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Research Article

# Monitoring visitor activity and informal trail disturbance in Yosemite Valley meadows to assess temporal changes in use and impacts

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ABSTRACT

Montane meadows provide vital habitat that supports ecosystems, regulate hydrological processes, and offer valuable recreational opportunities. Meadows account for 3 % of Yosemite National Park's area, including Yosemite Valley, and are particularly susceptible to human impacts such as formation of informal trails. We collected observational data on visitor activity and quantified social trail disturbance to compare with resource monitoring datasets and through similar parameters to Walden-Schreiner and Leung (2013) who studied visitor use and behavior in three Yosemite Valley meadows in 2011. We documented change in number of visitors per hour and primary activity pursued. We also compared trends of meadow disturbance (informal trail length and disturbed area) from the early 2000s - 2023. Informal trail length at El Capitan Meadow decreased from 2004 to 2018, followed by recent increases. Disturbed area for Cooks A, Sentinel A, Slaughterhouse B, Stoneman A, and Stoneman B sub-meadows increased from 2006 to 2023. Between 2011 and 2023, the proportion of those engaged in active versus stationary pursuits showed that visitors engaged in more active pursuits in two of three meadows. Moreover, there were >3.5 times more visitors per hour in Cooks, El Capitan, and Leidig meadows in 2023 compared to 2011, yet, most visitors utilized designated trails. Meadow locational context was linked to activity preference and types of impacts. Management strategies, such as fencing and signage have been effective at minimizing impacts in several meadows. Parsing nuances of informal trail use and drivers of disturbance for various meadows is crucial for informed park management decisions and actions.

## 1. Introduction

Montane meadows provide vital habitat that supports ecosystems by provisioning feeding and breeding grounds, regulate hydrological processes, and offer valuable recreational opportunities (Viers et al., 2013; Walden-Schreiner et al., 2017). Meadows in protected areas such as national parks are significant resources because of their distinct ecological characteristics and hydrological function, which support species and provide wildlife viewing and other passive and active recreational activities (Walden-Schreiner et al., 2017). Yet, meadows are particularly susceptible to human impacts such as the formation of informal trails (Barros & Pickering, 2015; Eagen et al., 2004; Pearce--Higgins & Yalden, 1997), and past research suggests that meadow vegetation is significantly affected by trail use (Foin et al., 1977; Leung, Newburger, et al., 2011; Sydoriak, 1989). Informal trails, often referred to as "social trails" created by visitors, are recognizable and uninterrupted trail sections that deviate from a park's official trail network (Leung, Bigsby, & Kollar, 2011). Unplanned and unconstructed, those paths often occupy unsuitable terrains and are typically neglected in terms of maintenance by park authorities, existing as a materialized tension between park preservation directives and visitor access preferences (Schmitt, 2016). At national parks, the impacts from informal trail use in meadows often necessitate restoration in order to avoid resource impairment while still facilitating tourism (Rochefort & Gibbons, 1992).

Recreational land managers deploy a combination of direct and indirect actions to dissuade visitors from contributing to further social trail proliferation, such as with fencing and messaging that educates visitors on the impacts of social trails (Goh, 2020; Hockett et al., 2017). While it only takes the first several initial users to form a social trail, once the majority of vegetation cover has been lost, soil compaction occurs

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quickly, and the incremental impact from subsequent users, even years after the initial trampling event, makes it difficult for soil and vegetation to recover (Hammitt et al., 2015; Marion, 2016). The growth of such trail networks can increase habitat fragmentation and edge effects, endanger delicate environments by altering water flow, and often serve as entry points for invasive species, all of which can limit the occupancy and movement of endemic species (Lucas, 2020; Marion et al., 2006). Consequently, monitoring those trails is beneficial to ensure integrity of the meadows is maintained or improved and inform future management strategies.

The extent and condition of informal trails is indicative of the contiguity and ecological functioning of meadows and wetland areas (Holmquist, 2004; National Park Service, 2014a, 2014b). Given that informal trails do not follow a park's formal trail system and are not planned or constructed, they are usually poorly located with respect to terrain and receive little or no maintenance by park staff (Leung, Newburger, et al., 2011). These factors substantially increase their potential to deteriorate meadows in comparison to formal trails. From a visitor management perspective, a web of informal trails creates a visually scarred landscape and may lead to safety and liability concerns, thus social trails can impair not only biophysical resources but also scenic resources and experiences that underpin the satisfaction and well-being of users (Marion et al., 2006).

Within Yosemite National Park in California, USA, historical data suggest that the meadows in Yosemite Valley were once more expansive and wetter than they are presently. Research indicates that there has been a dramatic reduction in the Valley's meadow land, dwindling from over 700 acres in the late 19th century to slightly above 300 acres in 2021 (National Park Service, 2021), and this is due to both anthropogenic forces and ecological drivers (D'Antonio & Monz, 2016; Walden-Schreiner & Leung, 2013). Meadow systems are a scarce resource, accounting for 3 % of Yosemite National Park's area, and monitoring of fragmentation due to informal trail proliferation is a well-established indicator protocol that serves as a warning sign of resource degradation and habitat disturbance (Leung, Bigsby, & Kollar, 2011; Viers et al., 2013).

We monitored visitor use in meadows of Yosemite National Park (Fig. 1) from August to October 2023. Walden-Schreiner and Leung (2013) conducted a study of visitor use and behavior in Yosemite Valley Meadows, specifically Cooks, El Capitan, and Leidig meadows. They observed where visitors were spatially located and the types of activities in which they engaged. One of the objectives of the current study is to compare how visitor use patterns have changed during a 10+ year period by employing similar methodology to Walden-Schreiner and Leung (2013). Additional objectives of this study were to document the current number of visitors per hour, nature of activities they engage in, patterns of their movement, and to investigate impacts to natural resources in meadows.

Monitoring both visitors within Yosemite meadows and trends in meadow impacts enables identifying areas with high visitor frequency and corresponding impacts, as well as, insights into current and past meadow management practices. The goal of this study is to inform actionable strategies for both the prevention of further meadow impacts caused by visitors and restoration of areas already affected by visitor impacts.

## 2. Methods

### 2.1. Visitor use observations

To monitor visitor use in meadows, including visitor locations and the type of activities they undertake, unobtrusive direct observation was employed similar to Walden-Schreiner and Leung (2013) who observed visitor activity in Cooks, Leidig, and El Capitan meadows. For the current study, observations were made in all Yosemite Valley meadows (Ahwahnee, Bridalveil, Cooks, El Capitan, Leidig, Sentinel,

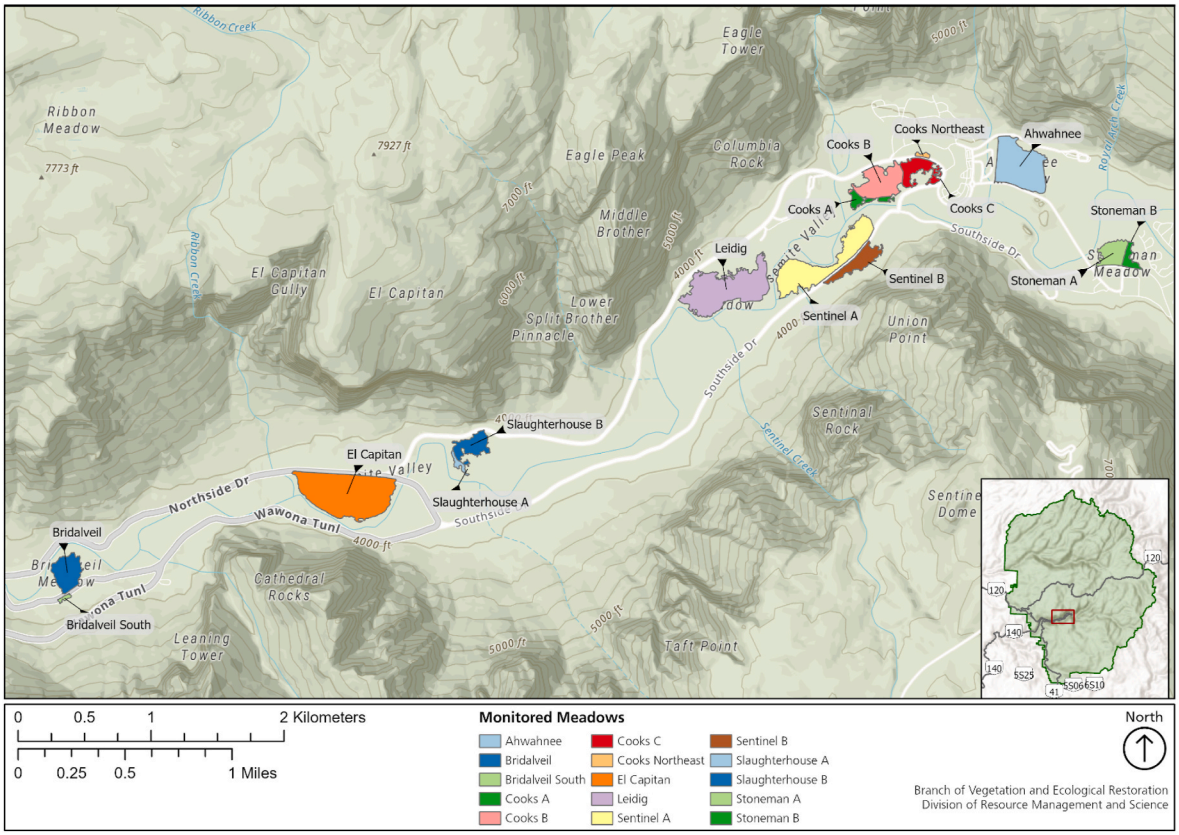



**Fig. 1.** Overview map showing location of Yosemite Valley meadows and delineated sub-meadows monitored during this study.

