Betchkal et al., 2023).

$$F_1 = \frac{2\ A_{in}}{2\ A_{in} + \ I_{in} + A_{out}}$$

Here, *A* is audible, *I* is inaudible, *in* is inside the active space, and *out* is outside of the active space.

Finally, it is noteworthy that here we use $L_{Aeq,\ 1s\ [20–1{,}250\ Hz]}$ rather than the $L_{Aeq,\ 1s\ [20–20{,}000\ Hz]}$ used in Betchkal et al. (2023). Most noise produced by human motorized activities is typically confined to lower frequency ranges, whereas many natural sounds, such as those made by insects and birds, occur at higher pitches. The ANS weighting ($L_{Aeq,\ 1s\ [20–1{,}250\ Hz]}$) filters out high-frequency sounds (like leaf rustling, equipment noise, and certain biological noises), enabling

more accurate comparisons of low-frequency ambient sound levels among various land use types, such as urban areas and protected regions (ANSI/ASA, 2014). Prior research at Cades Coves in 2023 indicated large differences between the two frequency ranges with respect to exceedance levels—likely due to insects and other biological activity (Table 2.1).

Table 2.1 *Time above metrics for Cade Cove 2023 (White & Rapoza, 2025)*

Site	Frequency range (Hz)	Time Above Sound Level (% of Daytime Hours, 07:00-19:00)				Time Above Sound Level (% of Nighttime Hours, 19:00-7:00)			
		35 dB[A]	45 dB[A]	52 dB[A]	60 dB[A]	35 dB[A]	45 dB[A]	52 dB[A]	60 dB[A]
Cades Cover (Summer 2023)	Full (12.5-20,000)	93.8	16.2	1.6	0.1	59.3	2.1	0.2	0.0
	ANS (20-1,250)	41.7	6.1	0.8	0.0	7.1	0.7	0.1	0.0

[A] dB $L_{Aeq,\ 1s}$ re: 20 μPa

Results

Ground truthing for two aircraft categories

Overflights data within the 10-mile boundary around the park, recorded by the ADS-B data logger deployed at the Cades Cove site, are shown below (Fig. 2.3). The 10-mile boundary was applied to clip the overflights to understand the flight paths beyond the park boundary and to ensure a large enough area to capture audibility from aircraft for Cades Cove. Overflight data and acoustic data were analyzed from June 6th to June 17th, 2023, and were used for annotation in the ground-truthing module.

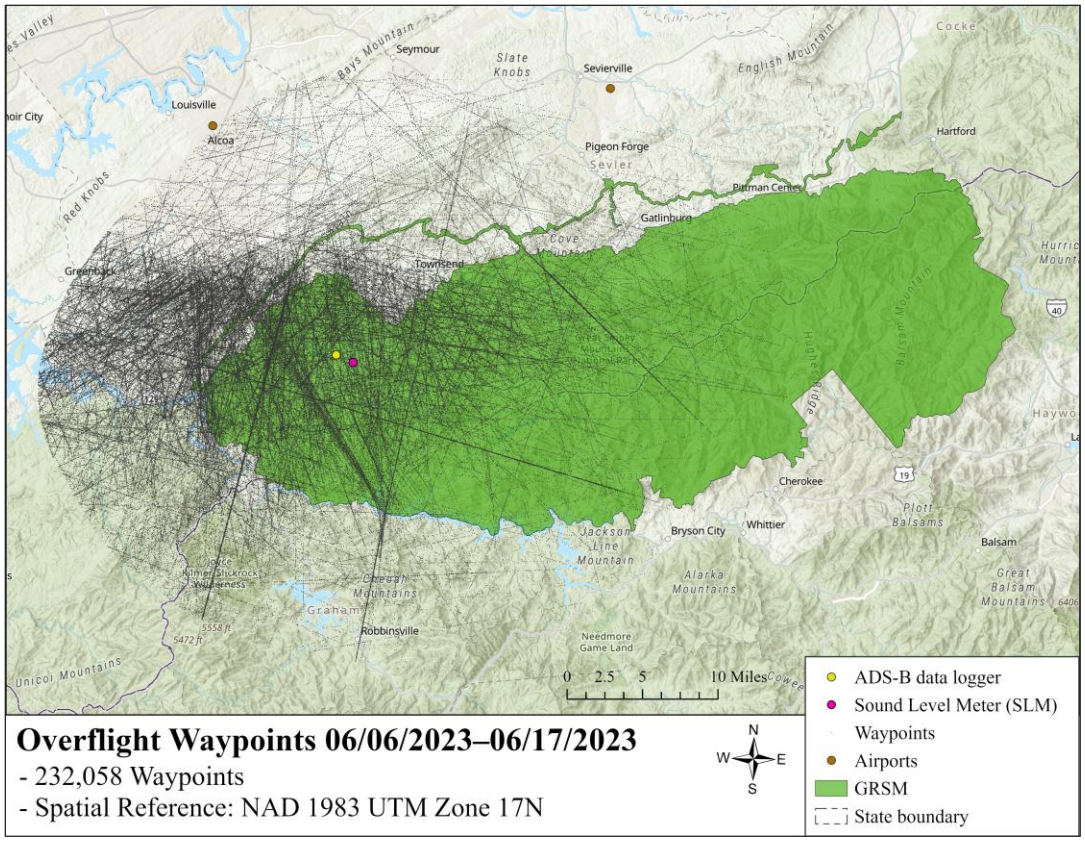

Figure 2.3 *Overflight waypoints within a 10-mile boundary of the GRSM, recorded by an ADS-B data logger deployed at the Cades Cove Site.*

The spatiotemporal pairing of acoustic and overflight data based on timestamps, as conducted using the Ground Truthing module, is shown below (Fig. 2.4). The spectrogram displays the spectral morphology, including noise emitted by a jet aircraft, with frequency on the *y*-axis and time on the *x*-axis. The square box at the top represents the study area boundary and shows the overflight track points and interpolated points along the flight path. The cross mark represents the location of the microphone (i.e., listener's position). An audible window, represented by a horizontal blue bar below the spectrogram, can be adjusted to encompass the duration of an aircraft noise event, including its onset and offset, by identifying recognizable spectromorphological features (noise signatures) relative to the residual sound level and the presence of Doppler shift (Lynch et al., 2011; Zellmann et al., 2018). As the audible section of

aircraft noise is selected in the spectrogram by adjusting the horizontal blue bar in the audible window, the corresponding blue line in the upper square box shifts accordingly, indicating the selection of overflight track points associated with that noise event.

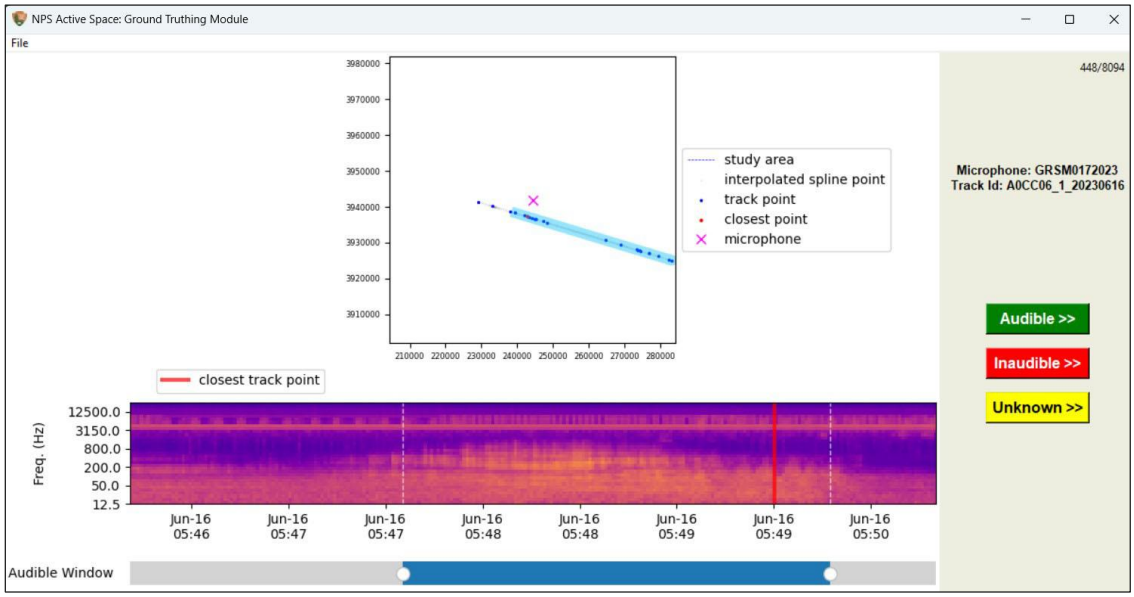

Figure 2.4 *A ground truthing module for jet aircraft in 80 km × 80 m study area boundary.*

For “Light” aircraft, 154 usable aircraft noise events were annotated on the spectrogram, of which 48 were identified as audible. For “Heavy” aircraft, 515 usable aircraft noise events were annotated, resulting in 157 audible events. Thus, a total of 205 aircraft noise events were analyzed. The inaudible track points had no corresponding noise signals, primarily due to sound attenuation (i.e., distance of the track from the microphone) or elevated background noise levels (i.e., local ambient sounds masking the noise from aircraft). Figure 2.5 displays a two-dimensional representation of audible and inaudible sections identified after spatiotemporal pairing for “Light” and “Heavy” aircraft. Blue lines indicate audible sections, while red lines represent inaudible sections. The Cades Cove site is marked by a white dot on the maps. Because the altitudes of flight track points are not represented in a two-dimensional plane and sound

pressure decreases with distance, the inaudible track points were likely located farther from the receiver than the audible track points.

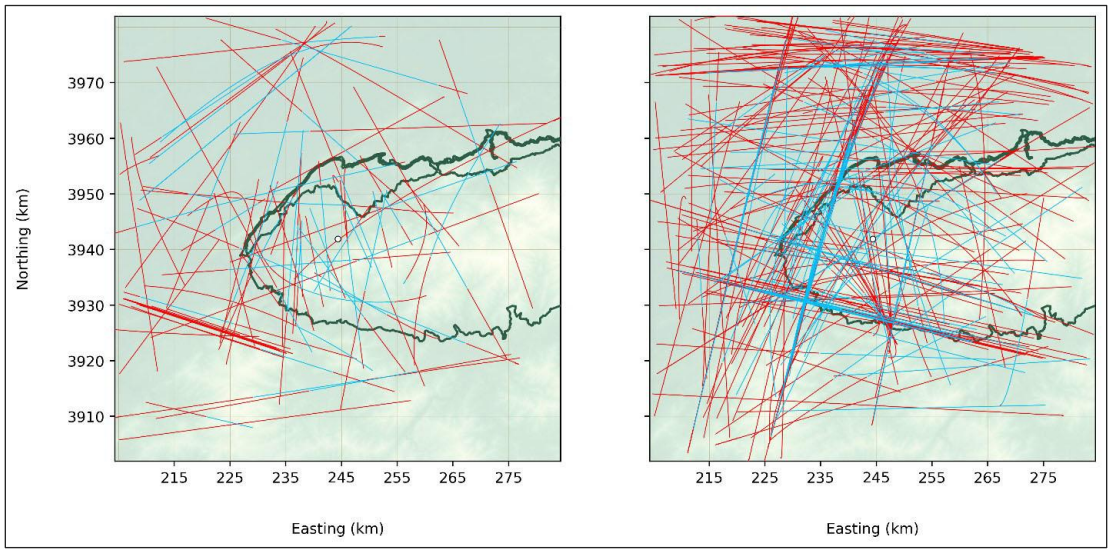

Figure 2.5 *The audible (blue tracks) and inaudible (red tracks) sections of aircraft noise events for aircraft type "Light" on the left panel and for aircraft type "Heavy" on the right panel*

Estimating audible distance at various sound level categories or thresholds (Research question 1)

The active space module of the toolkit calculated the audible distance from the microphone (immission point) to the aircraft (emission point), based on two functional effect categories, $L_{Aeq,1s} \geq 35$ dB and >52 dB, corresponding to the two aircraft types. The sound level categories of 35 dB and 52 dB were considered because $L_{Aeq,1s\ [12.5–20{,}000\ Hz]} = 35$ dB represents a threshold above which the outdoor experience is degraded, while 52 dB represents a threshold at which speech interference occurs between a speaker and listener at a distance of 5 m (or 16 ft) (Betchkal et al., 2023). Table 2.2 summarizes microphone-to-aircraft distances for all audible interpolated points at various sound level categories for "Light" aircraft. Additionally, the overall (mean) microphone-to-aircraft distance (slant distance) was 17.9 ± 0.1 km (standard error),

which resulted in a median $L_{Aeq,1s\ [20–1,250\ Hz]}$ of 49.1 dB and an interquartile range of 9.6 dB (Q3 – Q1). The mean thrust for this aircraft weight class was 17,906 Newtons.

Table 2.2 *Mean and median 3-dimensional distances from the microphone to the aircraft for three functional effect categories, aircraft type "Light"*

Estimated sound level category of the audible points ($L_{Aeq,1s}$)	Mean microphone to aircraft distance	Median microphone to aircraft distance	Point count
$L_p \leq 35$ dB	24.5 km (15.2 mi)	22.1 m (13.7 mi)	16
$35 < L_p \leq 52$ dB	17.2 km (10.7 mi)	13.8 km (8.6 mi)	3,594
$52 < L_p$	18.2 km (11.3 mi)	17.0 km (10.6 mi)	2,071

Table 2.3 summarizes the microphone-to-aircraft distances for all audible interpolated points at various sound level categories for "Heavy" aircraft. Additionally, the overall (mean) microphone-to-aircraft distance (slant distance) was 21.7 ± 0.1 km (standard error), which resulted in a median $L_{Aeq,1s\ [20–1,250\ Hz]}$ of 48.3 dB and an interquartile range of 9.0 dB (Q3 – Q1). The mean thrust for this aircraft weight class was 104,801 Newtons.

Table 2.3 *Mean and Median 3-dimensional Distances from the microphone to the aircraft for three functional effect categories, aircraft type "Heavy"*

Estimated sound level category of the audible points ($L_{Aeq,1s}$)	Mean microphone to aircraft distance	Median microphone to aircraft distance	Point count
$L_p \leq 35$ dB	26.4 km (16.4 mi)	26.6 km (16.5 mi)	496
$35 < L_p \leq 52$ dB	21.6 km (13.4 mi)	20.2 km (12.5 mi)	10,941
$52 < L_p$	20.7 km (12.9 mi)	18.5 km (11.5 mi)	5,097

The comparison of the overall microphone-to-aircraft distances (slant distances) at which aircraft were audible showed a mean difference of 3.8 km, with "Heavy" aircraft audible significantly farther from the receiver than "Light" aircraft (Welch's t-test, one-sided, $p < 0.029$).

Additionally, the theoretical increase in sound power level for "Heavy" aircraft relative to "Light" aircraft based on mean thrust values (104,801 N and 17,906 N) was calculated using the following expression, yielding a value of 7.6 dB.

$$\Delta L_w = 10 \log_{10} \left(\frac{Mean\ Thrust_H}{Mean\ Thrust_L} \right) = 7.6 \text{ dB} \quad (1)$$

Estimating active space (Research question 2)

The optimal active space and the planar detection distances for the two aircraft types are presented in Table 2.4. The mean altitude was 5367 ± 337 (standard error) meters MSL for "Light" aircraft and 8034 ± 183 (standard error) meters MSL for "Heavy" aircraft. The residual sound level measured as the 10th percentile (L_{ANS90}), $L_{Aeq,1s\ [20–1,250\ Hz]}$ was 12.7 dB. The corresponding broadband level (L_{A90}), $L_{Aeq,1s\ [12.5–20,000\ Hz]}$ was 22.2 dB. The F_1 scores were 0.38 for "Light" aircraft and 0.35 for "Heavy" aircraft. Similarly, the optimal gains were -50.5 dB for "Light" aircraft and -43.0 dB for "Heavy" aircraft.

Table 2.4 *Mean and maximum 3-dimensional detection distances from the listener to the active space boundaries estimated for two aircraft types*

Estimated detection distance, listener to aircraft	Aircraft type "Light"	Aircraft type "Heavy"
Mean	15.2 km (9.4 mi)	18.3 km (11.4 mi)
Maximum	18.2 km (11.3 mi)	18.5 km (11.5 mi)

Figure 2.6 presents the polygonal estimates of active space for the two aircraft types from the listener's point. The left panel represents the estimate for "Light" aircraft (mean altitude of 5,367 meters), while the right panel represents the estimate for "Heavy" aircraft (mean altitude of 8,034).

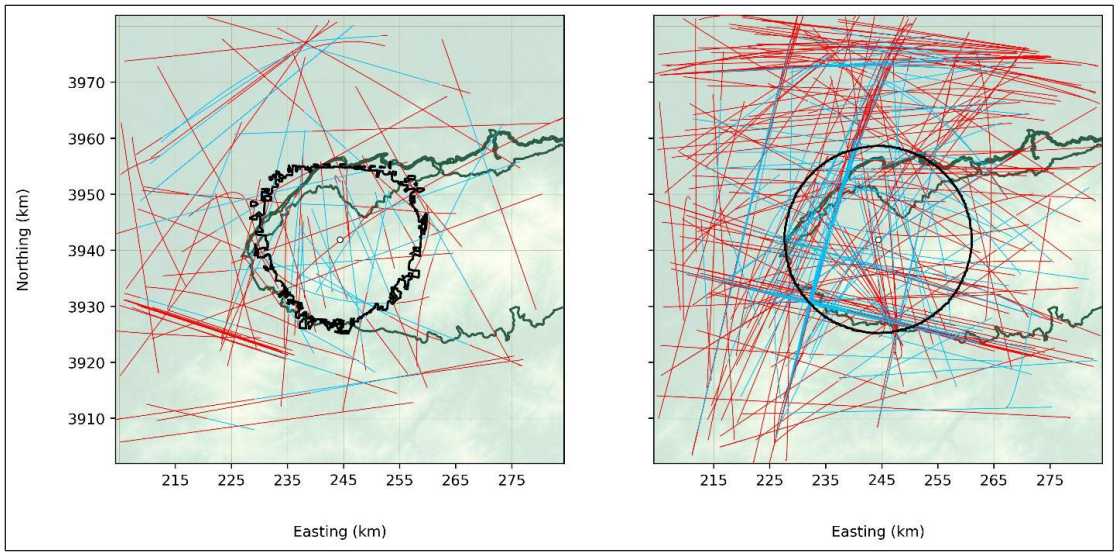

Figure 2.6 *Active space estimates for two aircraft types with mean altitudes of 5,367 meters (Light; left panel) and 8,034 meters MSL (Heavy; right panel)*

The offset distance for the active space for the "Heavy" aircraft as compared to "Light" aircraft was estimated using the following expression, yielding

$$Offset\ distance\ = \sqrt{(18.3 - 15.2)^2 + (8.0 - 5.4)^2} \approx 4.0 \text{ km} \qquad (2)$$

Here, 18.3 km and 15.2 km are the mean detection distances to the active space boundary for "Heavy" and "Light" aircraft, whereas 8.0 km and 5.4 km are the mean altitudes (*z*-values) for "Heavy" and "Light" aircraft.

