Title

Decreased air quality shows minimal influence on peak summer attendance at forested Pacific West national parks

Authors

Brown, Madeline

Jenkins, Jeffrey

Kolden, Crystal

Publication Date

2024-05-01

DOI

10.1016/j.jenvman.2024.120702

Journal of Environmental Management 358 (2024) 120702

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Decreased air quality shows minimal influence on peak summer attendance at forested Pacific West national parks

Madeline Brown [a,*,1], Jeffrey Jenkins [b], Crystal Kolden [b]

[a] Environmental Systems, University of California, Merced, 5200 N. Lake Road, Merced, CA, 95340, USA
[b] Management of Complex Systems, University of California, Merced, 5200 N. Lake Road, Merced, CA, 95340, USA

ARTICLE INFO

Handling Editor: Jason Michael Evans

Keywords:
Air quality
Visitation
Tourism
Environmental hazards
Public lands

ABSTRACT

Wildfires are increasing in duration and intensity across the United States' Pacific West region, resulting in heightened particulate matter from smoke in the atmosphere. Levels of peak particulate matter are concurrent to peak visitor attendance at National Parks, given seasonal alignment with summer vacation travel and heightened forest fire conditions. Particulate matter threatens visitor health and safety and contributes to poor visibility and a deteriorated visitor experience. To assess visitation response to diminished air quality, we utilized wildfire-generated particulate matter (PM2.5) data in conjunction with monthly attendance records for three ecoregions containing eight national parks in Washington, Oregon, and California from 2009 to 2019. We analyzed daily PM2.5 levels from data gridded at the 10 km scale for National Park Service units by Level III forest ecoregions within the National Park Service's Pacific West Unit. Data were then compared to normalized monthly visitation trends for each of the ecoregions using two statistical methods Kendall's Tau and Analysis of Variance (ANOVA) with post-hoc Tukey tests. Results demonstrate that attendance at these national parks does *not* decrease in response to increased PM2.5 levels. Instead, we see several statistically significant increases in attendance across these ecoregions during periods of reduced air quality. Of 115 shifts between air quality categories during the busy season of July to September, there are no significant decreases in attendance as air quality worsens. These findings suggest that visitors are willing to tolerate reduced air quality compared to other factors such as temperature or precipitation. Given that park units within each ecoregion feature diverse historical contexts, varied built environments, and unique ecological systems, our discussion specifically addresses managerial concerns associated with maintained high levels of visitation during suboptimal, and potentially dangerous, conditions. There is substantial need for specific, scalable approaches to mitigate adverse health and experiential impacts as visitors are exposed to increased risks during a range of exertional activities associated with diverse settings.

1. Introduction

Many United States national parks have repeatedly broken their attendance records in recent years (NPS, 2022), particularly in response to the COVID-19 pandemic. Simultaneously, climate change is contributing to increasingly large and recurrent devastating wildfires across western states (Abatzoglou and Williams, 2016; Crockett and Westerling, 2018), which release harmful aerosols hazardous to human health and well-being into the air (D'Evelyn et al., 2022). Unfortunately, national park visitation peaks in July across the western US, contemporaneous to the peak in area burned by wildfire (NPS, 2022; EPA, 2024). As the highest levels of visitors enjoy the great outdoors, they are potentially more likely to be exposed to adverse wildfire impacts, from physical harm due to breathing particulate matter to a negative user experience due to deteriorating visibility and services limiting engagement with park attractions. Adverse impacts resulting from high levels of particulate spread to mental health through multi-sensory experiences of seeing, smelling, and feeling (Velarde et al., 2007). Outdoor spaces have increased mental health benefits aligned with their specific components that draw visitors to National Parks such as scenic vistas and open spaces, bodies of water, and forests. When air quality impacts visitors' physical health and well-being degrades, they find themselves

* Corresponding author. Environmental Systems, University of California, Merced, 5200 N. Lake Road, Merced, CA, 95340, USA.
E-mail address: mbrown40@ucmerced.edu (M. Brown).
[1] Present Address: c/o University of California, Merced, 5200 N. Lake Road, Merced, CA 95340, USA

https://doi.org/10.1016/j.jenvman.2024.120702
Received 31 December 2023; Received in revised form 23 February 2024; Accepted 17 March 2024
Available online 16 April 2024

at odds with the very environments in which they intentionally sought respite (National Park Service, 2024).

Managing visitor experience is central to the National Park Service's underlying mandate, therefore they implement varied management strategies to limit adverse outcomes for visitors. Successful and sustainable park management relies largely on task predictability (Mohr and Wolfram, 2010), but predictability in public lands management is challenged by the complex system dynamics nested components, from pest management to legal challenges (Thomas, 1996). Management solutions are rarely "one size fits all." Decisions are primarily contextual, multi-dimensional, intentionally flexible, and may include having to make tradeoffs in the interest of the public and the ecological setting to preserve predictable, thereby safe, and sustainable, and prescriptive, outcomes (Schindler and Hilborn, 2015; Spernbauer et al., 2022). Maintaining predictable interactions and outcomes within National Parks expands into the built environment. Multiple sites limit access into specific park units or sections of parks to maintain predictable visitor movement outcomes. Devils Postpile National Monument (managed by the National Park Service), Denali National Park, and the Mariposa Grove of Giant Sequoia trees in Yosemite National Park, for example, are all primarily only accessible by shuttle bus or on foot. Shuttle bus use simultaneously decreases single-vehicle usage, thereby reducing congestion, and protects sensitive environments from physical wear (Manning et al., 2014; Monz et al., 2016).

Yosemite National Park management's response at the beginning of the COVID-19 pandemic in 2020 demonstrates a substantial tradeoff made in the public's interest. After wholly closing the park for several months, park management enacted a vehicle-based day-use reservation system in responding to public health recommendations and increased demand (Jenkins et al., 2021). These actions set the precedent for large-scale managerial access limitations in relation to a public health crisis. By reducing overall user demand, the strategy effectively increased visitor dispersal, which can decrease traffic congestion and crowding and improve the visitor experience (White, 2007; Lawson et al., 2009). The National Park Service explicitly and adaptively manages the 'visitor experience' through formal social-science-based practices encapsulated in the Interagency Visitor Use Management Framework (Cahill et al., 2018). While air quality has long been a consideration in managing the visitor experience, increasingly frequent poorer air quality associated with increased western US wildfire activity in recent years may predicate the need to adapt existing National Park Service management strategies. Despite long-established public perception of stationarity of Park lands, management is, and must continue to, dynamically adapt to climate change associated challenges without jeopardizing the foundational goals of the Organic Act (Biber and Esposito, 2016).

Poor air quality is strongly associated with acute and chronic health conditions and mortality rates worldwide (Kelly and Fussell, 2015). In the western US, decreased air quality is associated with summer wildfires that emit harmful aerosols, including ozone (O_3), carbon dioxide (CO_2), and particulate matter (Bowman et al., 2009; Williams and Abatzoglou, 2016), typically from July through September (Wiedinmyer et al., 2006). Of these, particulate matter is the most widely tracked, particularly the 2.5 μm size class (denoted as $PM_{2.5}$) composed of elemental and organic carbon, nitrate, and sulfate (Jacob and Winner, 2009) because PM2.5 poses the most significant health risk compared to other particulates as the particles are small enough to enter human lungs and bloodstreams (United States Environmental Protection Agency, 2022). The US Environmental Protection Agency (EPA) uses $PM_{2.5}$ to classify air quality categorically from Good to Hazardous based on specific ranges for the EPA Air Quality Index (AQI), as detailed in Table 1. The EPA cautions that fine particulates are the most harmful component of smoke, and that people should stay inside and avoid smoky conditions or wear specialty respirators outdoors. Additionally, it urges using "common sense" for being active during heightened air pollution (United States Environmental Protection Agency, 2022) (see Table 2).

Table 1
Per the EPA, the following air quality categories are associated with specified ranges of PM2.5 and corresponding risk, as well as potentially impacted groups.

