Forest Ecology and Management 603 (2026) 123385

Contents lists available at ScienceDirect

Forest Ecology and Management

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

# Mapping disturbance in California's rapidly changing National Forests

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ARTICLE INFO

Dataset link: Disturbance_raster_maker

*Keywords:*
Change detection
Drought
FACTS
Fuels management
Fuel reduction
Fuel treatment

ABSTRACT

Disturbances shape assemblages and spatial patterns of flora and fauna across the globe, with many disturbances increasing in severity and extent because of anthropogenic climate change and changes in land use. Accurate disturbance mapping and attribution can aid conservation science and decision-making in this era of rapid environmental change, but doing so remains challenging at fine resolutions and broad spatial scales. Here we demonstrate a novel approach for integrating remote sensing products with the US Forest Service's (USFS) Forest Activity Tracking System (FACTS) to map forest change and attribute those changes to wildfire, fuels management, and drought/other disturbance across 34,000 km$^2$ of USFS lands in the Sierra Nevada and Southern California (2003–2022). We compared FACTS fuels management areas with annual remote sensing derived estimates of canopy loss (Mortality Magnitude Index (MMI) in the eDaRT system for Landsat processing) to develop FACTS querying filters that accounted for nearly all fuels management detected by eDaRT. We overlaid these data with fire severity (composite burn index) and drought/other (MMI) to attribute annual forest canopy change to these three primary disturbance agents and found 74 % of the area disturbed. Of the 25,000 km$^2$ that experienced disturbance, wildfire dominated (69 %), followed by drought/other mortality (51 %), and fuels management (14 %; including prescribed fire), with overlap among categories. These results underscore recent widespread disturbance and the possible transformation of California forests and biodiversity. The accompanying disturbance dataset and code provide new and potentially powerful opportunities for scientists and managers studying and stewarding these rapidly changing ecosystems.

## 1. Introduction

Understanding the drivers of environmental change can facilitate appropriate and effective management interventions. In forest ecosystems, a multitude of disturbances can cause changes to forest structure and composition, result in tree death, and reset forest succession (Pickett and White, 1985, Turner, 2010). Natural and anthropogenic disturbances such as wildfire (Bond and Keeley, 2005), drought-induced tree mortality (Allen et al., 2010), insect outbreaks (Raffa et al., 2015), windfall (Baumann et al., 2014), tree harvesting (Kittredge Jr, Finley, and Foster, 2003) and grazing (Öllerer et al., 2019) can all influence forest dynamics. Forest managers intent on guiding the conservation of particular forest characteristics must understand how these disturbances interact to influence change, and incorporate such knowledge into management prescriptions (Leverkus et al., 2021). As the frequency, size, and intensity of disturbances and their interactions accelerate in many forest systems (Burton, Jentsch, and Walker, 2020), managers must also understand the nature and distribution of changing disturbances to optimize conservation decisions. Furthermore, financial investments by government or private entities supporting management activities are contingent upon accurate reporting thereof, such that subsequent work is appropriately allocated based on actual work accomplishments.

Despite the importance of understanding disturbance processes, detecting and accurately delineating the spatial and temporal boundaries of disturbances is challenging (Stahl et al., 2023). Some disturbances, such as wildfire, can be discrete in space (have clear boundaries) and abrupt (have clear start and end dates). Other disturbances, like

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https://doi.org/10.1016/j.foreco.2025.123385
Received 2 July 2025; Received in revised form 21 October 2025; Accepted 25 November 2025
Available online 6 December 2025

drought-induced tree mortality, are more gradual in nature, having less clear spatial footprints and start and end dates (Asner et al., 2015, Parry et al., 2016, Diaz et al., 2020). Discrete disturbances are relatively straightforward to map; gradual disturbances are not. Hidden subcanopy disturbances, such as surface fire or understory mechanical thinning, also challenge change detection (Jarron et al., 2020, Gao et al., 2020). Moreover, discrete and gradual canopy and subcanopy disturbances can interact in space and over time, creating a complex challenge in terms of attributing which factor was responsible for producing landscape change. Wildfire can occur within the context of an ongoing drought (Crockett and Westerling, 2018), and insect outbreaks can precede wildfires and influence their behavior (Wayman and Safford, 2021). The increasing likelihood of disturbance interactions and the task of accurate disturbance mapping challenge managers' ability to understand and respond appropriately to landscape change and quantify disturbance impacts to sensitive species and biodiversity.