Additionally, the estimated sound levels at audible points are mapped below for the two aircraft types, incorporating the results from Tables 2.2 and 2.3 and Fig. 2.5. The sound level thresholds of audible points were $L_{Aeq,\ 1s} \geq 35$ dB and ≥52 dB (Fig. 2.7). The left panel displays categorical sound levels of audible points for "Light" aircraft, while the right panel corresponds to "Heavy" aircraft.

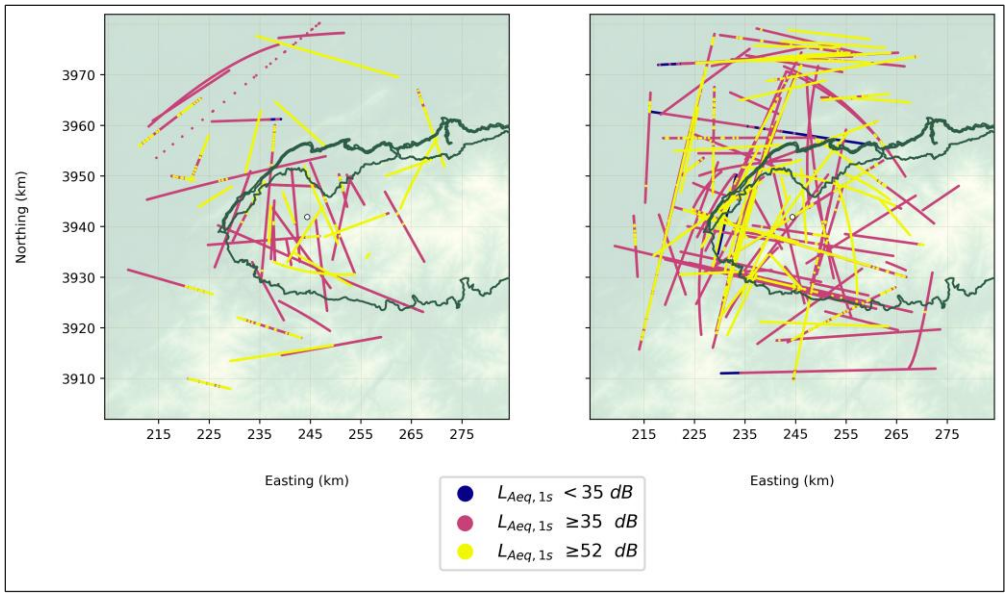

Figure 2.7 *Estimated sound levels of audible points based on the functional effect thresholds for the two aircraft types.*

Discussion

Overflights influence the acoustic environment at Cades Cove in GRSM, with the potential to disrupt both wildlife ecology and visitors' recreational experience. This study is the second of its kind to analyze specifically acoustic data, aircraft noise, alongside overflight position data using the NPS ActiveSpace toolkit. A previous study by Betchkal et al. (2023) examined aircraft noise in HAVO and DENA sites, also utilizing the NPS ActiveSpace toolkit, and calculated the microphone-to-aircraft distances for various sound level categories in those environments. The current study extends the methodology by differentiating the aircraft noise sources based on aircraft takeoff weight, classifying them into two categories: Light (<20,000 pounds) and Heavy (>20,000 pounds). Further, this study utilizes data from another park, GRSM, in an area with a more energetic existing ambience and less terrain shielding.

Aircraft noise exposure generally follows the noise-power-distance (NPD) table, where noise levels depend on the engine power and the distance from the noise source (Zellmann et al.,

2016). However, many other factors influence sound propagation, such as aircraft position and directivity, acoustic impedance, and meteorological disturbances. The noise exposure model is also sensitive to aircraft type (Dekoninck, 2020; Schäffer et al., 2014). Jetliners emit the highest sound levels at the tail, and their overall noise emission depends on the aircraft type, engine type, and engine configuration.

Here, we applied the FAA Releasable Database metadata to our ADS-B data to parse the jet aircraft (fixed wing multi-engine) into two categories based on their weight classes— "Light" and "Heavy"—for our analysis. The aircraft noise events in the dataset included sufficient audible samples for both aircraft types to construct the optimal active space. Tables 2.2 and 2.3 display the mean microphone-to-aircraft distances for various sound level categories for "Light" and "Heavy" aircraft (research question 1), and Figure 2.7 maps these relationships. The final columns of the two tables present the number of audible track points used to calculate the distance from the microphone to the aircraft across different sound level categories. A higher point count improves both the accuracy and precision of noise exposure modeling. For "Light" aircraft, the mean distance from the microphone to the aircraft decreased from 24.5 km to 17.2 km when moving $L_p \leq 35$ dB category to $35 < L_p \leq 52$ dB category. However, the mean distance increased slightly—from 17.2 km to 18.2 km—when moving from $35 < L_p \leq 52$ dB category to $52 < L_p$ category, contrary to the expected decreasing trend. The marginal increase rather than a decrease could be attributed to atmospheric absorption and meteorological uncertainty, and ground effects, which are known to affect noise attenuation. For "Heavy" aircraft, both the mean and median audible distances from the microphone to the aircraft decreased consistently as sound levels increased from $L_p \leq 35$ dB to $35 < L_p \leq 52$ dB, and further to $52 < L_p$. For "Heavy" aircraft, the flight within 20.7 km (12.9 miles) of the receiver could be loud enough to disrupt

speech at a 5-meter distance (Table 2.3), as noise levels exceeding 52 dB are known to interfere with speech communication at that range when using a normal speaking voice (Environmental Protection Agency (EPA), 1974; as mentioned in Betchkal et al., 2023). For “Light” aircraft, the flight within 18.2 km (11.3 miles) of the receiver could be loud enough to disrupt the speech at a 5-meter distance (Table 2.2) because the noise level would exceed 52 dB at the receiver’s point. The overall (mean) audible distance (microphone-to-aircraft distance) was greater for “Heavy” aircraft than for “Light” aircraft, primarily because the mean thrust generated by “Heavy” aircraft exceeded that of “Light” aircraft by a factor of more than five (104,801 N vs. 17,906 N) and were cruising at the higher altitudes. Engine thrust or jet velocity is the primary physical driver of jet noise (Zellmann et al., 2018). Consequently, the sound pressure level produced at the emission point by “Heavy” aircraft exceeded that of “Light” aircraft, with an overall (mean) audible microphone-to-aircraft distance (slant distance) of 21.7 km for “Heavy” aircraft compared to 17.9 km for “Light” aircraft from the listener’s point. Further, all things being equal, a higher flight would have a larger spatial footprint but lower noise intensity.

Two active spaces were generated using the mean altitudes for “Light” aircraft and “Heavy” aircraft, with “Heavy” aircraft having a higher mean altitude than that of “Light” aircraft, reflecting the higher cruising altitude of the heavier aircraft. Accordingly, the mean detection distance to active space boundary was greater for “Heavy” aircraft than for “Light” aircraft (Table 2.4) (Research question 2). Active space estimates based on the propagation model from the Cades Cove site were projected onto a two-dimensional (2-D) plane (Fig. 2.6), where the planar listening area associated with “Heavy” aircraft is larger than that associated with “Light” aircraft. However, the polygonal boundary of the active space for “Light” aircraft is

more granular compared to that of "Heavy" aircraft–likely a result of sample size (larger for "Heavy") and perhaps altitude differences (higher for "Heavy").

Similarly, based on the mean thrust values of the two aircraft types, we estimated a theoretical increase in sound power level of approximately 7.6 dB for "Heavy" aircraft relative to "Light" aircraft (Eq. 1). Given the geometric nature of sound propagation and the inverse square law, where the intensity decreases inversely with the square of the distance (Maekawa, 1970), this level increase is expected to extend the audible range of "Heavy" aircraft. Using the F_1-based optimization procedure (Betchkal et al., 2023), we found that the active space required an expansion of 4.0 km to encompass the audible points from "Heavy" aircraft (Eq. 2). This corresponded to an increase in optimal gain of 7.5 dB (difference in optimal gains between "Heavy" and "Light"), consistent with the theoretical expectation due to differences in thrust, i.e., $\Delta L_w \approx \Delta g$. This can be expressed as,

$$\Delta L_w \;=\; 10\,log_{10}\left(\frac{Mean\ Thrust_H}{Mean\ Thrust_L}\right) \approx \Delta g = (g_{large} - g_{small})$$

Additionally, the difference in microphone-to-aircraft distances (slant distances) at which aircraft were audible was statistically significant between "Light" and "Heavy" aircraft, with a mean difference of 3.8 km. The agreement among the theoretical prediction, the empirical active space optimization, and the statistical summary strengthens the interpretation that increased thrust and associated acoustic power result in a larger active space for "Heavy" aircraft (Weight Class 3) compared to "Light" aircraft (Weight Class 1 and 2).

Management implications

Aircraft noise presents a significant influence on the acoustic environment, natural and cultural resources, and visitor experiences in PPAs (National Park Service, 2022). In our analysis, the "Heavy" aircraft cruised at higher mean altitudes (MSL) than "Light" aircraft,

which aligns with aviation norms, where high-altitude commercial jets typically operate above lighter aircraft. Additionally, the overall (mean) microphone-to-aircraft distance (slant distance) at which aircraft were audible was greater for “Heavy” aircraft than “Light” aircraft. As a result, the aircraft distances at which normal conversation may be disrupted were identified at the Cades Cove site for both aircraft types, with the distance for “Heavy” aircraft being greater than that for “Light” aircraft. A lower cruising altitude or a shorter audible slant distance for “Heavy” aircraft would have indicated disproportionately high sound pressure levels at the listener’s point, potentially degrading visitor experience and adversely affecting the physiology and behavioral ecology of wildlife. Similarly, “Heavy” aircraft generated a larger active space than “Light” aircraft, due to their greater thrust and higher sound emission levels.

Prior researchers have noted a future goal of modeling aircraft noise across landscapes using aircraft tracking data (Betchkal et al., 2023; Peterson et al., 2022). This analysis brings that goal one step closer to reality by identifying 1) the importance of aircraft type in the consideration of any future models, and 2) general detection level distances for heavy and light jets.

This study also demonstrated the continued value of the NPS ActiveSpace toolkit for revealing a tangible spatial boundary within which the effects of noise must exist. However, this study also revealed an important consideration in the use of the toolkit. The GRSM site experienced higher ambient levels than the prior study’s locations at DENA and HAVO. In short, the existing ambient at the site masked the lower-level noise of aircraft, making identification of aircraft noise events at lower exceedance levels more difficult. These findings should be considered when protected area managers seek to use the NPS ActiveSpace toolkit for understanding aircraft noise at specific sites within parks. Further, to improve specificity, this

study focused on a band from 20–1,250 Hz rather than the wider 20–20,000 Hz acoustic band used in other documents. Such analytical specificity is useful for monitoring purposes because it improves the attribution of noise energy to a given source of interest, but it is perhaps best suited for cases that show a larger baseline difference between these bands. The tradeoff to such an approach is that the sound levels reported here may be less easily compared to other scientific work.

Managing aircraft within protected areas poses significant challenges for park managers, namely because airspace is generally managed and regulated by another government organization, specifically in the U.S., which is the Federal Aviation Administration (FAA). Without the ability to control airspace, park managers must work with the airspace regulator or directly with aircraft operators. Understanding the locations of noise-sensitive areas, existing flight patterns, noise detection distances, and exceedance levels can assist park managers when communicating with regulators or operators. Further, many protected areas use aviation services for administrative purposes, including transportation of supplies and emergency response personnel. Again, understanding aircraft patterns and related noise can assist park managers in identifying the best routes, altitudes, and set down/landing locations to minimize the impacts of noise on cultural and natural resources, as well as the visitor experience.

A listener's point can be a historic site for visitors (such as Cades Cove Historic District, Elkmont Historic District) or a wildlife hotspot for species such as bald eagles and peregrine falcons (National Park Service, 2022). While we focused on sound levels within three functional effect categories (below 35, between 35 and 52, and above 52), the microphone-to-aircraft distance can be estimated for various sound level values or categories at which the wildlife behavior and ecology are impacted. Similar to this study, park managers can identify sound level

thresholds for various sensitive sites, focusing on backcountry users, wildlife endemism, and cultural hotspots, to determine the direct 3-dimensional detection distances at which aircraft become audible: the listener's active space. These thresholds can also inform recommendations for minimum vertical and lateral distances or the adoption of quieter aircraft technologies over or along these areas. However, sufficient acoustic data samples within the study area boundary are necessary to precisely differentiate the aircraft types and the distances

Specifically, for GRSM's Cade Cove, our findings revealed that the majority of audible air traffic was associated with aircraft originating from nearby airports—specifically, McGhee Tyson Airport and Gatlinburg–Pigeon Forge Airport, located north of GRSM. Additionally, it would be valuable to examine the audible distance (microphone-to-aircraft distance) and detection distance for rotorcraft, as these aircraft constitute the majority of the air tours operated by the authorized agencies in the park (National Park Service, 2022)—and typically fly below the designated 5,000 ft above ground level within the park. Few of these air tours operate above Cades Coves, so a future study would be required to analyze air tours. This consideration is particularly important for the Cherokee Orchard site, as the nearby sampling location at Bullhead Trail experienced greater helicopter noise exposure than other sites (Carpenter & Beeco, 2021). However, such an analysis could require a full summer and fall of acoustic and ADS-B data collection to ensure robust results for important sites.

Limitations of the study

One area of concern could be the F_1 scores for both aircraft types, which were 0.38 for "Light" aircraft and 0.35 for "Heavy" aircraft. A higher F_1 score is desirable in such experiments, for example, $F_1>0.6$. The lower F_1 scores indicated fewer audible events (and more inaudible events) inside the Cades Cove active space boundary, which, in turn, could affect the precision

and accuracy of the estimated microphone-to-aircraft distance and the detection distance to the active space boundary. As discussed above, this is likely due to the increased background ambient of Cades Cove. Therefore, in areas with higher background level, increasing the volume of acoustic and aircraft tracking data within the study area boundary could help address this limitation. In the previous study by Betchkal et al. (2023), there were 25,047 audible points for the HAVO site and 32,777 audible points for the DENA site, with corresponding F_1 scores exceeding 0.7. Another area of concern was the number of flight track points (point count) used to estimate the mean microphone-to-aircraft distance for the sound level category, $L_p \leq 35$ dB, for both aircraft types (see the last columns of Tables 2.2 and 2.3). These point counts were substantially lower than those associated with the sound level categories, namely $35 < L_p \leq 52$ dB and $52 < L_p$. Estimates based on larger point counts are likely to be more accurate than those derived from fewer points.

Concluding remarks

The study demonstrated that active spaces can be simultaneously constructed and compared for different anthropogenic noise sources, as demonstrated by the two jet aircraft categories in GRSM. Based on the NPS Active Space modules, the two jet aircraft categories generated distinct active spaces at the Cades Cove point, with the active space and detection distance of "Heavy" aircraft exceeding those of "Light" aircraft. "Heavy" aircraft were dominant over the area due to a higher frequency of aircraft noise events. Similar experiments can be conducted at ecologically and culturally significant sites in the park to inform noise mitigation strategies that account for the minimum lateral and vertical distances between the noise sources and the sites.

Chapter 3 - Examination of aircraft tracking technologies for overflight monitoring in Denali National Park and Preserve

Abstract

Low-level overflights, especially air tours, are a popular means of experiencing the beauty of parks and protected areas (PPAs). However, low-level overflights are common sources of anthropogenic noise in PPAs, disrupting the acoustic environment for wildlife and visitors. It is important for managers to understand low-level overflight travel patterns to design strategies that mitigate noise impacts. Automatic Dependent Surveillance-Broadcast (ADS-B) is widely used to track aircraft in varied locations; however, onboard GPS navigation systems are also utilized in many areas, including Denali National Park and Preserve (DENA) in the U.S. Each tracking system has its strengths and limitations, depending on the surveillance infrastructure, operating airspace, geography, and legal framework. This study aimed to determine which tracking technology is most effective in DENA by comparing the captured flight length, spatial coverage (based on the distribution), and altitudinal discrepancies of the waypoints obtained from these two systems. Eleven aircraft with 223 total flight records from the onboard GPS data were matched to corresponding records in the ADS-B data. Results indicate that waypoints from the ADS-B data covered, on average, 70% to 81% of the flight length and 86.8% of the spatial coverage of waypoints from the onboard GPS data in DENA, despite ADS-B's higher signal update rate. The ADS-B data logger failed to receive some signals from aircraft in certain locations within the Alaska Range, suggesting a terrain shielding effect not seen in the onboard GPS data. Also, most flights exhibited statistically significant differences in the mean altitudes of waypoints between ADS-B and onboard GPS data. The results highlight the effectiveness of

onboard GPS for overflight monitoring in rugged, mountainous terrain, as compared to ADS-B technology.

Keywords: ADS-B, onboard GPS, aircraft surveillance, Denali National Park and Preserve, air tours

Introduction

Air tours have become a popular means of sightseeing in parks and protected areas (PPAs) (Beeco & Joyce, 2019). These tours involve low-level aircraft flying over PPAs specifically for sightseeing purposes (Peterson et al., 2022). Commercial air tours (sightseeing over the park) account for a notable proportion of airspace usage over some United States National Park Service (NPS) units. In 2019, there were 48,760 reported air tours at 50 NPS units, excluding the tours over the Grand Canyon, Alaska, and those over Lake Mead that were classified as "for transport only," while Grand Canyon accounted for over another 100,000 reported air tours and related flights in 2018 (Lignell, 2020).

In the U.S., the Federal Aviation Administration (FAA) has the authority to regulate airspace and to ensure the safety of aircraft and the efficient utilization of airspace (*Federal Aviation Administration Act,* 1958). The FAA conducts aircraft surveillance and monitoring. Flight data monitoring involves a systematic, proactive, and non-punitive use of digital flight data from routine operations to improve aviation safety and monitor flight compliance (Zarikoff et al., 2014). The NPS has a significant role in addressing anthropogenic noise in NPS units, as per the provisions of the NPS Organic Act (1916) and its amended Redwood Act of 1978 (Pancic, 1997). NPS Organic Act has the provision that NPS shall conserve scenery, natural

resources, and historic resources and provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for future generations.

These two disparate missions between agencies coalesced when the U.S. Congress passed the National Park Air Tour Management Act in 2000, as amended (49 USC 40128), requiring the FAA and NPS to work together to manage air tours over NPS units. The FAA Modernization and Reform Act of 2012 made it mandatory for air tour operators to submit their air tour data to NPS in a prescribed format, titled "Commercial Air Tour Reporting Data." The report follows a simple format, requiring operators to provide the date and hour of the tour, the model of the aircraft, and the name of the flight route (National Park Service, 2022).

Beginning in 2022, the FAA and NPS released several air tour management plans (ATMPs). These plans included new requirements for submitting flight monitoring data. The flight monitoring technology captures the spatiotemporal position of aircraft along with other key information, and the data are submitted as an attachment with the operator's semi-annual reports. The aviation community has been using various light-weight, low-cost, flexible flight monitoring equipment and software applications (Zarikoff et al., 2014). They include onboard GPS technologies supported by satellite navigation systems, such as Spidertracks and Garmin technology, that are widely used for flight surveillance.