Slaughterhouse, and Stoneman) (Fig. 1). Prior to data collection, reconnaissance was conducted to determine where an observer could stand in each meadow or portion of a meadow to make observations of all visitor activity. For this reason, several meadows were split into two zones due to their size and to ensure that an observer could accurately record activities. Data from meadow zones were combined to enable analysis of spatial and temporal patterns for each of the meadows.

Data were recorded using ArcGIS Field Maps (ver 23.1.1) on a tablet computer or handheld device. The Field Maps included National Park Service (NPS) data layers of each official meadow boundary, a 50 m grid system overlay, established (i.e., official) trails, and social trails that were mapped in 2022. This tool enabled collection of real time geospatial data to document where visitors were located when observed. Additional data collected included date, time, number of people, and type of activity. If multiple people were observed performing the same activity, one location was recorded with a tally of how many individuals were engaging in that activity. For instance, one "walking" observation could include multiple people, but was input as one observation point. This was done to facilitate rapid collection of data. The use of binoculars aided visual acuity on an as-needed basis.

Data were collected from August 3 – October 2, 2023, and included two time periods: 8:00 a.m.–12:00 p.m. and 12:00 p.m.–4:00 p.m. Observation effort was divided equally between morning (8 a.m.–12 p.m.), and afternoon (12 p.m.–4 p.m.). Data were collected continuously in 30-min time slots on the hour and half hour. Due to limited resources of staff time, meadows were assigned a higher or lower priority for observation time based on factors such as likelihood to receive visitors, size, and previous management observations about emerging impacts. High priority meadows (Cooks, El Capitan, Leidig, Sentinel, and Slaughterhouse) were observed for 3 h during each time period and low priority meadows (Ahwahnee, Bridalveil, and Stoneman) were observed for 2 h during each time period.

Visitors were classified as primarily engaged in active versus stationary activities such that all sedentary activities (e.g., sitting, standing, and photography) were categorized as stationary, while all activities that entailed movement (e.g., walking, running, and biking) were categorized as active. For the "active" category, options were documented included walking, biking, running, and log climbing. If a person was transitioning through a meadow and quickly captured 1–2 photos, they were counted as walking, whereas if someone was passing through a meadow to take photographs for several minutes or longer, then they were counted as stationary. Visitors engaging in multiple activities were recorded only once during each monitoring period. Whichever activity occupied the majority of the visitor's time in the meadow was recorded. Activity categories were established to understand visitor use and activity type in meadows of Yosemite.

For most meadows, monitoring observations were restricted to formally mapped meadow boundaries. Monitoring of visitor use along adjacent riverbanks and beaches was considered outside of the scope of this study with two exceptions: 1) observations outside the eastern boundary of El Capitan Meadow where extensive social trails and visitor impacts have been mapped since 2004 were included; 2) visitors were not counted along formal trails immediately adjacent to roadways, such as where Southside drive abuts Sentinel Meadow, or where Northside drive abuts Ahwahnee Meadow. Formal trail visitor use observations were thus limited to formal trails that directly traversed meadows, were adjacent to a meadow boundary and not also to a primary access road or were immediately adjacent to a meadow and connected one roadway to another.

Visitor use data were converted to number of visitors per observation hour to standardize data across meadows. The proportion of various activity types was assessed within each meadow and among all meadows. To compare the proportion of visitors between morning versus afternoon, and active versus stationary in each meadow, t-tests were conducted.

To compare visitor activity data collected during this study with data collected by Walden-Schreiner and Leung (2013) for Cooks, El Capitan, and Leidig meadows paired t-tests were used. Variables compared included number of visitors per hour in each meadow, proportion of visitors in morning versus afternoon, and proportion of active versus stationary visitors. Walden-Schreiner and Leung (2013) observed each meadow for a total of 8 h, with equal observation periods in morning and afternoon from Jul–Aug 2013, whereas we observed each meadow for a total of 6 h, with equal observation periods in morning and afternoon, from Aug–Oct 2023. Walden-Schreiner and Leung (2013) reported total number of visitors observed in each meadow and provided percentages for visitor use in morning (8 a.m.–12 p.m.), afternoon (12 p.m.–4 p.m.), and evening (4 p.m.–8 p.m.) periods. The evening period was not replicated during this study and thus excluded from comparisons of total number of visitors and proportion of visitors during temporal periods in each meadow. They reported percentages of stationary and active use which integrated all three time periods of their study and it was not possible to remove evening data from these percentages.

### 2.2. Meadows informal trails and disturbed areas

Trained field staff from the Visitor Use and Impact Monitoring Program (VUIMP) at Yosemite National Park have monitored Yosemite Valley meadows, including quantification of proliferation and condition of informal trails, since 2004 (National Park Service, 2014a, 2014b). Meadows are typically monitored between Jun–Aug, by mapping social trails and disturbed areas using GPS and GIS technologies following the methods of Leung, Newburger, et al. (2011). Informal trail length (m) and disturbed area ($m^2$) are classified according to trail condition class (e.g., stunted vegetation, some bare ground, or barren) (Leung, Newburger, et al., 2011; Walden-Schreiner et al., 2013) (Table 1). Meadows in Yosemite Valley that are mapped each year include Ahwahnee Meadow; Bridalveil Meadow and sub-meadow Bridalveil South; sub-meadows A, B, C, and Northeast within Cooks Meadow; El Capitan Meadow; Leidig Meadow; sub-meadows A and B within Sentinel Meadow; sub-meadows A and B within Slaughterhouse Meadow; and sub-meadows A and B within Stoneman Meadow (Leung et al., 2011a) (Fig. 1). Cooks northeast and Bridalveil South were excluded from further analysis due to limited disturbance mapping of these sub-meadows.

While data for informal trail length and disturbed area have been collected annually, they had not previously been analyzed across years to compare trends over time and changes in extent of social trails and disturbed areas. As the patterns of visitation to Yosemite National Park varied non-linearly from 2004 to 2023, impact metrics were analyzed using a non-linear approach. The influence of year on either trail length or disturbed area was analyzed using a series of generalized additive mixed models (GAMMs), which also incorporated temporal

**Table 1**
Informal trail condition class attributes (adapted from Walden-Schreiner & Leung, 2013; National Park Service, 2010).

| Informal trail condition class | Trail characteristics |
|---|---|
| Stunted vegetation | Distinct trail feature present |
| | Trail boundary present |
| | Moderate repeated human use evident Trampled and matted vegetation |
| | Noticeably impeded vegetation growth |
| Some bare ground | Heavy repeated human use evident |
| | Trampled and matted vegetation |
| | Noticeably impeded vegetation growth |
| | Some bare ground present in trail tread |
| | Distinct trail feature present |
| | Trail boundary present and distinct in most areas |
| Barren | Extensive repeated human use evident |
| | No vegetation present |
| | Bare ground present in trail tread throughout |

autocorrelation between years of observations. GAMMs were also conducted with condition classes (stunted vegetation, some bare ground, barren) associated with either informal trail length (m) or disturbed area ($m^2$) as response variables and time as the predictive variable. All trends analyses were conducted using R software (version 4.2) and the mgcv package (Wood, 2017). Informal trail length analyses (i.e., general trends and condition class) included 2004–2023, whereas disturbed area analysis included 2006–2023 and disturbed area condition class analysis included 2008–2023 due to a lack of data from the preceding years for disturbed areas.

GAMMs are a useful non-parametric modelling approach that can use regression splines to create smooth fits of the partial dependencies of predictor variables which have a non-linear relationship with the response variable (Wood, 2006). When GAMM results are significant (falling under an alpha of 0.05), and the model-fit is high (explaining at least 50 % of the deviation in the response variable), it indicates that the time-series can be interpreted as capturing specific trends over time. GAMMs have shown to be valuable tools in analyzing non-linear effects in natural systems (Johnston et al., 2019).

Percent impacted area was calculated for both informal trails, including a 5 m buffer, and for disturbed areas for each meadow. For each of these calculations, the amount of area associated with each impact type was divided by the total meadow area, excluding non-meadow features (e.g., boardwalks, paved paths) and converted to a percentage. A 5 m buffer was utilized around linear trail extent for Yosemite Valley social trails following work of Holmquist (2004) which demonstrated that impacts from social trails extended to 5 m on each side of the trail.