In western United States forests, wildfire is the dominant driver of landscape change and, as such, robust monitoring systems exist to track fire occurrence and severity (Eidenshink et al., 2007). Existing evidence, based on monitoring data produced by such systems, suggests that rapidly changing fire regimes have begun transforming western US forests (Coop et al., 2020, Parks and Abatzoglou, 2020, Hagmann et al., 2021). However, other forms of forest disturbance are becoming increasingly common and/or severe and are typically more difficult to map with high precision. Drought-induced tree mortality has increased in western US forests in recent years (Williams et al., 2015, Crockett and Westerling, 2018, USDA Forest Service, 2025a), but drought plays out over years, and sometimes trees do not die until after the drought has concluded (Young et al., 2017), challenging attribution. Although fuels management such as understory mastication, forest thinning, and other restoration projects regularly occur on USFS land, the pace and scale of this management needs to increase to mitigate fire and drought effects (North et al., 2015, Stephens et al., 2013). The US Forest Service maintains the Forest Activity Tracking System (FACTS), one of the largest databases describing fuels management projects (USDA Forest Service, 2025b). However, this system is error-prone and incomplete, with sometimes poorly delineated boundaries, blank data fields, and potential overreporting (Knight et al., 2022), and as such has not been widely utilized to understand the drivers of forest change. Data-driven forest management would critically benefit from an improved understanding of the relative and absolute influences of fire, fuels management, and drought on western US forest change, as well as the spatial and temporal distribution of these drivers.

Here, we present a novel approach for attributing forest disturbance to three major causal types (defined below in Section 2): wildfire, fuels management, and drought/other disturbance. Our approach is based on combining FACTS information with two previously existing datasets derived from satellite remote sensing at a Landsat 30 m scale, including burn severity represented by the composite burn index (CBI; (Key and Benson, 2006)) estimated with a Random Forest model (Parks et al., 2019), and disturbance event history data from the Ecosystem Disturbance and Recovery Tracker (eDaRT; (Koltunov et al., 2020, Slaton et al., 2025)), including disturbance onset timing and magnitude. Specifically, we 1) assessed the temporal and spatial alignment of FACTS fuels management polygons (including prescribed fire) with remotely sensed canopy cover loss across the northern portion of California's Sierra Nevada, and 2) compiled wildfire, fuels management, and drought/other disturbance into annual disturbance datasets across a 20-year period for California's Sierra Nevada and Southern California bioregions over the period 2003–2022. Our research questions included: 1) What is the spatial and temporal accuracy of the FACTS database without modification and what adjustments can increase that accuracy? 2) How sensitive are annual estimates of fuels management using different methods of summarizing FACTS entries with blank completion dates, and 3) what is the relative magnitude and spatial pattern of each disturbance type across 20 years, as well as their annual magnitude? Our rigorous accuracy assessment of fuels management activities can enable land managers to more confidently report accomplishments. The codebase and the geospatial dataset are made freely available to managers and scientists to refine, update, and expand to new areas, as needed. Our method and code for disturbance type attribution can serve as a much needed and repeatable approach to compare the relative proportions of the drivers of ecosystem change over time in National Forests and will facilitate forest planning, biodiversity conservation, and new scientific advances.

