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Spring Snowpack Influences on the Volume and Timing of Spring and Peak-Season Overnight Visitation to Yosemite Wilderness

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ABSTRACT: Wilderness visitation, particularly overnight use, is reactive to climate variability because backpackers face greater exposure to and dependence on environmental conditions. This study examines the effect that spring snowpack had on the timing and volume of permits issued for overnight use of the Yosemite Wilderness during peak and shoulder-season months (April–October) from 2002 to 2019. We categorize 1 April snowpack at Tuolumne Meadows into snow drought (<75%), high snowpack (>125%), and near-average snowpack (75%–125%). Results confirm wilderness-wide differences between snowpack categories, including change in spring overnight visitors (April–June: +20% snow drought and −28% high snowpack). Our findings confirm that snow drought allows for more access to high-elevation trailheads when seasonal roads are open earlier in spring (May–June: +74% Tioga Road and +81% Tuolumne Meadows). Mid- to high-elevation trailheads experience a sustained increase in use during high-snowpack years (June–October: +12% Yosemite Valley and Big Oak Flat; +15% Glacier Point Road and Wawona; +32% Hetch Hetchy) because a narrower seasonal access window leads to filled permit quotas in the high country and displaces use to lower-elevation trailheads. These findings have implications for wilderness stewards, including biophysical and experiential impacts on wilderness character from earlier and longer seasons, especially at higher elevation and in fragile alpine and subalpine areas, as snow drought in mountain-protected areas becomes more common. Recommendations to address greater early-season use and its attendant impacts include adaptively managing permits for different types of snowpack years, including potential changes in the number, timing, and destination of select trailhead quotas.

KEYWORDS: Social science; North America; Drought; Snowpack; Decision-making

1. Introduction

a. Climate and seasonal wilderness access

Visitation to parks and wilderness areas is reactive to climatic conditions given greater exposure to and dependence on environmental conditions (Smith et al. 2018), and visitors often select destinations based on expected weather, especially tourists traveling from afar (Hamilton and Lau 2006). At high-elevation parks and wilderness areas, snow plays a primary role in park and wilderness management (Bales et al. 2006), particularly in the western United States where in the past half-century, mountain snowpack has decreased (Mote et al. 2018). Climate projections suggest continued contraction of mountain snowpack in the region, resulting in less wilderness-dependent winter recreation activities such as cross-country skiing and backcountry snowshoeing (Wobus et al. 2017). Reduced spring snowpack has also been associated with earlier peak runoff and lower streamflow, lake, and reservoir levels, all of which can alter the availability of water-dependent outdoor recreation activities (Cutler et al. 2017; Jenkins 2022). Snow droughts can advance the onset of the dry season, which can increase fire potential and lead to restrictions in activities associated with fire risk (e.g., park closure, fire restrictions), impacts on infrastructure, and degraded air quality (Cutler et al. 2017; Jenkins 2022; Gellman et al. 2022; Scott et al. 2007).

For Mediterranean climates, visitation typically increases in the spring toward the peak summer months, when temperature conditions are most ideal and precipitation is limited, and declines in the winter with colder temperatures and greater likelihood of precipitation (Jedd et al. 2018). In these areas during winter, snow accumulates in the mountains, and during spring the snow melts. However, research shows warmer temperatures are expected to shift snow accumulation to higher elevations and expand the seasonal range for warm-weather recreation opportunities due to a reduction in the level and geographic extent of snowpack in locations with seasonal snowpack (Fisichelli et al. 2015; O'Toole et al. 2019; Peters-Lidard et al. 2021; Winter et al. 2021; Miller et al. 2022). Research shows that as temperatures warm as a result of climate change (Goshua et al. 2021), visitors may arrive earlier in the warm season and stay longer during that season to engage in snow-free activities (Marshall et al. 2018; Monz et al. 2021).

Studies have shown that visitors adjust their trip timing to parks and other outdoor recreation destinations based on factors including adverse weather conditions (Becken and Wilson 2013; Buckley and Foushee 2012), an effect modified by familiarity and sense of place attachment (Perry et al. 2021). But when exactly the season starts is highly variable due to snowpack levels in spring and the timing of road openings. Despite this, backcountry users have come to expect, or be hopeful of, a certain set of snowpack conditions and timing of seasonal

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snowmelt associated with trailhead conditions and access to the high country (Jenkins et al. 2021a).

Throughout Yosemite National Park, hereinafter the Park, visitor experiences, trip planning and reservations, and demand otherwise associated with coveted peak summer conditions in the high country are increasingly modified by wildland fires and associated air quality impacts, the effects of which generally become more impactful on visitation during the mid- to late-summer months when conditions are hotter and drier and when high average visitation can result in potentially more displaced use (Jenkins 2022). This has led many would-be Yosemite Wilderness users to plan for earlier-season departure dates in hopes of avoiding conditions associated with wildland fires and peak crowds, but this comes at the expense of relatively more users earlier in the season, particularly in drought years, than when the overnight permit system was first instituted (Jenkins et al. 2021a). In wet years, road closures resulting from snowpack can limit access to higher-elevation trailheads in the spring and early summer and have the effect of shifting use to later in the season, which creates a narrower window for access to high-country destinations amid already limited trailhead quotas.

b. Snow drought and seasonal road opening

Access to the Yosemite Wilderness is largely dependent on seasonal access to Tioga Road and Glacier Point Road. Park managers rely on the 1 April snow survey results from Tuolumne Meadows as a key indicator to determine the timing for when snowplowing operations and facilities maintenance can commence, which for Tioga Road takes approximately 1 month before roads can open to visitors.

Snowpack is highly variable from year to year in California's Sierra Nevada where Yosemite National Park is located. While such variability is a feature of a Mediterranean climate, a shift toward aridification with the megadrought across the broader southwestern United States since the turn of the millennium (Williams et al. 2020) has resulted in reduced snowpack and an increase in snow droughts (Zhang et al. 2019). Frequent and chronic drought conditions have the potential to affect both the quantity of users and the quality of wilderness-dependent experiences intermittently or permanently, particularly given the greater exposure to and dependency on environmental conditions that wilderness visitors face with being outside (e.g., water availability, temperature, air quality, and wildland fire hazards) as compared with a typical park visitor during peak summer months (Smith et al. 2018).

Figures 1a and 1b show that snow-drought years result in an earlier average opening for Tioga Road (11 May) and for Glacier Point Road (28 April) when compared with near-average-snowpack years (24 May for Tioga Road, 13 May for Glacier Point Road), and that opening day for high-snowpack years is later than average-snowpack years for Tioga Road (24 June) and for Glacier Point Road (20 May). If conditions allow, Park management tries to have these seasonal roads plowed and opened before the Memorial Day holiday weekend to facilitate access to high elevations and for entry through the east gate of the Park over Tioga Pass for the start of the summer season. From 1995 to 2019, Tioga Road has been opened 17 of 25 yr (68% of the time) and Glacier Point Road has been opened 23 of 25 yr (92% of the time) by Memorial Day.

The average closure day for Tioga Road is 13 November and for Glacier Point Road is 17 November. The closures of these roads are connected with seasonal snowfall in the late-fall or early-winter months, and with it, the beginning of the snow-based winter recreation season, which includes access along roads with snowshoes or cross-country skis to backcountry destinations for day or overnight use. As snow-drought years with earlier seasonal road openings become more common, so too have the lengths of the open season become longer (Figs. 1c,d). Visual interpretation shows that from 1995 to 2019 the average length of the season has increased by approximately 0.5 month for Tioga Road and approximately 1.5 months for Glacier Point Road, a trend with its attendant impacts on wilderness character.

c. Wilderness impacts and the overnight permit system

Open road access to trailheads does not necessarily mean accessible and safe backcountry conditions; stream crossings that are nonexistent during a dry year may be impassible or dangerous, and trails may remain wet, muddy, and more prone to erosion from use. Users may attempt to avoid these conditions by walking adjacent to trails, which can lead to vegetation trampling and proliferation of social trails. This is a concerning scenario for alpine and subalpine mountain-protected areas, as these places are sensitive to visitation given their limited ability to recover from trampling and compaction, especially given a narrow growing season and sensitive soil characteristics (Leung and Marion 1999; Walden-Schreiner et al. 2018). A common strategy to address these effects is to integrate biophysical and social impact prevention approaches (D'Antonio et al. 2013). For example, social science surveys can be used to understand visitor perspectives about biophysical conditions, which can help to identify and direct resources to priority areas and be leveraged to educate visitors about their own impacts (Peterson et al. 2018). Wilderness management utilizes a suite of approaches to track, assess, and respond to effects, including reoccurring inventories and assessments of wilderness campsite and social conditions that, through management actions to avoid impairment (e.g., campfire ring removal, trailhead quota limits), help to maintain wilderness character and untrammeled, natural, and undeveloped landscapes that provide opportunities for solitude and unique social and ecological value (Boyers et al. 2000; Fincher 2012).