### 2.3. Spatial comparison of informal trails and visitor use

Visitor observation data were mapped and point data were spatially compared with social trail data layers. Informal trail and disturbance mapping from 2023 and informal trails from 2022 were compared with point locations of visitor use observations to determine how many visitors were on formal versus informal trails within each meadow using ArcGIS Pro software (ver 3.3.1).

## 3. Results

### 3.1. Visitor use in Yosemite Valley meadows

For this study we assess visitor use in Yosemite Valley meadows by time of day and activity types, comparing changes in use over time, and through spatial comparisons of informal trails and visitor use.

#### 3.1.1. Time of day and activity types

There was no difference between visitor use in Yosemite Valley meadows between morning and afternoon ($p = 0.28$) across all meadows (Fig. 2). Yet, meadows such as El Capitan, Slaughterhouse, and Stoneman appeared to deviate from a 50/50 split between morning and afternoon such that approximately 32 %, 74 % and 19 % of visitation occurred in the morning in these meadows, respectively.

More visitors engaged in active activities (e.g., walking, running, biking, or log-climbing) compared to stationary activities in general for all meadows ($p < 0.001$) (Fig. 3). However, in El Capitan, more visitors (68 %) engaged in stationary activities. Stationary activities represented less than 20 % of meadow use for all meadows except El Capitan (68 %) and Bridalveil (43 %). Between 72 and 89 % of visitors were walking in Cooks, Leidig, Sentinel, Slaughterhouse, and Stoneman meadows. Biking was observed in all meadows except El Capitan and Bridalveil. Meadows with the most bikers per hour included Leidig (31 visitors/hour), Cooks (27 visitors/hour), and Sentinel (15 visitors/hour). Running was observed in five out of eight meadows but represented 2 % or less of the activity type for any meadow. Log climbing was only observed in El Capitan and represented a small amount of use at 2 %.

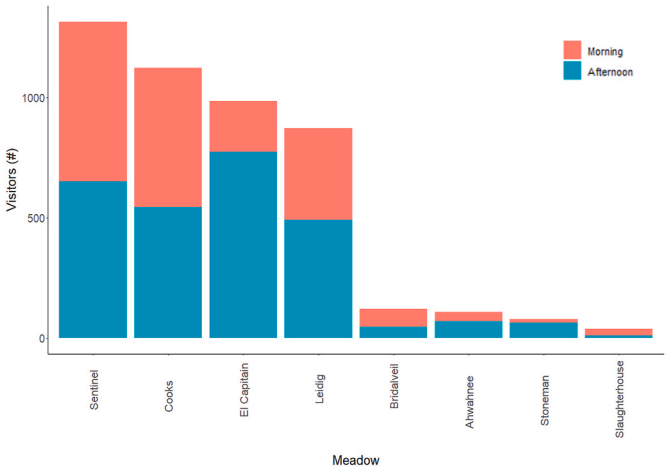



**Fig. 2.** Total number of visitors observed per meadow during the study period. Observations occurred during the morning (coral) and afternoon (teal). Meadows are presented in order of decreasing visitation. N.B. High-priority meadows (Sentinel, Cooks, El Capitan, Leidig, and Slaughterhouse) were observed for a total of 6 h and low-priority meadows (Ahwahnee, Bridalveil and Stoneman) were observed for 4 h.

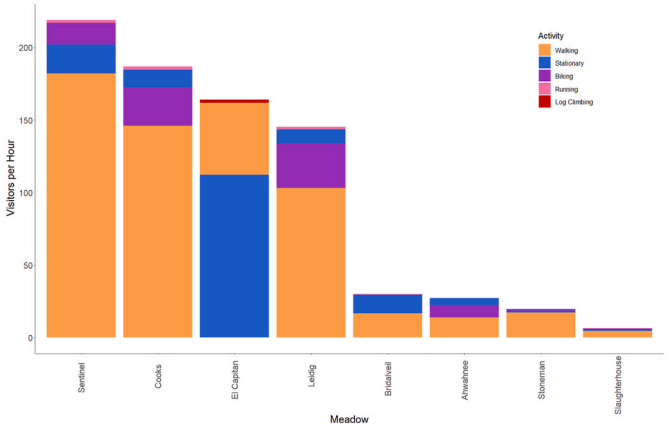



**Fig. 3.** Visitors per hour engaged in various activity types for each meadow. Activities observed included walking (orange), stationary (blue), biking (purple), running (pink) and log climbing (red). Meadows are presented in order of decreasing visitor activity and within each meadow by most common activity type. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Analyzing the activity distribution across various meadows revealed certain patterns. Across all meadows, walking was the predominant activity (67 %), followed by stationary activities (22 %), biking (10 %) and remaining activity types.

#### 3.1.2. Comparing changes in use over time

The total number of people recorded in our visitor survey was approximately three times greater than the study by Walden-Schreiner and Leung (2013) (Table 2). There were >3.5 times more visitors per hour in Cooks, El Capitan, and Leidig meadows in 2023 compared to 2011 ($p = 0.005$) (Table 2). Yet, proportion of visitors in each of these meadows in morning versus afternoon did not differ between sampling years ($p > 0.05$).

Proportion of stationary versus active activities for Cooks, Leidig, and El Capitan meadows did not differ between 2011 and 2023 per the results of a paired *t*-test ($p > 0.05$) (Fig. 4). However, the proportion of stationary use varied from 44 % 2011 to 6 % in 2023 in Cooks meadow, and 33 % in 2011 to 7 % in 2023 in Leidig meadow, while stationary use

**Table 2**
Observed percentage of visitors during morning and afternoon, visitors per hour, and total visitor use for Cooks, El Capitan, and Leidig meadows in 2023 and for similar data collected in 2011 by Walden-Schreiner and Leung (2013). N.B. Total use counts for Walden-Schreiner and Leung (2013) exclude evening data that were originally collected in their study.

| Meadow | Morning use (%) | Afternoon use (%) | Visitors per hour | Total use counts |
|---|---|---|---|---|
| *2023* | | | | |
| Cooks | 54 | 46 | 187 | 1186 |
| El Capitan | 26 | 74 | 164 | 1043 |
| Leidig | 44 | 56 | 144 | 886 |
| Overall Use | 46 ± 6 | 54 ± 6 | 165 ± 21 | 3115 |
| *2011* | | | | |
| Cooks | 36 | 64 | 53 | 427 |
| El Capitan | 26 | 75 | 39 | 310 |
| Leidig | 37 | 63 | 40 | 320 |
| Overall Use | 33 ± 6 | 67 ± 7 | 44 ± 8 | 1057 |

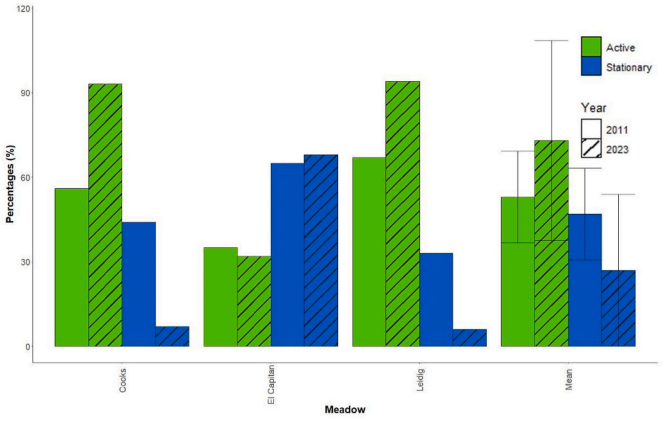



**Fig. 4.** Percentage of visitors engaged in active (green) versus stationary (blue) activity types in 2011 (solid bars) versus 2023 (hatched bars) across Cooks, El Capitan and Leidig meadows. Mean values across all meadows ±1 SD are presented in the final column. Data from 2011 were published in Walden-Schreiner and Leung (2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in El Capitan meadow was relatively consistent at 65 % in 2011 and 68 % in 2023. Average stationary use across these meadows in 2011 was 47 % ± 16 compared to 27 % ± 35 in 2023 (Fig. 4).

### 3.1.3. Spatial comparison of informal trails and visitor use

Mapped comparisons between trail condition classes and visitor use provide a visual assessment of visitor impact across the different meadows (Figs. 5 and 6). Across all meadows, a larger percentage of visitors (73–100 %) were observed on designated trails compared to informal trails (Supplemental Table 1). Results are presented for meadows with 1) high formal trail usage (Ahwahnee, Bridalveil, Cooks, Leidig, and Stoneman), 2) moderate formal trail usage (Slaughterhouse, Stoneman), and 3) meadows with solely informal trail usage (El Capitan).

Most visitor use in Ahwahnee, Bridalveil, Cooks, Leidig, and Stoneman meadows was primarily confined to formal trails (from 93 % to 100 %). In Ahwahnee Meadow, 93 % of visitors were observed using the paved official trail, which was delineated by a rope barrier along with signage discouraging off trail walking (Fig. 5a). Vegetation impacts were most discernible in the northwestern region adjacent to a road and parking area, where visitors occasionally short-cut across the meadow. Moreover, a designated and maintained helicopter landing zone likely contributes associated foot traffic. In Bridalveil Meadow, 100 % of visitors used the formal trail adjacent to Southside Drive (Fig. 5b). Notably, the 2022 social trails layer is more extensive and penetrates farther into the meadow interior compared with 2023. Impacts in 2023 are reduced north of the fence in stunted vegetation areas, relative to more barren and bare ground areas south of the fence.