## 2. Methods

### 2.1. Overview

Our methods consisted of the following major steps: 1) extract potential fuels management information from the FACTS database, 2) use established methods to estimate wildfire severity and an existing dataset to estimate canopy cover loss, 3) test for spatial and temporal alignment of the FACTS fuels management dataset with areas of clustered and substantial canopy cover loss, 4) compile major disturbance types (wildfire, fuels management, and drought/other disturbances) into an annual 30 m raster product, testing two methods of interpreting/incorporating the fuels management data in maximum and minimum disturbance scenarios, and 5) compare the annual trends and total disturbance across the Sierra Nevada and Southern California study areas.

### 2.2. Study area

The study areas were limited to USFS land and encompassed 19,871 km$^2$ in the Sierra Nevada and 14,045 km$^2$ in Southern California (Fig. 1). The climate is Mediterranean with warm, dry summers and cool, wet winters and elevations ranging from 226 to 3972 m in the Sierra Nevada and 102–3504 m in Southern California. The Sierra Nevada is primarily forested, including Sierra mixed conifer, subalpine forests, and oak woodlands, as well as non-forest areas including wet


**Fig. 1.** General locations of the Sierra Nevada and Southern California study areas. The northern 8-county area (used for FACTS validation) and US Forest Service (USFS) ownership are also shown. Analyses were performed only on USFS owned land to ensure data on fuels management existed. Map hillshade and basemap: Earthstar Geographics, Esri, and USGS.

meadows, shrub fields, and rocky areas. The Southern California study area is more sparsely forested and is primarily characterized by oak woodland and chaparral shrub fields. Because fuels management data were only available for USFS-owned lands, the study areas conformed to these ownership boundaries and were sometimes a checkerboard pattern. The study landscape is primarily influenced by three disturbance types: a) wildfires of different sizes and severities, b) fuels management efforts by the USFS, and c) drought that spiked at different times in the northern and southern Sierra Nevada as well as in Southern California.

### 2.3. FACTS fuels management data processing

The FACTS database (available online; (USDA Forest Service, 2025b)) provides nationwide data on activities related to fire, fuels, silviculture, and invasive species on USFS lands from as early as the 1850s up to the present, as well as treatments that are planned but not yet implemented. This database of spatially explicit polygons includes 113 attributes for each treatment polygon including treatment type, method, equipment used, award and completion date, funding information, project name, and National Environmental Policy Act (NEPA) details. Note that the polygons are typically hand-delineated using background imagery and maps, and often by managers who are not necessarily trained in spatial analysis. Previous work (Knight et al., 2022) found potential over-reporting of FACTS when comparing it with Landsat remote sensing data processed with the Continuous Change Detection and Classification algorithm (Zhu and Woodcock, 2014, Zhu et al., 2020) for the purpose of more accurately accounting for the area with fuels management across time. However, that analysis did not deeply explore temporal accuracy or potential omissions. Although this information-rich database could be a goldmine for researchers, FACTS has not been widely used in forest or biodiversity science, in part because of missing data and uncertainty around the spatial and temporal accuracy of the records. The FACTS database is used extensively by the USFS for reporting, however, emphasizing the importance of thorough assessment and data validation.

Although we were only interested in mapping fuels management implemented on the ground during 2003–2023, these activities can take over a decade to be completed. Therefore, to avoid ignoring potentially relevant records in FACTS, we analyzed treatments awarded since 1980 in the study area with one of 97 activities representing fuels management (of 483 possible activity types). These fuels management activities included prescribed fire, mechanical, and manual fuels reduction, and excluded wildfire and non-fuels management activities like planting or surveys as well as low-impact and spatially broad activities like Christmas tree harvests (personal communication, S. Coppeto and T. Moore; see Supplementary Table 1 for full list of the 97 activity codes used).