AQI Category	PM2.5 μg per square meter	Corresponding AQI Index Value	PM2.5 Specific Description
Good	0–12	0–50	Air quality is satisfactory, and air pollution poses little or no risk.
Moderate	12.1–35.4	51–100	Unusually sensitive people should consider reducing prolonged or heavy exertion
Unhealthy for Sensitive Groups	35.5–55.4	101–150	People with heart or lung disease, older adults, children, and people of lower socioeconomic status should reduce prolonged or heavy exertion.
Unhealthy	55.5–150.4	151–200	People with heart or lung disease, older adults, children, and people of lower socioeconomic status should avoid prolonged or heavy exertion; everyone else should reduce prolonged or heavy exertion.
Very Unhealthy	150.5–250.4	201–300	People with heart or lung disease, older adults, children, and people of lower socioeconomic status should avoid all physical activity outdoors. Everyone else should avoid prolonged or heavy exertion.
Hazardous	250.5+	301+	Everyone should avoid all physical activity outdoors; people with heart or lung disease, older adults, children, and people of lower socioeconomic status should remain indoors and keep activity levels low.

Decreased air quality hampers visitor experience aesthetically, but also by exposing visitors to health risks. In order to mitigate such risks, either visitors must first recognize the presence of particulate matter and take appropriate actions or parks must notify visitors of the risks and similarly take management actions. Public perception of pollution is not directly related to numerical air quality measurements in the United States (Brody et al., 2004). Instead, additional criteria influence whether people recognize pollution as being present, such as whether residents are urban or rural, a location's developmental context, and the pollution source. Pollution sources also largely determine how air quality is perceived– industrial pollution is more readily perceived, while pollution from wildfires may appear more "natural" within the context of national parks (Cori et al., 2020; Reames and Bravo, 2019). Previous research indicates that visitors can perceive very low pollution levels impacting views in national parks (Hyslop, 2009). The key question is whether this perception then leads to mitigation actions such as displacement from impacted areas.

Climate, topography, localized weather, seasonality, and other factors determine types of recreation undertaken in national parks, but extreme events exacerbated by climate change, such as heat waves, impact outdoor recreation and lead to recreationist displacement from preferred locations and activities (Halofsky et al., 2020). Similarly, wildfires and smoke may also produce localized displacement. For example, in Yosemite National Park, most visitors generally engage in

Table 2
Ecological descriptors and associated visitation averages for National Parks included in study. Attendance is normalized to each park's median values for July, August, and September for 2009–2019.

Eco-region	Park Unit	Description	Hectares	Median Summer Attendance
Cascades	North Cascades	The Cascades feature diverse landscapes, with lower elevations showcasing pine forests and higher elevations with subalpine meadows and alpine tundra. Air quality varies, with urban areas experiencing higher pollution levels, while higher elevations enjoy cleaner air and are influenced by down canyon winds. There are distinct seasons, with wet winters and dry, warm summers, and have historically experienced both low-intensity and high-intensity fires, although recent years have seen more intense wildfires due to climate change.	204,226	6752
	Crater Lake		74,148	111,194
	Mount Rainier		95,641	269,951
Coast Range	Redwood	Coast Range forests consist of evergreen and deciduous trees, including Redwoods. The Pacific Ocean moderates air quality, resulting in cool and moist weather with fog acting as a filter for pollution. However, fog can also trap particulates and release them during dry spells. While the region has been relatively spared from megafires, recent years have seen increased fire activity due to climate change.	31,450	57,666
	Olympic		369,643	515,266
Sierra Nevada	Sequoia-Kings Canyon	The Sierra Nevada feature diverse vegetation, ranging from oaks and chaparral in lower elevations up to coniferous giant sequoias, pines, and cedars. The Mediterranean climate brings hot, dry summers and cool, wet winters, with higher elevations receiving more precipitation and snow. Air quality varies, with pollution influenced by the Central Valley, but is good overall, improving with elevation. Natural processes and human activities have historically shaped fire regimes, with recent decades demonstrating fuel accumulation and increased incidence of extreme wildfires.	350,352	270,000
	Lassen Volcanic		43,101	90,517
	Yosemite		307,435	615,892

lower, shorter-term exertion activities such as walking and visiting interpretive facilities in Yosemite Valley. However, Yosemite Valley is subject to extreme inversion layers due to its topography during periods of decreased air quality, as its steep walls limit air mixing (Colette et al., 2003).

Given the significant increase in wildfire area burned in the western US over the last three decades due to anthropogenic climate change (Abatzoglou and Williams, 2016), there is a critical need to understand how National Park Service visitor experience is affected by, and potentially even responding to, increased wildfire smoke impacts during peak visitation season. Determining whether visitors are self-mitigating smoke exposure by not going to parks can help inform both park management strategies and education efforts around the risks of particulate matter to human health. Researchers have identified air quality and its potential influences on visitation within the greater context of climate change as a specific gap in the literature (Rutty et al., 2022). Clark et al. (2023) specifically assessed the impacts of remotely sensed black carbon on visitor attendance. They found no decrease in attendance, but one of the key limitations of their study was the coarse spatial resolution of the black carbon data they utilized and whether or not it reflected surface level air quality accurately.

We build on Clark et al. by using ground-level air quality observations to ask how diminished air quality from wildfire smoke affects visitor attendance at eight national parks in the western US. Specifically, we ask whether visitor attendance varies in relation to particulate matter during peak visitation season of July, August, and September. We explore results across three scales; individual park units, ecoregion, and National Park Service regions to discuss implications for park management, resource allocation, and challenges associated with seasonal environmental hazards in National Parks in the West.

2. Data and methods

2.1. Study area

For this study, we assessed eight Pacific West region national park units in Washington, Oregon, and California (Fig. 1), including Crater Lake, Lassen Volcanic, Mount Rainier, North Cascades, Olympic, Redwood, Sequoia-Kings Canyon, and Yosemite National Parks. The full name of Redwoods National Park, Redwoods National and State Parks reflects a unique partnership, pairing the National Park Service and the State of California in a collaborative management agreement and shared general plan for several non-contiguous units (National Park Service, 2022). However, attendance data are specific to the National Park component of the units. These eight parks all experience peak visitation in late summer, naturally occurring wildfire, and similar climate change impacts through increased drought, tree mortality, and wildfire (Halofsky et al., 2020; Kolden et al., 2015; Libby, 2017; Steel et al., 2015). They vary in attendance ranging from as few as roughly 2000 visitors per month (North Cascades) to over a quarter-million visitors per month (Yosemite).

2.2. Data sources

A national dataset of daily $PM_{2.5}$ levels at 10-km resolution generated from wildfire smoke (Childs et al., 2022) was utilized for the analysis. The data were derived from machine-learning using ground, remotely sensed, and reanalyzed data sources rather than chemical transport models. While the machine learning model performed well with overall and within R-squared aligning and explaining two-thirds of data variability, the authors validated their results against additional datasets. Author-identified uncertainty associated with this specific dataset includes focusing on total-smoke PM2.5 rather than differentiating into subtypes, as well as data being trained against non-smoke day's median PM2.5 measurements. Initial steps included overlay analysis in GIS software to select all grid polygons intersecting park unit

Fig. 1. The eight National Parks grouped by EPA Level III ecoregions stretching from Northern Washington south through Central California (EPA, 2023a). Map by authors. Layers via the National Park Service and EPA.

boundaries. PM2.5 data for each grid cell were merged with the geospatial layer based on an inner join in R Studio, and each grid cell received a unit-based code, e.g. Yosemite grid cells were identified as YOSE. $PM_{2.5}$ daily data were combined to calculate monthly means in alignment with the attendance data's monthly interval through grouping by grid cell ID, month and year, then summarized by park unit code. Then, an additional field of term-based categorization was added to the dataset for use as levels in R analysis. Limitations to the PM2.5 data through aggregation include loss of granularity for both spatial (10 km to unit wide) and temporal (day to month) scales.