In Cooks Meadow, 98 % of visitors were observed on formal trails, including paved walkways bisecting Cooks A and B, and a boardwalk bisecting Cooks B and C (Fig. 5c). In Cooks A, visitor associated barren areas were concentrated adjacent to the Merced River (Fig. 5c). In Cooks B, the most degraded areas also appeared to have higher visitation. While there are paved walkways in this region, several social trails of stunted vegetation extend from the boardwalk, indicating off-trail use into the meadow. Tour groups were observed frequently gathering in these areas for interpretive sessions of photography, art, or similar activities. In Leidig Meadow 96 % of visitors used formal trails and there is a fence along the eastern portion of the meadow adjacent to a paved formal trail (Fig. 6a). The eastern side of the meadow receives more use, though impacts are low along the fence line, while an area near the bridge shows the most impacts to vegetation. While the western side of the meadow received fewer visitors, impacts to vegetation were more pronounced in the northwest corner adjacent to the Valley Loop trail and river access points. In contrast, visitors in Stoneman Meadow displayed minimal impact on the surrounding vegetation with 100 % of use confined to the boardwalk (Fig. 6d). However, in the areas where the boardwalk was deteriorating, adjacent areas displayed stunted vegetation.

In Sentinel Meadow and Slaughterhouse Meadow, visitors exhibited greater reliance on informal trails. Only 73 % of visitors to Sentinel meadow adhered to official trails, including the paved path on the eastern edge and the u-shaped boardwalk in the middle of meadow (Fig. 6b). A prominent social trail from Superintendent's Bridge (i.e., the bridge connecting Cooks to Sentinel Meadow) to the boardwalk in the mid-section of the meadow displayed rutting, trail braiding, and barren ground. Visitor activity was also observed leading west from the boardwalk where there is a social trail which is marked with official signage (e.g., no pets, no bikes) and is intended for use as an official (i.e., park-maintained) trail. Moreover, numerous social trails along the river margins displayed regular use. In Slaughterhouse Meadow 73 % of visitors used the unpaved and unmarked formal trail (i.e., Valley Loop trail) bisecting the meadow from north to south (Fig. 6c). The 2023 informal trails map shows that Slaughterhouse Meadow has several disturbed areas, particularly in barren areas and swaths of some bare ground close to the adjacent road (Northside Drive) (Fig. 6c). There was limited visible usage of informal trails, yet some areas show disproportionately higher impact based on disturbed area condition monitoring maps. The 2022 informal trail maps do not show the 2023 mapped social trail that bisects a large portion of the meadow from east to west. One visitor was observed walking this informal trail and ultimately crossed from the western side of the meadow to the Valley Loop trail on the eastern side.

El Capitan Meadow, displayed the highest level of informal trail use as there are no formal trails. All visitor use (100 %) occurred on social trails, although when accounting for recreation-designed areas, 81 % of visitors used resource manager approved trails and locations (Fig. 5d). Following recommendations of Walden-Schreiner and Leung (2013), resource managers created fence breaks to access three primary viewing areas; however, the recommended raised platforms were not constructed. The northeastern area, which was intentionally designed for recreation and includes a picnic bench, exhibits extensive barren ground. In the central viewing area, which contains the highest concentration of visitors and stunted vegetation, social trails extend far into the meadow. Most visitors using this area are stationary as it provides a vantage point for photography and watching climbers on El Capitan. At times, 50 + individuals were observed congregating in the main hotspot for ~15 min or more and our observations highlight that at any given

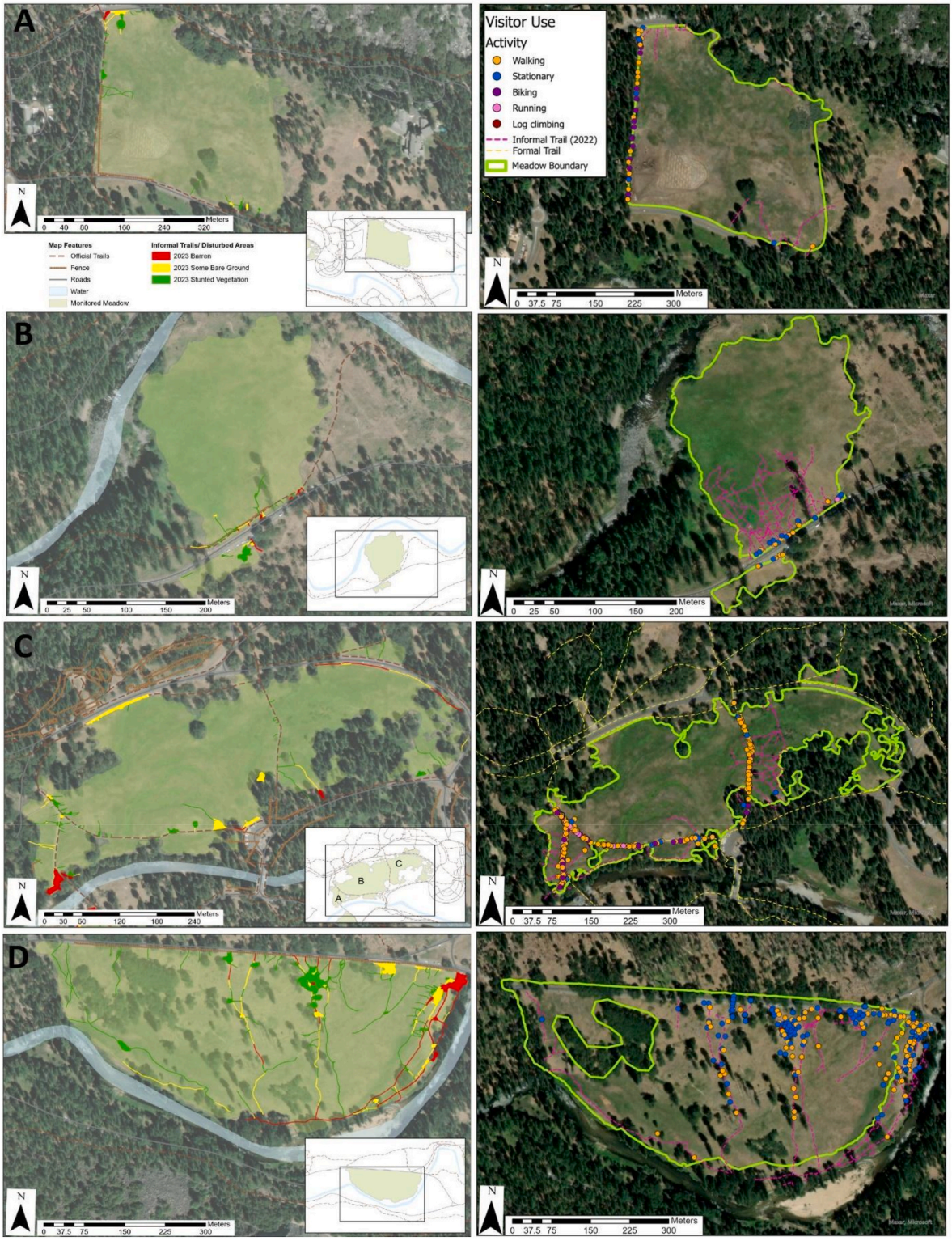



**Fig. 5.** Informal trails condition monitoring maps from 2023 (left column) and maps of visitor activity types with 2022 informal trails (right column) for a) Ahwahnee Meadow, b) Bridalveil Meadow, c) Cooks Meadow, and d) El Capitan Meadow. Inset maps show sub-meadows denoted by A, B, or C.

time ~5–10 individuals were leaving or entering the meadow for this "primary" viewing spot.