### 2.4. Wildfire severity and disturbance history analyses

We mapped wildfire severity for the Sierra Nevada and Southern California study regions from 2000 to 2022. We used the Random Forest model developed by Parks et al. (2019) within Google Earth Engine (Gorelick et al., 2017) to estimate a field-based metric of fire severity, the Composite Burn Index (CBI), at a 30 m resolution. CBI characterizes the effects of fire on soils and vegetation on a continuous scale from 0 to 3 (unburned/unchanged to high-severity; (Key and Benson, 2006)) and is modeled by Parks et al. (2019) as a function of several pre- and post-fire Landsat spectral indices, climate, and latitude. Following Cova et al. (2023), we applied the Parks et al. (2019) model to predict CBI within wildfire perimeters ≥ 4 ha obtained from the California Department of Forestry and Fire Protection's (CAL FIRE's) Fire and Resource Assessment Program's historical fire perimeters geodatabase (CAL FIRE, 2024).

The California vegetation disturbance history dataset used in this study was developed using the Ecosystem Disturbance and Recovery Tracker (eDaRT) system version 2.32, a mature Landsat processing system that utilizes dense (8–16 days apart) Landsat observations at a 30 m scale and a suite of advanced models to detect disturbance event onset timing and quantify the resulting vegetation cover loss (Koltunov et al., 2020). These outputs, available in a tiled raster format, have demonstrated high accuracy in California ecosystems, including the ability to detect subtle changes on the ground (Koltunov et al., 2020; Slaton et al., 2025). In this work, the eDaRT processing was limited to the period of May–November each year, which the system uses as a trade-off between the temporal accuracy of event detection and the product robustness with respect to Landsat observations frequently contaminated with clouds and snow.

For detected disturbance events, the canopy cover loss (as a percentage of the 30 m pixel area) is estimated in eDaRT using the Mortality Magnitude Index (MMI; (Slaton et al., 2025)). The canopy loss is computed in eDaRT on an annual basis with an RMSE of 13 % (Slaton et al., 2025). The MMI value at a pixel in a given year represents the canopy cover loss resulting from the disturbance event that started in that year; however to estimate the canopy loss, the MMI algorithm integrates and compares spectral data over temporal windows that may span more than one year, depending on the season and availability of clear view Landsat observations. Importantly, although the MMI model was calibrated to best represent live tree canopy loss resulting from tree mortality, the MMI values are computed for all disturbances detected. Therefore, in the absence of a disturbance type attribution capability in the current version of eDaRT, a given MMI value at a pixel could represent a variety of causes, including wildfire, fuels management, drought, disease, insect damage, windthrow, canopy water stress, and other disturbances. While all of these disturbances occurred in the study area, widespread and severe drought impacts were documented in California, especially during 2012–2015, followed by subsequent insect and disease damage (Moore et al., 2018, USDA Forest Service, 2025a, Asner et al., 2015).

We will therefore refer to all disturbance causes other than wildfire and fuels management as *drought/other*, with the assumption that most of these were caused by drought either directly or indirectly (e.g., insect and disease following/accompanying drought stress) and resulted in an observable loss of live tree canopy cover. We narrowed the definition of class drought/other to only include pixels with MMI ≥ 10 % because our intent was to analyze stand-level disturbance rather than loss of individual or relatively small numbers of trees that may be attributed to background population turnover. In view of the previously reported information about the very high accuracy of the 0–10 % MMI bin (Slaton et al., 2025), pixels in that category could reasonably be assumed to represent low-level canopy loss rather than stand-wide mortality related to drought or other causes relevant to the current analysis. Pixels were also excluded from the drought/other class (and thus considered undisturbed or insignificantly disturbed) in cases where 1) the MMI could not be computed in the eDaRT algorithm (e.g., too few clear images were available before the disturbance); or 2) the pixel was burned in that or the previous 3 years (i.e., had a categorized CBI score of 0–3; essentially any pixel that fell within a wildfire polygon), and thus would likely be influenced by secondary fire effects, superseding drought, and not need to be further analyzed using MMI. Tiled MMI rasters were mosaicked and snapped to align with a tile in the center of each study area (Sierra Nevada or Southern California) by taking the maximum MMI value of each pixel in the areas where they overlapped.