National park attendance for all recreation visits in recorded years was collected from the National Park Service's Integrated Resource Management Applications (IRMA) Park Visitor Use Statistics for each park. The data were then subset to 2009–2019. The decade range 2009 through 2019 was explicitly selected for the observational period, as it is after the most recent recession and before the Covid-19 pandemic. Attendance were then normalized into percentage deviation from the median through calculating the median monthly summer attendance across July, August, and September for 2009–2019 for each park ($n = 33$). We recognize trends associated with the 2016 National Park Service Centennial influenced increased park attendance and future research may explore which parks were most influenced and corresponding detrending of data may contribute to future methodological refinement. We then aggregated data to ecoregion and unit wide to facilitate comparisons at three total managerial scales and to increase the number of data points and to minimize anomalies associated with single park closure events. As the number of parks varies by ecoregion, the number of air quality-attendance month-pairs also varied with each

ecoregion (Cascades: n = 99; Coast Range: n = 66; Sierra Nevada: n = 99). Both PM2.5 measurements and calculated deviations from the median and non-normal.

2.3. Analysis methods

We utilized the non-parametric test Kendall's Tau for evaluating the association between monthly normalized median attendance deviation and $PM_{2.5}$ values at three scales-individual park unit, ecoregion, and the full Pacific West region (Kendall, 1938). We also utilized analysis of variance (ANOVA) and post hoc Tukey HSD tests to assess the relationship between continuous normalized attendance values and categorical air quality categories across each of the three scales (Tukey, 1949). We then summarized the data to assess the directionality of median values for each air quality category, providing additional insights into the relationship between air quality and attendance. We created supplemental box plots demonstrating departure from the median and results tables to visually present the statistical results and identify attendance trends reflecting air quality. Relying solely on categorical data can potentially obscure underlying trends due to aggregation, which is why both categorical and numerical data were considered in this analysis.

3. Results

3.1. Variation in peak visitation attendance across scales

3.1.1. Kendall's Tau

The Kendall's Tau analysis results, as detailed in Table 3, demonstrate a singular park at which there is a statistically significant relationship between increasing particulate levels and decreasing attendance- Yosemite National Park. Additionally, there are three statistically significant instances in which attendance increases as particulate matter increases, as seen in the North Cascades, Mount Rainier, and Olympic National Parks, respectively. When aggregated to ecoregion, results indicate a lightly positive relationship between increasing particulate matter and increasing positive deviations from median attendance for the Cascades ecoregion. There is no statistically significant relationship between particulate matter and deviations from median attendance across the Pacific West unit.

3.1.2. Analysis of variance

Of 115 instances of shifts between air quality categories at the park unit level, there are *no* statistically significant shifts in which attendance decreases below the median corresponding to increases in particulate matter (p adj = 0.05, 95% CI). There is one statistically significant result in which attendance increases corresponding to increases in particulate matter from the Good air quality category (−18% below median attendance) to Moderate (22% above median attendance). We visualize the ANOVA results as box plots in Fig. 2.

When aggregated to the ecoregion level, as well as full Pacific West unit level, there are no statistically significant shifts in which attendance decreases below the median corresponding to increases in particulate matter. For air quality category shifts in ecoregions, there are two statistically significant shifts within the Cascades ecoregion, both as air quality decreases from Good (−10.27% below median) to Moderate (12.38 above median), and Good to Unhealthy (23% above median). This positive increase in deviation from the median is also present at the Pacific West level in one instance shifting from Good to Moderate air quality. These shifts are supplementally visualized in Fig. 3.

Table 3
Kendall's Tau analysis results- Yosemite National Park is the singular entity exhibiting a statistically significant decrease in attendance.

By Park Unit		
Unit	Kendall's Tau	P-Value
North Cascades	0.2383223	0.05255*
Crater Lake	−0.0476655	0.6982
Mount Rainier	0.2438113	0.04716*
Redwood	−0.1883941	0.1248
Olympic	0.3063783	0.01255*
Sequoia-Kings Canyon	0.0589921	0.0589921
Lassen Volcanic	0.1547313	0.209
Yosemite	−0.3473384	0.004759*
By Ecoregion		
Cascades	0.1463273	0.03299*
Coast Range	0.07412769	0.3817
Sierra Nevada	−0.0197512	0.7739
Full Region		
Pacific West Region	0.0629798	0.1299

4. Discussion

Results suggest that attendance counts do not consistently decrease, corresponding to increased particulate matter in the air for Pacific West forested parks, regardless of analysis scale from individual park through full region. We emphasize that correlation does not imply causation in this context. Visitors are not attending at higher rates *due to* increased instances of reduced air quality; instead, they are still attending *in spite of,* air quality, as further discussed below. Our results demonstrate visitors are not changing behavior through decreased attendance, with attendance values remaining high despite hazardous air quality overall. Visitors therefore may be electing to displace within parks, seeking refugia from reduced air quality, or tolerating conditions despite risk. Visitors generally change their behavior based on conditions within their respective locations, which vary across based on park contexts and ecoregion considerations such as microclimate and topography, with more diverse parks featuring increased adaptive capacity (Wilkins et al., 2021). Attendance persisting during suboptimal conditions is supplemented by recent research in the Yosemite National Park region indicating that even with one or more park gates (i.e., park ingress) limited by wildfire-driven road closures, visitors choose to still access parks, rather than displace to gateway communities (Brown and Jenkins, 2023).

We anticipate multiple potential impacts and associated managerial implications for the lack of reduced visitation during decreased air quality periods as contributing factors related to climate change persist (Abatzoglou et al., 2021). Overall persistent attendance corresponding to high levels of particulate matter throughout summer requires specific reflection for addressing related challenges and outcomes. Managing visitors is an especially critical challenge regarding increased attendance volumes during instances of harmful air quality. Responses to managerial challenges associated with decision making reflective of decreased air quality may be complicated by the National Park Service juggling fundamentally conflicting mandates-whether the air is crystal clear or hazardous to breathe. The National Park Service is mandated …

> "… to conserve the scenery and the natural and historic objects and the wild life (sic) therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations …" - National Park Service Organic Act, 1916.

Summarily – to preserve functional environmental conditions while facilitating visitor experiences, while climatic and environmental conditions are degrading. For example, climate projections for the Sequoia-Kings Canyon region demonstrate increased climatic event extremes, increased overall temperatures, decreased precipitation, and increased levels of PM2.5 are expected to increase into the next century (Low, 2021; Ford et al., 2018). Researchers explicitly call for adaptive action as visitors will be increasingly exposed to reduced and harmful conditions in pursuit of recreation. We further reflect upon impacts on staff and