### 3.2. Trail disturbance trends

#### 3.2.1. Informal trail extent

From 2004 to 2023, informal trail length tended to decrease in El Capitan Meadow overall, but with an increase from 2019 to 2023 ($p < 0.001$) (Table 3, Fig. 7). Informal trail length from 2004 to 2023 in Slaughterhouse A tended to decrease ($p = <0.001$), while informal trail length in Slaughterhouse B tended to increase ($p = 0.02$). Both Ahwahnee and Leidig meadows showed trends of increases from 2004 to approximately 2016, followed by decreases thereafter ($p = 0.045$ and $p = 0.001$, respectively). The remaining meadows did not show any

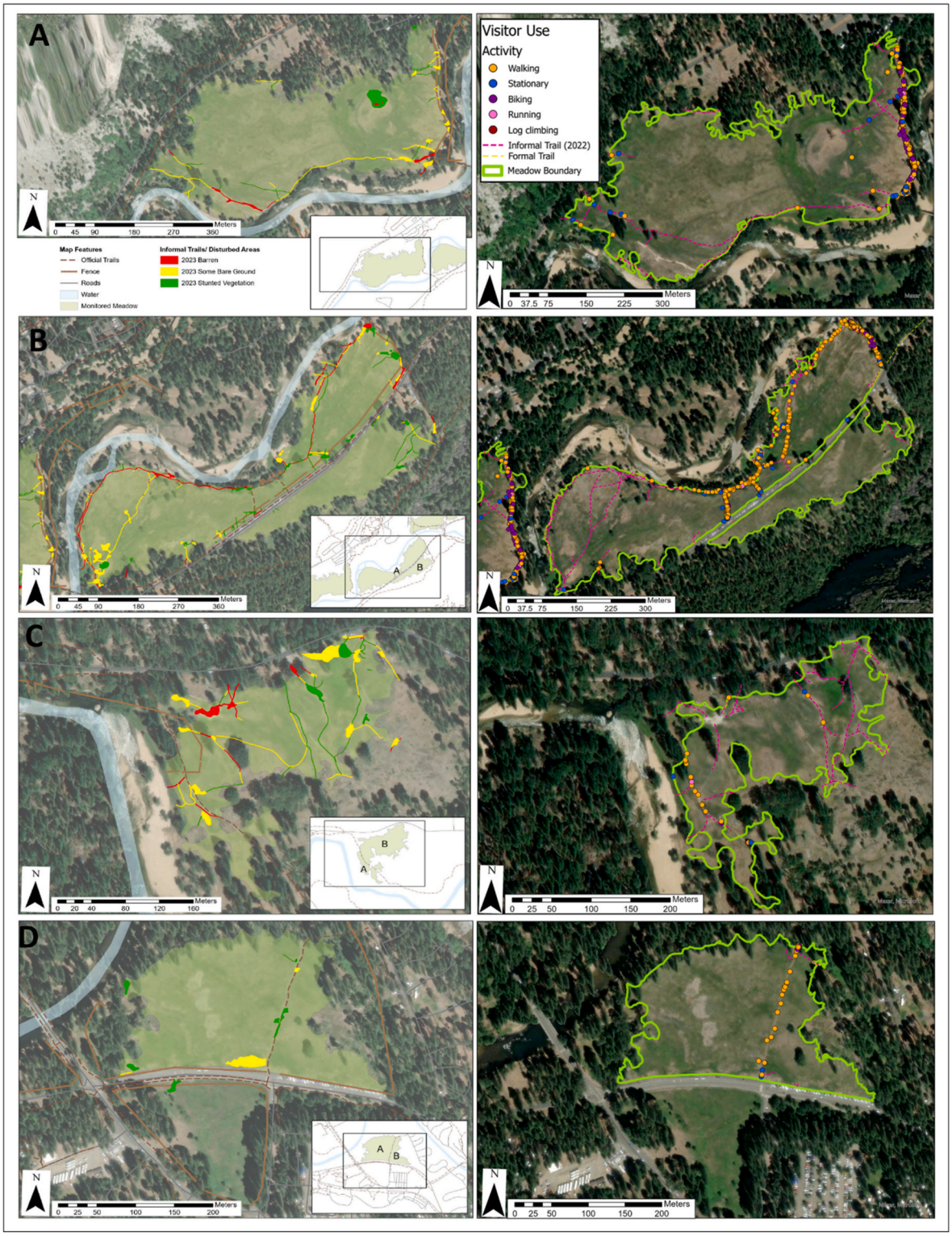



**Fig. 6.** Informal trails condition monitoring maps from 2023 (left column) and maps of visitor activity types with 2022 informal trails (right column) for a) Leidig Meadow, b) Sentinel Meadow, c) Slaughterhouse Meadow, and d) Stoneman Meadow. Inset maps show sub-meadows denoted by A, B, or C.

significant trends during this period. In 2023, measured informal trail length was below the mean of the 2004–2023 period for 9 of 13 valley meadows and sub-meadows (Table 3, Fig. 7). Meadows or sub-meadows where 2023 informal trail length was above the mean of the 2004–2023 period included Cooks C, El Capitan, Sentinel B, and Slaughterhouse B.

Trends in cover classes (i.e., stunted vegetation, some bare ground, or barren) were not significant for most cover types and meadow areas (Supplemental Fig. 1). The following trends were observed: a decrease in barren area in Cooks A ($p = 0.01$), and increases, followed by decreases in both stunted vegetation and some bare ground in this sub-meadow ($p = 0.01$ for each cover class). In El Capitan, some bare ground increased from 2004 to 2011, followed by decreases ($p = 0.005$). In Sentinel A, some bare ground increased until the mid-2010s, followed by a decrease ($p = 0.049$). In Slaughterhouse B, some bare ground tended to increase,

**Table 3**
Mean informal trail length (m) and mean disturbed area ($m^2$) for all meadows monitored from 2004 (or 2006)-2023 and 2019–2023, and p-values of generalized additive mixed models (GAMM) from 2004 (or 2006) - 2023. Means are presented with ±1 standard deviation (SD). * indicates that there were fewer than three detections of either informal trail length or disturbed area during the associated time period. Bold values indicates significance at α = 0.05.

| Meadow | Informal Trail Length (m) | | | Disturbed Area ($m^2$) | | |
|---|---|---|---|---|---|---|
| | 2004–2023 | 2019–2023 | GAMM p-value | 2006–2023 | 2019–2023 | GAMM p-value |
| Ahwahnee | 810 ± 384 | 466 ± 75 | **0.045** | 936 ± 509 | 898 ± 375 | 0.10 |
| Bridalveil | 875 ± 572 | 960 ± 610 | 0.31 | 172 ± 157 | 229 ± 182 | 0.20 |
| Cooks A | 613 ± 213 | 480 ± 212 | 0.12 | 484 ± 290 | 609 ± 322 | **0.03** |
| Cooks B | 362 ± 297 | 230 ± 76 | 0.74 | 850 ± 569 | 886 ± 416 | 0.60 |
| Cooks C | 414 ± 236 | 487 ± 268 | 0.13 | 300 ± 245 | 370 ± 224 | 0.15 |
| El Capitan | 3989 ± 1146 | 2874 ± 1291 | **0.001** | 4502 ± 2094 | 4575 ± 2644 | 0.57 |
| Leidig | 2484 ± 679 | 1623 ± 302 | **0.001** | 2383 ± 1119 | 2190 ± 401 | 0.97 |
| Sentinel A | 2554 ± 1213 | 2178 ± 187 | 0.11 | 1453 ± 938 | 2270 ± 1076 | **0.01** |
| Sentinel B | 196 ± 92 | 227 ± 131 | 0.39 | 297 ± 198 | 385 ± 106 | **0.049** |
| Slaughterhouse A | 147 ± 93 | 83 ± 27 | **<0.001** | 86 ± 48 | 94 ± 25 | 0.47 |
| Slaughterhouse B | 500 ± 259 | 771 ± 231 | **0.02** | 643 ± 582 | 1178 ± 467 | **0.01** |
| Stoneman A | 166 ± 113 | 164 ± 176 | 0.92 | 380 ± 324 | 760 ± 57 | **<0.001** |
| Stoneman B | 37 ± 54 | 36 ± 34* | 0.31 | 47 ± 46 | 91 ± 30 | **<0.001** |

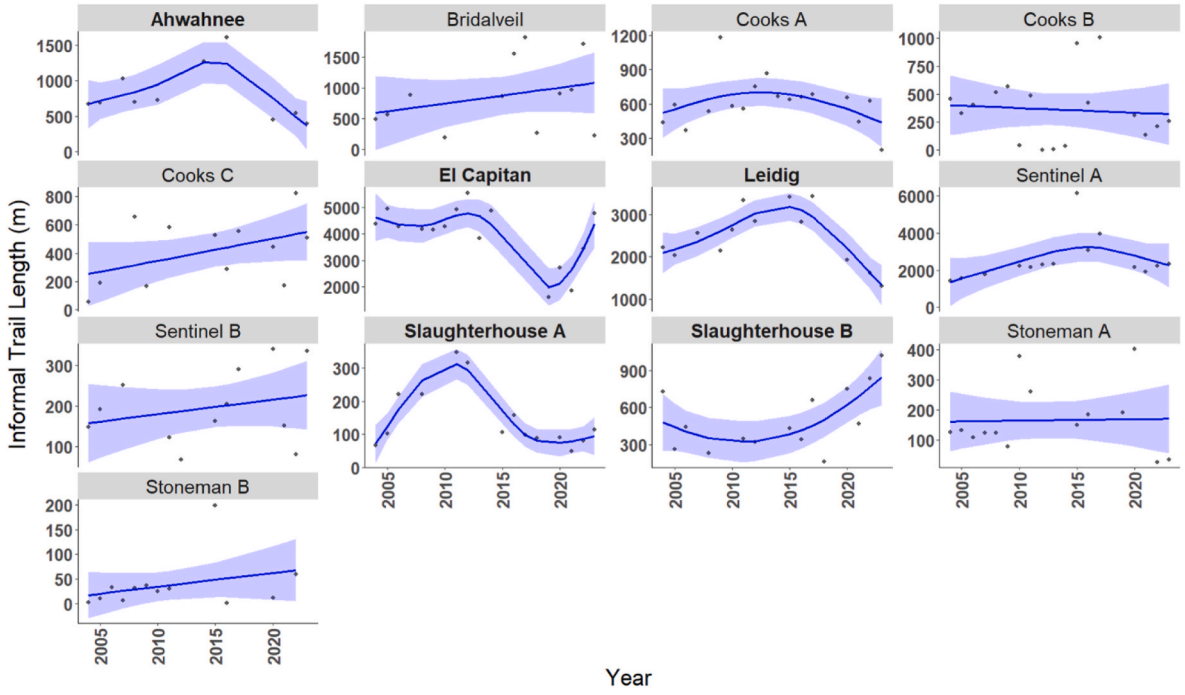



**Fig. 7.** Trends of informal trail length (m) within each meadow from 2004 to 2023. Significant trends, with shaded areas indicating 95 % confidence intervals, shown with bolded meadow name.

especially since circa 2018 (p = 0.001), and in Stoneman A, barren cover decreased (p = 0.03).