### 2.5. FACTS temporal and spatial accuracy assessment

We first developed a reference dataset to compare against FACTS fuels management polygons. Although no dataset perfectly represented fuels management, clustered areas of high canopy loss within fuels management polygons should be reliable indicators of fuels management and can therefore be used to assess the temporal accuracy of the polygons. We also visually examined clusters outside fuels management polygons to assess their cause and inform our spatial accuracy assessment. Based on existing information about the history of substantial fuels management and relatively few areas of intense drought-related tree mortality in the northern portion of the study area (Moore et al., 2018), we assumed that after masking out wildfires, the remaining spatially clustered regions of substantial canopy loss that overlapped FACTS fuels management polygons in space and relative time would primarily represent fuels management and clusters that did not overlap fuels management polygons would have a lower prevalence of drought or other disturbance in the northern portion of our study area, allowing us to better focus this visual assessment on fuels management that was poorly documented/undocumented in FACTS. We therefore performed these analyses for the northern 30 % of the Sierra Nevada study area only (covering 9636 $km^2$ of the following counties: Butte, Lassen, Nevada, Plumas, Shasta, Sierra, Tehama, and Yuba; Fig. 1). Our reference dataset delineated spatially clustered areas of high canopy change, henceforth referred to as HCC clusters. To generate the HCC clusters, we first identified pixels with high canopy change neighborhoods defined as $5 \times 5$ pixel windows where at least 60 % of pixels had MMI $>$ 20 %. These relatively high thresholds ensured that extraneous noise, drought, or other causes of canopy loss in the MMI layers was eliminated and that most HCC clusters visually aligned with existing fuels management apparent in the NAIP aerial imagery (areas similar to those shown in Supplementary Fig. 2). This ensured that the HCC clusters were capturing areas of obvious canopy cover change for this test. Finally, we merged these high canopy change neighborhood pixels that were orthogonally contiguous into patches and removed any patches $<$ 0.9 ha (10 pixels) in area.

Temporal inaccuracy in the FACTS data included errors in entered completion dates, missing completion dates, and activities that took multiple years to complete. To assess the temporal accuracy of FACTS fuels management data, we compared the area where HCC clusters overlapped FACTS fuels management polygons, annually, from five years before to five years after the reported FACTS completion year (e.g., activity date). We thus compared HCC clusters from 2004 to 2022 that overlapped completion years from 2009 to 2017 (254 $km^2$). We then examined the distribution of these overlaps in relation to the completion year to determine a temporal window that captured the majority of this change. The temporal window was then used to guide further analyses and to delineate fuels management pixels in our ultimate disturbance dataset. Importantly, the MMI dataset and resulting HCC clusters captured change between growing seasons and thus were not a perfect match to FACTS reported years. Thus, the temporal "accuracy" of FACTS should account for both cases where the HCC cluster occurred in the year of and the year after the reported FACTS completion.