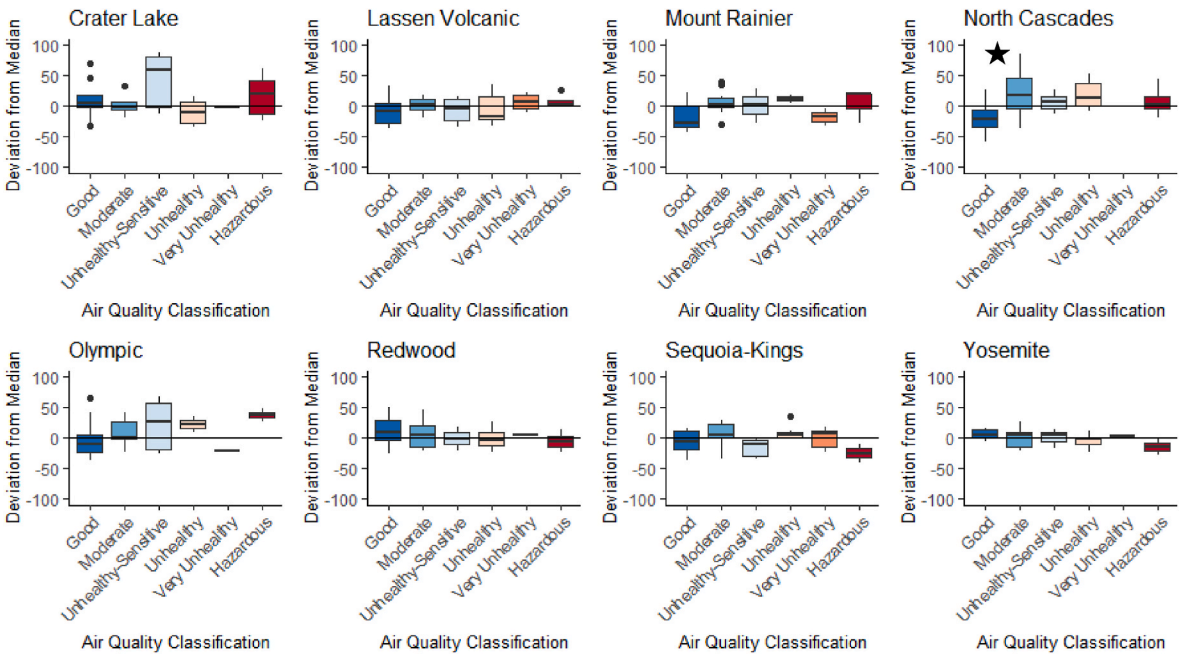

Fig. 2. Categorical shifts from Good air quality through Hazardous air quality for each of the eight national parks, visually demonstrating general overall increases in attendance departure from median attendance corresponding to decreases in air quality category. The star for the North Cascades chart indicates the statistically significant transition from Good air quality levels to Moderate.

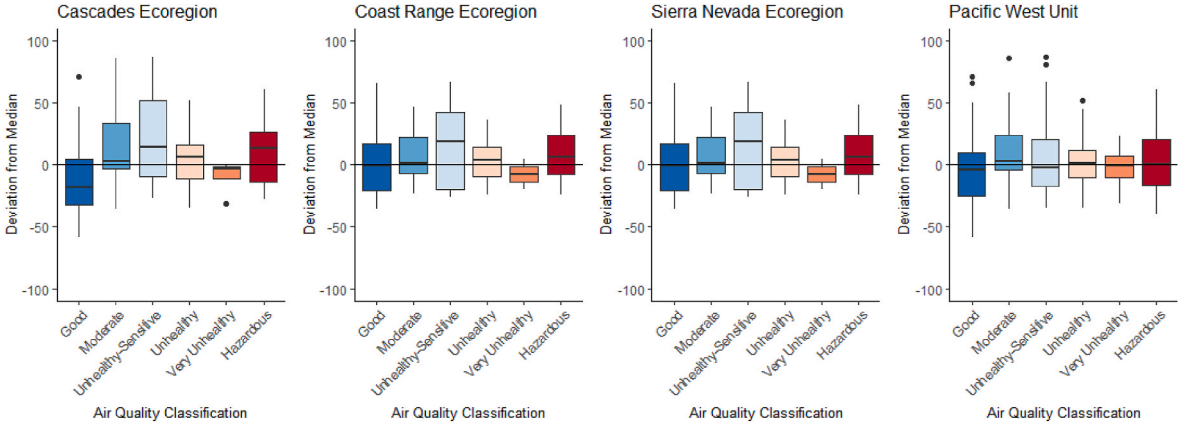

Fig. 3. Categorical shifts from Good air quality through Hazardous air quality for each of the three ecoregions and the overall Pacific West, visually demonstrating light overall increases in attendance departure from median attendance corresponding to decreases in air quality category.

management resources across three dimensions: visitor experience, ecological degradation, and managerial implications.

Scenic viewpoints, popular destinations across the full Park Service landscape, as these viewpoints significantly enhance the overall visitor experience and operate as a microcosm of the interface between visitors and decreased air quality condition. Visitors collect at pre-determined destinations, often congested with people, vehicles, and in these instances – particulate matter. Despite degraded visuals and harmful air quality conditions, scenic vistas and overlooks still operate as a "checkbox" for visitors to complete associated with auto-centric evolution for park consumption, such as Yosemite's Tunnel View (Louter, 2006; Taff et al., 2013). Promoting less congested park areas can disperse visitors to different microclimates (such as higher elevations), thereby decreasing densities in areas with increased particulate matter levels.

As air quality diminishes, visitors may face increased physical discomfort and health risks depending on personal health, exposure duration, and exertion levels. Managers have historically encouraged displacement to other areas of the park that have improved air quality to mitigate these concerns. They may further consider offering alternative, designated respite, as seen frequently in other situations harmful to public health-such as heatwaves experienced in these western ecoregions. For example, 2023 research in Mariposa County (home to Yosemite National Park) identifies that medically sensitive adults intentionally seek out physical interventions to mitigate health impacts, specifically from heat and wildfire smoke, including accessing air filtration systems and avoiding outdoor activity (Hoshiko et al., 2023). The concept of a public cooling center may be directly translated into a designated relief space in instances of reduced air quality, particularly in parks with other limited infrastructure and access to ventilation and air quality-controlled environments. Other state and federal public agencies including Departments of Education and the California Air Resources Board (CARB) exercise limitations recommended by institutions such as the during instances of reduced air quality. School facilities have operated as Cleaner Air and Cooling Centers with guidance from the Environmental Protection Agency, in direct response to Pacific Northwest

heatwaves and air quality issues in 2021, utilizing Covid-19 American Rescue Plan (ARP) funding (EPA, 2023b).

Additionally, as seen with Covid-19, supplemental filtration systems may be utilized to improve localized air quality, such as in a campground restroom facility. By proactively managing crowds and promoting healthier alternatives, park managers can ensure visitors can recreate more safely, as results demonstrate attendance persisting (often increasing) despite air quality levels in Unhealthy for Sensitive Populations and beyond.

Departures from the medians potentially reflect visitors who would have attended during periods of improved quality with the ability to withdraw at short notice (i.e., those within reasonable drive time or increased schedule flexibility to "try again"). Locals can stay home and reschedule on comparatively shorter notice, while a substantial proportion of visitors have traveled further and may be more inclined to not miss their opportunity given financial and planning costs associated with accessing national parks, such as booking flights, limited back country permits, or stringent accommodations policies (Brown and Jenkins, 2023). Meanwhile, outside of visitors' accommodations within and proximate to parks, air quality is correspondingly reduced. Though visitor attitudes are shifting toward recognizing smoke as a component of vital, natural ecological processes, visitors have not yet fully embraced the concept of smoke being an essential part of the park environment (Zajchowski et al., 2019). Mixed results indicate varied tolerance of smoke depending on the smoke source (e.g., prescribed versus managed wildfire), as well as a division between those who see fire as a needed tool and those who do not (Ellison et al., 2021; Peterson et al., 2022).

Recreation is a significant driver of park visitation and given increased attendance levels during instances of reduced air quality, we can ascertain corresponding levels of exertion based on specific activities available at the included parks. As one of the most exertional activities, hiking is present across all parks for varied distances, weather conditions, and required exertion levels for desired outcomes. For example, visitors can drive to the Rim Village Visitor Center within a quarter-mile of Crater Lake's rim at Crater Lake National Park and enjoy the vista with minimal physical exertion required. The lake is directly visible from within the Visitor Center. Wizard Island, a prominent cinder cone within Crater Lake, is a popular vista for sightseers and photographers. With wildfire smoke and particulate matter contributing directly to decreased visibility, vista-specific features require consideration of their scene-dependent qualities (Malm et al., 2018). Meanwhile, other locations, such as Sahale Glacier in North Cascades National Park, feature a strenuous hike across complex terrain, rewarding hikers with scenic vistas and extended cardiovascular exercise.