Another type of flight monitor technology is Automatic Dependent Surveillance-Broadcast (ADS-B). ADS-B Out emits radio signals relaying real-time information about the aircraft, including its latitude, longitude, altitude, and unique identification code (Beeco & Joyce, 2019). This information is broadcast to ground stations and other aircraft, which increases operators' situational awareness, safety, and surveillance. The FAA requires all aircraft entering

designated airspace to be equipped with ADS-B Out Avionics beginning from January 1, 2020 (14 CFR § 91.225 and 14 CFR § 91.227).

Each technology, onboard GPS and ADS-B, possesses distinct benefits and areas of improvement. The adoption of a particular technology is dictated by various factors, such as the cost of installation on the aircraft, the cost of surveillance infrastructure on the ground, the cost of broadcasting or receiving radio signals, the extent of spatial coverage in rugged or mountainous topography, accessibility to ground equipment sites, etc. However, there is a research gap regarding which technology would be more effective at tracking aircraft in the mountainous United States national parks.

Flight surveillance, including flight compliance monitoring, has always been a challenge in the aviation sector, especially over protected areas that are remote, mountainous, have little infrastructure, and are not easily accessible—all qualities that make these areas attractive to commercial air tours. Previous studies showed ADS-B technology as a viable method for tracking and broadly understanding overflight patterns over PPAs (Beeco & Joyce, 2019). However, multiple years of analyzing flight patterns at PPAs suggest that ADS-B data likely do not have the fidelity to ensure compliance with ATMP requirements, especially in mountainous topography (Beeco et al., 2020). Far fewer analyses have been conducted for onboard GPS technologies, though the technology would seem to be more capable of providing the fidelity needed for checking compliance with ATMP conditions. Moreover, a comparative analysis of onboard GPS and ADS-B technologies at PPAs is a research gap.

This research is guided by the broad management question:

Is ADS-B or onboard GPS more effective for tracking aircraft above PPAs?

The study compares ADS-B data and onboard GPS data by analyzing the captured flight length, spatial coverage, and altitude distributions of the waypoints. To date, the only national park in which both onboard GPS data and ADS-B datasets are available is Denali National Park and Preserve (DENA), Alaska, U.S.

Literature Review

Onboard GPS satellite communication devices for aircraft surveillance

Onboard GPS navigation systems include various lightweight flight data recorders and advanced data acquisition units, capable of real-time event reporting and automated post-flight wireless data transfer procedures (Zarikoff et al., 2014). Third-party vendors provide standardized interfaces for obtaining flight data, including Spidertracks, Web Sentinel, Garmin, GSat, ForeFlight, and inReach. Iridium (or similar) satellite constellations or networks are increasingly used in low-cost satellite communication devices in the aviation sector (Glasgow & Niehus, 2012). Iridium represents a group of 66 low-earth orbiting satellites with global coverage, providing commercial voice and data services (Glasgow & Niehus, 2012). Many vendors have developed Iridium-based devices that are smaller and cost-effective in providing information and surveillance data to their clients. For example, Spidertracks is an Iridium-supported device that can be installed in a light or smaller plane and is connected to the central computer via satellite, providing essential flight information, data, and insights about the aircraft to its clients or subscribers. Spidertracks has been adopted in more than 100 countries, with the U.S. being its largest market (Downs & Dickinson, 2018).

Lockheed Martin developed and deployed its high-level model for the Surveillance-Enhanced Search and Rescue (SAR) system, with Spidertracks being the first supported Iridium

device, in 2013 (Glasgow & Niehus, 2012). Currently, Spidertracks provides integrated end-to-end hardware and software support to its clients in the aviation sector. Spidertracks has global connectivity via a satellite network, ensuring minimal signal loss in its spatial coverage. Spidertracks is a private and secure network system that employs high-level encryption for transmitted information, which can only be accessed with proper authorization. Real-time tracking involves monitoring an aircraft's flight route, including information about its location, velocity, altitude, and precise GPS position at defined intervals along the route. These onboard GPS systems are subscription-based, and depending on the plan package, operators may be charged per "ping"—adding a cost to the operators using or required to use such services.

Automatic Dependent Broadcast – Surveillance (ADS-B)

The FAA's Next Generation (NextGen) Initiative mandated that starting January 1, 2020, all aircraft flying in designated or controlled airspace or into any airport requiring a transponder must be equipped with ADS-B Out avionics (Larsen, 2020). ADS-B surveillance technology is cooperative and dependent, with the aircraft aiding the surveillance process by transmitting its location to ground controllers and other aircraft. This surveillance capability relies on the equipment installed in the aircraft (Samuelson et al., 2006). ADS-B technology automatically (A) transmits data without operator or pilot input; is dependent (D) on the other navigational systems for position and velocity in space; conducts identification of other aircraft and surveillance (S) of the area; and broadcasts (B) its position and information using a radio signal (Larsen, 2020). The cooperative equipment or a data link transmitter is installed on the aircraft and periodically emits its position, derived from the Global Navigation Satellite System (GNSS), along with other information such as a unique identification code, altitude, and velocity. This information is transmitted to both ground-based and space-based receivers for processing and

display at air traffic control facilities or on other suitably equipped aircraft (Federal Aviation Administration, 2023). ADS-B represents an improvement over secondary surveillance radar (SSR), as it allows information to be received by other aircraft, thereby enhancing situational awareness (Giladi, 2020).

In addition to the U.S., many countries in the Asia-Pacific region adopted ADS-B technology after testing and evaluating its performance in the late 2000s. An assessment of aircraft data conducted in western China found the performance and accuracy of ADS-B to be superior to radar (Zhang et al., 2011). The update rate of radar data is one message every 4 seconds, while ADS-B provides one message every 0.5 seconds, offering significantly better temporal resolution. ADS-B data can be freely acquired, decoded, and analyzed by deploying relatively simple and inexpensive ADS-B receivers or data loggers on the ground (Beeco & Joyce, 2019; Giladi, 2020). Installing ADS-B equipment or transponders in smaller aircraft is particularly critical, as smaller aircraft often go undetected by radar.

The issue of terrain shielding is prevalent in the ADS-B system because ADS-B data loggers must remain in the line of sight of transmitted signals from ADS-B Out avionics. The terrain shielding is particularly pronounced in areas with substantial terrain changes or drastic variations over short distances, such as mountains, canyons, and volcanic landscapes—common terrain types in PPAs.

In perhaps the first examination of aircraft tracking over a protected area, ADS-B data loggers were tested at Haleakalā National Park (HALE) in the U.S., and it was found that terrain shielding disrupted the ADS-B signals from aircraft (Beeco & Joyce, 2019). The effect of terrain shielding was minimized by deploying two loggers simultaneously, which improved the data capture rate to 70% in a 2019 experiment at HALE (Beeco et al., 2020).

Low-level overflights tracking and compliance monitoring in PPAs

Low-level overflights impact the acoustic environment and can disrupt natural resources, cultural resources, and the visitor experience (Peterson et al., 2022). The FAA recommends that aircraft flying over noise-sensitive areas, including National Parks, National Wildlife Refuges, Waterfowl Production Areas, and Wilderness Areas, should maintain an altitude of at least 2,000 feet above ground level (Federal Aviation Administration, 2004). This practice helps conserve the natural acoustic environment and minimizes interference with wildlife and visitors' experiences.

With the introduction of ADS-B technology in aircraft, the U.S. NPS has been able to passively collect flight data using ADS-B data loggers installed on the ground with expansive skyward exposure. These terrestrial data loggers can collect ADS-B data because it is unencrypted and publicly accessible (Beeco & Joyce, 2019). The NPS has collected ADS-B data to analyze spatial patterns of overflights in many PPAs such as Hawai‘i Volcanoes National Park, Haleakalā National Park, Great Smoky Mountains National Park, Glacier National Park, and Grand Canyon National Park (National Park Service, 2024).

Many countries, including those within the European Union, Canada, Singapore, Taiwan, Vietnam, and Australia, have mandated ADS-B in their designated airspace (Aircraft Owners and Pilots Association, 2024). FAA’s Capstone Project from 2000-2004 demonstrated that ADS-B improved aviation safety in Alaska (Ali et al., 2015). Over 40 ADS-B ground stations are providing operational networks and filling major gaps, particularly in low-altitude routes in Alaska (Federal Aviation Administration, 2024). Aircraft have also been using onboard navigation systems or onboard GPS, particularly those for commercial air tours flying outside FAA-designated airspace. Signal loss is rare because aircraft remain in the satellite's line of

sight. Signal update intervals may vary depending on the aircraft or device, and these signals are not publicly accessible. Additionally, signal transmission is not automatic; it depends on the operator or pilot. Researchers have compared the performance of ADS-B with radar (Zhang et al., 2011), but a comparison of ADS-B with onboard GPS, especially for low-level overflights above mountainous PPAs, is unknown to the authors.

Study Objectives

This study compared the overflight tracking data obtained from onboard GPS systems and ADS-B data loggers to evaluate performance effectiveness in DENA. The two monitoring tools are widely used in aircraft tracking in DENA. This study's objective is addressed through the following specific research questions.

RQ1: Are there differences between onboard GPS and ADS-B technologies in their flight length?

RQ2: How do GPS and ADS-B technologies compare for spatial coverage—operationalized as the number of standardized grid cells encountered?

RQ3: Are there significant altitude discrepancies between the waypoints from onboard GPS and ADS-B data?

Methods

The first task of this analysis was to identify and screen the same aircraft and flight from the two datasets—onboard GPS and ADS-B—using geospatial tools (ArcGIS Pro and `ArcPy`). The key steps in this analysis include:

1. Generate (multi-point) feature classes from the geospatial data obtained from the onboard GPS and ADS-B data logger.
2. Segment data across aircraft by identifying unique registration numbers in the onboard GPS data.
3. Apply the same aircraft registration numbers from the onboard GPS data to the ADS-B data.
4. Using a unique registration number (representing an aircraft), apply the timestamp (departure time and landing time) of waypoints from the onboard GPS data to select corresponding waypoints from the ADS-B data for each aircraft's flight.
5. Map and compare the same flight recorded by the onboard GPS and ADS-B systems by analyzing flight length, waypoints distribution, and altitudinal differences. Use this information to examine the issue of signal latency.
6. Develop an automated toolbox containing two custom geoprocessing tools from the Python codes: one for parsing the data by registration number, and another for screening waypoints based on timestamps.

All maps in this study were created using ArcGIS Pro software by ESRI.

A flowchart illustrating the methodological steps is presented below (Fig. 3.1).

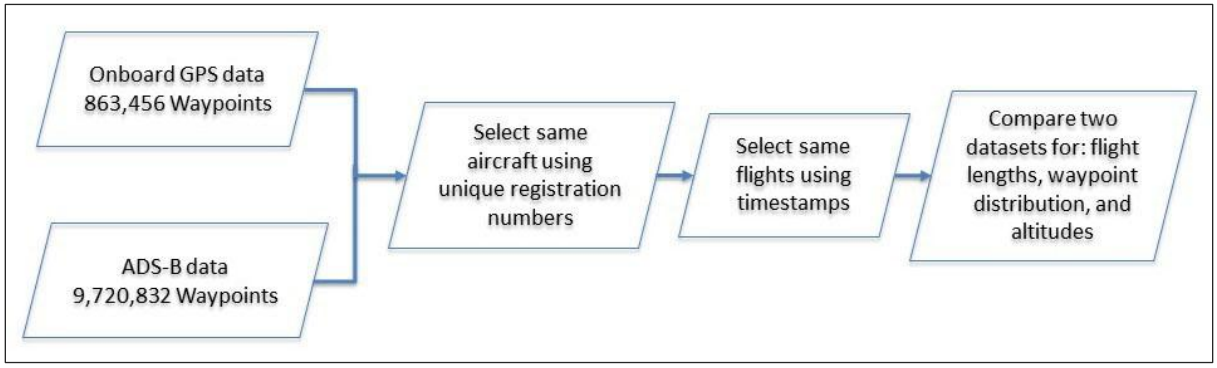

Figure 3.1 *Flowchart of methodological steps.*

The `ArcPy` script and link to the ArcGIS custom toolbox are provided in the Appendix (as supplementary materials).

Study Site

DENA is located in south-central interior Alaska (Fig. 3.2) and encompasses six million acres of wild land, with two million acres as designated wilderness (within the national park), and the remaining four million acres managed as wilderness (in the national preserve and the remaining part of the national park). DENA contains some of the most iconic glaciers in Alaska, including Ruth Glacier, Kahiltna Glacier, and Muldrow Glacier (National Park Service, 2023a). Mount McKinley, the highest mountain in North America, stands at 20,310 feet above mean sea level (MSL). The park's ecosystems include lowland taiga forests, braided glacial stream floodplains, meandering sloughs, subalpine woodlands, meadows, tundra, and steep peaks. There are 39 species of mammals, 165 species of birds, 15 species of fish, and 750 species of vascular plants. Birds migrate to DENA from as far away as South America, Asia, and Africa.

DENA faces threats on multiple fronts, including glacial retreat, shifts in vegetation, increased tourism, and development (Hooge et al., 2006). The annual number of recreation visitors peaked at 601,152 in 2019, dropped during the COVID-19 pandemic in 2020, and has gradually increased since, reaching 427,562 in 2022 and 498,722 in 2023 (National Park Service, 2023b). Buses are the primary means of accessing the interior of the park (Tranel, 2006), and there is only one road leading to the park, part of which is occasionally inaccessible. After the designation of Mount McKinley National Park as Denali National Park and Preserve in 1980, the NPS issued concession permits for aircraft glacier landings, particularly near Ruth Glacier (Tranel, 2006). Today, DENA draws thousands of mountaineers each year, as well as even more backpackers and explorers (Carpenter, 2014), which, in turn, generates a high volume of air taxi

services and air tours into the area. Inherent differences among park users are evident, including concerns about aircraft noise (Tranel, 2006). Such low-level overflights frequently hinder wilderness users from enjoying remoteness, solitude, and natural soundscape (Tranel, 2006).

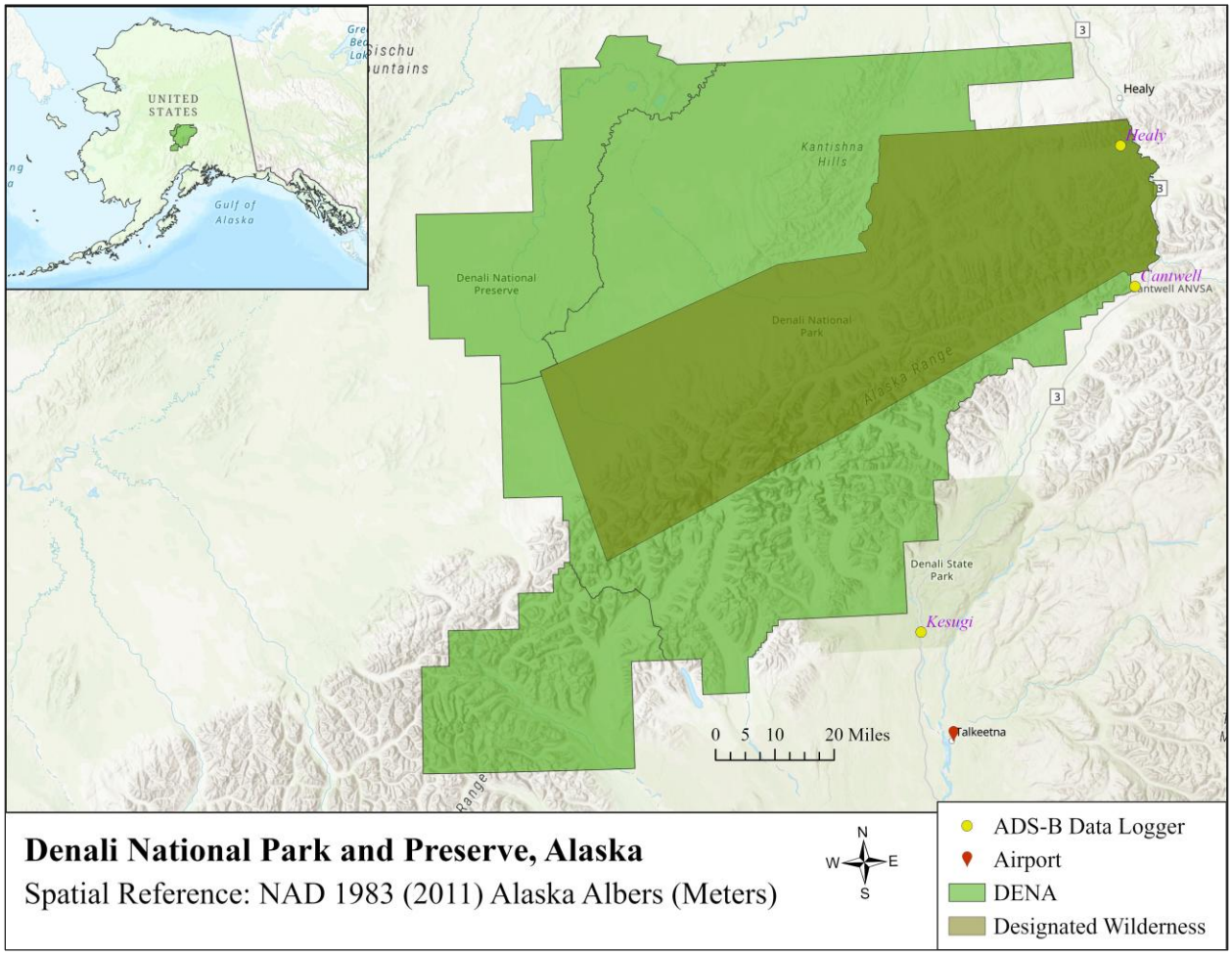

Figure 3.2 *Denali National Park and Preserve (DENA).*

Data collection

Aircraft onboard GPS and ADS-B data were analyzed, which is the first time that park administrators have collated these datasets. The two datasets were collected for the same geographic scope; thus, this provided the ideal criteria for comparing onboard GPS and ADS-B technologies.

The first set of data comprised onboard flight monitoring data recorded by five commercial air tour companies and 28 unique aircraft. Onboard GPS devices recorded flight tracks using various commercial platforms, including AFF, Garmin, GSat, ForeFlight, inReach, Spidertracks, and Web Sentinel. The aircraft monitoring datasets were recorded in different years, depending on the aircraft company (Table 3.1). These datasets were parsed into an SQL database and subsequently converted to JSON format and then to geodatabase feature classes.

The second set of geospatial data were collected using ADS-B data loggers deployed at three locations in and around DENA during various periods in 2021, 2022, and 2023: Old Town Cantwell (-148.959643, 63.395081), Healy Radio Repeater (-148.981483, 63.73855), and K'esugi Ken Ranger Station (-150.231063, 62.592057). ADS-B data were retrieved and converted to TSV format and then converted to a geodatabase feature class using ADS-B Overflight Analysis Toolbox (Hutchinson & Peterson, 2023). The dates of flight data from the two sources overlapped, and the datasets were compared.