A suitable management strategy to mitigate impacts on parks and wilderness areas associated with high levels of use, at different times of the year and with visitor hotspots at highly trafficked locations, is to establish permit systems with daily trailhead-specific quotas to regulate the timing and magnitude of visitation (Marshall et al. 2018; Jenkins et al. 2021a). The Yosemite Wilderness permit system was first introduced in the Park in 1972 in response to backcountry surveys that found high levels of use and proliferation of campfire rings and campsite footprints around popular lakes,

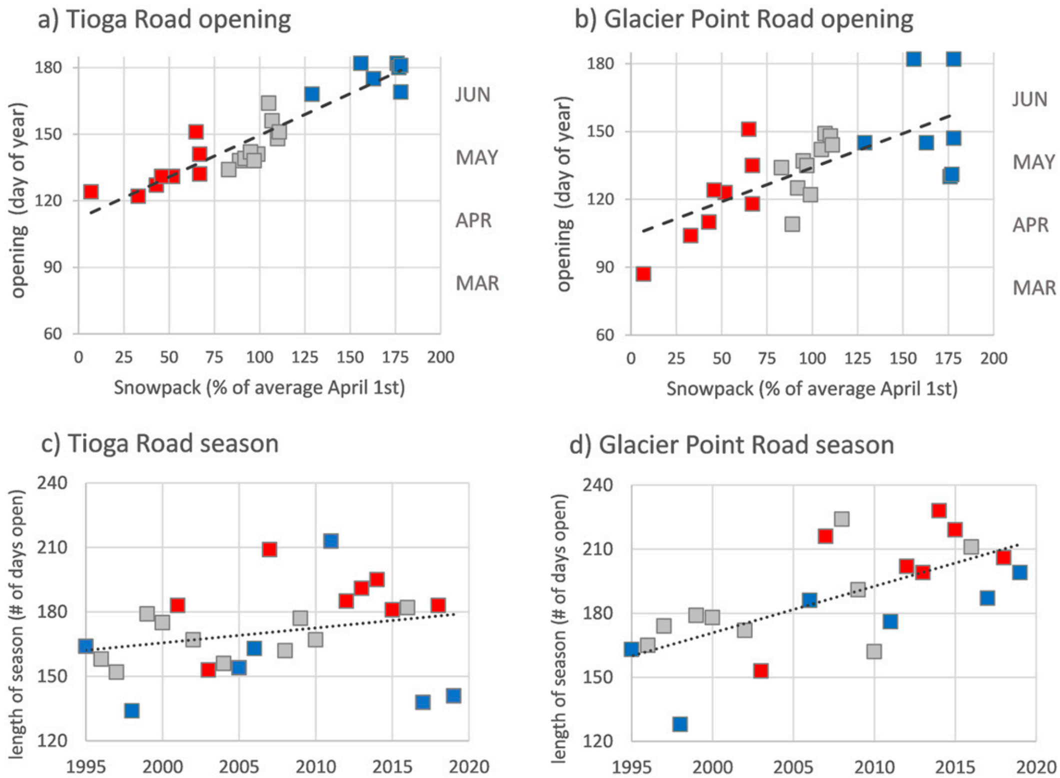

FIG. 1. Mean opening (day of year) by percent of avg 1 Apr snowpack for (a) Tioga Road and (b) Glacier Point Road (1995–2019), with trend lines for visual interpretation. Also shown is total length of season (No. of days) for (c) Tioga Road and (d) Glacier Point Road (1995–2019), with trend lines (red = snow drought, gray = near avg, and blue = high snowpack). Annual opening dates and 1 Apr percent avg snowpack data are available online from Yosemite National Park (https://www.nps.gov/yose/planyourvisit/seasonal.htm).

trail intersections, vistas, and water sources (Jenkins et al. 2021a). While the permit system has greatly reduced the overall impact associated with unfettered use, many of these hotspots continue to receive relatively concentrated use today, in part due to travel patterns associated with the permit system and high demand for certain trailheads. The trailhead-based overnight permit system has been effective in distributing overall use while maintaining freedom of exploration, as backcountry visitors begin their trip at a trailhead associated with a particular wilderness travel zone where they must remain for their first night before continuing their travel (van Wagtendonk and Coho 1986). These zone capacities and the distance and locations where backpackers were willing to travel to (in an era of higher snowpack than the present era of intermittent snow drought) were originally based on the number of acres in a wilderness travel zone, the miles of trail it contained, and its ecological fragility (van Wagtendonk 1986). In a similar way, demand for earlier-season use in May and June is partly a vestige of the initial permit system, which was designed to reduce summer crowding by setting use limits during peak months with the intention of displacing this use (to months with more potential snowpack and thus access to fewer higher-elevation destinations) without reducing overall visitation (van Wagtendonk 1981). Thus, some spatial and temporal patterns of overnight travel in the Yosemite Wilderness today are influenced, at least in part, by past management actions that operated with certain assumptions about the timing and extent of snowpack.

But permit systems reliant on consistent snowpack levels may no longer be effective in reducing the biophysical and experiential impacts associated with overuse if the parameters of the system remain static and visitors shift their plans. According to Buckley and Foushee (2012), the average timing of peak visitation to national parks has shifted to four days earlier since 1979 as visitors adjust their behavior in response to climate change. Fisichelli et al. (2015) projected that warming associated with climate change will likely result in an 8%–23% increase in annual national park visitors and expand the visitation season by 13–31 days, and this has been shown to be mainly associated with changes in shoulder-season use (Hewer et al. 2016). Management of the permit system should thus take into account the changing patterns of overnight use over time and across areas of the Park that encompass different elevation ranges, road openings, and access points and consider the impacts associated with both the timing and severity of changing climatic conditions, such as prolonged drought. Wilderness land managers of high-elevation areas should consider that warm summer conditions are lasting longer and subsequently extending the number of desirable days in the season that may increase aggregate visitation and its experiential and biophysical impacts on wilderness character.

Therefore, it is important to understand how wilderness visitation at high-elevation areas is affected by the effects of climate change, including snow drought. This information can be used by managers to implement adaptive permitting systems informed by recent climatic conditions to provide quality wilderness experiences to visitors while controlling for further biophysical impacts from overuse of wilderness.

d. Study objectives

Most prior studies relating to the interannual variability of climate and outdoor recreation have focused on temperature (Fisichelli et al. 2015; Gössling and Hall 2006; Hewer and Gough 2019; Ma et al. 2023). We expand on this knowledge by focusing on the role that snowpack levels play in the volume and timing of overnight use at Yosemite Wilderness. Except for research conducted within the same mountain range at Sequoia and Kings Canyon National Parks (Marshall et al. 2018), which took a phenological approach to assess visitor sensitivity to hydroclimatic variables in determining how climate affects backcountry visitation, scarce research analyzing long-term permit data has been conducted to specifically understand how visitation to wilderness areas changes with interannual variability in snowpack levels. Overnight wilderness users, including those in mountain regions, are a group that is particularly sensitive to changes in snowpack given that it may impede or enable travel; these users have been understudied in climate change and tourism assessments yet are an important group given their multiday trips in relatively undisturbed areas (Marshall et al. 2018).

Our study examines peak-summer and shoulder-season (April–October) wilderness visitation from 2002 to 2019 through analysis of annual spring-snowpack records and monthly overnight use permits during these years. We compare how the categories of snow drought and high-snowpack and near-average-snowpack conditions affect the timing and volume of use across the Yosemite Wilderness. Specifically, for the overall wilderness, we assess variability in timing and volume associated with the category of snowpack on 1 April to determine when the greatest variability in conditions and uncertainty around permit utilization occur. Second, we assess the differences in timing and volume for different snowpack-year categories through an analysis of five trailhead districts that constitute the wilderness, which allows us to compare use and infer potential displacement in trailhead permit selection between districts due to snow drought or high-snowpack conditions. And we assess the relative change in use from an overall monthly average among each of the five trailhead districts for different snowpack-year categories. Collectively, these assessments of past conditions provide a template for us to project what to expect in future years, especially as drought conditions become more common and demand for overnight wilderness use remains high.

2. Methods

a. Case study

Overnight permits for Yosemite Wilderness are required year-round, and 60% of trailhead quotas for a given date can be reserved up to 24 weeks, or approximately 6 months, in advance of the requested entry date, which is a standard time used in other camping forecast models (Rice et al. 2019). Preplanning trips months in advance is a real-world scenario for most backcountry visitors who must plan around work and other obligations in coordination with family and other trip members, and in cases for high-demand trailheads, must apply early to ensure a spot in a limited pool of daily trailhead permits. Approximately 40% of each trailhead's quota typically remains available as a day-of/walk-up permit during the peak and shoulder seasons. From November through April, wilderness permit reservations are not available; instead, trailhead permits are granted in person, although permits are required and quotas are in effect year-round and can fill up regularly. The trip leader who requested the permit must pick it up in person for it to be issued, and this includes a basic orientation on backcountry guidelines and an opportunity to review trail conditions before their trip begins. Locations for pick-up in summer include Big Oak Flat Information Station, Yosemite (Valley) Wilderness Center, Hetch Hetchy Entrance Station, Tuolumne Meadows Wilderness Center, and Wawona Visitor Center. These locations correspond to the five trailhead districts used to issue overnight wilderness permits (Fig. 2), each of which consists of trailheads with different quota levels that allow access to a corresponding first-night zone, are designed to mitigate collective biophysical impacts (e.g., soil erosion and compaction), and maintain desired experiential conditions (e.g., minimize total daily encounters) among high levels of overall use (Jenkins et al. 2021a).