Across park sites, topography, time of day, climatic conditions, and other influences determine the level of potential particulate entrainment. In Redwoods National and State Parks, the proximity to the Pacific Ocean moderates weather and air moisture content, leading to predictable temperatures throughout the day, but can also trap particulates close to the ground due to a lack of air mixing (Hurt, 2021). Meanwhile, in Sequoia-Kings Canyon National Parks, further inland and to the south, conditions reverse as temperatures can shift substantially due to elevation, diurnal patterns, and upslope wind patterns in the morning can flush the region of pollution trapped by nightly inversion layers (Buysse et al., 2018). Visitors must weigh the benefits of exposure to potentially harmful air quality with the goals and potential outcomes of their exertional decision-making related to other biophysical experiences (Tainio et al., 2021). National Park sites regularly feature a limited number of ingress and egress corridors (i.e., limited ways in and out during emergency scenarios), such as complete closures and mass evacuation seen with the 2021 Dixie Fire in Lassen National Park (National Park Service, 2021). Particulate matter, observed as reduced visibility, negatively impacts visitor experience, and exposes visitors and employees to increased risks, particularly for drivers. In unfamiliar environments, visitors encounter heightened risks of accidents even under clear conditions; reduced visibility associated with wildfire smoke further exacerbates these risks (Federal Highway Administration, 2023).

As ecological protections are a significant component of the National Park Service's guiding policy, considering individual ecoregions is essential for reflecting upon impacts of persistent attendance during instances of increased particulate matter. Ecologists observe multiple interactions where PM 2.5 influences ecological processes. Fire is an inherently natural process, with landscapes in the West long-adapted to recurring fire to reduce ladder fuels and underbrush, induce plant generation, and provide shelter to a variety of species, amongst other benefits (Sugihara et al., 2006; Van Wagtendonk and Lutz, 2007; Montagné-Huck and Brunette, 2018; Urgenson et al., 2017). After a century of extreme fire suppression, public land managers are turning more often to managed fire, including facilitating natural lightning ignitions (managed wildfire, beginning in the 1970s) and increased site-specific control burns in more populated regions (Van Wagtendonk et al., 2012; Jones et al., 2022). Despite shifting paradigms towards fire, ecological function, and conservational efforts may be negatively impacted by visitation retention during reduced air quality, as reflected in our analysis.

Multiple fern species (*Polystichum munitum, Struthiopteris spicant*) in Redwood National and State Parks are highly susceptible to disruption. They currently face extirpation due to climate change– particularly rising temperatures - would be vulnerable to compound stressors, exacerbated in areas of understory disruption (e.g., trails) (Kassuelke et al., 2022). Coast Redwoods (*Sequoia sempervirens*) in Redwood National and State Parks, and Giant Sequoia (*Sequoiadendron giganteum*) trees in Sequoia and Kings Canyon National Parks feature shallow and sensitive root systems and are incrementally undergoing protections to remove direct human impacts at popular groves (Koopman et al., 2014; Jenkins and Brown, 2019). In Yosemite Valley, the most heavily trafficked portion of Yosemite National Park, fragile meadow ecosystems and unique plant species are particularly susceptible to compounded hazards as they already face degradation due to social trails and drought stressors (Walden-Schreiner and Leung, 2013). Sensitive vegetation cannot adapt quickly enough to shift limited geographic ranges to reduce physical and environmental stressors.

Maintained high levels of visitation during instances of decreased air quality compounds negative ecological impacts. Compounded hazards to ecological settings, or "multiple stressors", are more harmful-beyond simply additive-to ecological function and healthy environments than singular damaging influence (Paine et al., 1998; Pirotta et al., 2022). Reduced air quality weakens plant growth and function (Weber and Grulke, 1995). PM2.5 negatively impacts plants through deposition directly on foliage and through uptake in soil moisture, disrupting plant metabolic processes (Leser, 2021). Furthermore, PM2.5 impacts how foliage breakdown and reincorporates into the soil by reducing breakdown speeds. In turn, PM2.5 dissolution into the soil impacts aquatic ecosystems, perpetuating cyclical ecological functions and potentially contributing to biodiversity loss (Wu and Zhang, 2018; Leser, 2021). Therefore, in a region already enduring degradation by social trails (walking off established paths), vegetation is subject to increased wear resulting from compound stressors of decreased air quality and human behavior of persisting visitation levels during reduced air quality.

Our findings augment that of other recent studies utilizing large scale remotely sensed data through increased spatial granularity and in-situ data (Clark et al., 2023). We echo their recommendation to limit visitor access reflecting air quality conditions. We expand further within the context of park management decision-making. Park managers may explore effective crowd management strategies already utilized within other contexts to combat ecological, resource, and experiential challenges associated with decreased air quality. One approach is the implementation of timed entry systems, which can help regulate the flow of visitors and reduce congestion during peak reduced air quality time frames.

In recent decades, select sites within the National Park Service have

implemented quota and access systems to limit entry to public areas to maintain predictable thresholds for visitation to sensitive destinations. For example, Zion National Park's shuttle system, implemented in 2000, directly resulted from overcrowding and degradation in the popular Zion Canyon (Wadsworth, n.d.). The National Park Service maintains the ability to adjust shuttle timing and frequency as a function of demand, resulting in desired prescriptive, sustainable outcomes (Mace et al., 2013; Schindler and Hilborn, 2015). Implementing the shuttle system to combat a dynamic challenge is an example of park management incorporating adaptive management principles, generally defined as the ongoing update and improvement of management strategies and approaches in response to changes in information and the environment (Prato, 2006). Adaptive management relies on data-driven decision--making to observe and evaluate decisions, then adapt as needed to reach specific goals. Managing predictable anthropogenic disturbances at localized scales, such as social trail degradation, contributes to ecological system resilience, while much of ecosystem conservation is based in unpredictable or computationally difficult to model ecological dynamics (Sasaki et al., 2015).

National park size and associated levels of infrastructure requiring upkeep pose specific challenges- and competition-for financial resources. Allocating financial resources is a foundational component for safe and effective public lands management of the National Park Service (Ascher, 2001; Dilsaver, 2016). The National Park Service has been combatting maintenance challenges and budgetary shortfalls in recent years (Loris, 2020; Walls, 2022). Resource allocation, which includes managing person-hours, is essential to ensure the safety and sustainable enjoyment of visitors. Moreover, managers must adapt resource allocation strategies to address specific environmental factors, including air quality. For instance, during periods of poor air quality, parks may require staffing changes to address the associated challenges, such as interpretive rangers communicating directly with visitors, or placing literature information and "sandwich boards", in contrast to times when air quality is improved. Despite a 9% increase in visitation over the past decade, there has also been a 9% reduction in staffing across the National Park Service. Ultimately, fewer people perform park-sustaining tasks during normal conditions (Congressional Research Service, 2020). The most significant paradigm (and resource) shift in demand across public lands, National Parks included, has been increased strain on firefighting resources in both emergency response and proactive, planned control burns (and managed wildfire).

As a direct response to the Covid-19 pandemic, multiple National Parks implemented visitor reservation systems beginning in 2020 – an adaptive management approach using data to drive decision-making to achieve a specified goal with updates to the plan as needed based on changes in data. Reservation systems were designed to reduce crowding and meet social distancing guidelines, with the additional benefit of easing congestion and mitigating impacts of overuse, particularly at popular trails and front country destinations (Jenkins et al., 2021). Parks implementing reservation systems had visitors access a web-based permitting system, allowing visitors to select the day and time frame they would like to enter. The National Park Service, leveraging the web platform www.recreation.gov, has implemented, removed, and adjusted reservation systems multiple times, previously utilizing it to book recreational reservations. Instead of fluctuating services as a function of demand (as with shuttle systems), operational adjustments were made based on infection levels and guidance at a park-by-park level. The flexibility of the web booking system offers visitors the ability to manage reservations reflecting current and forecast air quality conditions. Following the decline of the most extreme Covid-associated limitations, Yosemite National Park continues to utilize their reservation system to manage visitation during popular weekends and during the busy season. Simultaneously, reservation systems allow management to not only adaptively limit visitation to reduce exposure to harm for humans and ecological systems alike directly in response to the sum of conditions and associated impacts, but also utilize reservations to project demand and use during harmful conditions.