Table 3.1 *Dates of data recorded by onboard GPS and ADS-B data loggers*

Onboard GPS (air tour companies)	**Date**	**ADS-B data logger**	**Date**
First	03/17/2021–10/16/2023	Cantwell	09/18/2021–06/06/2022
Second	05/08/2021–09/26/2021	Healy	06/17/2023–09/12/2023
Third	06/05/2018–08/30/2019	K'esugi	05/20/2022–10/06/2022
Fourth	04/22/2021–07/31/2023		(with gaps in the dates)
Fifth	05/14/2021–07/28/2023		05/25/2023–09/13/2023

Comparing the flight length

The waypoints in the onboard GPS and ADS-B datasets were compared by measuring the length of the flights in each dataset (feature class) in miles using ArcGIS Pro. The same flight ID

appearing in both datasets (onboard GPS and ADS-B) was manually identified, and the corresponding flight lengths were recorded for ratio or proportion estimation.

Spatial coverage of waypoints

Spatial coverage was estimated based on the distribution of waypoints across the study area. This was analyzed to understand the coverage and gaps between the two systems. To understand spatial coverage, a grid analysis was used, and the grid cell size was determined using a spatial statistical approach. The steps are shown below:

1. Aircraft waypoints were identified using unique registration numbers and matched for the two datasets. The two datasets were merged and labeled for each aircraft.
2. The ArcGIS Pro tool "Calculate distance band from neighbor Count" was applied to the merged data, and the "maximum 1 neighbor distance" was considered for grid cell size, which was calculated for each aircraft.
3. The "Grid index features" tool was applied to generate digital grids for onboard GPS and ADS-B datasets.
4. Grid cells occupied by onboard GPS waypoints and ADS-B waypoints were counted separately, and the ratio was calculated for each aircraft.
5. Steps 1–4 were repeated for all remaining matched aircraft and resulted in different grid cell sizes for each aircraft. The number of grid cells occupied was calculated for onboard GPS waypoints and ADS-B waypoints for each aircraft.

The grid cell size was calculated separately for each registration number because each aircraft equipped with an onboard GPS had a unique signal update rate based on its subscription to the third-party service provider. Therefore, the waypoint distributions were different for each

aircraft. Additionally, kernel density analysis was conducted to assess the density distribution of onboard GPS and ADS-B waypoints, separately over DENA.

Comparing altitude distributions of onboard GPS and ADS-B waypoints

The altitude distributions were analyzed by comparing each matched flight's *z*-values measured in MSL in meters. ADS-B measured altitude based on barometric pressure, which relied on the standard atmospheric temperature profile. Onboard GPS measured geometric altitude, obtained directly from satellite signals. What became readily apparent is that no waypoints between these datasets aligned perfectly in space or time, which created challenges in making exact locational comparisons. Therefore, pairing the waypoints from the onboard GPS and ADS-B datasets for the same flight was not possible. The waypoints were saved in CSV format, and a two-sample t-test in R was used to compare altitude discrepancies between waypoints from the same flights in the onboard GPS and ADS-B datasets.

We attempted to pair waypoints temporally using the timestamps of waypoints from the onboard GPS dataset (feature class) and selecting the corresponding waypoints from the ADS-B dataset. However, timestamp pairing was unsuccessful due to slightly differing time intervals between onboard GPS and ADS-B waypoints. Alternatively, waypoints were paired spatially by manually assessing the proximity of ADS-B waypoints to onboard GPS waypoints. This was achieved using the "Multiple Ring Buffer" and "Generate Trade Area Rings" tools with buffer distances of 20, 30, 40, and 50 meters around the onboard GPS waypoints. ADS-B waypoints were selected based on their proximity to the onboard GPS waypoints.

Results

Parsing datasets using registration numbers

A total of 863,456 onboard GPS waypoints were collected for the five air tour companies. These data contained 28 unique registration numbers (aircraft) as listed below, because air tour companies often have many aircraft in their fleet.

- The first company's dataset contained 12 unique registration numbers (aircraft) and was parsed into 12 smaller datasets (feature classes): N_A1 through N_A12.
- The second company's dataset contained two unique registration numbers and was parsed into two smaller datasets (feature classes): N_B1 and N_B2.
- The third company's dataset contained four unique registration numbers and was parsed into four smaller datasets (feature classes): N_C1 through N_C4.
- The fourth company's dataset contained three unique registration numbers and was parsed into three smaller datasets (feature classes): N_D1 through N_D3.
- The fifth company's dataset contained seven unique registration numbers and was parsed into seven smaller datasets (feature classes): N_E1 through N_E7.

The ADS-B data contained 9,720,832 waypoints for 22,685 flights. The 28 unique registration numbers from the onboard GPS datasets (feature classes) were applied to screen and parse the waypoints in the ADS-B dataset. Twenty-five registration numbers were found in the ADS-B dataset, which indicates that 25 aircraft were equipped with both onboard GPS and ADS-B systems.

A visual example of these datasets is seen in Figure 3.3, which is for a single aircraft referred to as "N_A12". For this aircraft, its ADS-B dataset had 75,434 waypoints and 69 flights, and its onboard GPS dataset had 2,856 waypoints and 15 flights. This example shows the difference in temporal resolution of the two tracking technologies. Interestingly, the onboard

GPS data were collected along glaciers located between steep mountains, which are seen in the northern areas of Figure 3.3.

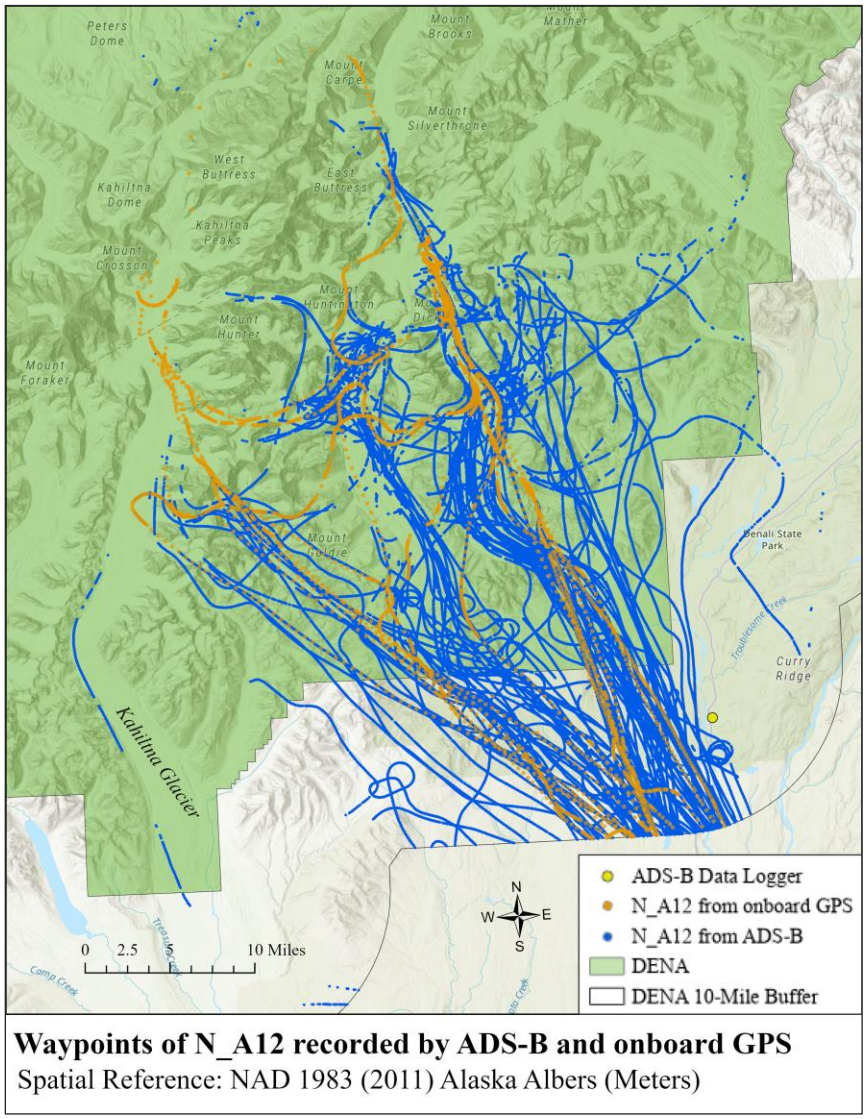

Figure 3.3 *Waypoints of aircraft N_A12 recorded by onboard GPS and ADS-B data logger.*

Using timestamps to select same flights (waypoints) from onboard GPS and ADS-B datasets

Next, the analysis focused on individual flights by the selected aircraft. The same flights were selected from the two datasets using timestamps. The "departure time" and "landing time" of the onboard GPS dataset were applied to screen the ADS-B dataset, and 223 flights from 11

aircraft met the timestamp criteria (Table 3.2). Ten aircraft belonged to one air tour company, while one aircraft belonged to another company. All matched aircraft were fixed-wing single-engine planes with propeller-type engines. The average signal update rate for the onboard GPS ranged from 3 to 24 seconds.

Table 3.2 *Aircraft with matching flights in onboard GPS and ADS-B datasets; bold text indicates the highest and lowest signal update rate*

Matched registration numbers	Number of matched flights	Onboard GPS waypoints	ADS-B waypoints	Signal update rate of onboard GPS in seconds
N_A1	6	59	3,661	**24.1**
N_A2	4	683	3,158	8.5
N_A4	32	4,997	21,480	9.0
N_A5	6	1,064	4,216	7.1
N_A6	31	4,404	19,765	9.7
N_A7	28	4,211	16,369	9.2
N_A9	26	5,434	21,763	8.3
N_A10	40	6,093	26,839	9.7
N_A11	29	4,116	20,021	12.7
N_A12	4	936	3,340	7.7
N_D2	17	25,174	26,136	**3.1**
Total	**223**	**57,710**	**166,747**	

As an example, aircraft N_A12 had four matching flights (2 pairs each), which are displayed in Figure 3.4. These waypoints represent four flights that occurred on June 15 and 16, 2023. Corresponding waypoints were connected by thin blue (ADS-B) and brown (onboard GPS) lines. These flights exhibited a typical travel pattern associated with air tours and air taxi services originating from Talkeetna Airport, which is located south of DENA. They followed a

route along Ruth Glacier, Tokositna Glacier, and Kahiltna Glacier until reaching the base of Mt. McKinley.

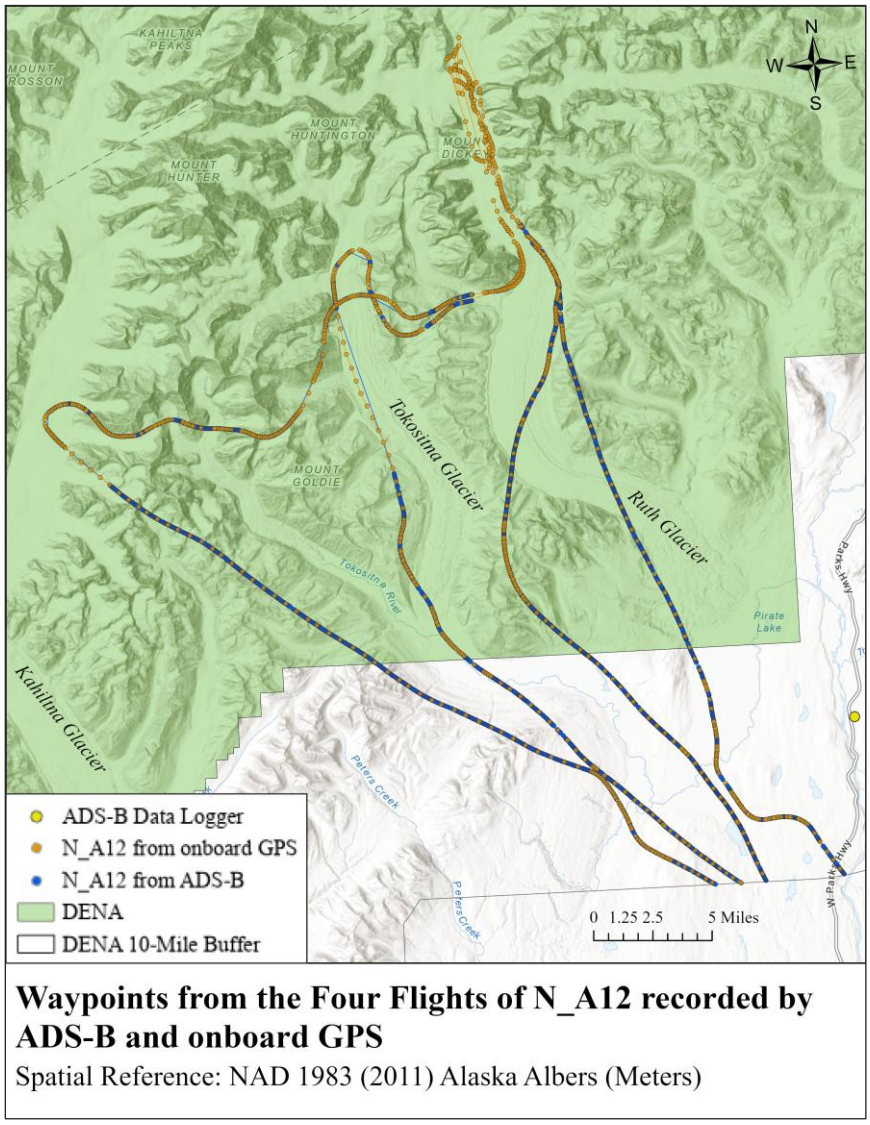

Figure 3.4 *Four flights (two pairs) of aircraft N_A12, recorded by onboard GPS and ADS-B data logger.*

Research Question 1: Comparison of flight lengths

The ratio or percentage of the flight length was calculated for each flight from the ADS-B dataset to the onboard GPS dataset (Table 3.3). We compared the lengths of 194 flights out of the 223 matched flights from the onboard GPS and ADS-B datasets, excluding 29 flights due to

errors in ADS-B waypoints' timestamps. In Table 3.3, the average ratio represents the mean of all ratio values for a given aircraft, while the minimum and maximum indicate the lowest and highest ratio values, respectively. On average, the ADS-B waypoints covered 69.9% to 80.7% of the flight length of the onboard GPS waypoints.

Table 3.3 *Comparison of recorded flight lengths from ADS-B and onboard GPS datasets; bold text indicates the highest and lowest ratios*

Registration number	Number of flights compared	Average ratio	Minimum ratio	Maximum ratio
N_A1	4	76.3	67.1	81.6
N_A2	4	80.3	72.2	86.5
N_A4	29	76.9	40.8	95.8
N_A5	6	80.4	66.1	85.1
N_A6	23	76.3	63.6	97.6
N_A7	24	**80.2**	49.3	99.8
N_A9	21	80.7	58.4	98.4
N_A10	38	75.6	12.8	94.6
N_A11	24	73.0	14.9	94.8
N_A12	4	76.8	50.2	94.7
N_D2	17	**69.9**	55.5	96.9

Welch's two-sample t-test was conducted on the 194 flight length values from the onboard GPS and ADS-B datasets. The results indicate a statistically significant difference in flight lengths between the two datasets (Table 3.4).

Table 3.4 *A Two-sample t-test for the same flight lengths from onboard GPS and ADS-B datasets*

Method	Alternative	Mean 1	Mean 2	$M_1 - M_2$	t	df	p	95% CI

Welch Two Sample t-test	two.sided	40.08	53.87	-13.79	-6.62	344.09	< .001***	[-17.89, 9.69]

Research Question 2: Analysis of waypoints' spatial coverage using a digital grid

The grid cell size was estimated separately for 11 aircraft using the ArcGIS Pro tool "Calculate distance band from neighbor Count." The spatial coverage for each aircraft was calculated based on grid cell size and grid occupancy by waypoints from the ADS-B and onboard GPS datasets and is presented in Table 3.5. On average, the spatial coverage of ADS-B waypoints was 86.8% of that of onboard GPS waypoints in DENA. Grid sizes varied by aircraft due to gaps in waypoints caused by differences in signal update rates of onboard GPS waypoints and terrain-induced shielding of ADS-B waypoints.

Table 3.5 *Spatial coverage estimated from grid occupancy by waypoints; bold text indicates the highest and lowest ratio*

Registration number	Grid size (meters)	Grids occupied by ADS-B waypoints	Grids occupied by onboard GPS waypoints	Ratio
N_A1	2918	69	74	93.2
N_A2	3444	68	81	84.0
N_A4	2480	253	310	81.6
N_A5	1006	309	320	**96.6**
N_A6	1283	714	782	91.3
N_A7	2296	316	377	83.8
N_A9	1598	446	485	92.0
N_A10	4054	134	168	79.8
N_A11	4041	142	171	83.0
N_A12	922	323	338	95.6
N_D2	430	3,554	4,808	**73.9**

Average	**86.8**

As an example, Figure 3.5 shows the digital grid for aircraft N_A12 with the ADS-B and onboard GPS waypoints; this digital grid had a grid cell size of 922 meters. This figure shows that there are many grid cells that are occupied by onboard GPS waypoints but not by ADS-B waypoints. Notably, the spatial coverage for ADS-B is lacking in the northern areas of the figure, which is an area characterized by rugged mountains and glacial canyons.

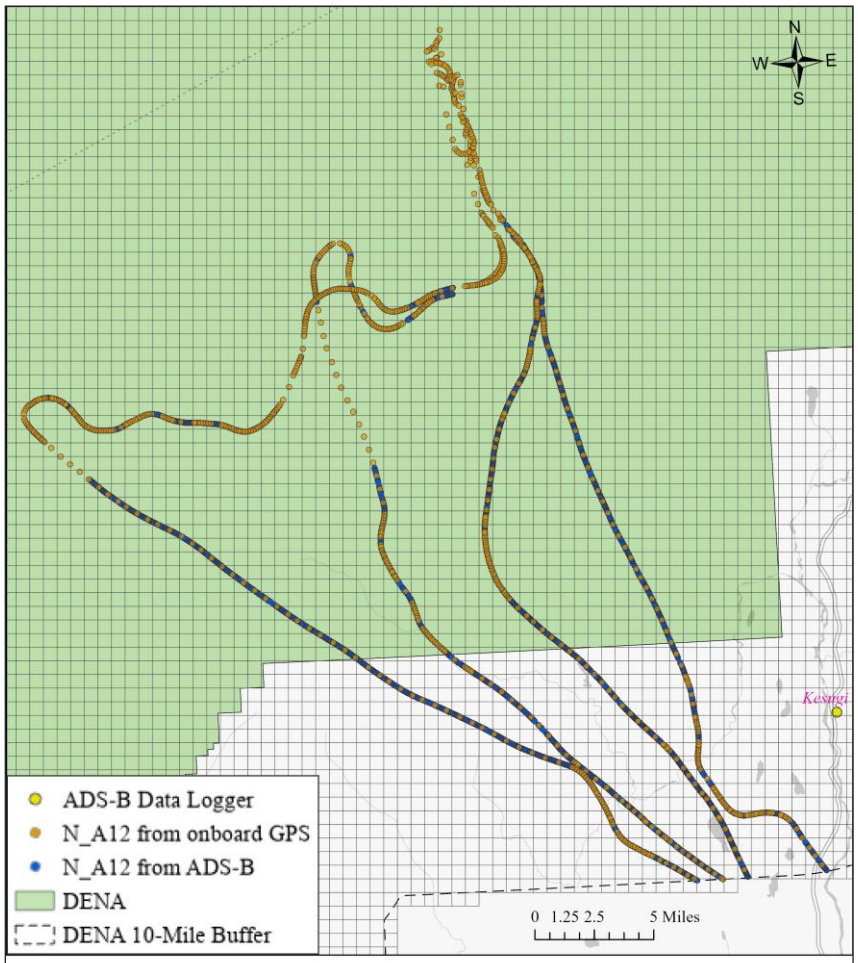

Figure 3.5 *ADS-B and onboard GPS waypoints over the grids for aircraft N_A12.*

Kernel density analysis displayed density hotspots for onboard GPS waypoints near mountainous regions (Fig. 3.6), whereas those for ADS-B waypoints were located in lower areas of DENA (Fig. 3.7). The signal update rate (i.e., temporal resolution) of ADS-B was higher than that of onboard GPS, resulting in a higher density of ADS-B waypoints. The geoprocessing tool, "Band Collection Statistics," showed a weak correlation (r = 0.36) between the two raster images.