The timing of reservation requests is often predicated on people's knowledge and expectations (e.g., through experience, reading the Park's website, social media, blogs, travel guides), which are relied on for attempting to forecast desired weather conditions (Hamilton and Lau 2006). For instance, demand for permits at Tuolumne Meadows [elevation of approx. 8600 ft (2867 m)] is high in July and August as people anticipate the seasonal Tioga Road to be open and for trails to be clear of snowpack, and before conditions for available water sources dry up too much (e.g., seasonal streams). Given the region's interannually variable snowpack, wet conditions can persist into the late summer in the high country during high-snowpack years.

Although permit users are supposed to follow their itinerary (which is submitted upon arrival, while picking up a permit), current conditions can influence them to change their plans midtrip. Some permits that are issued end up not being utilized in the way they were planned, and when this is the case, it is often due to displacement from inaccessible or hazardous conditions, namely, higher-than-anticipated snowpack or melt in the spring or early summer, and increasingly the direct threat of wildland fire and its related impacts (e.g., air quality) on backcountry use. In the period 1976–78 (classified as drought years), field surveys found that after arriving, 41% of parties deviated temporally, 48% spatially, and 27% both temporally and spatially, while in a similar study conducted in 2010 (classified as a high-snowpack year), 36% of parties deviated temporally, 54% spatially, and 25% both temporally and spatially, with larger groups less likely to deviate and deviation

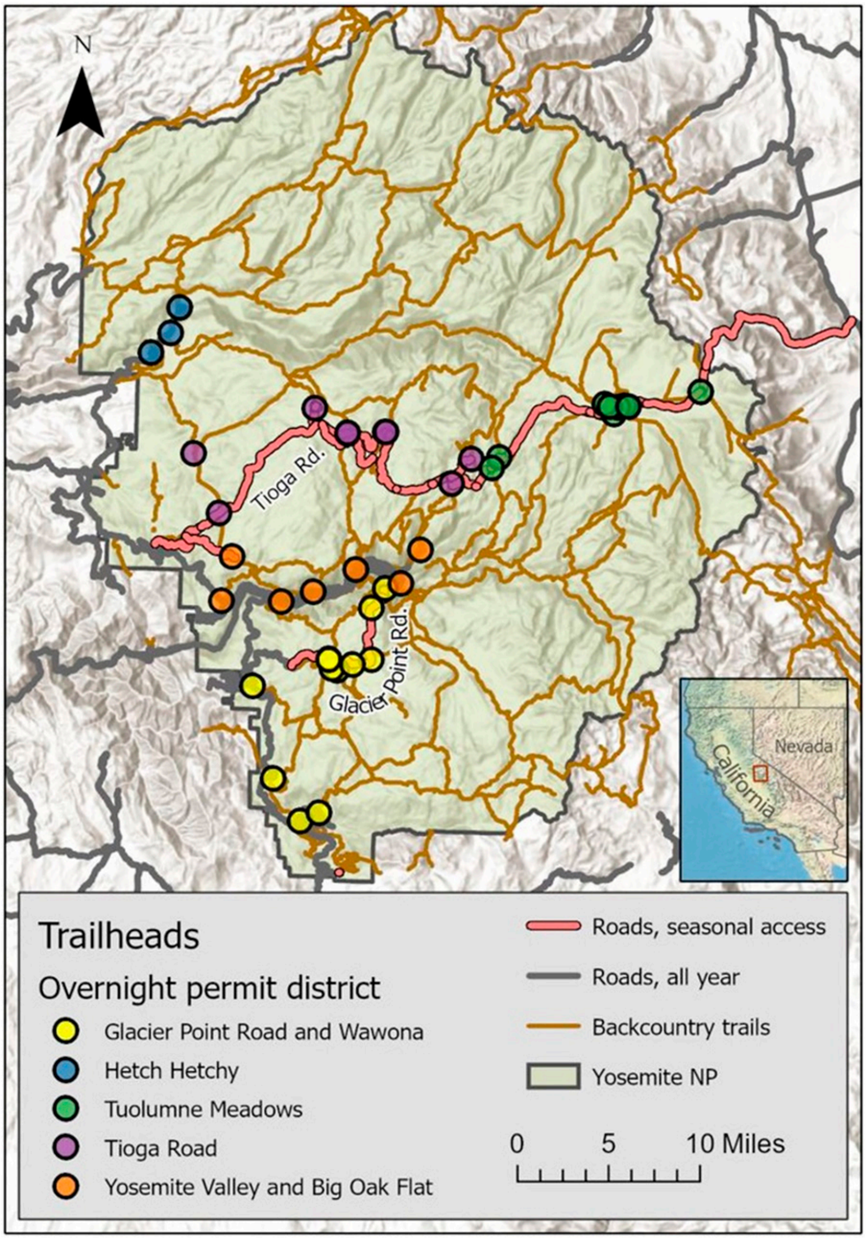

FIG. 2. Yosemite Wilderness, showing trails and trailheads by overnight permit district, along with roads, including all-year and seasonal access. Specific details on backcountry travel and requirements for obtaining an overnight wilderness permit are available online from Yosemite National Park (https://www.nps.gov/yose/planyourvisit/wildpermits.htm).

decreasing as days of trips progress (van Wagtendonk and Benedict 1980; Van Kirk et al. 2014). From this, we can broadly understand that displacement from intended trip itineraries generally takes place at comparable levels in either snow-drought or high-snowpack years, although the rationale for displacement and the changes to trip plans are materially different and can vary by time of year, elevation, and general location. While we cannot measure displacement due to conditions encountered in the backcountry (this study did not include pre- and post-trip or field-based visitor surveys), we can assess differences in timing and volume of permits between snow-drought and snowpack years to infer patterns of displaced use, including shifts between trailhead districts in similar snowpack years.

b. Data

We assess the effect of spring snowpack on the timing and volume of overnight wilderness permits that were issued, regardless of whether they were reservation based or day-of pickup, for the Yosemite Wilderness spanning the years 2002

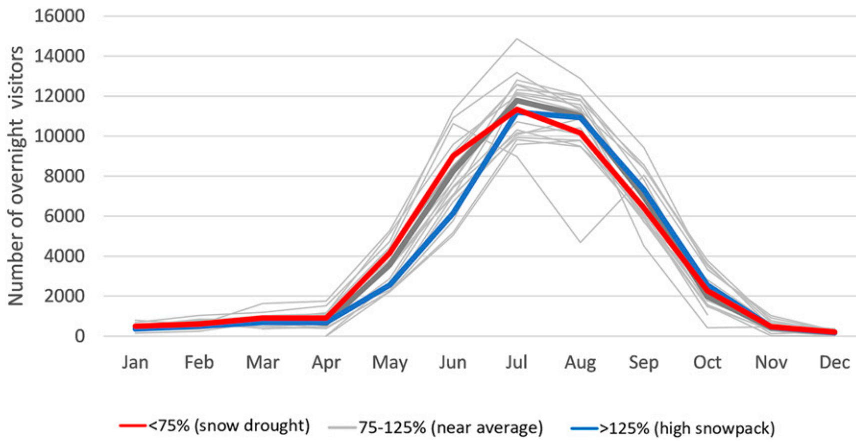

FIG. 3. No. of overnight visitors per month in different snow-drought, near-avg-snowpack, and high-snowpack years (2002–19). In July and August of 2018, portions of the Park were closed due to the Ferguson Fire, but access to wilderness remained open throughout much of the Park.

to 2019. The years analyzed here cover the most complete and accurate daily use levels by trailhead for peak-summer and shoulder-season months. We constrained our analysis to pre-COVID-19 pandemic years (2019 and earlier) to strengthen the comparability of overnight visitors between years due to snow drought or high snowpack. Certain changes in obtaining an overnight wilderness permit were put in place with the pandemic that altered the conditions for obtaining a permit, including moving the in-person permit pick-up and the day-of/walk-up quota to the online reservation system in accordance with pandemic health and safety guidelines (Jenkins et al. 2021b).

Our visitation data consist of approximately 325 000 unique overnight wilderness permits or users, which includes data on entry trailhead, exit trailhead, and trip dates, among other details like group size. While one person per trip is required to serve as the lead permit holder, each permit record reflects the number of individuals per an issued permit. Thus, we analyze total backcountry use as total number of individuals, which is a greater indicator of demand (than number of groups) and serves as a proxy to understand biophysical and experiential impacts on wilderness character. Furthermore, our preliminary analysis shows that there is little appreciable difference in group size between high-snowpack and snow-drought years. We limit our analysis to the peak-summer and shoulder-season months from April through October when the majority of use occurs in the Yosemite Wilderness. For overnight permits, and general park visitation, the shoulder season in spring includes April and May as snowpack begins to melt and seasonal roads are opened. The summer spans the months from June through September, with July and August typically the highest of the peak season. The fall shoulder season includes October; visitor services are reduced throughout much of the Park after 30 September, and snowpack usually leads to seasonal road closures and limits travel by November. We did not examine permit data from November to March, when overnight visitation is usually limited by snow and wet conditions, because snowpack categories do not show much variance (Fig. 3), whereas use tends to fluctuate in the spring and peak season based on drought or wet conditions. The National Park Service centennial year of 2016 is representative of maximum peak visitation during an average-snowpack year. The Ferguson Fire of 2018 (when sections of the Park were closed but much of the wilderness remained open) is representative of the visitation effects of wildland fire and smoke in an extreme drought year, especially to overnight wilderness users who face greater environmental exposure.