The implementation of Covid-19 associated park access constraints (i.e., reduced visitation limits and reservation systems) serves as a strong example of adaptive management to mitigate public health risks. For over three decades, the National Park Service has studied, monitored, and communicated with the public on air quality concerns (Beissinger et al., 2016). They currently operate an extensive system across 65 park units actively monitoring air quality conditions and taking action to limit access when air quality levels deteriorate to the most extreme health-threatening conditions (National Park Service, 2023). Other public agencies exercise the capacity to limit public health risks directly related to air quality. State Departments of Education maintain limitations for student activity at public school facilities. Based on duration of exposure and intensity of activities, school sites actively manage recess, physical education classes, athletic practice, and sporting competitions – each of which are comparable to various exertional activities undertaken in National Parks (hiking, rock climbing, backpacking, etc.) (California Department of Education, 2019). Notably, one in three visitors to National Parks in under the age of 18 and would largely experience the same physical activity limitations while at public school settings (Xiao et al., 2022).

Recommendations and constraints on exposure to reduced air quality highlight the importance of utilizing adaptive management strategies to address public health risks, as these results demonstrate relying solely on individuals to mitigate health risks is insufficient. Recalling that an essential component of successful management is predictability, it is essential to update and improve of management strategies as a response to fluctuations, generating consistency in, visitation thresholds during instances of increased PM2.5 and reduced air quality (Prato, 2006). Managers maintain broad discretionary decision-making abilities and may adapt park policy reflective of anthropogenic climate change driven challenges without competing with Organic Act mandates (Biber and Esposito, 2016). The National Park Service may operationalize access constraints, such as reservation systems and dynamic attendance thresholds reflective of current and forecast air quality conditions while upholding its foundational principles.

To maintain focus on implications for National Park Service management, this paper does not include discussion on other parks and protected areas. We suggest further research avenues expanding into how visitors recreate within different operational contexts including National Forest Service and Bureau of Land Management spaces. Additionally, we recognize that while we analyze and discuss if people are visiting Parks during instances of reduced air quality, and how management may manage attendance during air quality public health concerns, we do not address the why of persistent visitation. We encourage future research on driving factors of persistent visitation, whether related to limitations of available personal time for visitors, reservation constraints, economic considerations, and other factors. Additional data sources that may be utilize to further explore visitation trends within National Parks and other public lands include the publicly available IMPROVE dataset out of Colorado State, which monitors protected visual environments.

5. Conclusions

Despite risks to personal health and degradation of experiences, visitation does not decrease at select National Parks, corresponding to increased levels of particulate matter. To preserve visitors' health and experience, the national park service may choose to implement adaptive quotas like those utilized during Covid-19 to decrease the number of visitors exposed to particulate matter's harmful effects. Specific actions parks can take immediately include increasing public education around risks associated with recreating in reduced air quality conditions, providing supplemental rest and clean-air facilities, limiting access to especially sensitive ecological areas, and encouraging dispersal into other park microclimates and destinations. We promote further analysis

of PM2.5 impacts at individual park scales and more granular data levels to better understand the influence of particulate matter and air quality from park-area microclimates and anticipated trends in future visitation to National Parks.

CRediT authorship contribution statement

Madeline Brown: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jeffrey Jenkins:** Writing – review & editing, Supervision, Conceptualization. **Crystal Kolden:** Writing – review & editing, Writing – original draft, Validation, Methodology.

Declaration of competing interest

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

Data availability

Data associated with this article are publicly available at Mendeley Data, V1, https://doi.org/10.17632/kh6z6syf3m.1 (reserved).

References

Abatzoglou, J.T., Battisti, D.S., Williams, A.P., Hansen, W.D., Harvey, B.J., Kolden, C.A., 2021. Projected increases in western US forest fire despite growing fuel constraints. Communications Earth & Environment 2 (1), 227. https://doi.org/10.1038/s43247-021-00299-0.

Abatzoglou, J.T., Williams, A.P., 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proc. Natl. Acad. Sci. USA 113 (42), 11770–11775. https://doi.org/10.1073/pnas.1607171113.

Ascher, W., 2001. Coping with Complexity and Organizational interests in natural resource management. Ecosystems 4 (8). Article 8.

Biber, E., Esposito, E.L., 2016. The national park service organic Act and climate change. Nat. Resour. J. 56 (1). Article 1. JSTOR.

Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J. E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., et al., 2009. Fire in the earth system. Science 324 (5926), 481–484. https://doi.org/10.1126/science.1163886.

Brody, S.D., Peck, B.M., Highfield, W.E., 2004. Examining localized patterns of air quality perception in Texas: a spatial and statistical analysis. Risk Anal. 24 (6), 1561–1574. https://doi.org/10.1111/j.0272-4332.2004.00550.x.

Brown, M., Jenkins, Je S., 2023. Wildfire-driven entry closures influence visitor displacement and spending to alternative park entrance corridors and gateway communities around Yosemite National Park. Journal of Outdoor Recreation and Tourism. https://doi.org/10.1016/j.jort.2023.100675.

Buysse, C.E., Munyan, J.A., Bailey, C.A., Kotsakis, A., Sagona, J.A., Esperanza, A., Pusede, S.E., 2018. On the effect of upwind emission controls on ozone in Sequoia National Park. Atmos. Chem. Phys. 18 (23), 17061–17076. https://doi.org/10.5194/acp-18-17061-2018.

Cahill, K., Collins, R., McPartland, S., Pitt, A., Verbos, R., 2018. Overview of the interagency visitor use management Framework and the uses of social science in its implementation in the national park service. George Wright Forum 35 (1), 32–41.

California Department of Education, 2019. *Get Smart about wildfire smoke—clear Guidelines for Schools and wildfire smoke* [memo]. https://www.cde.ca.gov/ls/ep/documents/airqualityguidance.pdf.

Childs, M.L., Li, J., Wen, J., Heft-Neal, S., Driscoll, A., Wang, S., Gould, C.F., Qiu, M., Burney, J., Burke, M., 2022. Daily local-level estimates of ambient wildfire smoke PM $_{2.5}$ for the contiguous US. Environmental Science & Technology 56 (19), 13607–13621. https://doi.org/10.1021/acs.est.2c02934.

Clark, M., Killion, A., Williamson, M.A., Hillis, V., 2023. Increasing wildfire smoke has limited impacts on national park visitation in the American West. Ecosphere 14 (6), e4571. https://doi.org/10.1002/ecs2.4571.

Colette, A., Chow, F.K., Street, R.L., 2003. A numerical study of inversion-layer breakup and the effects of topographic shading in idealized valleys. J. Appl. Meteorol. 42 (9), 1255–1272. https://doi.org/10.1175/1520-0450(2003)042<1255:ANSOIB>2.0.CO, 2.

Congressional Research Service, 2020. *National park service appropriations: ten-YearTrends* (R42757). https://crsreports.congress.gov/product/pdf/R/R42757/35.

Cori, L., Donzelli, G., Gorini, F., Bianchi, F., Curzio, O., 2020. Risk perception of air pollution: a systematic review focused on particulate matter exposure. Int. J. Environ. Res. Publ. Health 17 (17), 6424. https://doi.org/10.3390/ijerph17176424.

Crockett, J.L., Westerling, A.L., 2018. Greater temperature and precipitation extremes intensify western U.S. Droughts, wildfire severity, and Sierra Nevada tree mortality. J. Clim. 31 (1), 341–354. https://doi.org/10.1175/JCLI-D-17-0254.1.

D'Evelyn, S.M., Jung, J., Alvarado, E., Baumgartner, J., Caligiuri, P., Hagmann, R.K., Henderson, S.B., Hessburg, P.F., Hopkins, S., Kasner, E.J., Krawchuk, M.A., Krenz, J. E., Lydersen, J.M., Marlier, M.E., Masuda, Y.J., Metlen, K., Mittelstaedt, G., Prichard, S.J., Schollaert, C.L., et al., 2022. Wildfire, smoke exposure, human health, and environmental justice need to be integrated into forest restoration and management. Current Environmental Health Reports 9 (3), 366–385. https://doi.org/10.1007/s40572-022-00355-7.

Dilsaver, L.M. (Ed.), 2016. America's National Park System: the Critical Documents, second ed. Rowman & Littlefield.