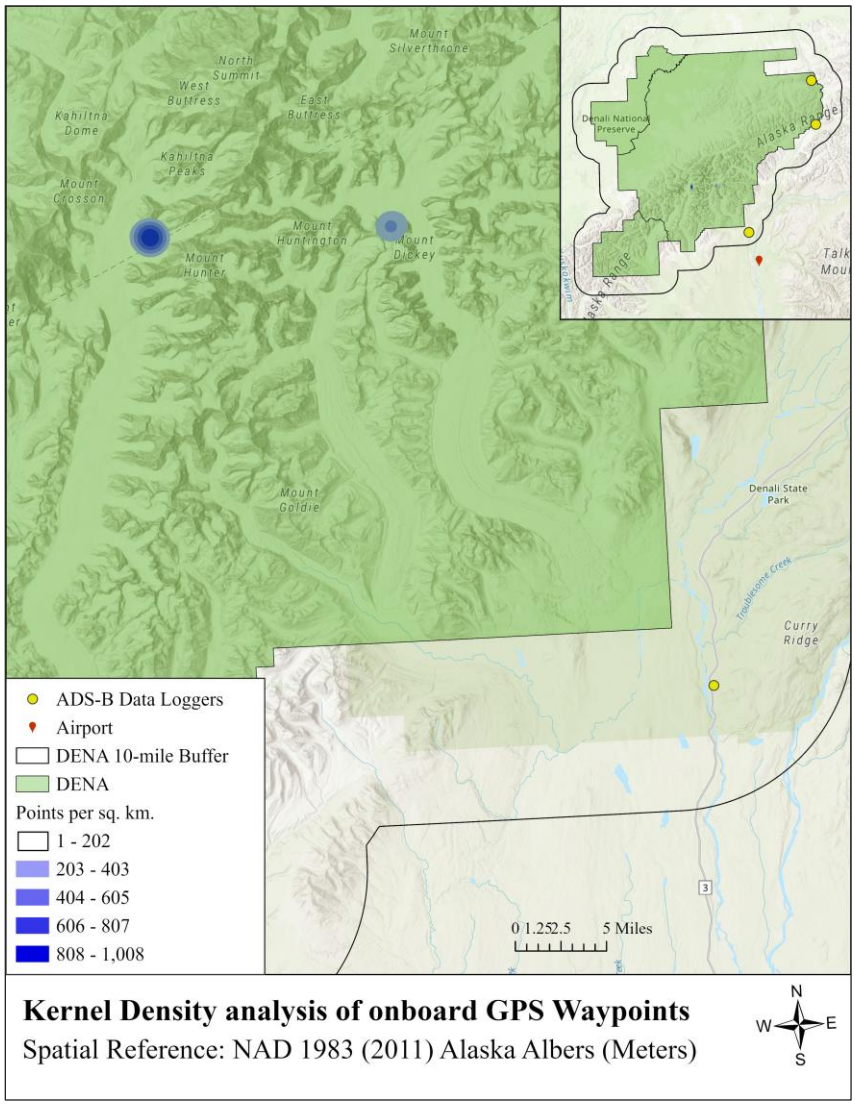

Figure 3.6 *Kernel density of onboard GPS waypoints.*

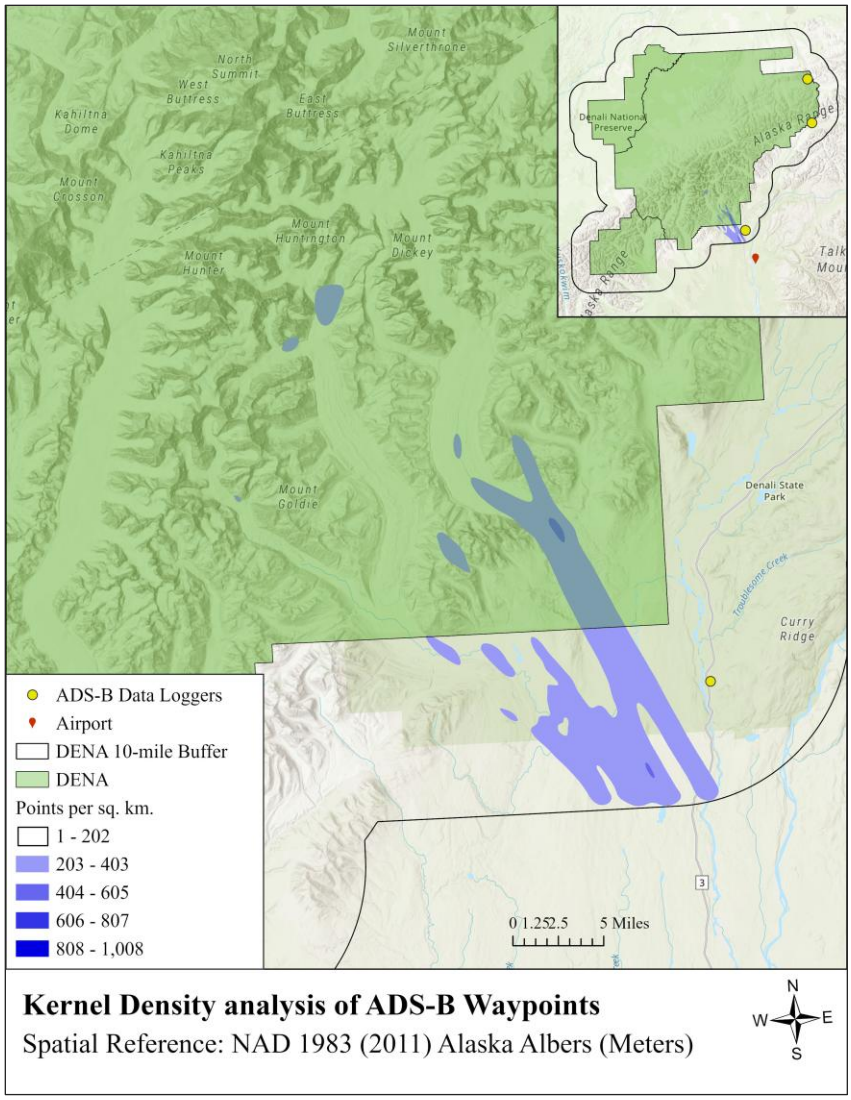

Figure 3.7 *Kernel density of ADS-B waypoints.*

Research Question 3: Comparison of altitude distributions

Comparison of altitudes between onboard GPS and ADS-B waypoints was conducted without pairing the waypoints because few waypoints aligned in space and time. A two-sample t-test was conducted on all the waypoints from 223 flights from the onboard GPS and ADS-B datasets. At a 95% confidence level, 171 flights showed statistically significant differences in the mean altitudes (MSL) of the waypoints from onboard GPS and ADS-B datasets or feature classes

(52 flights did not show statistically significant differences for mean altitudes). For 160 flights, the mean altitudes of waypoints from the ADS-B datasets were lower than those from the corresponding onboard GPS datasets. ADS-B used barometric pressure to measure the altitudes, whereas onboard GPS used geometric altitudes.

As an example, two representative cases from the 171 t-tests are presented in Figures 3.8 and 3.9: one showing no statistically significant difference in altitude distribution, and the other showing a statistically significant difference. The distribution of waypoints from a flight by aircraft N_A12 (referred to as N_A12_1) is shown in the box-and-whisker plot (Fig. 3.8). The distribution of altitudes (MSL in meters) for the two groups of waypoints was nearly identical.

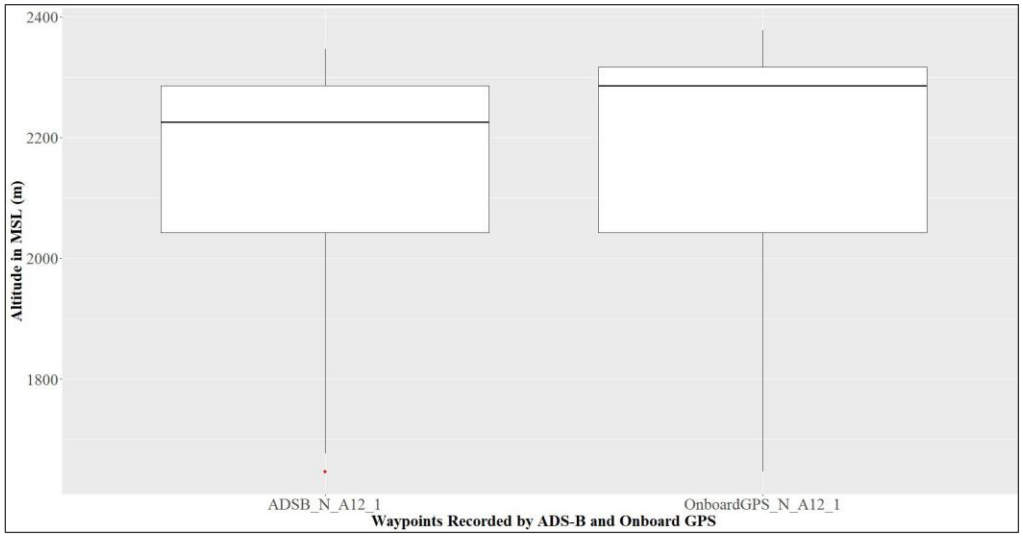

Figure 3.8 *Box-and-whisker plot of the waypoints for N_A12_1.*

To further examine this result, a two-sample t-test for N_A12_1 is shown in Table 3.6. At a 95% confidence level, the p-value was 0.223, the t-statistic was -1.22, the mean altitude for ADS-B was 2149.22 meters, and the mean altitude for the onboard GPS was 2166.47 meters (n_1 = 646, n_2 = 217). The test results indicate that the difference in mean altitudes was not statistically significant (two-tailed test) at the 95% confidence level or the 5% significance level

for waypoints from flight N_A12_1. Similarly, the effect size was calculated in R, and Cohen's d-value was 0.10 for these datasets, indicating a small effect size.

Table 3.6 *Two-sample t-test of MSL altitudes for waypoints from onboard GPS and ADS-B datasets for flight N_A12_1*

Method	Alternative	Mean 1	Mean 2	M_1 - M_2	*t*	*df*	*p*	95% CI
Welch Two Sample t-test	two.sided	2,149.22	2,166.47	-17.25	-1.22	384.12	.223	[-45.05, 10.05]

In another case, an altitudinal difference between waypoints for the two datasets was observed for a flight by aircraft N_D2 (referred to as N_D2_16). The distribution of altitudes of waypoints from the ADS-B and onboard GPS datasets, measured in MSL (meters), was analyzed using a box-and-whisker plot (Fig. 3.9) and a two-sample t-test in R (Table 3.7). The analysis revealed a significant difference in mean altitude between the two sets of waypoints (n_1 = 1452, n_2 = 731, *p-value* < 0.001). Similarly, the effect size was calculated in R, and Cohen's d-value was 0.88 for these datasets, indicating a large effect size. The ADS-B data, using barometric pressure for altitude measurement, showed higher altitude readings.

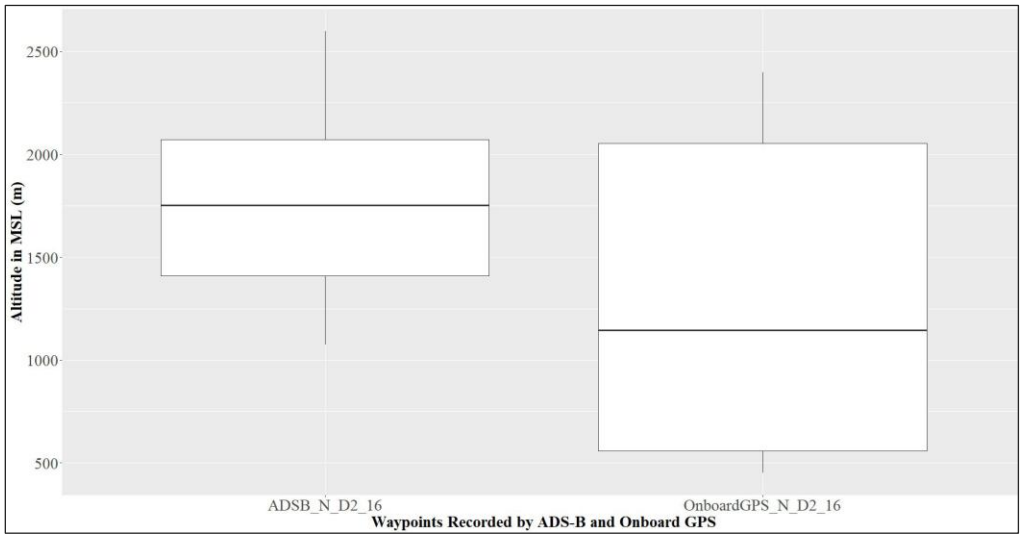

Figure 3.9 *Box-and-whisker plot of waypoints for flight N_D2_16.*

Table 3.7 *Two-sample t-test of MSL altitudes for waypoints from onboard GPS and ADS-B dataset for flight N_D2_16*

Method	Alternative	Mean 1	Mean 2	M_1 - M_2	*t*	*df*	*p*	95% CI
Welch Two Sample t-test	two.sided	1,757.49	1,303.37	454.12	16.38	977.06	< .001***	[399.71, 508.54]

Discussion

The purpose of this study was to examine whether ADS-B or onboard GPS is more effective for tracking low-level overflights, most specifically air tours, above mountainous protected areas. Both data types, collected over the same study area, had not previously been examined in comparison for tracking overflights above PPAs. The analysis focused on flight length, spatial coverage of waypoints, and a comparison of the altitudes of the measured waypoints. The results showed that onboard GPS is more effective for tracking overflights above DENA, particularly in remote, mountainous regions, for both flight length and spatial coverage. However, results related to differences between altitudes were indeterminable.

On average, ADS-B waypoints covered 70% to 81% of the flight length and 86.8% of the spatial coverage of the onboard GPS waypoints in DENA (Tables 3.3 and 3.5). Several factors likely contributed to these results, including the ADS-B data logger's location and the effect of terrain shielding on ADS-B signals (particularly in the undulating and mountainous topography of DENA). ADS-B requires line of sight with terrestrial loggers, making terrain shielding, or the blocking of radio signals, much more pronounced in areas with substantial terrain changes over shorter aerial distances; thus, the radio signals could not reach the ADS-B data logger. This issue can be mitigated in some locations by deploying multiple ADS-B data loggers at the same time, a strategy that has improved effectiveness for some parks but requires additional financial and human resources (Beeco et al., 2020). However, the issue remains prevalent for aircraft on low-

altitude routes, such as air tours and air taxi operations in DENA, where ADS-B data loggers were deployed at three different locations: Healy Radio Repeater, Old Town Cantwell, and K'esugi Ken Ranger Station. None of the ADS-B data loggers could receive radio signals when the aircraft approached Ruth Glacier head even though the aerial distance from K'esugi to the head of the glacier was less than 40 miles (Fig. 3.3 and Fig. 3.4). Conversely, onboard GPS data, which does not depend on terrestrial data loggers, provided more robust route length and spatial coverage, providing coverage anywhere, and thus, the signal loss is quite rare even in mountainous terrain. More ADS-B ground stations or data loggers would need to be installed at appropriate locations to fill the gaps, especially in low-altitude aircraft tracking. This would require additional resources, and in many cases, would be too impractical due to the remoteness of appropriate sites.

Comparing altitude values between onboard GPS and ADS-B waypoints proved more difficult than anticipated. This was because the timestamps of the two datasets were not perfectly aligned in space and time. Pairing the waypoints based on timestamps revealed latency in the data. The total latency, or uncompensated latency, in the ADS-B system arose from the difference between the time of broadcasting the aircraft's position and the time of applicability of the position measurement (Ali et al., 2015). Similarly, this could result from an uncorrelated time interval between the onboard GPS (at the aircraft level) and the ADS-B data logger installed on the ground (Ali et al., 2017). Clock errors during the configuration of timestamps in the aircraft or the data logger could also account for the difference or latency. Similarly, pairing the waypoints from the onboard GPS and ADS-B feature classes based on spatial proximity was not feasible for 223 overflights (57,710 waypoints). In an attempt to explore the question of altitude to at least some level of depth, the altitudinal discrepancies between the two sets of waypoints

(without pairing each waypoint) were assessed, revealing a statistically significant difference in mean values in the majority of the cases. However, because of the spatial gaps in ADS-B coverage, complete comparisons across the entire sample have severe limitations. Two example cases were presented to showcase the process we followed (Tables 3.6 and 3.7): the first case showed no significant difference in altitude measurements, whereas the second case showed a significant difference. In the second case, the barometric altitude by ADS-B displayed higher readings than the geometric altitude by the onboard GPS, as observed in a previous study, with the mean difference being marginally greater than the average difference of 1,404 feet (428 meters) reported in that study (Ali & Taib, 2019). This altitudinal discrepancy could have resulted from lower temperatures or colder air than the International Standard Atmosphere (ISA) standard temperature for the flight altitude, leading to higher barometric readings (Yee & Yee, 2008). The aircraft would be lower than the altimeter indication in such a situation. Overall, the difference in altitude between the two different systems was indeterminable.

This study was conducted at DENA, a park with significant topographical changes. The findings are transferable to other protected areas with similar mountainous topography, such as Glacier National Park, Great Smoky Mountains National Park, Hawai'i Volcano National Park, and Olympic National Park. Previous research at Great Smoky Mountains National Park and Haleakalā National Park deployed multiple ADS-B loggers to overcome terrain shielding and collect data, even still finding significant coverage gaps (Gurung et al., 2025; Peterson et al., 2023). However, protected areas or landscapes with less topographic variation, such as White Sands National Park, are likely to yield different results for flight length and spatial coverage.

This study identified other potential areas for future research on overflight data. The large gaps in the onboard GPS and ADS-B waypoints may have led to less precise flightlines. The

issue of large gaps can be addressed by interpolating points, such as with the cubic spline function on the feature class. Using a cubic spline function or algorithm with boundary conditions, it may be possible to accurately interpolate point data; however, it has yet to be applied to a geodatabase feature class in `ArcPy`, with time as an independent variable. Another area of research could involve developing a tool to pair waypoints from the onboard GPS dataset (feature class) and the ADS-B dataset (feature class), followed by assessing the altitudinal discrepancies between the paired waypoints. Future research should also consider collecting social data from overflight operators to understand their perceptions about using ADS-B and onboard GPS, as well as which technology they think would be more useful for helping protected area managers. Finally, newer technology should continuously be evaluated for performance, such as whether space-based ADS-B could help with gaps in both spatial extent and coverage gaps, while also providing high temporal fidelity (i.e., faster signal update rate).