Numerous drought indicators have been used and applied in the literature (Wilhite and Glantz 1985; Liang et al. 1994; Robeson 2015). We restrict our focus here to snow drought typified by anomalously low snow water equivalent in the spring (Hatchett and McEvoy 2018). Snow droughts can develop via several pathways including low winter precipitation, average-to-low winter precipitation coincident with warm temperatures, or frequent rain-on-snow events that rapidly deplete snowpack. We utilize the annual percent of average 1 April snowpack (1930–2019), which for Tuolumne Meadows is a percent of approximately 57 in. (145 cm). Data are collected as part of a snow survey conducted by the Park on the first of the month, four to five times in the winter. The 1 April snow water equivalent is a standard indicator for water supply forecasts in the region and often coincides with maximum snow water equivalent across mountains of the western United States. (Kapnick and Hall 2010). We use this single measurement as a sentinel for snowpack across the broader region, given previous studies (Henn et al. 2016) and the use of the 1 April snow survey by Yosemite Wilderness managers as a key indicator. As has been done effectively in other studies (Shrestha et al. 2021), we categorize our results into three groupings of snowpack level, which allows for greater comparison of extreme drought and wet conditions: snow drought (<75% of average snowpack level), near-average snowpack (75%–125% of average snowpack level), and high snowpack (>125% of average snowpack level). Snowpack data as a percent of 1 April average for years 2002–19 are shown in Fig. 4.

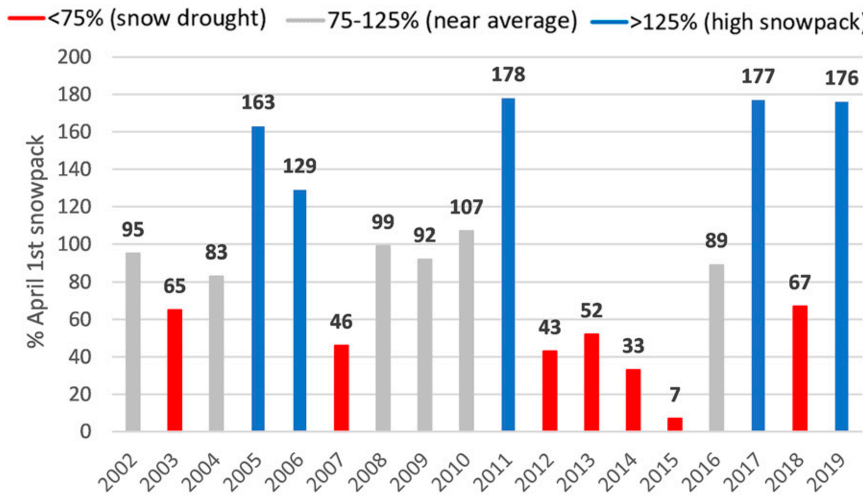

FIG. 4. Percent 1 Apr snowpack (1930–present) for Yosemite National Park (Tuolumne Meadows), with annual survey percent shown above each bar. Snow-drought years (<75%) are shown with a red bar, near-avg-snowpack years (75%–125%) are shown with a gray bar, and high-snowpack years (>125%) are shown with a blue bar. Data and information on snow surveys are available online (https://www.nps.gov/yose/learn/nature/snow-surveys.htm).

c. *Methods*

A percent of average 1 April snowpack category (snow drought, <75%; near-average snowpack, 75%–125%; and high snowpack, >125%) was assigned for each year of overnight permits to Yosemite Wilderness, during peak- and shoulder-season months, based on snow survey records. Months are used for the unit of analysis as this allows us to see the range of overnight users over a comparable period between snowpack and snow-drought years and to see how levels of use and the amount of variance change over the course of the season due to factors associated with different months (e.g., uncertainty of snowpack, peak visitation, wildland fires):

1) Since visitation is variable at the Park-wide scale because of interannual snowpack differences, monthly variance in overnight use of Yosemite Wilderness during each type of averaged snowpack category was found through a box plot analysis that provides the inner quartiles of the data for each category and the total range for each month.
2) The average was found for each of the three snowpack categories for each month and plotted to visualize timing and volume of use. Since visitation conditions vary across space and time, this process was conducted for the five trailhead districts that wilderness managers use for issuance of overnight trailhead permits specifically because each represents different elevations and road closures and opening connections with snowpack.
3) The average value of each category was then compared with the average of all data to find percent *relative* change from the 2002 to 2019 monthly average for each trailhead district. Relative change is important because the change in visitation can be relative to such ongoing management implications as staffing and patrol levels, budget and available resources, and the magnitude of trail and campsite impacts, which in spring, for instance, can be more pronounced as wetter conditions facilitate soil compaction and trail incisions.

3. Results

a. *Wilderness-wide overnight use and variability by snowpack level*

Our findings confirm that during snow-drought years there are more early-season visitors as open roads provide access to higher-elevation trailheads (with +28% more visitors from April to June than in an overall average month) and slightly more overall use during the peak- and shoulder-season months of April–October. We find that in high-snowpack years, there is a later start to the season (with 20% fewer visitors in April–June than in an overall average month) as seasonal roads may remain closed into mid-June and high-elevation trailheads are not yet accessible, and less overall visitation during the peak- and shoulder-season months of April–October. We also find that in near-average-snowpack years, there is a slight increase in visitation across summer (with 5.5% more visitors from May to September) when compared with the overall average number of visitors during these months.

Our analysis of overnight wilderness permits shows variance in the range of data between snowpack categories by month as well as different overall average levels of use by peak- and shoulder-season month (Fig. 5). In April, overnight use is consistently low, with only a small range in the data owing to the persistence of winter snowpack and closure of seasonal roads. Notably, our analysis shows that in May and June, there are statistically significant differences between high-snowpack years and both average and snow-drought years. The greatest number of overnight permits are issued in

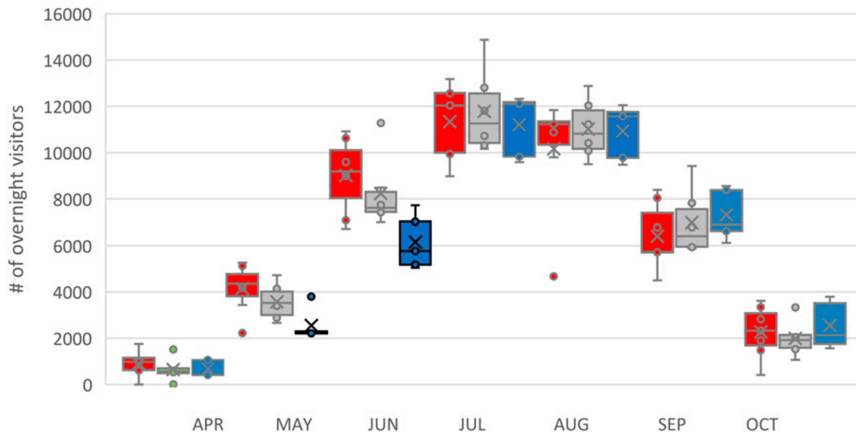

FIG. 5. Yosemite Wilderness overnight permits by percent of avg 1 Apr snowpack in peak-summer and shoulder-season months. Values are plotted with ±25% quartile range of box (50% of data inclusive of the mean). Statistically significant different months of May and June in high-snowpack years are indicated by black crosses (mean) and border. Whiskers show high–low value range with an extreme low outlier (represented by a red dot) in August 2018 that is due to wildland fire closure for a portion of the month.

July and August, and ranges between categories are more similar than other months, which suggests that this is when permits are most in demand, with many high-elevation trailhead quotas saturated to the same level across snowpack categories. One visible outlier in August shows less overnight wilderness use because of partial closure of the Park from the Ferguson Fire in 2018. Wildland fires and indirect impacts such as smoke make for uncertain conditions and increased variability in visitation in late summer and into fall, especially in snow-drought years, and visitation can be slightly more in high-snowpack years this time of year owing to displaced demand from earlier in the season.

b. *Trends in volume and timing for trailhead districts by snowpack category*

The timing and volume of overnight permits for Yosemite Wilderness varies by trailhead as a function of snowpack category, and for many trailheads, snowpack is directly related to the timing of snowplowing and road openings that provide access to high-elevation trailheads (Fig. 6). Snow droughts generally lead to earlier access in spring, especially for higher-elevation trailheads where roads would otherwise be closed in the spring of a high-snowpack year. Accordingly, high-elevation trailheads that are cut off from access in the spring of high-snowpack years have much greater use in the months of June and July, suggesting displacement over time for would-be early-season visitors, from earlier to later in the season. More visitors than average also visit lower-elevation destinations in June and July of high-snowpack years, likely owing to a combination of displacement from high-elevation destinations where conditions are still wet and seasonal stream crossings potentially limit access, the backlog of demand for high-elevation trailhead quotas given earlier road closures, and the fact that lower elevations are not as hot and dry (without a water source) by middle summer of high-snowpack years.