Ellison, A., Huber-Stearns, H., Frederick, S., Coughlan, M., McCaffrey, S., Olsen, C., 2021. Perceptions of wildland fire smoke: literature review and synthesis. Scholars' Bank. https://scholarsbank.uoregon.edu/xmlui/handle/1794/26158.

Environmental Protection Agency, 2023a. Level III and IV ecoregions of the continental United States. United States Environmental Protection Agency. https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states.

Environmental Protection Agency, 2023b. Schools as community cleaner air and cooling centers. https://www.epa.gov/arp/schools-community-cleaner-air-and-cooling-centers.

Environmental Protection Agency, 2024. Progress report—air quality. Clean Air Power Sector Programs. https://www.epa.gov/power-sector/progress-report-air-quality#pm.

Federal Highway Administration, 2023. Road weather managment system: low visibility. Federal Highway Administration. https://ops.fhwa.dot.gov/weather/weather_events/low_visibility.htm#:~:text=Visibility%20distance%20is%20reduced%20by,variance%2C%20which%20increases%20crash%20risk.

Ford, B., Val Martin, M., Zelasky, S.E., Fischer, E.V., Anenberg, S.C., Heald, C.L., Pierce, J.R., 2018. Future fire impacts on smoke concentrations, visibility, and health in the contiguous United States. GeoHealth 2 (8), 229–247. https://doi.org/10.1029/2018GH000144.

Halofsky, J.E., Peterson, D.L., Harvey, B.J., 2020. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. Fire Ecology 16 (1), 4. https://doi.org/10.1186/s42408-019-0062-8.

Hoshiko, S., Buckman, J.R., Jones, C.G., Yeomans, K.R., Mello, A., Thilakaratne, R., Sergienko, E., Allen, K., Bello, L., Rappold, A.G., 2023. Responses to wildfire and prescribed fire smoke: a survey of a medically vulnerable adult population in the wildland-urban interface, Mariposa county, California. Int. J. Environ. Res. Publ. Health 20 (2), 1210. https://doi.org/10.3390/ijerph20021210.

Hurt, T., 2021. Super fog and fires. https://www.weather.gov/media/tbw/workouts/2021feb02_ww_superfog.pdf.

Hyslop, N.P., 2009. Impaired visibility: the air pollution people see. Atmos. Environ. 43 (1), 182–195. https://doi.org/10.1016/j.atmosenv.2008.09.067.

Jacob, D.J., Winner, D.A., 2009. Effect of climate change on air quality. Atmos. Environ. 43 (1), 51–63. https://doi.org/10.1016/j.atmosenv.2008.09.051.

Jenkins, J., Arroyave, F., Brown, M., Chavez, J., Ly, J., Origel, H., Wetrosky, J., 2021. Assessing impacts to national park visitation from COVID-19. Case Studies in the Environment 5 (1), 1434075. https://doi.org/10.1525/cse.2021.1434075.

Jenkins, J., Brown, M., 2019. Giant sequoia—forest, monument, or park?: political-legal mandates and socio-ecological complexity shaping landscape-level management. Soc. Nat. Resour. 1–17. https://doi.org/10.1080/08941920.2019.1672843.

Jones, M.W., Abatzoglou, J.T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., Smith, A.J.P., Burton, C., Betts, R.A., Van Der Werf, G.R., Sitch, S., Canadell, J.G., Santín, C., Kolden, C., Doerr, S.H., Le Quéré, C., 2022. Global and regional trends and drivers of fire under climate change. Rev. Geophys. 60 (3) https://doi.org/10.1029/2020RG000726.

Kassuelke, S.R., Dymond, S.F., Feng, X., Savage, J.A., Wagenbrenner, J.W., 2022. Understory evapotranspiration rates in a coast redwood forest. Ecohydrology 15 (3). https://doi.org/10.1002/eco.2404.

Kelly, F.J., Fussell, J.C., 2015. Air pollution and public health: emerging hazards and improved understanding of risk. Environ. Geochem. Health 37 (4), 631–649. https://doi.org/10.1007/s10653-015-9720-1.

Kendall, M.G., 1938. A new measure of rank correlation. Biometrika 30 (1/2), 81–93.

Kolden, C.A., Abatzoglou, J.T., Lutz, J.A., Cansler, C.A., Kane, J.T., Wagtendonk, J.W.V., Key, C.H., 2015. Climate contributors to forest mosaics: ecological persistence following wildfire. Northwest Sci. 89 (3), 219–238. https://doi.org/10.3955/046.089.0305.

Koopman, M., DellaSala, D., van Mantgem, P., Blom, B., Teraoka, J., Shearer, R., LaFever, D., Seney, J., 2014. Managing an ancient ecosystem for the modern world: coast redwoods and climate change. Geos Institute. https://climatewise.org/images/projects/coast-redwoods-report-manuscript.pdf.

Lawson, S., Newman, P., Choi, J., Pettebone, D., Meldrum, B., 2009. Integrated transportation and user capacity research in yosemite national park: the numbers game. Transport. Res. Rec.: J. Transport. Res. Board 2119 (1). https://doi.org/10.3141/2119-11. Article 1.

Leser, N.H., 2021. Plants and Particulate Matter: air quality around construction sites and the impact on vegetation health. https://blogs.iu.edu/ecohealth/2021/12/13/plants-and-particulate-matter-air-quality-around-construction-sites-and-the-impact-on-vegetation-health/.

Libby, W.J., 2017. Why Are Coast Redwood and Giant Sequoia Not where They Are Not? *Gen. Tech. Rep. PSW-GTR-258*, vol. 258. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, pp. 423–427, 423-427.

Loris, N.D., 2020. Tackling the Enormous Deferred Maintenance Backlog for America's National Parks, vol. 3500, p. 3500. Article 3500.