Management considerations

While not specifically analyzed in this study, differences in data density (update rate) are considered. After screening the same aircraft from the onboard GPS and ADS-B datasets, it became evident that the waypoint density in the ADS-B dataset was much higher than that in the onboard GPS dataset (Fig. 3.3). The differences in Figure 3.3 can mostly be explained by the requirements to submit onboard tracking data to DENA managers which applies to flights that include landings in the park—not air tours alone—so there are simply more flights in the ADS-B dataset. Figure 3.3 also presents the discrepancy in the density of points. This is due to the signal update rate. ADS-B provided finer resolution data than onboard GPS. The update rate of ADS-B signals is one ping per 0.5 seconds (Zhang et al., 2011), whereas the onboard GPS signal update rate in this study varied from a few seconds (e.g., one signal every 3 seconds) to tens of seconds

(last column of Table 3.2). Air tour companies may choose a lower update rate to save costs, as faster signal update rates result in higher costs for subscribers or customers. In onboard GPS technology, there is a trade-off between recurring costs and finer data quality, but air tour companies may not be interested in finer data quality.

ADS-B signals are unencrypted and publicly accessible, whereas onboard GPS signals are available only to subscribers or clients. For compliance with flight conditions (such as an ATMP that includes specific routes and altitude requirements), determining the length of a signal update rate is an important consideration. The question becomes, at this time, what is the minimum update rate needed to effectively track overflights and examine compliance while minimizing cost? Our experience with these data and the results of this study suggest that an update rate of half second (similar to ADS-B) would produce an unnecessary level of fidelity. Conversely, an aircraft traveling at 90 knots for 2 minutes would travel approximately 3.4 miles, which is a distance that is likely too far for ensuring compliance due to the large gaps that could be presented. The ATMPs recently established by the FAA and NPS require operators to submit flight monitoring data at an interval of 15 seconds. At this rate, an aircraft traveling at 90 knots for 15 seconds would travel approximately 0.4 miles (644 meters). Our analysis generally suggests a 15-second interval will likely provide the needed data fidelity for compliance checks with spatial requirements (i.e., routes and altitudes). Future study of these considerations would also provide useful information.

Another consideration is for protected areas that cannot require aircraft operators to submit onboard GPS data. ADS-B can provide a suitable alternative when detailed compliance measures across large landscapes are not needed. ADS-B has proven to provide a broad understanding of aircraft travel patterns over many protected areas (including in this analysis at

DENA), and has near-ubiquitous adoption in the U.S., but it has several limitations that require cautious use when applied to compliance assessment.

In closing, this study conducted a comparative spatial analysis of overflights recorded simultaneously by ADS-B and onboard GPS in DENA. Given the mountainous topography of DENA, onboard GPS technology provided better flight length and spatial coverage of overflights, particularly for low-altitude routes, albeit with a lower signal update rate. The ADS-B signal update rate was significantly higher but was hindered by terrain shielding effects for low-altitude flights. For a detailed compliance assessment, onboard GPS with appropriate signal update rates is likely to be more effective across a variety of landscapes. However, when practical, multiple ADS-B ground stations or data loggers can be used to capture the entire route of low-altitude flights. Furthermore, while this study could not conclude verifiable differences in altitude between systems, ADS-B technology would likely benefit from incorporating geometric altitudes supported by GNSS, especially in mountainous regions.

Limitations of analysis

For the flight length, limitations apply in cases of large gaps in the waypoints, particularly in the ADS-B dataset. The flightlines generated by a geoprocessing tool from the waypoints of ADS-B and the onboard GPS did not perfectly align when there were large gaps between consecutive waypoints. Yet, regardless of mitigating the gaps, large gaps create errors in the estimation of route length because a straight line must be assumed between two time-adjacent points. Because of this, we included spatial coverage, which used a different technique from flight length, to provide another similar metric, though the findings were similar.

As mentioned above, calculating altitude discrepancies proved too fallible to determine differences. Understanding the difference between barometric pressure altitude and geometric altitude would provide useful information and should be considered in future studies.

Chapter 4 - Understanding visitors' preferences for recreation sites during wildfire- and drought-induced displacements

Abstract

The four national forests in Southern California are dominated by the chaparral biome and are visited by millions of people annually. These forest ecosystems are impacted by wildfires and drought, which coincide with the peak outdoor recreation season (late summer and fall). Wildfire creates disamenities for recreation through fire damage and smoke exposure, whereas drought dries up water bodies at recreational sites. The impact varies among socio-demographic groups in both displacement scenarios. This study applied a discrete choice experiment to understand visitors' preferences for site and environmental attributes in wildfire- and drought-induced displacement scenarios and the heterogeneity in choices across socio-demographic groups. Two surveys were conducted: one for a wildfire scenario and another for a drought scenario. Wildfires impact forest ecosystems, leading to immediate closure of forest areas, whereas drought dries up water bodies, leading to the loss of water-based recreation opportunities. Regression model results for the wildfire scenarios indicate that park visitors preferred "wildland-urban" and "wildlands" viewscapes compared to "city" viewscapes in the alternative recreation sites. For drought scenarios, preferences for alternative recreation sites farther away from their homes ("1–2 hours" and ">2 hours" of travel time compared to "less than 1 hour" travel time), as well as for "difficult" trails compared to "easy" trails. Models examining the influence of preferences for attributes across socio-demographic factors showed that visitors with "intermediate" and "committed" levels of outdoor recreation expertise preferred "moderate" and "difficult" trails in the wildfire survey, compared to "easy" trails, all relative to visitors with a "general or casual" level of outdoor expertise. In the drought survey, visitors in a group with

kids preferred “wildlife” and “water” features compared to “mountain” features, relative to visitors in a group with only adults. The results can help forest managers devise recreation and resource management strategies by identifying the key site attributes.
Keywords: discrete choice experiment, Southern California national forests, outdoor recreation, displacement, wildfires, drought

Introduction

Wildfires and drought are ecological disturbances and environmental stressors in forest ecosystems. In forest management, a fire or wildland fire is a non-structure fire occurring in wildlands, including both prescribed fires and wildfires (National Wildfire Coordinating Group, 2012). Human factors contribute to modifying the underlying drivers of wildfire events in many landscapes (Pausas & Keeley, 2021). The number and extent of large fires increased across the western United States from 1984 to 2011, with a significant trend in the southern and mountain ecoregions, coinciding with increased drought severity (Dennison et al., 2014). The average warm-season burned area in the western United States from 2001 to 2020 was nearly double that of 1984 to 2000, and the area burned by 2020 warm-season wildfires was more than five times the average for the 1984–2000 record (Zhuang et al., 2021). In California, the annual burned area increased fivefold from 1972 to 2018, largely due to an eightfold increase in the extent of summer wildfires (Williams et al., 2019). Wind events and the delayed onset of winter precipitation are also the causes of fall wildfires. In Southern California, the majority of large fires occur in the fall, driven by wind events, particularly Santa Ana windstorms (Keeley et al., 2009). The 2020 wildfire season was disastrous in California when nearly 10,000 fires burning

over 4.2 million acres, or more than 4% of the state's roughly 100 million acres of land (CalFire, 2020).

Drought is a result of prolonged periods of precipitation levels below normal, leading to the loss of surface and groundwater (Richman & Leslie, 2015). Drought is commonly categorized into four types: meteorological, hydrological, agricultural, and socioeconomic (Rasmussen et al., 1993). Temperature plays an important role in the water balance function and, thus, highlights the impact of a warming climate on drought occurrence and severity. Drought is not a new phenomenon in California, which has experienced prolonged multi-year droughts resulting in significant social and economic losses since the reliable instrumental record period starting in 1895 (Richman & Leslie, 2015). Severe droughts include the late 1920s–early 1930s (the 'Dust Bowl' drought), 1976–1977, the late 1980s–early 1990s, and 2012–2014. Drought events were often characterized by precipitation deficits in the past, but the latest significant drought event of 2012–2014 was unique, manifesting a combination of low precipitation and high temperatures. This led to a heat-based drought in California with one of the warmest years ever recorded since 1895 (Richman & Leslie, 2015). In addition to its evident impact on agriculture and ranching, drought caused massive forest die-offs, severe wildfires, and significant water deficits in river basins (Flint et al., 2018).

Four national forests with chaparral-dominated landscapes surround the Los Angeles and San Diego metropolitan areas: Los Padres, Angeles, San Bernardino, and Cleveland National Forests, which are popular for hiking, mountain biking, camping, and nature activities (Garnache et al., 2018). These landscapes represent Mediterranean-type, warm climate regions dominated by woody shrubland, with herbaceous understory and fire return intervals (FRIs) of 30 years or more (Van De Water & Safford, 2011). An analysis of wildfires between 2000 and 2020 showed

that wildfires in California burned biodiverse areas critical to endemic species in addition to impacting forest areas (Calhoun et al., 2022). Droughts have led to reduced streamflow, low lake and reservoir levels, impaired scenic resources (e.g., dried waterfalls), and drier soil and vegetation (Flint et al., 2018).

Wildfires and drought pose challenges for outdoor recreation in the western United States because the peak outdoor recreation season coincides with wildfire and drought seasons (Gellman et al., 2022). Wildfires and resulting smoke reduce the amenity value of recreation sites. Drought adversely affects recreation directly by limiting water-based recreation opportunities and indirectly by desiccating vegetation, disrupting wildlife habitats, and inducing wildfires (Jenkins et al., 2023). Research is being conducted to understand visitor behavior in response to ambient wildfire smoke in the American West and the associated risks to human health and welfare loss (Clark et al., 2023; Gellman et al., 2022). As more intense, prolonged, and larger fires, in tandem with severe drought, become more prevalent due to anthropogenic climate change (Balch et al., 2022), forest closures are becoming more frequent, restricting public access to recreation sites in the chaparral-dominated landscapes of Southern California.

Limited research has focused on the recreational services provided by chaparral landscapes. Research on visitor displacement due to wildfire and drought is sparse, particularly in drought scenarios, because the drought effect is often estimated by its effect on agriculture (Thomas et al., 2013). Therefore, additional research is necessary to understand the impact of environmental stressors and site degradation on recreational benefits, and their disproportionate effects on under-represented groups (Garnache et al., 2018). Moreover, it remains unclear how visitors, including those engaged in water-based activities, adapt their use of recreational sites to increasing incidences of drought and wildfires and changes in precipitation and temperature in

Southern California (Garnache et al., 2018). This study contributes to addressing research gaps in recreational visitors' responses to wildlife- and drought-induced displacement in the chaparral biome of Southern California. The study identifies the site attributes or environmental dimensions that influence visitors' choice of recreation sites under such displacement scenarios in the four national forests of Southern California. The study also examines the differences in preference for site attributes or environmental dimensions across demographic groups. Understanding the effects of site attributes and spatial configuration of sites on ecosystem services—and subsequently on public recreation preferences—can help decision-makers allocate resources to benefit the public (Garnache & Lupi, 2018).

Literature Review

Wildfire, drought, and displacement

Public lands, including protected areas, provide space for outdoor recreation, but these areas are increasingly confronted with undesirable conditions such as crowding, conflict in resource use, and poor resource conditions (Arnberger & Brandenburg, 2007). Crowding is the most common and visible phenomenon in popular recreation sites. Apart from crowding, researchers identified that park regulations (Hall & David, 2020) and wildfire-driven closures (Brown & Jenkins, 2023) can also influence the response and behavior of visitors.

When there is an interference with their recreational experience, visitors will adopt a coping strategy to obtain a quality recreational experience (Fefer et al., 2024). Displacement is one of the coping mechanisms visitors adopt to reduce stress and avoid undesirable experiences (Richard S. & Susan, 1984). Displacement involves a process of moving away from places that have changed to an unacceptable level, rather than simply moving toward a more optimal one

(Becker, 1981). Researchers have developed a typology to document and describe displacement behaviors, which include spatial displacement, temporal displacement, and activity substitutability (also known as product or activity displacement) (Hall & Shelby, 2000).

As a discrete situational factor in visitation dynamics, wildfire was found to significantly and negatively affect visitation in four of Utah's five national parks with an aggregate visitation loss or displacement of 0.5% to 1.5% in a typical fire year (Kim & Jakus, 2019). In an experiment involving two types of recreational users—bikers and hikers—demand decreased for both groups as the burned area increased and the amount of burned area visible from the trail grew in four national forests in Montana (Hesseln et al., 2004). The impact of wildfires on the demand for forest recreation is complex because demand varies by time, type of recreation use, fire characteristics, landscape attributes, and availability of substitute sites (Garnache & Lupi, 2018). Wildfires and smoke led to campsite cancellations, with differential impacts on recreational activity across the 11 western continental U.S. states (Gellman et al., 2022).

The four national forests of Southern California attract millions of visitors due to their proximity to major cities, but are also increasingly impacted by climate change (e.g., more frequent and severe wildfires and droughts) (Shaw et al., 2011). An estimated seven million recreational users visit the four national forests annually, the majority of whom are day trips by residents (Garnache & Lupi, 2018). The national forests are likely to be overused (exceeding their carrying capacity) by the growing population seeking wilderness and are increasingly impacted by climate change (e.g., changes in precipitation, temperature, drought, and wildfire patterns) (Garnache et al., 2018).

There are few studies on visitors' responses to wildfires and drought in California's recreation areas. A study was conducted in the Angeles National Forest to understand visitor

displacement and behavioral responses in wildfire conditions using a choice experiment survey. Four attributes—plants, lakes or streams, fire history, and driving distance—were considered for preference analysis (Tanner et al., 2022). The study revealed a preference for tree cover over shrubs, as well as a preference for water sites, but a dislike for forest fire damage. This highlighted preference heterogeneity for certain attributes, particularly the response of the minority group (Hispanic) to shrub fires. Another study estimated an access value of 23 dollars per trip for a typical site in the four national forests, incorporating the presence of past wildfires in the estimation (Garnache & Lupi, 2018). The travel cost term was statistically significant and negative in the nested logit model with the time-varying effects, indicating that higher travel costs reduce the indirect utility of the site.

Periodic surveys are conducted in each national forest, and some studies have focused on the recreational behavior of Hispanic or Latino populations in these areas (Chavez & Olson, 2009). Another study examined the influence of drought on visitation at selected National Park Service units from mountain, arid, and coastal ecozones in California. The study found a decline in annual visitation at mountain parks during extreme drought years (Jenkins et al., 2023). A choice experiment covering the entire chaparral-dominated biome of Southern California has not yet been undertaken. This study represents an ambitious and novel effort to implement a discrete choice experiment across all four Southern California national forests under increasing wildfire and drought conditions.

Choice experiments and survey

Discrete choice experiments (DCEs) are a type of stated-preference valuation method that can help assess preferences or trade-offs between choices and attributes of choices in a hypothetical behavioral setting, such as users' selection of recreational sites (Holmes et al., 2017;

Train, 2009). Stated choice modeling has been widely employed for recreational assessments. For example, a study at Bear Lake in Rocky Mountain National Park (RMNP) to evaluate alternative transportation systems (e.g., shuttle bus services) aimed at facilitating visitor access, reducing traffic congestion, improving visitor experiences, and protecting park resources (Pettebone et al., 2011). The study found that park visitors preferred private vehicles over shuttle bus services but were willing to make trade-offs to use shuttle buses and avoid crowding on trails and vehicle traffic. Another study on visitor use management considered transport-related attributes such as entrance wait time, parking availability, traffic speed, and traffic volume when analyzing visitor preferences and trade-offs in Grand Teton National Park, Wyoming. Parking was identified as the most important attribute for visitors, along with variations based on age groups (Newton et al., 2020).

Study Objectives

The study aims to examine the displacement behavior of recreational users in the four national forests under negative resource conditions such as wildfire and drought. Additionally, the study examines heterogeneity in preferences among different visitor groups based on their socio-economic characteristics. This analysis culminates in three key research questions.

RQ1: Which site attributes are significant in visitors' recreation choices in the case of wildfire?

RQ2: Which site attributes are significant in visitors' recreation choices in the case of drought?

RQ3: What are the preference heterogeneities based on the socio-economic characteristics of the visitors?

Methods

This study applied a discrete choice model by asking individuals to select between recreational alternatives differing in attributes under wildfire and drought scenarios. The discrete choice experiment followed the seven key steps for designing and analyzing a choice experiment, following Holmes et al. (2017) and Train (2009). The choice experiment was embedded in a larger survey that also collected recreational, perceptions, and demographic information from respondents. The research team identified the problem or the drivers of displacement, developed the questionnaire, tested the surveys using Qualtrics, and rolled out in sites prioritized in consultation with forest managers.

Study area and survey sites

The four Southern California national forests are classified as Urban National Forests (UNFs) (Fig. 4.1). The four national forests span over 3.8 million acres, with Los Padres accounting for nearly two million acres, Angeles 655,387 acres, San Bernardino 675,000 acres, and Cleveland approximately 567,000 acres. The national forests include wilderness areas that protect some of Southern California's wildest and most pristine landscapes, with elevations ranging from sea level along Los Padres' Monterey coast to approximately 11,500 feet at the peak of San Gorgonio Mountain in the San Bernardino National Forest (USDA Forest Service, 2021). The chaparral vegetation type dominates all the national forests, except for San Bernardino, where coniferous vegetation prevails. The national forests span ten counties, which collectively have a population of just over 24 million people (United States Census Bureau, 2023). An estimated eight million people live within a one-hour drive of these forests as of 2014 (Garnache et al., 2018). The forests offer a wide range of recreational opportunities, such as

hiking, camping, OHV riding, watching wildlife, stream play, fishing, and so on, but these recreational opportunities face significant threats from environmental stressor (Garnache et al., 2018).