### 3.2.2. *Disturbed area*

From 2004 to 2023, there were significant increases in disturbed area in several sub-meadows including Cooks A (p = 0.03), Sentinel A (p = 0.01), Slaughterhouse B (p = 0.01), Stoneman A (p < 0.001), and Stoneman B (p < 0.001) (Table 3, Fig. 8). Sentinel B showed a decrease in disturbed area from 2004 to 2010, followed by a rise in disturbed area (p = 0.049). In 2023, the amount of disturbed area was higher than the mean value from 2004 to 2023 in 10 out of 13 Yosemite Valley meadows and sub-meadows.

Trends in disturbed area cover classes (i.e., stunted vegetation, some bare ground, or barren) increased in 6 of 13 valley meadow areas from 2008 to 2023 (Supplemental Fig. 2). The following increasing cover class trends were observed: stunted vegetation cover in Ahwahnee (p = 0.01), barren cover in Cooks A (p < 0.001), barren cover in El Capitan (p = 0.001), some bare ground in Sentinel A (p < 0.001), some bare ground in Stoneman A (p = 0.031), and stunted vegetation in Stoneman B (p = 0.004). The only other significant trends in disturbed area cover classes were for stunted vegetation and some bare ground in Cooks A (p = 0.02 for each cover type), both of which showed variable trends with increases in the respective cover type over time followed by subsequent decreases (Supplemental Fig. 2).

The percentage of impacted area associated with informal trails or disturbed areas ranged from a 46 % in Cooks A to 3 % in Stoneman B and from 3 % in Cooks A to 0.4 % in both Stoneman B and Bridalveil, respectively (Fig. 9).

## 4. Discussion and conclusions

### 4.1. *Visitor activity*

Statistical insights from visitor counts and activity preferences revealed that visitors tended towards active pursuits in meadows during the study period. Our findings also show that certain meadows attract

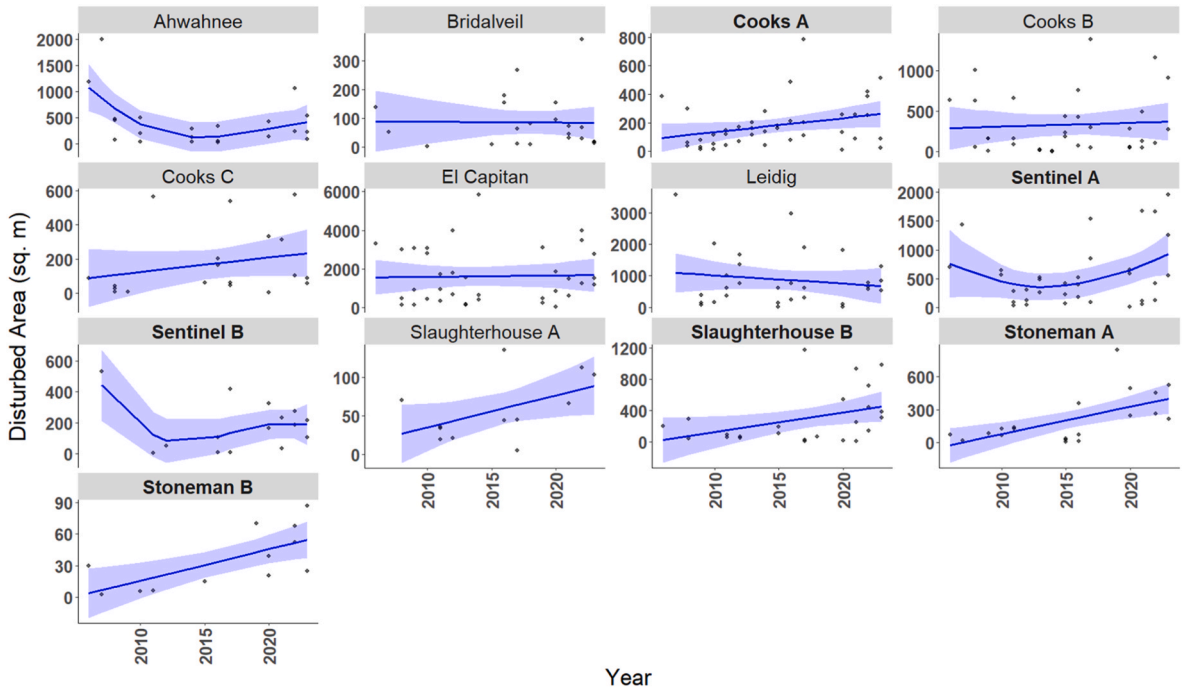



**Fig. 8.** Trends of amount of disturbed area ($m^2$) within each meadow from 2006 to 2023. Significant trends, with shaded areas indicating 95 % confidence intervals, shown with bolded meadow name. N.B. The years 2004–2005, which were included in informal trail length cover type trends analyses, were excluded from disturbed area trends analyses due to lack of data.

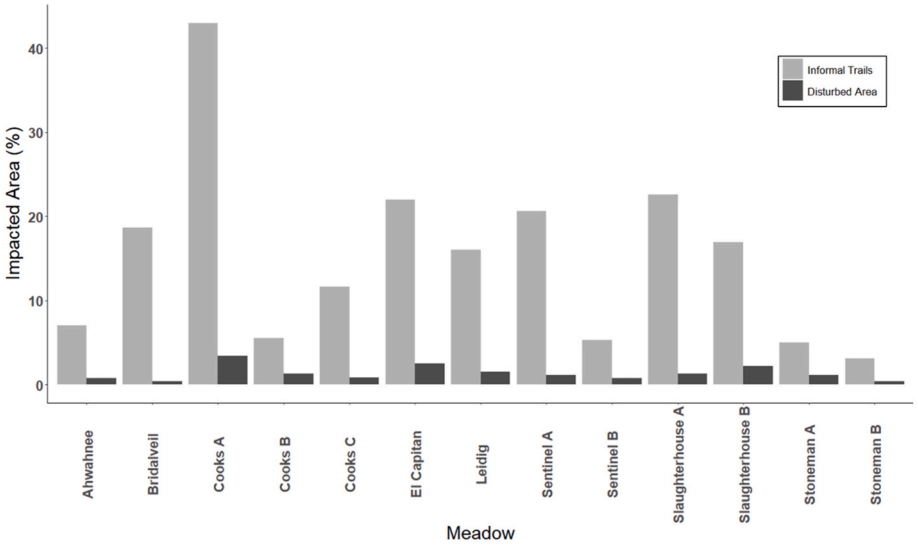



**Fig. 9.** Impacted area within each meadow as associated with either informal trails, which included a 5m buffer, or disturbed area (unbuffered). Each respective impact type was divided by total meadow area to determine the impacted area.

more visitors than others (e.g., Sentinel, Cooks, El Capitan, and Leidig meadows). Spatial comparisons of informal trails and visitor activity provided insights into visitor use and impacts in meadows. In areas with clear delineation of formal trails and barriers, such as fencing, boardwalks, or paved paths, visitors tended to stay on formal trails and cause less meadow vegetation and soil impacts.

Time of day (i.e., morning vs. afternoon) did not affect visitor counts significantly across all meadows, nor were there differences between 2011 and 2023 for temporal use in the three meadows compared between years (e.g., Cooks, El Capitan and Leidig meadows) (Walden-Schreiner and Leung (2013). In 2023, two of the three meadows deviated from equal temporal visitation with fewer visitors in the morning. In El Capitan Meadow, the visitor count varied from a total of 211 in the morning to 773 in the afternoon. For Stoneman Meadow, there were 15 visitors counted in the morning compared to 63 in the afternoon. Potential reasons for this discrepancy might be due to their location within Yosemite Valley, adjacent to rock faces, where these meadows remain shaded for longer periods and shadows linger over certain portions of the meadows during morning hours. This factor may become particularly pronounced in the transition from late summer to fall when temperatures in shaded meadows tend to be considerably cooler compared to sunlit areas.