Louter, D., 2006. Windshield Wilderness: Cars, Roads, and Nature in Washington's National Parks. University of Washington Press.
Low, K., 2021. Anthropogenic climate change in Sequoia and Kings Canyon national parks, California, USA. University of California, Berkeley. http://npshistory.com/publications/seki/climate-change-2021.pdf.
Mace, B.L., Marquit, J.D., Bates, S.C., 2013. Visitor assessment of the mandatory alternative transportation system at zion national park. Environ. Manag. 52 (5), 1271–1285. https://doi.org/10.1007/s00267-013-0164-z.
Malm, W., Cismoski, S., Prenni, A., Peters, M., 2018. Use of cameras for monitoring visibility impairment. Atmos. Environ. 175, 167–183. https://doi.org/10.1016/j.atmosenv.2017.12.005.
Manning, R., Lawson, S., Newman, P., Hallo, J., Monz, C., 2014. Principles of sustainable transportation in the national parks. George Wright Forum 31 (3).
Mohr, G., Wolfram, H.-J., 2010. Stress among managers: the importance of dynamic tasks, predictability, and social support in unpredictable times. J. Occup. Health Psychol. 15 (2), 167–179. https://doi.org/10.1037/a0018892.
Montagné-Huck, C., Brunette, M., 2018. Economic analysis of natural forest disturbances: a century of research. J. For. Econ. 32, 42–71. https://doi.org/10.1016/j.jfe.2018.03.002.
Monz, C., D'Antonio, A., Lawson, S., Barber, J., Newman, P., 2016. The ecological implications of visitor transportation in parks and protected areas: examples from research in US National Parks. J. Transport Geogr. 51, 27–35. https://doi.org/10.1016/j.jtrangeo.2015.11.003.
National Park Service, 2021. Lassen volcanic national park closed due to Dixie fire. Lassen Volcanic National Park. https://www.nps.gov/lavo/learn/news/park-closed-due-to-dixie-fire.htm.
National Park Service, 2022. NPS stats: national park service visitor use Statistics. https://irma.nps.gov/STATS/Reports/Park/.
National Park Service, 2023. How we measure smoke. Air Water Pollut. Rep. https://www.nps.gov/subjects/air/howwemeasure-smoke.htm.
National Park Service, 2024. Values embodied in geoheritage. Science - Measuring Value. https://www.nps.gov/articles/series.htm?id=29E0CA29-A137-25A5-51554A2D50C99586&utm_source=article&utm_medium=website&utm_campaign=experience_more.
Paine, R.T., Tegner, M.J., Johnson, E.A., 1998. Compounded perturbations yield ecological surprises. Ecosystems 1 (6), 535–545. https://doi.org/10.1007/s100219900049.
Peterson, D.L., McCaffrey, S.M., Patel-Weynand, T. (Eds.), 2022. Wildland Fire Smoke in the United States: A Scientific Assessment. Springer International Publishing. https://doi.org/10.1007/978-3-030-87045-4.
Pirotta, E., Thomas, L., Costa, D.P., Hall, A.J., Harris, C.M., Harwood, J., Kraus, S.D., Miller, P.J.O., Moore, M.J., Photopoulou, T., Rolland, R.M., Schwacke, L., Simmons, S.E., Southall, B.L., Tyack, P.L., 2022. Understanding the combined effects of multiple stressors: a new perspective on a longstanding challenge. Sci. Total Environ. 821, 153322 https://doi.org/10.1016/j.scitotenv.2022.153322.
Prato, T., 2006. Adaptive management of national park ecosystems. George Wright Forum 23 (1), 72–86. JSTOR.
Reames, T.G., Bravo, M.A., 2019. People, place and pollution: investigating relationships between air quality perceptions, health concerns, exposure, and individual- and area-level characteristics. Environ. Int. 122, 244–255. https://doi.org/10.1016/j.envint.2018.11.013.
Rutty, M., Hewer, M., Knowles, N., Ma, S., 2022. Tourism & climate change in North America: regional state of knowledge. J. Sustain. Tourism 1–24. https://doi.org/10.1080/09669582.2022.2127742.
Sasaki, T., Furukawa, T., Iwasaki, Y., Seto, M., Mori, A.S., 2015. Perspectives for ecosystem management based on ecosystem resilience and ecological thresholds against multiple and stochastic disturbances. Ecol. Indicat. 57, 395–408. https://doi.org/10.1016/j.ecolind.2015.05.019.
Schindler, D.E., Hilborn, R., 2015. Prediction, precaution, and policy under global change. Science 347 (6225), 953–954. https://doi.org/10.1126/science.1261824.
Spernbauer, B., Monz, C., Smith, J.W., 2022. The effects and trade-offs of alternative transportation systems in U.S. National Park Service units: an integrative review. J. Environ. Manag. 315, 115138 https://doi.org/10.1016/j.jenvman.2022.115138.
Steel, Z.L., Safford, H.D., Viers, J.H., 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. Ecosphere 6 (1), 1–23. https://doi.org/10.1890/ES14-00224.1.
Sugihara, N., Van Wagtendonk, J., Fites-Kaufman, J., 2006. Fire as an ecological process. In: Fire in California's Ecosystems, pp. 58–74.
Taff, D., Newman, P., Pettebone, D., White, D.D., Lawson, S.R., Monz, C., Vagias, W.M., 2013. Dimensions of alternative transportation experience in yosemite and rocky mountain national parks. J. Transport Geogr. 30, 37–46. https://doi.org/10.1016/j.jtrangeo.2013.02.010.
Tainio, M., Jovanovic Andersen, Z., Nieuwenhuijsen, M.J., Hu, L., De Nazelle, A., An, R., Garcia, L.M.T., Goenka, S., Zapata-Diomedi, B., Bull, F., Sá, T.H.D., 2021. Air pollution, physical activity and health: a mapping review of the evidence. Environ. Int. 147, 105954 https://doi.org/10.1016/j.envint.2020.105954.
Thomas, J.W., 1996. Stability and predictability in federal forest management: some thoughts from the chief. Publ. Land Resour. Law Rev. 17.
Tukey, J.W., 1949. Comparing individual means in the analysis of variance. Biometrics 5 (2), 99. https://doi.org/10.2307/3001913.
United States Environmental Protection Agency, 2022. Particulate matter (PM) pollution: how smoke from fires can affect your health. https://www.epa.gov/pm-pollution/how-smoke-fires-can-affect-your-health.
Urgenson, L.S., Ryan, C.M., Halpern, C.B., Bakker, J.D., Belote, R.T., Franklin, J.F., Haugo, R.D., Nelson, C.R., Waltz, A.E.M., 2017. Visions of restoration in fire-adapted forest landscapes: lessons from the collaborative forest landscape restoration program. Environ. Manag. 59 (2) https://doi.org/10.1007/s00267-016-0791-2. Article 2.
Van Wagtendonk, J.W., Lutz, J.A., 2007. Fire regime attributes of wildland fires in yosemite national park, USA. Fire Ecology 3 (2), 34–52. https://doi.org/10.4996/fireecology.0302034.
Van Wagtendonk, J.W., Van Wagtendonk, K.A., Thode, A.E., 2012. Factors associated with the severity of intersecting fires in yosemite national park, California, USA. Fire Ecology 8 (1), 11–31. https://doi.org/10.4996/fireecology.0801011.
Velarde, Ma D., Fry, G., Tveit, M., 2007. Health effects of viewing landscapes – landscape types in environmental psychology. Urban For. Urban Green. 6 (4), 199–212. https://doi.org/10.1016/j.ufug.2007.07.001.
Wadsworth, R. E. (n.d.). Shuttle to serenity: The history and impact of Zion National Park's transportation system. https://doi.org/10.34917/1363238.
Walden-Schreiner, C., Leung, Y.-F., 2013. Spatially characterizing visitor use and its association with informal trails in Yosemite Valley meadows. Environ. Manag. 52 (1), 163–178. https://doi.org/10.1007/s00267-013-0066-0.
Walls, M., 2022. Economics of the US national park system: values, funding, and resource management challenges. Annual Review of Resource Economics 14 (1), 579–596. https://doi.org/10.1146/annurev-resource-111920-021401.
Weber, J.A., Grulke, N.E., 1995. Response of stem growth and function to air pollution. In: Plant Stems. Elsevier, pp. 343–363. https://doi.org/10.1016/B978-012276460-8/50017-5.
White, D.D., 2007. An interpretive study of yosemite national park visitors' perspectives toward alternative transportation in Yosemite Valley. Environ. Manag. 39 (1), 50–62. https://doi.org/10.1007/s00267-006-0061-9.
Wiedinmyer, C., Quayle, B., Geron, C., Belote, A., McKenzie, D., Zhang, X., O'Neill, S., Wynne, K.K., 2006. Estimating emissions from fires in North America for air quality modeling. Atmos. Environ. 40 (19), 3419–3432. https://doi.org/10.1016/j.atmosenv.2006.02.010.
Wilkins, E.J., Chikamoto, Y., Miller, A.B., Smith, J.W., 2021. Climate change and the demand for recreational ecosystem services on public lands in the continental United States. Global Environ. Change 70, 102365. https://doi.org/10.1016/j.gloenvcha.2021.102365.
Williams, A.P., Abatzoglou, J.T., 2016. Recent advances and remaining uncertainties in resolving past and future climate effects on global fire activity. Curr. Clim. Change Rep. 2 (1), 1–14. https://doi.org/10.1007/s40641-016-0031-0.
Wu, W., Zhang, Y., 2018. Effects of particulate matter (PM2.5) and associated acidity on ecosystem functioning: response of leaf litter breakdown. Environ. Sci. Pollut. Control Ser. 25 (30), 30720–30727. https://doi.org/10.1007/s11356-018-2922-1.
Xiao, X., Lee, K.J., Larson, L.R., 2022. Who visits U.S. national parks (and who doesn't)? A national study of perceived constraints and vacation preferences across diverse populations. J. Leisure Res. 53 (3), 404–425. https://doi.org/10.1080/00222216.2021.1899776.
Zajchowski, C.A.B., Brownlee, M.T.J., Rose, J., 2019. Air quality and the visitor experience in parks and protected areas. Tourism Geogr. 21 (4) https://doi.org/10.1080/14616688.2018.1522546. Article 4.