Differences between trailhead district for snow-drought and high-snowpack years, along with a description of access considerations for each district, are listed in Table 1 and summarized below.

c. *Trends in relative change for trailhead districts by snowpack category*

Seasonal changes to overnight use (as a percentage difference from overall monthly average) are generally most substantial in the spring and early-summer months, when the influence of high snowpack can limit access to high-country destinations and displace use into later in the season or when snow drought leads to earlier than expected road openings and trailhead access (Fig. 7). It is important to note that early-spring months have consistently fewer total overnight visitors from year to year when high-snowpack or wet conditions generally limit access, so percent difference from monthly average visitation should be considered in relation to absolute average monthly visitation volume (shown in Fig. 6).

Results show that overnight use in snow-drought years increased notably in early spring for mid- to high-elevation trailhead districts that are typically fully open year-round (+28% in April and May at Yosemite Valley and Big Oak Flat) or partially open year-round (+40% in May at Glacier Point Road and Wawona), with slightly lower-than-average use in both districts during the remainder of the peak season. Overnight use increased substantially in the late spring of snow-drought years at the high-elevation trailhead districts that are typically less accessible due to snowpack (+74% in May and June at Tioga Road and +81% in May and June at Tuolumne Meadows). The roads to these trailheads are either open or closed, so visitation is accordingly much higher when snow has been cleared from roads, although snow and wet conditions may still be present in the high country. Overnight use was greater in early spring at lower-elevation Hetch Hetchy

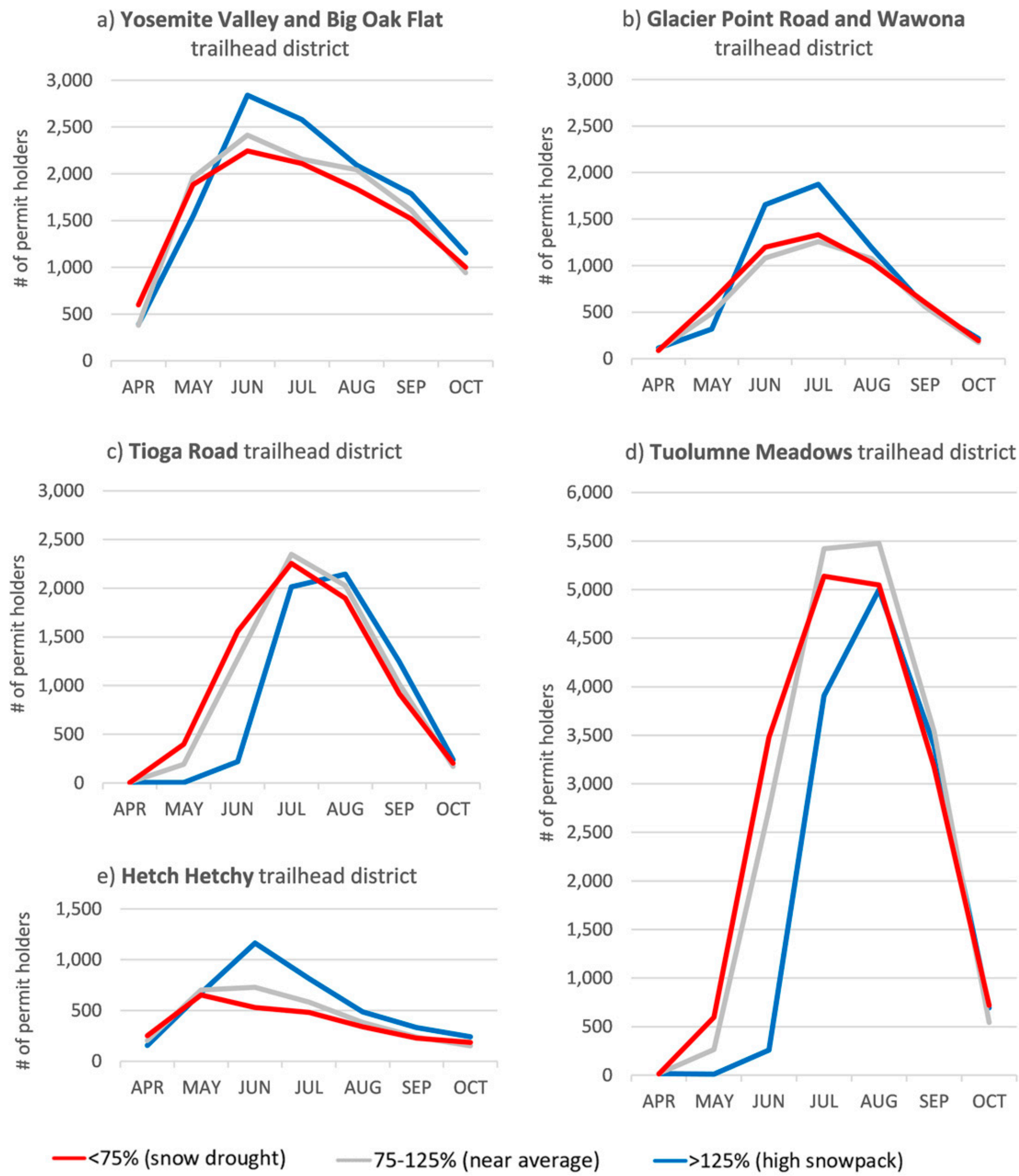

FIG. 6. Volume and timing of Yosemite Wilderness overnight permits by percent of avg 1 Apr snowpack category during peak-summer and shoulder-season months for trailhead districts: (a) Yosemite Valley and Big Oak Flat, (b) Glacier Point Road and Wawona, (c) Tioga Road, (d) Tuolumne Meadows, and (e) Hetch Hetchy.

trailheads (+22% in April), with average visitation levels in May, and less use for the remainder of summer (−21% for June–October), given many would-be visitors are drawn to access at higher-elevation destinations and that water sources dry up and conditions heat up earlier at lower elevations during snow-drought years.

Analysis of high-snowpack years reveals that overnight use decreased in the spring for the mid- to high-elevation trailhead district that is typically fully open year-round (–15% in April and May at Yosemite Valley and Big Oak Flat) and then increased for the remainder of the peak season (+12% from June through August). Access decreased in the spring of high-snowpack years before increasing in the summer for the mid- to high-elevation district that is partially open year-round (−35% in May and +15% from June through October at Glacier Point Road and Wawona), given overnight users are displaced from higher-elevation destinations with road closures remaining in effect through spring of high-snowpack years (Glacier Point Road generally opens a couple of weeks before Tioga Road and visitors routinely use Glacier Point Road and Yosemite Valley trailheads to reach alternative high-country routes). Overnight use in high-snowpack years decreased substantially

TABLE 1. The effect of extreme drought, extreme snowpack, and moderate snowpack on overnight use of Yosemite Wilderness. Monthly changes to visitation are based on relative change from the overall monthly mean by snowpack category.

Wilderness trailhead district {avg trailhead elev [ft (m)]}	Description	How snow drought impacts overnight use		How high snowpack impacts overnight use	
		Seasonal change	Summary of findings	Seasonal change	Summary of findings
Yosemite Valley and Big Oak Flat [4538 ft (1452 m)]	Most of the valley falls within a no-camping zone, so all overnight trips require a hike of at least 4 mi (6.6 km) and a min elev gain of 2500 ft (833 m); water is limited in late summer; the most popular and crowded area of the Park	Apr–May: +28%; Jun–Oct: −5%	More use in spring; near same rest of summer; same overall use	Apr–May: −15%; Jun–Oct: +12%	Slightly less use in spring; slightly more use in summer; slightly more overall use
Glacier Point Road and Wawona [6564 ft (2188 m)]	At the southern end of the Park with Wawona at lower elev and trail connections from Glacier Point Road to Yosemite Valley and east toward the Clark Range; in late summer, trails become hot and dry; Glacier Point Road is closed seasonally with snowpack	May: +40%; Jun–Jul: −3%	More use in spring; near same peak summer; same overall use	May: −35%; Jun–Oct: +15%	Less use in spring; more peak-summer use; more overall use
Tioga Road [7619 ft (2540 m)]	Trails heading south from the western portion of Tioga Road lead to views of the Yosemite Valley, and, to the north, trails lead to lakes and peaks; Tioga Road is closed seasonally with snowpack	May–Jun: +74%	Much more early-summer use; slightly more overall use	May–Jun: −89%l; Sep–Oct: +19%	Much less early-summer use; more late-season use; less overall use
Tuolumne Meadows [8664 ft (2888 m)]	Trails leaving from Tuolumne Meadows require hikes of at least 4 mi (6.6 km); the mountainous high country is significantly cooler than other areas of the Park; this district is very popular with backpackers during summer, including those pursuing the John Muir Trail and Pacific Crest Trails; Tuolumne Meadows is accessed by Tioga Road, which is closed seasonally with snowpack	May–Jun: +81%	Much more early-summer use; slightly more overall use	May–Jun: −93%	Much less early-summer use; less overall use
Hetch Hetchy [4214 ft (1405 m)]	The immediate area around the reservoir is a no-camping zone; Hetch Hetchy tends to be busiest in the spring and during summer when higher-elev trailheads are not yet accessible; summer can be very arid and hot	Apr: +22%; Jun–Oct: −21%	Less peak-summer use; less overall use	Apr: −25%; Jun–Oct: +32%	More peak-summer use; more overall use