Among the activity types observed, walking, an active activity, emerged as the predominant choice in 2023 sampling. Moreover, a

noteworthy observation was the reduced percentage of stationary activities in Leidig and Cooks meadows and the stability of activity types in El Capitan Meadow when compared to 2011 data. Statistically, there were no differences in proportion of visitors engaged in active versus stationary activities in 2011 compared to 2023. This is likely due to one data value to compare for each of the three meadows, leading to a small sample size for analysis. Moreover, El Capitan had almost the exact same proportion of visitors who engaged in stationary activities in 2011 as in 2023 (63 % versus 68 %), while the proportions were less similar in Leidig and Cooks. The comparisons in visitor activity types in these meadows (El Capitan, Cooks, and Leidig) from 2011 to 2023 were not statistically significant, but the decreased stationary use in Cooks and Leidig does represent a substantial change in use type from the perspective of recreation management.

In comparing between visitor use observed by Walden-Schreiner and Leung (2013) and the present study, there were >3.5 times more visitors per hour and approximately triple the total number of visitors. The increase in visitor use in meadows is particularly notable given that Walden-Schreiner and Leung (2013) sampled primarily during peak visitation (Jul–Aug), while observations made during this study occurred during a peak use month of Aug and continued during the shoulder season. Moreover, Walden-Schreiner and Leung (2013) sampled each meadow for 8 h total, while meadows were sampled for 6 h total in the current study. This study documents substantially more meadow use with fewer total observation hours and with some of those hours occurring during a period (Sep–Oct) of traditionally lower park visitation compared to peak months. It will be important to maintain visitor use activity and impact monitoring programs during these shoulder season months given that already high peak season demand and hazards associated with climate change (e.g., flood, fire, poor air quality) have the potential to displace visitors to other times of the season, other locations in the park, or limit their access entirely (Brown & Jenkins, 2023; Jenkins, 2022; Pröbstl-Haider et al., 2021).

Analyzing activity types across different meadows showed unique patterns for various meadows. El Capitan Meadow had a higher proportion of stationary individuals relative to those participating in active pursuits, likely attributed to climbers and photographers frequenting the area (Walden-Schreiner & Leung, 2013). El Capitan Meadow is situated in a prime location facing the iconic El Capitan rock formation, a magnet for climbers from around the world. Cooks, Leidig, and Sentinel Meadows attracted more bikers per hour relative to other meadows. Well-maintained, paved trails or boardwalks and strategic locations adjacent to and connecting different roads in these meadows allow for easy bike access. Sentinel Meadow also appeared to be a preferred spot for walkers, with the most visitors per hour walking, possibly due to its location connecting roads and multiple meadows (i.e., Cooks and Leidig), access to the Merced River, and captivating scenic vistas (e.g., Yosemite Falls is viewable from this meadow). Many walkers and bikers were observed exiting Cooks and entering Sentinel or vice-versa. Our results suggest visitors often traverse between some meadows (e.g., Cooks, Sentinel, Leidig) to experience attractions on either side, and that official trails may be perceived by users as transportation corridors to destinations outside meadows as opposed to providing access to pursue activities within the meadows themselves (Shafer et al., 2000).

Specific areas, such as those proximal to roadways and parking spaces, appear to be associated with increased visitor activity. These zones, easily accessible and offering picturesque views, emerge as hotspots for certain activities. Meadows like El Capitan and Sentinel facilitate distinctive visitor behaviors. El Capitan Meadow, with its panoramic view of its eponymous rock wall and associated climbers, attracts substantial stationary activities. Past observation of visitors at El Capitan Meadow has shown that, contrary to conventional thinking, visitors tend to disperse (i.e., spread out) less at high use levels and disperse more with fewer other visitors (D'Antonio & Monz, 2016). This pattern indicates that El Capitan Meadow could potentially have increased off-trail use without increasing ecological impacts as long as visitors continue to disperse less (i.e., cluster) at these high use levels and use areas that are already impacted. Other studies that have assessed intra-site use patterns have shown the spatial footprint of visitor activity to be similar across use levels, which may help to explain the observed visitor compliance (73–100 %) with formal trails across meadows in 2023, despite much higher levels of hourly use when compared to 2011 (Sidder & Hall, 2024). In contrast, Sentinel's riverside areas attract visitors due to beaches offering inviting picnic or dipping spots and thus the impact on vegetation and soils in the surrounding areas appears higher as evidenced by a substantial amount of stunted vegetation and barren areas. River access is likely a leading cause for specific social trails in meadows such as Sentinel, Leidig, and Slaughterhouse and careful consideration of providing ample river access points and paths should be considered when deciding on appropriate management actions.

There were distinctive patterns of visitor movement and corresponding degree of environmental impacts across different meadows. There was a prevalent trend of adherence to official trails, likely attributed to well-maintained and physically delineated paths, such as elevated wooden walkways or wooden fences (Marion & Wilkins, 2024; Park et al., 2023). These structures are effective in guiding visitor movement, minimizing direct impact on delicate meadow ecosystems. However, there were also high impacts to vegetation and soils in some meadows and meadow areas, potentially from cumulative seasonal or yearly impacts of long-standing social trails, adjacency to rivers, lack of barriers, lack of signage, or ambiguous distinctions between formal and informal trails. In combination, these factors highlight the necessity for strategic conservation strategies to address the suite of potential causes for meadow impacts from visitation.

Signage can be more effective with graphic design that leverages eye-catching typography and recognizable imagery to capture peoples' attention and may be designed with educational messaging in mind to encourage informed compliance as opposed to prohibitive messaging that restricts use without explanation (D'Antonio & Monz, 2016; Duncan & Martin, 2002; Rice et al., 2023). The high rates of observed formal trail compliance may be due to several factors, including effective signage in previously identified high use areas, more active use by visitors transiting through the meadows, and the use of paved trails and boardwalks, which are purposefully more durable, and provide a strong cue to be utilized. Sanctioning of some of the perennially unpaved social trails, like those that provide river access and closures of others could help to concentrate use where impacts are already occurring and thereby reduce the extent of disturbance and social trails across meadows overall (Marion et al., 2011; Marion & Wilkins, 2024; Svadja et al., 2013). Additionally, the spatial distribution of informal trails can inform the need for location of formal trails, as visitors "vote with their feet" (Marion, 2014; Marion & Wilkins, 2024; Wimpey & Marion, 2011).

Yet, there are risks with unofficial trails, where paths, possibly perceived as official, invite unintended trespasses, further impacting meadows (Schwartz et al., 2018). For instance, in Sentinel Meadow, there are informal trails stemming from the east and west of the official boardwalk in the middle of the meadow. To the east, the informal trail also has official signage, indicating that it has been formalized by resource managers, but the trail to the west does not, rendering this segment ambiguous for visitors. Additionally, the official trail is also not well-marked in Slaughterhouse A sub-meadow and formal and informal trails are indistinguishable in this meadow. We observed one visitor traversing an informal trail across sub-meadows in Slaughterhouse. Lack of official signage and distinction between formal versus informal trails is confusing for visitors and National Park Service staff alike in determining which paths are acceptable to tread and which are to be avoided, or discouraged from use (Goh, 2020). Moreover, some visitors may prefer to have a range of trail types available including paved and non-paved paths (De Valck et al., 2017), such that visitors seeking out less established trail surfaces may gravitate towards these trails which appear to be in a more natural state, and associated with less crowds

among other attributes that implicitly inform visitor behavior (Sever & Verbič, 2018).

The introduction of physical barriers might be an unavoidable necessity for certain areas and are generally more effective with signage that communicates access restrictions (Park et al., 2008). Such barriers serve dual purposes: aiding the restoration of areas that have endured significant wear and ensuring that visitors remain on well-maintained paths, thereby limiting further impacts (Hockett et al., 2017). A network of formal trails provides clear demarcation between official trails and the actual meadow, guiding visitors effectively and reducing unintended trespassing into sensitive areas and the negative impacts of trampling, thereby limiting widespread degradation that would otherwise occur with a less structured pattern of visitor activity (Svadja et al., 2016). This strategy has been employed effectively for several meadows in Yosemite Valley already, such as Bridalveil and Leidig, and could be considered further for meadows showing continual and extensive impacts.

Additionally, there are some caveats for the visitor observation portion of this study. We did not observe people using all mapped social trails and this may be explained by several reasons, such as, disturbed areas and vegetation impacts to trails generally take years to recover and thus informal trails persist from season to season, regardless of use in the current year (Marion et al., 2016). Also, this study was limited to a maximum of six observation hours per meadow. It is likely that with more observation hours, visitors would be observed on some of the lesser used social trails; however, the current study design identifies the most predominantly used trails. Previous research on social trails has shown that even with relatively few passes along a social trail, signs of use can persist for long periods of time (Cole, 2019).