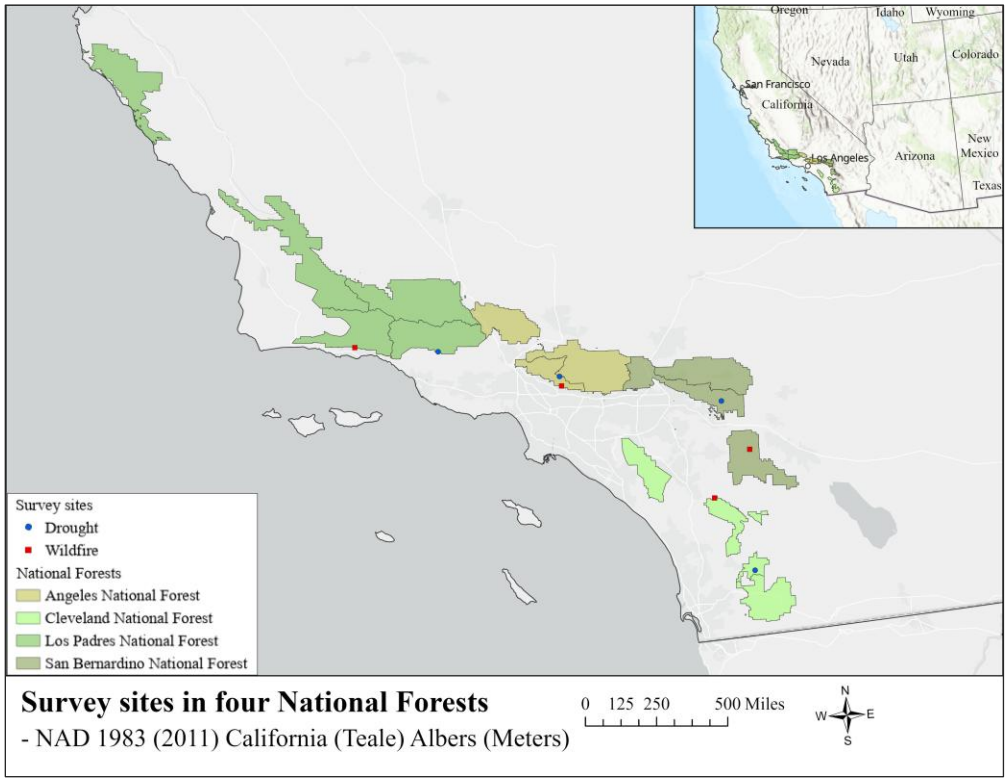

Figure 4.1 *Four national forests and eight survey sites.*

In consultation with US Forest Service managers, survey sites were selected from a list of priority recreation sites—two from each national forest—based upon three factors: high usage, high fire risk, and potential drought conditions (Table 4.1). The drought survey sites contained a water feature (e.g., waterfall, water pools).

Table 4.1 *Survey sites for wildfire and drought surveys in four national forests*

Survey	Survey sites	Forest
Wildfire	Cobb Estates	Angeles
	Dripping Springs Trailhead	Cleveland
	Humber Park	San Bernardino

	Jesusita Trail	Los Padres
Drought	Switzers Day Use Area	Angeles
	Three Sisters Trail	Cleveland
	Big Falls	San Bernardino
	Santa Paula Canyon	Los Padres

The Discrete Choice Experiment

Six attributes and their levels were developed with forest managers to analyze factors influencing visitors' utility-maximization behavior in forest recreation (Table 4.2).

Table 4.2 *Choice experiment site attributes and their levels*

Attributes	**Levels**
Activity	Same activity
	Different activity
Travel time	1 hour
	1-2 hours
	> 2 hours
Facility	Primitive
	Semi-developed
	Developed
Trails	Easy
	Moderate
	Difficult
Views	City
	Wildland-urban
	Wildlands
Feature	Mountain
	Wildlife
	Wildflower
	Water

A collective full factorial design is represented as L^{NA}, where L denotes the number of attribute levels, A the number of attributes, and N the number of alternatives. Given the number and levels of attributes, the full factorial design, if all possible combinations were considered, would result in 648 rows or combinations of attributes and their levels (L^A). The number of rows or combinations increased when the number of alternatives (N) for the experiment was included in the complete full factorial design. This approach generated an impractically large number of choice sets for respondents in the field. Consequently, a fractional factorial design with blocks was implemented to create a manageable subset of the complete factorial design while ensuring efficient estimation of the effects of interest. A *D*-efficient optimal orthogonal design (97.2659) was constructed in SAS 9.4 (SAS Institute Inc., 2023). This design optimized statistical efficiency by maximizing the amount of information gathered about the parameters of the attributes. The fractional factorial design produced eight blocks, each containing nine choice sets with distinct combinations of attributes and levels (SAS Institute Inc., 2014). Blocks were randomly assigned to respondents. The choice sets included two alternatives with generic labels ("Site 1" and "Site 2") and a status quo option ("Stay home" for the wildfire survey or "Continue with the same plan" for the drought survey). The blocks and choice sets were transferred into Qualtrics, which facilitated the random assignment of blocks to respondents. An example choice set within a block is presented below in Fig. 4.2, and each respondent received nine such choice sets in the survey.

Site #1	Site Attributes	Site #2
Participate in a different primary activity	**Primary activity at new site**	Participate in the same primary activity
1–2 hours (61–120 miles) one-way driving distance from home	**One-way travel time/distance from home to new site**	Up to an hour (up to 60 miles) one-way driving distance from home
Primitive (dirt parking lot, no toilet, no potable water)	**Facility type at new site**	Developed (paved parking area, flushable toilets, potable water, picnic tables)
Difficult—steep and rocky terrain	**Trail type at new site**	Difficult—steep and rocky terrain
View of wildland-urban interface where human development meets undeveloped wildland	**Views from new site**	View of city and lands developed by humans
Water feature (stream, waterfall, etc.)	**Unique feature found at new site**	Mountain peak
I prefer… (select only one below)		

◯ Site #1 ◯ Site #2 ◯ Neither. Stay Home

Figure 4.2 *A choice set from the questionnaire.*

Survey design and administration

A potential wildfire or drought scenario at the recreation site was presented to respondents at the beginning of the questionnaire. In the wildfire scenario, respondents were presented with a situation in which the recreation site was closed due to wildfire, and they either stayed at home or selected an alternative site based on a set of site-specific attributes. In the drought scenario, the water-based recreation site lacked available water, and respondents either chose to recreate at the dried site or sought an alternative based on the same site attributes. Additionally, the Qualtrics survey included questions about respondents' socio-economic characteristics, such as race and ethnicity, level of expertise in outdoor recreation, income, age, gender, and visiting with or without kids.

The survey was distributed at eight sites during high-use periods (summer months) from 13 June to 3 August 2024. Two research technicians administered the survey, spending seven hours a day, five days (Thursday–Monday) a week, at each site, and used a census approach when intercepting visitors with tablets. Each visitor leaving the recreation site was approached to participate in the survey, and in the case of a group, the individual with the most recent birthday was selected. A QR code was provided to visitors who did not have enough time to respond on-site to complete the survey on their own device.

Recreational choice model

Consumers choose a product or service that maximizes their utility when faced with a range of alternatives in their daily decision-making, such as visiting a park, choosing a recreational activity, or a travel destination (McFadden, 1972). The nature of such decision processes is influenced by human choice behavior, which is shaped by factors that are difficult to control. Population choice behavior models, based on random utility models, are deduced and estimated based on the nature of decision processes and observed behavior. The choice behavior is assessed based on a set of alternatives available to decision-makers and the alternative attributes.

For this study, we assume individual i receives utility, U_{ij}, from a given recreational activity j, which is influenced by activity attributes ($\boldsymbol{x}_j$) and individual characteristics ($\boldsymbol{s}_j$). That is:

$$U_{ij} = V_{ij}\,(\boldsymbol{s}_i, \boldsymbol{x}_j) + \varepsilon_{ij}$$

where, $\boldsymbol{s}_i$ is a vector of individual characteristics (age, income, race, ethnicity, education level) of an individual i, $\boldsymbol{x}_j$ is a vector of attributes for recreational alternative j (travel time, facilities, recreational options, etc.), V_{ij} represents the systematic observed component of utility, while ε_{ij} represents the idiosyncratic or random (unobserved) component (McFadden, 1972).

From the set of alternatives (e.g., choosing a car), an individual chooses an alternative that maximizes utility. The probability that individual *i* chooses alternative *j* from a set of alternatives *C* is because the utility is greater from alternative *j* than alternative *k,* and is represented as,

$$\boldsymbol{P}\text{ (alternative } j \text{ is chosen)} = \boldsymbol{P}\left(V_{ij}\left(\boldsymbol{s}_i, \boldsymbol{x}_j\right) + \varepsilon_{ij} > V_{ik}\left(\boldsymbol{s}_i, \boldsymbol{x}_k\right) + \varepsilon_{ik}\right)\ \forall j,k \in C$$

We assume that $V_{ij}\left(\boldsymbol{s}_i, \boldsymbol{x}_j\right)$ is a linear function in the parameters and the attributes. That is:

$$V_{ij}\left(\boldsymbol{s}_i, \boldsymbol{x}_j\right) = \boldsymbol{\beta}' \boldsymbol{x}_j + \varepsilon_{ij}, \textit{ for all } j \in C,$$

where $\boldsymbol{\beta}$ is a vector of parameters to be estimated. The vector $\boldsymbol{s}_i$ enters as a stratification variable both linearly in the regression and as an interaction term with the attributes (i.e., $V_{ij}\left(\boldsymbol{s}_i, \boldsymbol{x}_j\right) = \boldsymbol{\beta}' \boldsymbol{x}_j + \gamma s_{i,r} + \boldsymbol{\lambda}'\left(s_{i,r}\, \boldsymbol{x}_j\right) + \varepsilon_{ij}$, where γ and $\boldsymbol{\lambda}$ are additional coefficients to be estimated. An important property of this approach is the differences in utility between alternatives, which affect the choice probabilities, not the absolute level of utility. The choices are made based on the utility differences across alternatives, allowing us to only identify utility differences (Train, 2009).

We assume that respondents' or people's preferences vary randomly across the population and are not completely observed, a common assumption in DCE. Given that preferences are captured by the marginal utilities (i.e. $\boldsymbol{\beta}$) and randomly vary across the population, we assume that $\boldsymbol{\beta}$~**N**ormal(**b, Ω)**, where **b** is a vector of parameter means to be estimated and $\boldsymbol{\Omega} = \boldsymbol{\sigma}\mathbf{I}$ where, $\boldsymbol{\sigma}$ is a vector of variances to be estimated for each parameter and **I** is an identity matrix of size equal to the number of parameters in the vector $\boldsymbol{\beta}$ (Train, 2009). Assuming the parameters are random allows for capturing potential dependence between choice questions answered for a given respondent (e.g., repeated measure data) (Train, 2009).

We estimated two primary regression models for the DCE for each scenario: a conditional logistic regression model and a mixed logit model, to assess if the mixed logit model

was a proper choice (i.e., that there was unobserved preference heterogeneity). NLOGIT 6 was used to estimate all regression models. For the mixed logit models, we set the number of Halton Draws to 100 and used the BFGS algorithm (Econometric Software, Inc., 2024). Nonlinear effects of variables or attributes were estimated using dummy variables coded as 0 or 1, representing L – 1 levels for an attribute. Each attribute included a reference level or category. The reference categories for each variable or attribute are "same activity," "1 hour," "primitive," "easy," "city," and "mountain." The main effects of site attributes were analyzed separately for wildfire and drought scenarios using separate regression models.

Respondent-specific variables (or socio-economic characteristics) cannot be directly examined in the model; thus, we used a stratification approach as discussed earlier. We estimated logistic regression models that included interactions with alternative-specific attributes to identify differences in attribute parameters based on individual characteristics. Socio-economic characteristics can help capture variation (heterogeneity) in respondents' observed preferences. Most socio-economic variables were categorical, except for income and age. Income and age were converted into categorical variables: income was divided into low- and high-income groups based on the median income of the ten counties, and age was grouped into three intervals. The median income (USD 109,200) was calculated as the average of the median household incomes across the ten counties (Department of Housing and Community Development, 2023).

Dummy variables were generated for the socio-economic variables to incorporate them into the random utility models. Models incorporating interaction terms of dummy variables for socio-economic characteristics—such as race and ethnicity, level of recreation expertise, income, gender, age, and group type—with site attributes were used to assess factors contributing to preference heterogeneity. For race and ethnicity, dummy variables for Hispanic or Latino and

Asian were interacted with site attributes. For the level of recreation expertise, dummy variables for intermediate and committed levels of expertise were interacted with site attributes. For income, the dummy variable for the high-income group was interacted with site attributes. For gender, the dummy variable for male respondents was interacted with site attributes. For age, two age categories—46–65 and >65—were interacted with site attributes. For group type, the dummy variable for groups with children was interacted with site attributes. NLOGIT 6 (Econometric Software, Inc., 2024) was used to estimate the conditional logit or multinomial logit models for the wildfire and drought datasets. All the interactions were assessed using one regression for the wildfire datasets and another for the drought dataset.

Results

Exploratory data analysis (EDA)

Table 4.3 presents the socio-economic characteristics of respondents, displaying only the levels with the highest values. The detailed table is provided in the Appendix. Hiking and walking were the primary activities for most respondents in both surveys. Picnicking was a notable activity among some respondents in the drought survey. Regarding visit frequency, most respondents reported visiting "a few times a year," accounting for 32% of wildfire survey respondents and 29% of drought survey respondents. In terms of time spent at the sites, 26% of respondents spent 1–2 hours, and another 26% spent 2–3 hours in the wildfire survey, whereas 27% spent 2–3 hours in the drought survey. Group size also differed between the surveys: 50% of respondents traveled in groups of 2–5 people in the wildfire survey, while 45% were solo travelers. In contrast, 74% of respondents in the drought survey traveled in groups of 2–5 people. Outdoor recreation expertise levels also differed: 44% of respondents in the wildfire survey

identified as committed, and another 44% as intermediate-level experts. In the drought survey, 41% identified as intermediate-level experts.

Respondents' priorities for attributes varied. In the wildfire survey, 42% ranked "activity" as the top priority attribute, followed by 28% ranking "travel time." In the drought survey, 29% ranked "activity" as the top priority, followed by 21% for "travel time" and 20% for "views." Most respondents in both surveys were White, followed by Hispanics, Asians, and other minorities. In the wildfire survey, 66% of respondents were White, 32% were Hispanic or Latino, 6% were Asian, and 13% were other minorities, whereas in the drought survey, 38% were White, 30% were Hispanic or Latino, 14% were Asian, and 14% were other minorities. Income classification revealed that 54% of respondents in the wildfire survey belonged to the high-income group, while 30% in the drought survey were in the high-income group. The majority of respondents belonged to the 18–45 age group, with 46% in the wildfire survey and 71% in the drought survey. 17% of respondents in the wildfire survey were over 65, compared to a mere 2% in the drought survey. Finally, 10% of respondents in the wildfire survey visited in a group with kids, compared to 20% in the drought survey. The distance traveled by respondents to each site was estimated in miles using the centroid of their home ZIP codes in Google Maps. The wildfire survey included 110 unique zip codes, compared to 129 in the drought survey. The overall median distance traveled was 9.9 miles for the wildfire survey and 35.8 miles for the drought survey.

Table 4.3 *Summary statistics of selected characteristic variables of respondents*

Variables	Levels	Wildfire		Drought	
Primary Activity	**Hiking/Walking**	**203**	**82%**	**127**	**78%**
	Picnicking	2	1%	9	6%
Frequency of visit	**A few times a year**	**79**	**32%**	**48**	**29%**
	This is my first time	29	12%	**48**	**29%**

Time spent	**1–2 hour**	**65**	**26%**	30	18%
	2–3 hour	**64**	**26%**	**44**	**27%**
	4–6 hour	47	19%	**38**	**23%**
How many people are in the group?	1 or solo	111	45%	21	13%
	2 to 5	**124**	**50%**	**121**	**74%**
Checking site conditions	**Always**	**80**	**32%**	**67**	**41%**
Outdoor recreation expertise	**Intermediate**	**109**	**44%**	**67**	**41%**
	Committed	**108**	**44%**	46	28%
Ranking attributes (Most important = 1)	**Activity**	**103**	**42%**	**48**	**29%**
	Travel time	70	28%	35	21%
	Views	25	10%	33	20%
Ethnicity	**White**	**163**	**66%**	**62**	**38%**
	Hispanic or Latino	32	13%	49	30%
	Asian	14	6%	23	14%
Gender	Male	**134**	**54%**	73	45%
	Female	106	43%	**81**	**50%**
Income (Median=$105,990) (Avg. median of 10 counties)	Above Median	**134**	**54%**	49	30%
	Prefer not to say	41	17%	30	18%
Age	**Age 18–45**	**115**	**46%**	**116**	**71%**
	Age 66 and above	43	17%	4	2%
With kids	With kids	25	10%	32	20%
Number of unique zip codes		110		129	
Distance traveled (miles) (median value)		9.9		35.8	

Baseline conditional logistic regression results—wildfire and drought scenarios (Research questions 1 and 2)

Estimation results for the conditional logistic regression models for the wildfire and drought scenarios are presented in Table 4.4. In the wildfire scenario, findings suggest a strong preference for “views” or viewscapes, specifically for “wildland-urban” views and “wildlands”

views, relative to "city" views. All other attribute coefficients in the wildfire scenario were not statistically significant, indicating no difference in preference between the baseline category and other levels of that attribute.

Table 4.4 *Conditional logit model with main effects; bold values indicate statistically significant parameters*

Attribute	**Level**	**Wildfire**	**Drought**
		Coefficient (*p*-value)	**Coefficient (*p*-value)**
Activity	Different activity	0.01368 (0.8248)	0.03828 (0.6225)
Travel time	1–2 hours	−0.09960 (0.1830)	**0.15913*** (0.0794)
	> 2 hours	0.02644 (0.7257)	**0.15666*** (0.0968)
Facility	Semi-developed	−0.04892 (0.5190)	−0.15045 (0.1032)
	Developed	−0.00401 (0.9577)	−0.08648 (0.3556)
Trails	Moderate	−0.01060 (0.8863)	0.02183 (0.8068)
	Difficult	0.03424 (0.6509)	**0.20926**** (0.0226)
Views	Wildland-urban	**0.12971*** (0.0817)	0.05834 (0.527)
	Wildlands	**0.14118*** (0.0633)	−0.07752 (0.4016)
Feature	Wildlife	0.00428 (0.9606)	0.09212 (0.387)
	Wildflower	0.05796 (0.5024)	0.15616 (0.1365)
	Water	0.04406 (0.6025)	0.06153 (0.5543)
Sample size		*248*	*163*
No. of observations		*2232*	*1467*
AIC		*4619.6*	*2945.4*
Log Likelihood		*−2295.78785*	*−1458.69094*

Note: *P*-values in parentheses: ****P*<0.01, ***P*<0.05, **P*<0.1.

Under the drought scenario, the attributes "travel time" and "trails" were statistically significant (Table 4.4). For the attribute "travel time," the dummy variables for "1–2 hours" and ">2 hours" were positive and statistically significant. These results indicate strong preferences for "1–2 hours" of travel time compared to the reference level ("less than one hour" of travel

time), or ">2 hours" of travel time compared to the reference level in the drought scenario. For the attribute "trails," the dummy variable for "difficult" trails was statistically significant, suggesting a preference for "difficult" trails compared to the reference group ("easy" trails). All other attribute coefficients were not statistically significant.

Preference heterogeneity—considering differences across demographic groups (Research question 3)

Tables 4.5 and 4.6 present the conditional logistic regression models with interaction terms between socio-economic characteristics and site attributes for the wildfire and drought scenarios. Only the statistically significant interaction variables are presented in the tables for brevity; the complete models are provided in the Appendix.