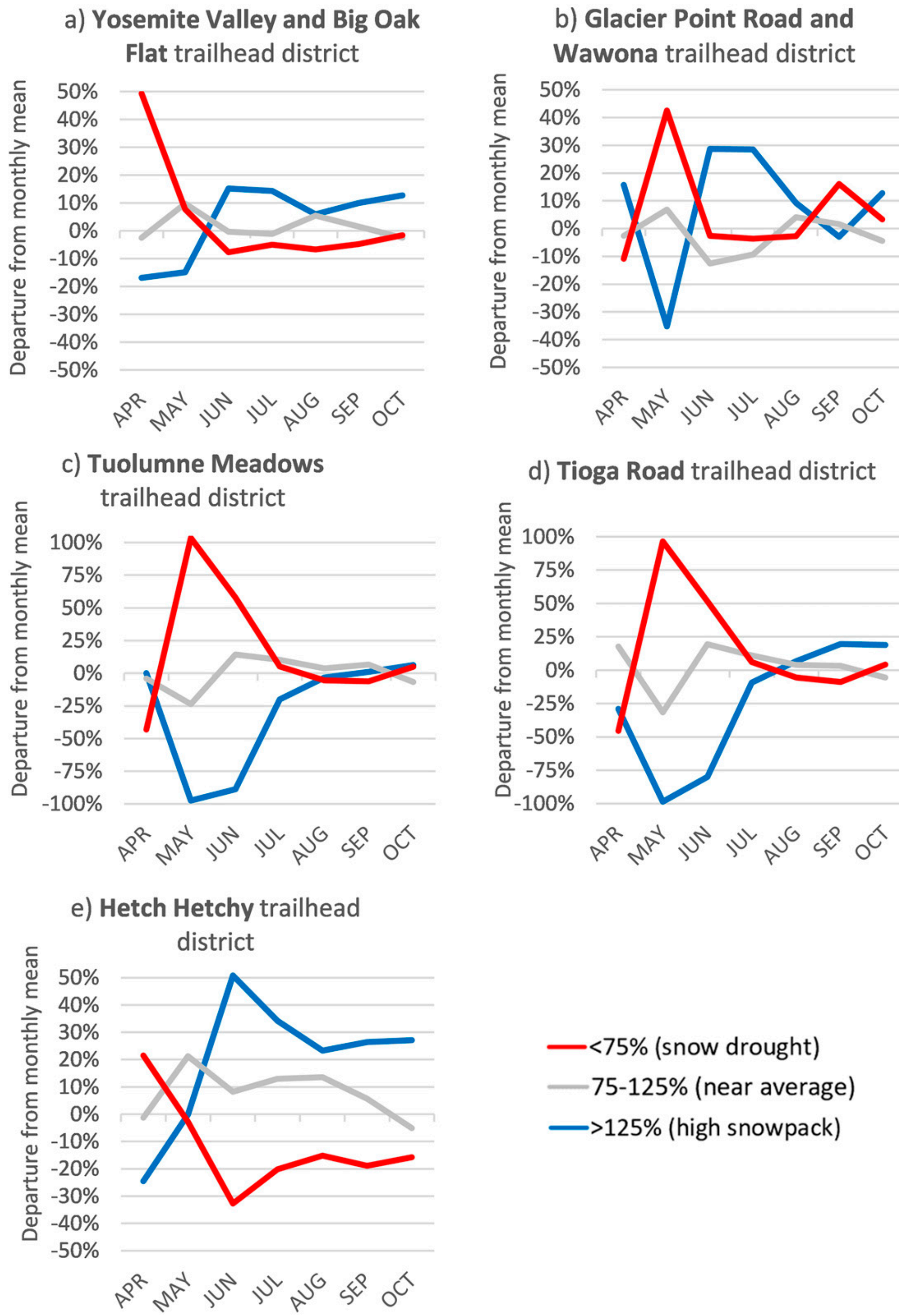

FIG. 7. Relative diff (from overall monthly avg) of Yosemite Wilderness overnight permits by percent of avg 1 Apr snowpack category during peak-summer and shoulder-season months for trailhead districts: (a) Yosemite Valley and Big Oak Flat, (b) Glacier Point Road and Wawona, (c) Tioga Road, (d) Tuolumne Meadows, and (e) Hetch Hetchy.

from spring to early summer on the high-elevation trailhead districts where snow can lead to sustained road closures (−89% in May and June at Tioga Road and −93% in May and June at Tuolumne Meadows). Additionally, Tioga Road has more late-season use in high-snowpack years (+19% in September–October) as demand for higher-elevation destinations (e.g., Tuolumne Meadows trailheads) is pushed into a later and narrower access window and some would-be users become displaced over time and others may choose alternative trailhead districts for entry. Users often utilize Yosemite Valley and sometimes Glacier Point Road trailheads to access the high country when the Tioga Road is closed into early summer during a high-snowpack year. Overnight use is lower in spring and higher throughout the remainder of the season in high-snowpack years for the trailhead district that is accessible at a lower elevation (−25% in April, typical levels in May, and +32% from June to October at Hetch Hetchy) as overnight users first face limited access due to snow in spring at low elevations and others are displaced by high snowpack and road closures in the high country.

4. Discussion

These findings have implications for wilderness stewards of alpine and subalpine protected areas, including biophysical and experiential impacts on wilderness character from earlier and longer seasons associated with snow drought and more intense summer use in a narrower window during high-snowpack years. Research has shown that backcountry use associated with wet soil conditions has a disproportionate effect on trail and campsite soil compaction and erosion (Leung and Marion 1999) and that these conditions can exist to varying degrees in both wet and dry years as trampling resistance correlates with sunlight intensity (Cole and Monz 2002). This diminishes the potential for quality wilderness-dependent experiences for subsequent users, especially in the same season; while soil compaction is limited by higher moisture levels, it can occur rapidly with limited traffic once organic materials are substantially lost, with the majority of impact occurring in the initial days and weeks of early-season use (Marion et al. 2016). In addition, the geography of impacts on wilderness character will shift as patterns of use change to different destinations at different times in snow-drought and high-snowpack years. Managers must therefore anticipate and plan for extreme dry or extreme wet conditions, both of which can lead users to choose a different time, location, or alternative activity, or to potentially forgo plans entirely (Jenkins et al. 2023, manuscript submitted to *PLOS Climate*).

The physical landscape of the Yosemite Wilderness continues to be altered by ongoing impacts from prolonged drought, including scenic impacts from tree mortality and safety and accessibility impacts from wildland fire and smoke, among other hazards (Jenkins 2022). As such, overnight visitors will need to either adapt their travel plans to alternative locations (or elevations) in or near the Park, shift the timing of entry dates for their backpacking trip, or pursue another activity that is more suitable in light of anticipated changes to climatic conditions (Perry et al. 2021). For instance, Yosemite Valley and Big Oak Flat trailheads see more overall use than other trailheads early in snow-drought years as visitors attempt to access high-country routes before Tioga Road and Glacier Point Road open for the season. Conversely, lower-elevation trailheads, like those out of Hetch Hetchy, receive more use in the summer of high-snowpack years, as higher-elevation trailheads do not become accessible until later and when they do they are in much higher demand for overnight permits. These seasonal differences have important implications as winter and spring snowpack recedes, snow drought becomes more frequent, and the annual timing of peak snowpack becomes more variable (Marshall et al. 2019; Siirila-Woodburn et al. 2021). Further studies might consider comparing visitation with additional months of snow survey data to better understand intraseasonal variability, associated environmental conditions, and impacts related to human use among qualitatively different types of snow-drought years (Hatchett and McEvoy 2018).

Amid this ongoing climatic and environmental change, wilderness areas should be managed for the protection of wilderness-dependent recreational experiences, including adventure and risk, athleticism, and solitude and reflection, where specific activities including backpacking are adapted to and suitable for what seasonal conditions may provide as the likelihood of snow drought becomes more common from year to year (Fincher 2012). In natural areas, including Yosemite Wilderness, experiential and biophysical components of a recreation experience are linked spatially and temporally (D'Antonio et al. 2021) because recreation is a spatiotemporal-conditioned process (Peterson et al. 2020) affected by biophysical conditions. This is notable because according to the time–geography framework (Hägerstrand 1970), every human behavior and experience occurs at a specific location and at a specific time; and the location and timing of human behaviors in wilderness helps managers understand where and when biophysical impacts are likely to be caused by visitors. This omnipresent tripartite relationship between human experiences, location, and time is influenced by many variables, including biophysical and climatic conditions, which connect to the Interagency Visitor Use Management Framework (IVUMF). The IVUMF, which is used by the National Park Service, includes social science applications to encourage visitor access, improve experiences, and protect biophysical resources (Cahill et al. 2018). When managers understand the location and timing of visitor behaviors, it helps inform targeted approaches to limit associated impacts, such as social and environmental impacts. A feature of the IVUMF is that it considers the provision of a range of recreation opportunities across various settings to facilitate quality visitor experiences while adapting and being flexible to changing social and biophysical conditions (Cahill et al. 2018). However, information is needed on how often to adapt to changing conditions in order for the IVUMF to function as intended. Our research shows annually variable climatic conditions at the Park that influence visitor trends. This information can be adopted by Park managers when implementing the IVUMF and inform them that annually monitoring and adapting to conditions is necessary to effectively conserve experiential and biophysical resources so that they can continue provisioning quality visitor experiences.