### 4.2. Informal trail disturbance

During the period from 2004 to 2023, informal trail length only increased in Slaughterhouse B sub-meadow. Trends in cover classes for informal trails (i.e., stunted vegetation, some bare ground, or barren) were also not significant for most cover types and meadow areas. Notably, some bare ground from informal trails increased in Slaughterhouse B, which was coupled with significant increases in informal trail length in this sub-meadow from 2011 to 2023. Although trends across the entire studied period (2004–2023) showed decreased informal trail length in El Capitan Meadow. Additionally, there were four meadows or sub-meadows (Cooks C, El Capitan, Sentinel B and Slaughterhouse B) where the 2023 informal trail length was above the 2004–2023 mean. Some of these results may be attributed to the decreased visitation during reservation system pilots during 2020–2022, with higher visitation in 2023 causing an uptick in social trailing; however, given that two of these meadow areas showed significant decreases in the context of the larger temporal scale, it is worth considering how management has changed in these areas and if there are additional management actions that can be taken to maintain the decreasing trend in informal trail length since 2004. The period of 2019–2023 is the most realistic for expectations of social trail impacts during periods of managed access given the reservation system pilots that were in place between those years.

From 2004 to 2023, disturbed area increased in five valley meadow areas (Cooks A, Sentinel A, Slaughterhouse B, Stoneman A, and Stoneman B), yet informal trail length did not increase during this time in these meadows. This suggests that perennial social trails serve as conduits for visitors to areas that may be disturbed, and thereby have cumulative impacts despite not increasing in length. In addition, in 2023, informal trail length was lower than the 2004–2023 mean for 9 of 13 valley meadow areas, but disturbed area was higher than the 2004–2023 mean for 10 of 13 valley meadow areas. This indicates that though informal trail lengths may be showing reduced impacts in these meadows (i.e., due to being lower than the mean value), disturbed areas showed increased impacts. While some of the disturbed area mapped in meadows can be attributed to human causes, in some cases drainage and hydrological patterns, restoration efforts, or other factors contribute to the amount of disturbed area mapped. The winter of 2022–2023 was particularly wet and consequently, many meadows were flooded during the spring of 2023, while standing water dried down by the time of sampling in August–October 2023. In addition, current (e.g., Ahwahnee) or past (e.g., Leidig or Stoneman) restoration work in some meadows may influence the amount of disturbed area. Future management actions for revegetation of meadow systems may consider focusing on protecting existing priority restoration areas and preventing further increases in disturbed area, when it can be attributed to anthropogenic causes, in these meadows (Rochefort & Gibbons, 1992).

Disturbed area associated with multiple cover types is of special concern for park managers as it indicates potential for further proliferation of social trails and associated impacts. Moreover, trends in cover classes (i.e., stunted vegetation, some bare ground, or barren) of disturbed areas increased in six of 13 valley meadow areas (e.g., Ahwahnee, Cooks A, El Capitan, Sentinel A, Slaughterhouse A, and Stoneman B). Most of these increases were associated with impact classes indicative of better condition (i.e., stunted vegetation or some bare ground) rather than barren areas. To prevent further disturbance and reduce current disturbance in these meadows, recreational land managers could consider taking actions such as installation of fencing, signage and/or restoration, dependent upon real-world constraints.

Informal trail length has been relatively stable since 2004 for most meadow areas (>90 %), while disturbed area increased in 40 % of Yosemite Valley meadows or sub-meadows. Yet, some meadows experienced more variability and had a wider range of informal trail length from 2004 to 2023 than others. For example, informal trail length in both Ahwahnee and Bridalveil has varied from less than 400 m to greater than 1500m during the study period, while in sub-meadows such as Sentinel B or Stoneman A, length has varied from less than 100 m to greater than 350 m. While there may not be statistical trends of note in meadows such as Ahwahnee or Bridalveil from 2004 to 2023, from an ecological and resource managerial context of impacts, 1500 m may be less acceptable in an ecological or management sense than shorter informal trail lengths. However, the threshold informal trail length for an ecological limit of acceptable change is likely different from what is deemed socially acceptable, or desirable, by a range of visitors with different experience, activity types, access needs and knowledge of impacts (Cahill et al., 2008; Floyd et al., 1997). Holmquist (2004) observed that social trails negatively influence higher trophic levels to an approximate distance of 5 m from the trail. Many of the meadow or sub-meadow areas in this study had approximately 20 % of their total area impacted by informal trails with one sub-meadow exhibiting 40 % impacted area. In addition to gauging and responding to trends in proliferation of informal trails and disturbed areas from season-to-season and across longer temporal scales, managers can also address impacts associated with persistently high visitation by using tools such as setting triggers and targets for management action based on the amount of impacted area (Cahill et al., 2008; Marion & Wilkins, 2024).

Consideration of meadow locational context and combined results from multiple facets of analyses in this study highlights specific meadows as targets of management action. For instance, significantly increased informal trail length in Slaughterhouse B and increased cover of some bare ground indicate worsening conditions over time. Our results can inform potential management action to prevent further disturbance to soils and vegetation from trampling, reduce habitat impacts, and inform restoration efforts for eventual recovery of vegetation at high impact locations, which may differ from year-to-year based on visitor use and hydrology (Kuss & Graefe, 1985). Several factors could explain recent increases in disturbed area in this meadow including shifting meadow hydrology, drainage patterns, and changing use as a result (Cooper & Wolf, 2006). It is likely that some of the more solidified social trails are channelized from culvert water outflow in the winter and spring while other adjacent trails exist to get around the 'legacy'

social trails that are now effectively an outflow channel to the seasonal pond (i.e., Woskys Pond in Slaughterhouse Meadow). Impacts to soil and vegetation typically vary by season with the per person impact from trampling being highest when soil and vegetation are wetter, and lower per person impacts when conditions are drier (Kuss & Graefe, 1985). Thus soil and vegetation recovery efforts should incorporate differences in seasonal climate and the timing and volume of visitors when assessing impacts, as well as spatial proximity to roads and other access points when anticipating future disturbances (Barros et al., 2020; Wolf & Croft, 2014).

While some of the increased disturbed area in Slaughterhouse Meadow is likely attributed to changing patterns in hydrology, there has also been an increase in informal trail length in this meadow since informal trail monitoring started in 2004 and informal trail length increased from 158 m–1026 m between 2018 and 2023. We did not observe a high volume of visitors in Slaughterhouse Meadow; however the primary Yosemite Valley trail (Valley Loop) is adjacent to Slaughterhouse B and provides access to a popular location for recreational use (i.e., Devil's Elbow), which may encourage some users to traverse the meadow instead of staying on the road-adjacent trail. The Valley Loop trail also bisects Slaughterhouse A and the substrate of the official (i.e., sanctioned), yet unmarked, trail is barren ground, virtually indistinguishable from social trails that bisect other portions of the meadow. While Slaughterhouse Meadow may not be the highest management priority for intervention when comparing level of visitor use to other meadows, it provides an ideal example demonstrating the complexity of interactions among visitors and types of impacts, while also indicating that relatively few visitors can cause a disproportionate amount of impacts to sensitive habitats (Cole, 2019).

### *4.3. Management considerations*

Spatial data on informal trails and visitor use within sensitive habitats, such as meadows, can assist recreational land managers in determining the extent and condition of existing impacts and identifying locations that are particularly susceptible to visitor use. Synthesizing multiple sources of data may be necessary to determine how visitors are recreating within a sensitive area (e.g., active versus stationary), type of disturbance (e.g., linear informal trail versus disturbed area), and driver of disturbance (e.g., anthropogenic versus natural), where possible. Standardizing monitoring protocols and data collection techniques so that they are replicable from year-to-year is critical to minimize potential inconsistencies between measures and mappers, to reduce uncertainty about trends, and to take informed management actions that are responsive to changing resource conditions. Consistent monitoring and data collection can help in linking trends in resource impacts with patterns of informal trail use and drivers of disturbance for sensitive habitats, which is crucial for informed management decisions of protected areas.

## CRediT authorship contribution statement

**Sheri A. Shiflett:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Jeffrey S. Jenkins:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Rachel F. Mattos:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Kai Thiry:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Peter C. Ibsen:** Writing – review & editing, Formal analysis. **Melissa Booher:** Writing – review & editing, Validation, Data curation. **Angela Tricomi:** Writing – review & editing, Validation, Data curation. **Nicole D. Athearn:** Writing – review & editing, Conceptualization.

## Management implications

- Greater active use and less stationary activity in meadows suggests visitors are increasingly utilizing meadows as transitory zones between destinations.
- A range of trail types (paved, non-paved, boardwalk) and access points within meadows and nearby river features can provide access for visitors with different capabilities and preferred experiences.
- Near riverine social trails, which appear official, are particularly impactful given the opportunities they present for water access and the susceptibility of riverbanks to erosion. Signage and fencing can be effective tools to clarify whether trails are official and appropriate for public use; however, recreation managers could also consider formalizing well-used social trails and a subset of river access points.
- Consideration of meadow locational context and combined results from multiple facets of analyses in this study highlight specific meadows as targets of tailored management action based on types of recreational use and impacts.

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## Declaration of competing interest

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jort.2025.100896.

## Data availability

Data will be made available on request.

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