Spatial inaccuracy of FACTS polygons could be due to poor manual digitizing or operations not adhering to planned boundaries. To assess the spatial accuracy of FACTS fuels management polygons and other fuels management activities (e.g., unreported/poorly-dated USFS fuels management or activities on private land that might have extended into USFS ownership), we first deleted any high change area that overlapped a FACTS fuels management polygon with a completion date between one year before and two years after the year of change (based on the results from the analyses described in the previous paragraph). We then visually examined 1 m NAIP imagery where HCC clusters did not overlap with probable FACTS fuels management for the years 2013, 2015, and 2017 (using NAIP from 2012, 2014, 2016, and 2018 to compare changes from before and after the year of supposed change). We then classified the cluster's disturbance type as 1) edge, 2) drought/other, 3) open (i.e., non-forest), 4) wildfire, or 5) fuels management, with some classes composed of multiple subcategories for a more detailed breakdown. The HCC cluster was classified as edge when it appeared to be a fuels management activity that extended from either a) an edge with non-USFS ownership or b) the edge of a FACTS polygon, indicating inaccurate treatment boundary mapping. The HCC cluster was classified as a) confirmed drought/other when red stage or needle drop was visible in the NAIP at the site of the HCC cluster or b) presumed drought/other when no disturbance was visible in the NAIP. These two subcategories were both considered to be drought/other. We classified areas as open when the area appeared to be grass, shrub, or rock in the NAIP. Although eDaRT does detect disturbances in non-forest areas, MMI is specifically calibrated for tree canopy cover loss. Because these regions had relatively few open areas, we assumed that errors resulting from these in the final dataset would be negligible, but still wanted to test this assumption. While recently burned areas should have been eliminated from potential HCC clusters, wildfire perimeters were not always accurately mapped, and were included as a category in our classification after we noticed a few instances in the dataset where wildfire extended beyond the mapped boundaries. Finally, if the NAIP showed fuels management where there was no FACTS record (within the two years before to one year after temporal window), we noted whether it was a) shrub mastication or b) forest management. When fuels management occurred, it was often obvious, with even canopy reduction (e.g., trees removed at even intervals throughout an area), skid trails, and piled/burned fuels visible. There were often also clear boundaries to these areas (e.g., clearly bordered a road or property boundary or had straight edges). Although it is possible that some areas classified as presumed drought/other could have been lower intensity fuels management that was unobservable in the NAIP, our methods that focused on HCC clusters representing substantial canopy cover loss helped reduce these potential errors. We also visually examined the spatial accuracy around boundaries of both USFS ownership and FACTS fuels management polygons to anecdotally determine whether any additional spatial inaccuracies were present that were not captured by the HCC clusters. Finally, we performed an additional exploratory analysis to gain insight into an appropriate timeframe and method for fuels management polygons with missing completion dates in the FACTS database (Supplementary Material).

### 2.6. Annual disturbance compilation and assessment

For each disturbance cause class (wildfire, fuels management, and drought/other), we developed annual maps in raster format across 20 years for the Sierra Nevada and Southern California and used these maps to summarize the disturbance history in the area. Note that because the FACTS database only included USFS fuels management activities, we were only able to map disturbance on USFS land. When mapping the above disturbance classes, wildfire took precedence (i.e., we assigned any burned pixel to the class "wildfire," even if that pixel also underwent fuels management or drought/other), assuming that the primary disturbance agent in that pixel in that year was wildfire. Next, we mapped the class "fuels management," and finally we mapped the class "drought/other" to the remaining unclassified pixels that met the criteria for drought/other (see the following paragraphs for detailed descriptions of each disturbance class criterion).

Importantly, a given disturbance in the output datasets spanned four years to capture either a) the duration of the disturbance, or b) the temporal uncertainty of the disturbance, explicitly for fuels management. This manifested as either a) an extension of the disturbance duration after wildfire and drought/other to account for secondary effects or a prolonged period of drought, or b) a temporal envelope around fuels management dates to account for both the temporal uncertainty associated with FACTS reporting and fuels management activities that were implemented across multiple years. See the following paragraphs for specific justification for using the four-year span for each disturbance type. Note that integrating the disturbances this way inherently underpredicted drought when it was close temporally and spatially to either other disturbance type (and underpredicted fuels management when it was spatially and temporally close to wildfire). For example, fuels management is often implemented shortly after intense drought-related tree mortality, meaning that the drought disturbance type would be missed. Similarly, fuels management in the form of salvage logging or other activities also closely follows wildfire (see Supplementary Fig. 4 for an exploration of the magnitude of this difference in classifying these areas as wildfire versus fuels management). Because the span was four years for all three disturbance types, we assumed that the relative magnitude of the different disturbance types would be comparable in any given year, or overall, and that the potential omission of subsequent disturbances during the four-year post-disturbance period would not significantly affect relative comparisons of the total area for the mapped classes across time.