Managers must have processes in place at the beginning of spring and throughout the season to assess resource conditions and to anticipate the decision-making of recreational users in response to changing conditions within and between seasons. Adaptive management for wilderness visitation is characterized by cycles of monitoring visitor use and behavior and evaluating the relationships between use level, wilderness character, and visitor safety, and culminates in planning for and taking management action (Reigner et al. 2012). Yosemite Wilderness has maintained different monitoring programs in some form since the early 1970s, including campfire ring proliferation and campsite condition monitoring at various hotspots (Jenkins et al. 2021a), and overnight permits include information on destinations and routes, which, along with biophysical surveys and park planning priorities, are used to focus trail and campsite restoration activities. But part of maintaining wilderness character entails limiting biophysical impacts in the first place, the severity of which depends on initial early-season use.

More flexible tools for management of overnight wilderness use could entail implementation of a sliding scale of permit quotas to raise or lower trailhead capacity depending on drought status, much like how the Park's day-use reservation system tiers created in the context of COVID-19 risk levels are now applied seasonally to guide use levels in the contexts of wildland fires and other hazards (Jenkins et al. 2021b). This could also entail voluntary reductions in use, including reductions in use later in snow-drought years, when wilderness-dependent experiences are increasingly impacted by wildland fire and smoke amid already hot and dry conditions, or voluntary limits earlier in high-snowpack years, when soil and ecology are sensitive. Another consideration could be to open up more permits for lesser-used areas of the Park, shift some use to pass-throughs, or specifically allocate some capacity for off-trail-only travel. Dispersal could be particularly effective at improving wilderness-dependent recreational opportunities in the peak summer months of July and August, while reductions in shoulder-season use, which occur semiregularly already with early-season snowpack or wet conditions and later-season wildland fire exposure, could also help to maintain experiential conditions while reducing impacts on soil and ecology components at hotspots.

5. Conclusions

We have shown how the timing and volume of overnight visitation to Yosemite Wilderness differ between snow-drought and high-snowpack years, with earlier spring visitation and more overall use occurring in snow-drought years, and later and slightly less visitation occurring in high-snowpack years. This has the potential to lead to more overall use and impacts on wilderness character with snow drought expected to be more common and the timing of peak snowpack (and subsequent spring melt) to be more variable in years going forward. Further impacts on wilderness character remain likely given both the greater amount of overall use associated with snow-drought years and the more intense use in a shorter accessible season associated with high-snowpack years, and in all years, the push to earlier spring start dates as individuals and groups self-displace to avoid biophysical and experiential impacts associated with compounded use later in the season. It remains incumbent upon wilderness managers at mountain-protected areas to track differences in the volume, timing, and location of use associated with different climatic conditions, namely, early-spring snow-drought or high-snowpack status, which can be used as a key indicator when projecting demand and travel patterns associated with particular areas, elevations, and routes. With this information and ongoing wilderness character monitoring efforts, wilderness managers can begin to construct an adaptive management program that is targeted to the timing and location of potential impacts, be it associated with earlier, longer, more concentrated, or greater overall use.

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Data availability statement. Wilderness overnight permit data were obtained from Yosemite National Park through the National Park Service scientific research and collecting permit application process (YOSE-2022-SCI-0064). As such, access is subject to National Park Service authority, including the general conditions of the research permit that specifies prior approval and oversight of data sharing. Road closure timing, snowpack data, and information on wilderness trailheads are available freely from Yosemite National Park's website (https://www.nps.gov/yose).

REFERENCES

Bales, R. C., N. P. Molotch, T. H. Painter, M. D. Dettinger, R. Rice, and J. Dozier, 2006: Mountain hydrology of the western United States. *Water Resour. Res.*, **42**, W08432, https://doi.org/10.1029/2005WR004387.

Becken, S., and J. Wilson, 2013: The impacts of weather on tourist travel. *Tourism Geogr.*, **15**, 620–639, https://doi.org/10.1080/14616688.2012.762541.

Boyers, L., M. Fincher, and J. van Wagtendonk, 2000: Twenty-eight years of wilderness campsite monitoring in Yosemite National Park. *Wilderness Science in a Time of Change Conf.*, Vol. 5, U.S. Department of Agriculture, 105–109, https://www.fs.usda.gov/treesearch/pubs/21850.

Buckley, L. B., and M. S. Foushee, 2012: Footprints of climate change in US national park visitation. *Int. J. Biometeor.*, **56**, 1173–1177, https://doi.org/10.1007/s00484-011-0508-4.

Cahill, K., R. Collins, S. McPartland, A. Pitt, and R. Verbos, 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**, 32–41.

Cole, D. N., and C. A. Monz, 2002: Trampling disturbance of high-elevation vegetation, Wind River Mountains, Wyoming, U.S.A. *Arct. Antarct. Alp. Res.*, **34**, 365–376, https://doi.org/10.1080/15230430.2002.12003507.

Cutler, A., and Coauthors, 2017: The effects of drought on recreation and wilderness. USDA Forest Service Rep., 7 pp., https://www.climatehubs.usda.gov/sites/default/files/droughtrecreationwilderness2018o320with508.pdf.

D'Antonio, A., C. Monz, P. L. Newman, S. Lawson, and D. Taff, 2013: Enhancing the utility of visitor impact assessment in parks and protected areas: A combined social–ecological approach. *J. Environ. Manage.*, **124**, 72–81, https://doi.org/10.1016/j.jenvman.2013.03.036.

——, and Coauthors, 2021: Integrating aspatial and spatial data to improve visitor management: Pairing visitor questionnaires with multiple spatial methodologies in Grand Teton National Park, WY, USA. *J. Park Recreation Adm.*, **39**, 67–84.

Fincher, M., 2012: Humans apart from nature? Wilderness experience and the Wilderness Act. *Proc. RMRS-P-66: Wilderness Visitor Experiences: Progress in Research and Management*, Missoula, MT, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 152–157, https://www.fs.usda.gov/treesearch/pubs/40920.

Fisichelli, N. A., G. W. Schuurman, W. B. Monahan, and P. S. Ziesler, 2015: Protected area tourism in a changing climate: Will visitation at US national parks warm up or overheat? *PLOS ONE*, **10**, e0128226, https://doi.org/10.1371/journal.pone.0128226.

Gellman, J., M. Walls, and M. Wibbenmeyer, 2022: Wildfire, smoke, and outdoor recreation in the western United States. *For. Policy Econ.*, **134**, 102619, https://doi.org/10.1016/j.forpol.2021.102619.

Goshua, A., and Coauthors, 2021: Addressing climate change and its effects on human health: A call to action for medical schools. *Acad. Med.*, **96**, 324–328, https://doi.org/10.1097/ACM.0000000000003861.

Gössling, S., and C. M.Hall, 2006: Uncertainties in predicting tourist flows under scenarios of climate change. *Climatic Change*, **79**, 163–173, https://doi.org/10.1007/s10584-006-9081-y.

Hägerstrand, T., 1970: What about people in regional science? *Pap. Reg. Sci.*, **24**, 7–24, https://doi.org/10.1111/j.1435-5597.1970.tb01464.x.

Hamilton, J. M., and M. A. Lau, 2006: The role of climate information in tourist destination choice decision making. *Tourism and Global Environmental Change: Ecological, Economic, Social and Political Interrelationships*, S. Gössling and C. M. Hall, Eds., Routledge, 229–250.

Hatchett, B. J., and D. J. McEvoy, 2018: Exploring the origins of snow drought in the northern Sierra Nevada, California. *Earth Interact.*, **22**, https://doi.org/10.1175/EI-D-17-0027.1.

Henn, B., M. P. Clark, D. Kavetski, B. McGurk, T. H. Painter, and J. D. Lundquist, 2016: Combining snow, streamflow, and precipitation gauge observations to infer basin-mean precipitation. *Water Resour. Res.*, **52**, 8700–8723, https://doi.org/10.1002/2015WR018564.

Hewer, M. J., and G. A. Gough, 2019: Using a multiyear temporal climate-analog approach to assess climate change impacts on park visitation. *Wea. Climate Soc.*, **11**, 291–305, https://doi.org/10.1175/WCAS-D-18-0025.1.

——, D. Scott, and A. Fenech, 2016: Seasonal weather sensitivity, temperature thresholds, and climate change impacts for park visitation. *Tourism Geogr.*, **18**, 297–321, https://doi.org/10.1080/14616688.2016.1172662.

Jedd, T. M., M. J. Hayes, C. M. Carrillo, T. Haigh, C. J. Chizinski, and J. Swigart, 2018: Measuring park visitation vulnerability to climate extremes in U.S. Rockies National Parks tourism. *Tourism Geogr.*, **20**, 224–249, https://doi.org/10.1080/14616688.2017.1377283.