Under wildfire scenario (Table 4.5), the interaction terms for Hispanic and Asian (characteristic "ethnicity") with the attributes for "moderate" and "difficult" trails were positive and statistically significant, indicating Hispanics or Latinos and Asian respondents' preference for "moderate" and "difficult" trails compared to "easy" trail types, relative to white respondents. Additionally, the interaction term for Hispanics or Latinos with the attribute for "wildlands" views relative to "city" views indicated Hispanics or Latino respondents preferred "wildlands" views over "city" views, relative to White respondents. Regarding the level of outdoor recreation expertise, respondents with intermediate and committed group preferred "moderate" and "difficult" trails over "easy" trails, relative to the general or casual recreation group. However, both groups disliked "wildland-urban" views compared to "city" views, relative to the general or casual group. The intermediate group disliked "developed" facilities compared to "primitive" facilities, relative to the general or casual group. Male respondents preferred "moderate" and "difficult" trails compared to "easy" trails, relative to female respondents. The visitors traveling

with children preferred “semi-developed” facilities over “primitive” facilities, relative to groups composed solely of adults.

Table 4.5 *Logit Model with interaction effects for wildfire survey*

Variable	Level	Wildfire Coefficient (p-value)
Hispanic × Trails	Moderate	0.72876* (0.0708)
	Difficult	0.85644* (0.0556)
Hispanic × Views	Wildlands	0.89011** (0.0292)
Asian × Trails	Moderate	1.36638* (0.0607)
	Difficult	0.96814* (0.0867)
Intermediate × Facility	Developed	−0.68801* (0.0843)
Intermediate × Trails	Moderate	0.89718** (0.0351)
	Difficult	0.89056* (0.05)
Intermediate × Views	Wildland-urban	−1.54839*** (0.0002)
Committed × Trails	Moderate	0.89249** (0.0477)
	Difficult	1.01345** (0.0322)
Committed × Views	Wildland-urban	−0.97941** (0.0256)
Male × Trails	Moderate	0.70700*** (0.0048)
	Difficult	0.48678* (0.0632)
Group with kids × Facility	Semi-developed	0.53001* (0.094)
Sample size		*248*
No. of observations		*2232*
AIC		*2087.8*
Log Likelihood		*−921.92403*

Note: *P*-values in parentheses: ***$P<0.01$, **$P<0.05$, *$P<0.1$.

Table 4.6 presents the interaction variables of socio-economic characteristics with site attributes for the drought scenario. The interaction term for the Asian group with a dummy variable for a “developed” facility was negative and statistically significant, indicating that Asian respondents disliked “developed” facilities compared to “primitive” facilities, relative to White

respondents. Additionally, the interaction term for Asian respondents with a dummy variable for a “wildflower” feature was positive and statistically significant, indicating Asian respondents preferred the “wildflower” feature over the “mountain” feature, relative to White respondents. The committed group disliked “difficult” trails compared to “easy” trails, relative to the general or casual group. The high-income group disliked the “water” feature compared to the “mountain” feature, relative to the low-income group.

The 46–65 age group disliked engaging in a “different activity” compared to the “same activity,” relative to the 18–45 age group. The same 46–65 age group disliked “wildland-urban” views compared to “city” views, relative to the 18–45 age group. However, the 46–65 age group preferred a “wildlife” feature compared to a “mountain” feature, relative to the 18–45 age group. The >65 age group preferred the “wildflower” feature over the “mountain” feature, relative to the 18–45 age group; however, the >65 age group constituted a mere 2% of the total sample. The visitors with children preferred the “wildlife” and “water” features compared to the “mountain” feature, relative to groups composed solely of adults.

Table 4.6 *Logit Model with interaction effects for drought survey*

Variable	Level	Drought Coefficient (p-value)
Asian × Facility	Developed	−1.08214** (0.0148)
Asian × Feature	Wildflower	1.02597** (0.0339)
Committed × Trails	Difficult	−0.69799** (0.0336)
High-income × Feature	Water	−0.88222*** (0.0059)
Age 46–65 × Activity	Different activity	−0.70070*** (0.0072)
Age 46–65 × Views	Wildland-urban	−0.65480** (0.0279)
Age 46–65 × Feature	Wildlife	0.62577* (0.077)
Age >65 × Feature	Wildflower	2.01238* (0.0943)
Group with kids × Feature	Wildlife	0.79593** (0.0155)
	Water	0.53492* (0.0942)

Sample size	*163*
No. of observations	*1467*
AIC	*1969.5*
Log Likelihood	*−862.77084*

Note: *P*-values in parentheses: ****P*<0.01, ***P*<0.05, **P*<0.1.

Discussion

This study was part of a larger project assessing environmental stressors like wildfires and droughts and their impact on visitor displacement in the four national forests of Southern California. The present study applied a discrete choice experiment to evaluate visitor preferences for environmental and site attributes in recreation sites during displacement. The socio-demographic characteristics observed in this study align with trends reported in previous studies and surveys conducted in these forests, including findings from the US Forest Service (USDA Forest Service, 2025). The majority of respondents in both surveys listed “hiking/walking” as their primary recreation activity, which aligns with findings from the NVUM program in Southern California's four national forests (Garnache et al., 2018). Individuals identified as Whites constituted the majority of visitors in both surveys. Notably, the percentage of Hispanic visitors was comparatively higher (30%) in the drought survey sites, nearly equal to Whites (38%). This finding was consistent with previous research, in which Hispanics largely preferred sites for picnicking or barbecuing, with some also participating in stream play for recreation (Chavez & Olson, 2009; Flores & Sánchez, 2020). The higher percentage of Hispanics in the drought survey potentially indicates an increasing trend of Hispanic participation in outdoor recreation sites with water features. Visitors came from a wide range of locations (identified by home zip codes) and traveled longer distances, as evidenced by the median distance traveled

from the centroid of their zip code to drought survey sites (sites with a water feature) compared to wildfire survey sites. This finding is supported by the conditional logit model with main effects (Table 4.4), which revealed that visitors in the drought survey preferred longer "travel time."

In terms of preferences for environmental or site attributes, respondents in the wildfire survey showed a preference for "wildland-urban" and "wildlands" views over "city" views in the sites during wildfire-induced displacement. This indicates a stronger valuation of naturalness in the viewshed compared to urban, semi-natural, or city views. A similar preference for natural landscapes was observed in a study conducted in urban-proximate recreation settings in the province of Antwerp, Belgium (De Valck et al., 2017). In the drought survey, respondents preferred "difficult" trails over "easy" ones at recreation sites during drought-induced displacement, suggesting a preference for day hiking as another recreation activity around the water sites.

Preferences for an attribute vary among individuals within a population. Models incorporating interaction terms revealed how respondents' choices for site attributes varied by socio-demographic characteristics in both surveys. In the wildfire survey, Hispanic respondents preferred "moderate" and "difficult" trails as well as "wildlands" views (Table 4.5). This finding highlights that Hispanic preferences extend beyond water-based activities, and facilities and amenities noted in earlier studies (Chavez & Olson, 2009; Flores & Sánchez, 2020; Garnache et al., 2018). In line with previous studies, Hispanic or Latino respondents exhibited a broader range of outdoor recreation preferences, including hiking and viewshed. In the wildfire survey, respondents in the intermediate and committed groups disliked "wildland-urban" views compared to "city" views, relative to casual or general group, a somewhat unexpected outcome

(Table 4.5). Additionally, the intermediate group expressed a dislike for “developed” facilities. This tendency aligns with findings from a study on committed users in off-road vehicle parks, who also showed lower preferences for developed facilities (McCole et al., 2022). Gender and group composition also influenced preferences. Visitors with children preferred “semi-developed” facilities over “primitive” facilities. This finding is important for forest managers, as children under 16 constitute a substantial percentage of visitors, ranging from 8.8% in the Angeles National Forest to 19.5% in the San Bernardino National Forest (USDA Forest Service, 2025).

The variation in preferences among respondents from different socio-demographic groups in the drought survey differed slightly from those observed in the wildfire survey. One notable result was the dislike of the “water” feature by the high-income group compared to the “mountain” feature, relative to the low-income group in the drought survey (Table 4.6). Income or socioeconomic status determines an individual’s position in society and influences outdoor recreation behavior, including their ability to adapt recreation patterns during a crisis (Beasley et al., 2024). The stark difference in preferences for feature attributes between high-income and low-income groups in a drought scenario is important for management and is also associated with constraints to outdoor recreation, particularly for the low-income group. There were also differences in preferences for site attributes by age group. Respondents aged 46–65 disliked adopting a “different activity” compared to the “same activity,” indicating that the age group 18–45 preferred a “different activity” in the drought-induced displacement. The majority of visitors tend to prefer “same activity” in their substitution behavior across the four national forests (USDA Forest Service, 2025). Therefore, it would be valuable to further examine the substitution behavior of the 18–45 age group in the drought-induced displacement. Previous studies have

shown the correlation between age and visitation rates to recreation sites in both normal and crisis scenarios (Beasley et al., 2024). This study presented specific preferences for environmental and site attributes across age groups. The preferences of different age groups and visitors with children can help inform appropriate management actions in response to drought-induced displacement.

Limitations of the study

There was insufficient evidence to establish the statistical significance of many variables, especially parameter estimates with "borderline" *p*-values. One potential explanation for this limitation is that the study aggregated data across all four national forests, which constrained forest-level analysis and interpretation. Future research could focus on a single national forest to examine behavioral choices related to environmental and site attributes in the context of displacement caused by resource or environmental conditions. Additionally, the closure of the Three Sisters Falls during the drought survey period further limited data collection efforts at that location.

Management Implications

Our findings can help forest and park managers identify and prioritize attributes that visitors value most during displacements, enabling targeted investments to enhance the recreation experience. Minority groups and low-income groups, in particular, are disproportionately affected by these changes and face unique socio-economic and cultural barriers to outdoor recreation (Johnson et al., 2007; Thomas et al., 2022). For instance, the Angeles National Forest receives a comparatively higher percentage of Hispanic visitors, along with a growing number of Asian visitors. This study highlighted a broader range of preferences among Hispanics, suggesting the need for further research to thoroughly assess the choice

behavior of Hispanic and emerging Asian communities in outdoor recreation. Although Asians comprised a smaller proportion of respondents in both surveys, the findings suggested a growing number of Asians participating in forest recreation. In addition to race and ethnicity, this study revealed variations in site attribute preferences across different age groups, income levels, outdoor recreation expertise levels, and groups visiting with children. These insights can help forest managers tailor site improvements to specific visitor demographics, such as semi-developed facilities in areas frequented by visitors with children. However, visitors with committed and intermediate levels of expertise may still prefer a primitive level of facilities in the recreation site. Therefore, forest- or site-specific analyses (or rapid assessments) should be conducted to support targeted recreation planning that addresses the displacement of a demographic group in a particular area. Furthermore, the estimation of median travel distances using visitors' home zip codes can be extended to calculate travel costs and willingness to pay (WTP). Overall, this study not only showcased visitor preferences under wildfire and drought scenarios but also identified potential areas for future outdoor recreation research and resource management within the chaparral biome of Southern California.

This study also demonstrated that a questionnaire survey is a valuable method for directly monitoring and assessing visitors' experiences in forest recreation. The use of online surveys and QR codes has further enhanced this monitoring approach. Additionally, the discrete choice experiment technique contributed to understanding respondents' behavioral choices and coping mechanisms in response to wildfire- and drought-induced displacement from the recreation sites. The discrete choice experiment is increasingly being applied in outdoor recreation research, extending beyond its traditional use in economics and resource economics. This monitoring tool and technique can be replicated in recreation areas experiencing adverse social and

environmental conditions that result in crowding, conflict, and displacement. Furthermore, the methodology can also be adapted to monitor and assess the public preferences for natural resources in other contexts, such as conserving wetlands and public parks.

Chapter 5 - Conclusion

This chapter presents the overall research conclusions, including the key findings of three studies, the broader implications of these findings for management, the limitations of each study, and opportunities for future research. This research contributes to the broader field of natural resource monitoring and inventory, including the evaluation of visitors' preferences in forest recreation. The three discrete studies employed both direct and indirect monitoring methods in ecologically significant areas, such as national parks and forests. Monitoring tools and techniques continue to evolve, becoming increasingly efficient and effective through the integration of emerging scientific advancements.

Aircraft noise is one most common sources of anthropogenic noise in many national parks, including GRSM. Aircraft noise disturbs the park's acoustic environment, which is important for wildlife populations and visitors. The first study entailed estimating 'active space' at a listener's location, or immission point, in GRSM at Cades Cove site based on noise from two jet aircraft categories, namely "Heavy" and "Light"—classified based on their maximum takeoff weight. We analyzed the acoustic data and overflight data from June 6 to 17, 2023, at Cades Cove using the NPS ActiveSpace toolkit. In the ground truthing module, the acoustic and the overflight datasets were spatiotemporally joined using timestamps as the primary key. In the active space module, the previous annotated file was applied along with the sound receiver location (listener's position), the spectral residual sound level at the listener's position, the study area around the receiver point, and a 30-meter Digital Elevation Model (DEM) spanning the study area. The overall (mean) microphone-to-aircraft distance was estimated for three functional effect categories for "Light" and "Heavy" aircraft. The estimated active space was greater for "Heavy" aircraft than "Light" aircraft, with a mean detection distance of 18.3 km for "Heavy"

and 15.2 km for “Light” aircraft. The “Heavy” aircraft produced greater thrust and frequently operated above GRSM. Regarding the limitation, the number of aircraft noise events and corresponding track points was lower than in the previous experiment conducted by Betchkal et al. (2023). Similar experiments can be conducted at culturally and historically significant sites or biodiversity hotspots, and recommendations can be made to reduce noise in those areas.

The second study compared the two flight monitoring technologies—the ADS-B system and onboard GPS—in Denali National Park and Preserve (DENA). The ADS-B waypoints and onboard GPS waypoints were analyzed based on the flight lengths, spatial coverage (distribution), and altitude discrepancies (*z*-values). The waypoints represented overflights in DENA at different times in 2021, 2022, and 2023. The flight lengths recorded by the ADS-B data logger and onboard GPS were measured. Regarding the flight length, ADS-B waypoints covered 70% to 81% of the onboard GPS waypoints in DENA. Spatial coverage was estimated using grid analysis, and measuring the distribution of waypoints over those square grids in the experimental space. Based on grid occupancy, the spatial coverage of ADS-B waypoints ranged from 74% to 97% (or 86.8% on average) of the area covered by onboard GPS waypoints in DENA. The ADS-B system used barometric pressure for altitude measurement, whereas the onboard GPS used geometric altitude. The discrepancies in altitude between ADS-B and onboard GPS waypoints were measured by comparing differences in the *z*-values of waypoints. A two-sample t-test was conducted on waypoints from 223 flights. At a 95% confidence level, 171 overflights showed statistical differences in mean altitude between ADS-B and onboard GPS data. The update interval of ADS-B signals is twice per second (Zhang et al., 2011), provided that the data logger mounted on the ground remains in the line of sight of the aircraft (transponder). However, larger gaps were observed in ADS-B signal reception because the

mountainous terrain blocked the signals from reaching the data logger at K'esugi. Data loggers failed to receive ADS-B signals when the aircraft reached the head of the glaciers. The average signal update rate of onboard GPS varied from one signal per 3 seconds to 24 seconds, depending on the aircraft and the subscription rate with third-party service providers such as Spidertracks, Garmin, and Web Sentinel. Regarding the limitations, there were large gaps in the waypoints in both datasets, especially the gaps were larger in the ADS-B waypoints. The flightlines generated from the waypoints, whether interpolated or not, did not perfectly represent the actual route of the aircraft. This introduced some degree of error in the measurement of flight length. Another limitation was the uncorrelated time interval between the ADS-B and onboard GPS. This affected the altitude comparison between the two sets of waypoints, especially for the absolute value of altitude differences. An ideal comparison would be pairing ADS-B and onboard GPS waypoints based on their synced timestamp and then conducting an altitude comparison. The study indicated that onboard GPS is more effective in aircraft tracking in the rugged, mountainous terrain of DENA. However, a consistent signal update rate (e.g., 15 seconds) should be maintained for onboard GPS, as signals were frequently lost, possibly due to coverage gaps in low-Earth orbit communication satellites over the Arctic Circle. ADS-B data loggers should be installed at multiple sites to mitigate terrain shielding of ADS-B signals, which can be impractical in such inaccessible terrain.

The third study employed a discrete choice experiment, an econometric model, to assess visitors' preferences for recreation alternatives and site attributes under wildfire- and drought-induced displacement scenarios. Two surveys were conducted in four national forests in Southern California, which are dominated by the chaparral biome and a Mediterranean-type climate. In the wildfire survey, the "views" attribute was statistically significant in maximizing

the consumer's utility. Respondents preferred "wildland-urban" and "wildlands" views compared to the reference level, "city" views. In the drought survey, two attributes— "travel time" and "trails"—were statistically significant. Respondents preferred "1–2 hours" and ">2 hours" of travel time compared to "1 hour" travel time. Respondents preferred "difficult" trails compared to the reference level, "easy" trails.

The interaction terms between site attributes and demographic characteristics revealed the factors influencing preference heterogeneity across the population. In the wildfire survey, preference heterogeneity was observed among ethnic groups for "trails" and "views" attributes. A similar difference in preference was observed for "trails," "facilities," and "views" attributes among groups with varying levels of outdoor expertise. Preferences for "trails" differed between male and female respondents. Additionally, visitors with children preferred "semi-developed" facilities over "primitive" facilities compared to groups composed solely of adults. In the drought survey, the interaction terms showed preference heterogeneity among ethnic groups for "facility" and "feature" attributes. A difference in preference was observed among the groups with different levels of expertise in outdoor recreation for the "trails" types. A difference in preference between the high-income and low-income groups was observed for the "feature" attribute. Similarly, differences in preference among age groups were observed for "activity," "views," and "feature" attributes. People visiting with children preferred "wildlife" and "water" feature types compared to the "mountain" feature type, relative to groups composed solely of adults.

The findings of this study inform the design of future studies focusing on specific socio-demographic groups or specific recreation areas facing similar social and environmental conditions. The findings on visitors' preferences could be integrated into forest recreation

management to enhance site attributes and environmental conditions in those recreation areas. One major limitation of the study was the relatively smaller number of complete responses in both surveys. The recreation sites are visited by millions of people annually. Increasing the sample size improves the statistical power of the study and provides more insights into the parameters and their statistical significance.

The three discrete studies highlighted the application of various monitoring tools and techniques in assessing natural resource conditions and visitors' preferences in selected parks and forests. The first study examined the extent of aircraft noise in parks. Similar experiments could be conducted in PPAs with high aircraft activity by deploying an ADS-B data logger and an SLM simultaneously at a site with minimal acoustic impedance and terrain obstruction. Similarly, the comparative study on aircraft tracking technologies identified suitable technology for monitoring low-altitude flights in similar parks and similar landscapes. Future experiments could synchronize the clocks in ADS-B and onboard GPS systems to improve the accuracy and precision of the results, especially for the waypoints altitude comparison. The third study identified key site attributes and environmental factors preferred by recreation visitors during wildfire- and drought-induced displacement in Southern California. Similar studies could be replicated in high-risk wildfire and drought areas frequented by diverse groups of recreation users. Overall, the three studies presented tools, methods, and results that can be customized and replicated to monitor natural resources and visitors' experience in similar contexts.

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Appendix A - ArcPy Script for Automated Toolbox

Provided as two PDF files.

Appendix B - Complete Logit Model (Interaction Terms)

Provided as two PDF files.

Appendix C - Survey Questionnaire

Provided as one PDF file.