We categorized the severity of burned pixels using the CBI scores described in Section 2.3, where pixels with CBI $\geq$ 2.25 were classified as high severity wildfire, and pixels with CBI 0–2.25 were classified as low/moderate severity (Miller and Thode, 2007). Note that while a CBI score of 0 equates to unburned/very low severity areas within a wildfire perimeter, we wanted to err on the side of caution and attribute any potential disturbance within these areas to wildfire as opposed to other factors (like fuels management or drought). Secondary fire effects after the year of the wildfire (e.g., delayed tree mortality due to injury from the fire) extended for up to 6 years post-fire in our study system (Van Mantgem et al., 2011), but most (70–88 %) mortality occurred within 2 years after fire and leveled off after 3 years (Hood, Smith, and Cluck, 2010). We further tested this by monitoring areas burned at different severities in 2003 and calculating the mean MMI in each year thereafter up to 20 years, filtering out any areas that subsequently burned or where fuels management occurred (Supplementary Fig. 3). In order to account for the majority of secondary fire effects without excluding subsequent disturbances, we assigned a four-year duration of any burned pixel (the year of the fire plus the following three years) of a given severity class. For instance, a pixel that burned at high severity in 2010 was classified as high severity in 2010–2013. We acknowledge that this may have masked the effects of post-fire fuels management such as salvage logging, and have distinguished between post-fire areas, fuels management after fire, and salvage logging activities after fire in our final publicly available dataset so that these effects can be explored more thoroughly in the future.

Results from the analysis of temporal uncertainty for FACTS-reported fuels management supported implementing a four-year envelope, with the vast majority of HCC clusters within FACTS polygons occurring between two years before to one year after the reported completion date, when it existed. Because of the remaining uncertainty about the potential errors of omission or commission associated with fuels management with blank completion dates, we calculated each