Jenkins, J., 2022: Science and the evolving management of environmental hazards at Yosemite National Park. Parks Stewardship Forum 38, 17 pp., https://escholarship.org/content/qt82h4x507/qt82h4x507_noSplash_cb2634636ae2a9b89097247c308c5ae7.pdf.

——, M. Fincher, and J. van Wagtendonk, 2021a: The evolution of management science to inform overnight visitor use carrying capacity in Yosemite Wilderness. *Int. J. Wilderness*, **27**, 23–39.

——, F. Arroyave, M. Brown, J. Chavez, J. Ly, H. Origel, and J. Wetrosky, 2021b: Assessing impacts to national park visitation from COVID-19: A new normal for Yosemite? *Case Stud. Environ.*, **5**, 1434075, https://doi.org/10.1525/cse.2021.1434075.

Kapnick, S., and A. Hall, 2010: Observed climate–snowpack relationships in California and their implications for the future. *J. Climate*, **23**, 3446–3456, https://doi.org/10.1175/2010JCLI2903.1.

Leung, Y., and J. Marion, 1999: Recreation impacts and management in wilderness: A state-of-knowledge review. *Wilderness Science in a Time of Change Conf.: Wilderness Ecosystems, Threats, and Management*, Vol. 5, U.S. Department of Agriculture, 23–48, https://www.fs.usda.gov/rm/pubs/rmrs_p015_5/rmrs_p015_5_023_048.pdf.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, 1994: A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *J. Geophys. Res.*, **99**, 14 415–14 428, https://doi.org/10.1029/94JD00483.

Ma, S., C. A. Craig, S. Feng, and C. Liu, 2023: Climate resources at United States national parks: A tourism climate index approach. *Tourism Recreation Res.*, https://doi.org/10.1080/02508281.2021.1946652, in press.

Marion, J. L., Y.-F. Leung, H. Eagleston, and K. Burroughs, 2016: A review and synthesis of recreation ecology research findings on visitor impacts to wilderness and protected natural areas. *J. For.*, **114**, 352–362, https://doi.org/10.5849/jof.15-498.

Marshall, A., V. Butsic, and J. Harte, 2018: The phenology of wilderness use: Backcountry recreation in a changing climate. *Wea. Climate Soc.*, **10**, 209–223, https://doi.org/10.1175/WCAS-D-17-0087.1.

——, J. T. Abatzoglou, T. E. Link, and C. J. Tennant, 2019: Projected changes in interannual variability of peak snowpack amount and timing in the western United States. *Geophys. Res. Lett.*, **46**, 8882–8892, https://doi.org/10.1029/2019GL083770.

Miller, A. B., P. L. Winter, J. J. Sánchez, D. L. Peterson, and J. W. Smith, 2022: Climate change and recreation in the western United States: Effects and opportunities for adaptation. *J. For.*, **120**, 453–472, https://doi.org/10.1093/jofore/fvab072.

Monz, C. A., K. J. Gutzwiller, V. H. Hausner, M. W. Brunson, R. Buckley, and C. M. Pickering, 2021: Understanding and managing the interactions of impacts from nature-based recreation and climate change. *Ambio*, **50**, 631–643, https://doi.org/10.1007/s13280-020-01403-y.

Mote, P. W., S. Li, D. P. Lettenmaier, M. Xiao, and R. Engel, 2018: Dramatic declines in snowpack in the western US. *npj Climate Atmos. Sci.*, **1**, 2–, https://doi.org/10.1038/s41612-018-0012-1.

O'Toole, D., and Coauthors, 2019: Climate change adaptation strategies and approaches for outdoor recreation. *Sustainability*, **11**, 7030, https://doi.org/10.3390/su11247030.

Perry, E. E., X. Xiao, J. M. Nettles, T. A. Iretskaia, and R. E. Manning, 2021: Park visitors' place attachment and climate change-related displacement: Potential shifts in who, where, and when. *Environ. Manage.*, **68**, 73–86, https://doi.org/10.1007/s00267-021-01480-z.

Peters-Lidard, C. D., and Coauthors, 2021: Indicators of climate change impacts on the water cycle and water management. *Climatic Change*, **165**, 36, https://doi.org/10.1007/s10584-021-03057-5.

Peterson, B. A., M. T. Brownlee, and J. L. Marion, 2018: Mapping the relationships between trail conditions and experiential elements of long-distance hiking. *Landscape Urban Plann.*, **180**, 60–75, https://doi.org/10.1016/j.landurbplan.2018.06.010.

——, ——, J. C. Hallo, J. A. Beeco, D. L. White, R. L. Sharp, and T. W. Cribbs, 2020: Spatiotemporal variables to understand visitor travel patterns: A management-centric approach. *J. Outdoor Recreation Tourism*, **31**, 100316, https://doi.org/10.1016/j.jort.2020.100316.

Reigner, N., S. Lawson, B. Meldrum, D. Pettebone, P. Newman, A. Gibson, and B. Kiser, 2012: Adaptive management of visitor use on Half Dome, an example of effectiveness. *J. Park Recreation Adm.*, **30**, 64–78.

Rice, W. L., S. Y. Park, B. Pan, and P. Newman, 2019: Forecasting campground demand in US national parks. *Ann. Tourism Res.*, **75**, 424–438, https://doi.org/10.1016/j.annals.2019.01.013.

Robeson, S. M., 2015: Revisiting the recent California drought as an extreme value. *Geophys. Res. Lett.*, **42**, 6771–6779, https://doi.org/10.1002/2015GL064593.

Scott, D., B. Jones, and J. Konopek, 2007: Implications of climate and environmental change for nature-based tourism in the Canadian Rocky Mountains: A case study of Waterton Lakes National Park. *Tourism Manage.*, **28**, 570–579, https://doi.org/10.1016/j.tourman.2006.04.020.

Shrestha, R. R., B. R. Bonsal, J. M. Bonnyman, A. J. Cannon, and M. R. Najafi, 2021: Heterogeneous snowpack response and snow drought occurrence across river basins of northwestern North America under 1.0°C to 4.0°C global warming. *Climatic Change*, **164**, 40, https://doi.org/10.1007/s10584-021-02968-7.

Siirila-Woodburn, E. R., and Coauthors, 2021: A low-to-no snow future and its impacts on water resources in the western United States. *Nat. Rev. Earth Environ.*, **2**, 800–819, https://doi.org/10.1038/s43017-021-00219-y.

Smith, J. W., E. Wilkins, R. Gayle, and C. C. Lamborn, 2018: Climate and visitation to Utah's 'Mighty 5' national parks. *Tourism Geogr.*, **20**, 250–272, https://doi.org/10.1080/14616688.2018.1437767.

Van Kirk, R., S. Martin, K. Ross, and M. Douglas, 2014: Computer simulation modeling to determine trailhead quotas for overnight wilderness visitor use. *J. Park Recreation Adm.*, **32**, 29–48.

van Wagtendonk, J., 1981: The effect of use limits on backcountry visitation trends in Yosemite National Park. *Leisure Sci.*, **4**, 311–323, https://doi.org/10.1080/01490408109512970.

——, 1986: The determination of carrying capacities for the Yosemite Wilderness. U.S. Forest Service General Tech. Rep. INT-212, 456–461, https://pubs.er.usgs.gov/publication/2002164.

——, and P. R. Benedict, 1980: Travel time variation on backcountry trails. *J. Leisure Res.*, **12**, 99–106, https://doi.org/10.1080/00222216.1980.11969429.

——, and P. R. Coho, 1986: Trailhead quotas. Rationing use to keep wilderness wild. *J. For.*, **84**, 22–24.

Walden-Schreiner, C., S. D. Rossi, A. Barros, C. Pickering, and Y.-F. Leung, 2018: Using crowd-sourced photos to assess seasonal patterns of visitor use in mountain-protected areas. *Ambio*, **47**, 781–793, https://doi.org/10.1007/s13280-018-1020-4.

Wilhite, D. A., and M. H. Glantz, 1985: Understanding: The drought phenomenon: The role of definitions. *Water Int.*, **10**, 111–120, https://doi.org/10.1080/02508068508686328.

Williams, A. P., and Coauthors, 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, **368**, 314–318, https://doi.org/10.1126/science.aaz9600.

Winter, P. L., J. J. Sánchez, and D. D. Olson, 2021: Effects of climate change on outdoor recreation in the Sierra Nevada. USDA Forest Service Pacific Southwest Research Station General Tech. Rep. PSW-GTR-272, 181–244, https://www.fs.usda.gov/research/treesearch/63219.

Wobus, C., and Coauthors, 2017: Projected climate change impacts on skiing and snowmobiling: A case study of the United States. *Global Environ. Change*, **45**, 1–14, https://doi.org/10.1016/j.gloenvcha.2017.04.006.

Zhang, B., Y. Xia, L. S. Huning, J. Wei, G. Wang, and A. AghaKouchak, 2019: A framework for global multicategory and multiscalar drought characterization accounting for snow processes. *Water Resour. Res.*, **55**, 9258–9278, https://doi.org/10.1029/2019WR025529.