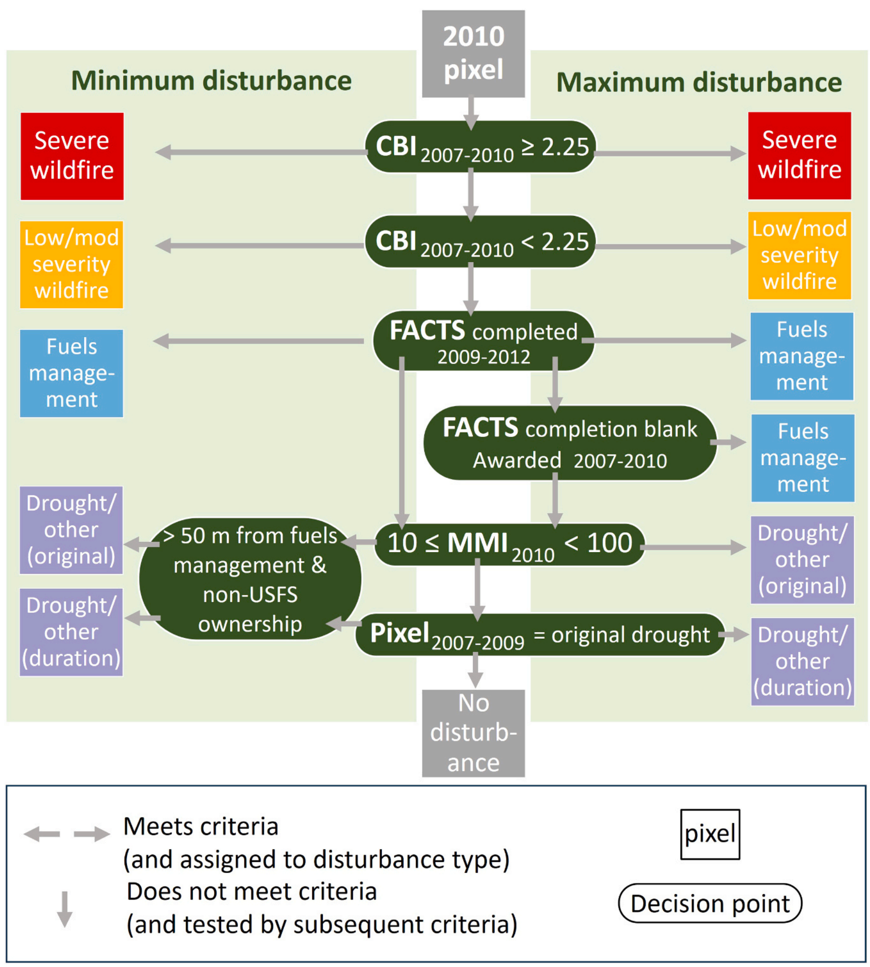


**Fig. 2.** Decision tree for determining the disturbance type of an example pixel in 2010 under the minimum (only FACTS polygons with completion dates) and maximum (incorporating FACTS polygons without completion dates based on the year they were awarded) disturbance scenarios (light green boxes), based on the input data. The three main input datasets include the annual composite burn index (CBI), FACTS, and the Mortality Magnitude Index (MMI). The unclassified pixel at the top is tested by a series of decision points (dark green ovals). If the pixel satisfies the condition of the decision point, the classification follows the arrows left and/or right (pertaining to the minimum and maximum disturbance scenarios, respectively) and the pixel is classified as the disturbance type in the square box. Otherwise, the pixel continues down the decision tree to be tested by subsequent decision points. If none of the criteria are met, the pixel is classified as having no disturbance in the given year. Note that vertical arrows in the middle denote tests for both disturbance scenarios, while arrows within the light green boxes are specific to the given disturbance scenario. Although drought/other is ultimately not classified into "original" (pertaining to drought/other in the given year) and "duration" (pertaining to pixels classified as "original" drought/other in the preceding three years), we included those terms here to clarify the workflow.

disturbance type based on a maximum and minimum disturbance scenario (Fig. 2). The minimum disturbance scenario only used fuels management polygons with a completion date (using the duration of two years before to one year after the completion date; Fig. 2). Conversely, in the maximum disturbance scenario, we used fuels management polygons regardless of whether a completion date was entered in the FACTS database. When the completion date field was blank, we used a temporal range from the year of the award (the most recent year of the two fields: "award date" and "date awarded") to three years thereafter. Also see Supplementary Fig. 1 for a more detailed breakdown of the input data and decisions used to assess the FACTS data alone.

We defined drought/other disturbance in the minimum and maximum disturbance scenarios differently, but in both cases, pixels with MMI $< 10\,\%$ were considered undisturbed or insignificantly disturbed, thus minimizing erroneous disturbance reporting. In both disturbance scenarios, pixels affected by fire or fuels management in a given year were excluded from potential classification as drought/other in that year. In the minimum disturbance scenario, we also excluded pixels within 50 m of either a USFS ownership boundary or a fuels management polygon to eliminate potential spatial spillover of fuels management. For example, a pixel with MMI $\geq 10\,\%$ within 50 m of a USFS ownership boundary and otherwise undisturbed would be classified as drought/other in the maximum disturbance scenario and undisturbed in the minimum disturbance scenario. Examples of the resulting disturbance types on NAIP imagery are shown in Supplementary Fig. 2. While drought can cause delayed mortality at a decadal timespan, mortality that could be confidently attributed to drought occurred within one to two years of the drought event in Switzerland (Bigler et al., 2006) and within four years in the southwest US, depending on species (Kane, Kolb, and McMillin, 2014). These results indicated that a four-year span was reasonable to account for delayed drought mortality.

We calculated the annual area affected by each disturbance type under the maximum and minimum scenarios to evaluate the range between the two scenarios, the trends of each disturbance type across the 20-year span, and the relative magnitude of each disturbance in relation to the other disturbance types. Because the difference between these scenarios was minimal across the disturbance types and the two study areas, we used the maximum disturbance scenario to track cumulative disturbed area across time and to map each disturbance type and all disturbances across the full 20-year span.

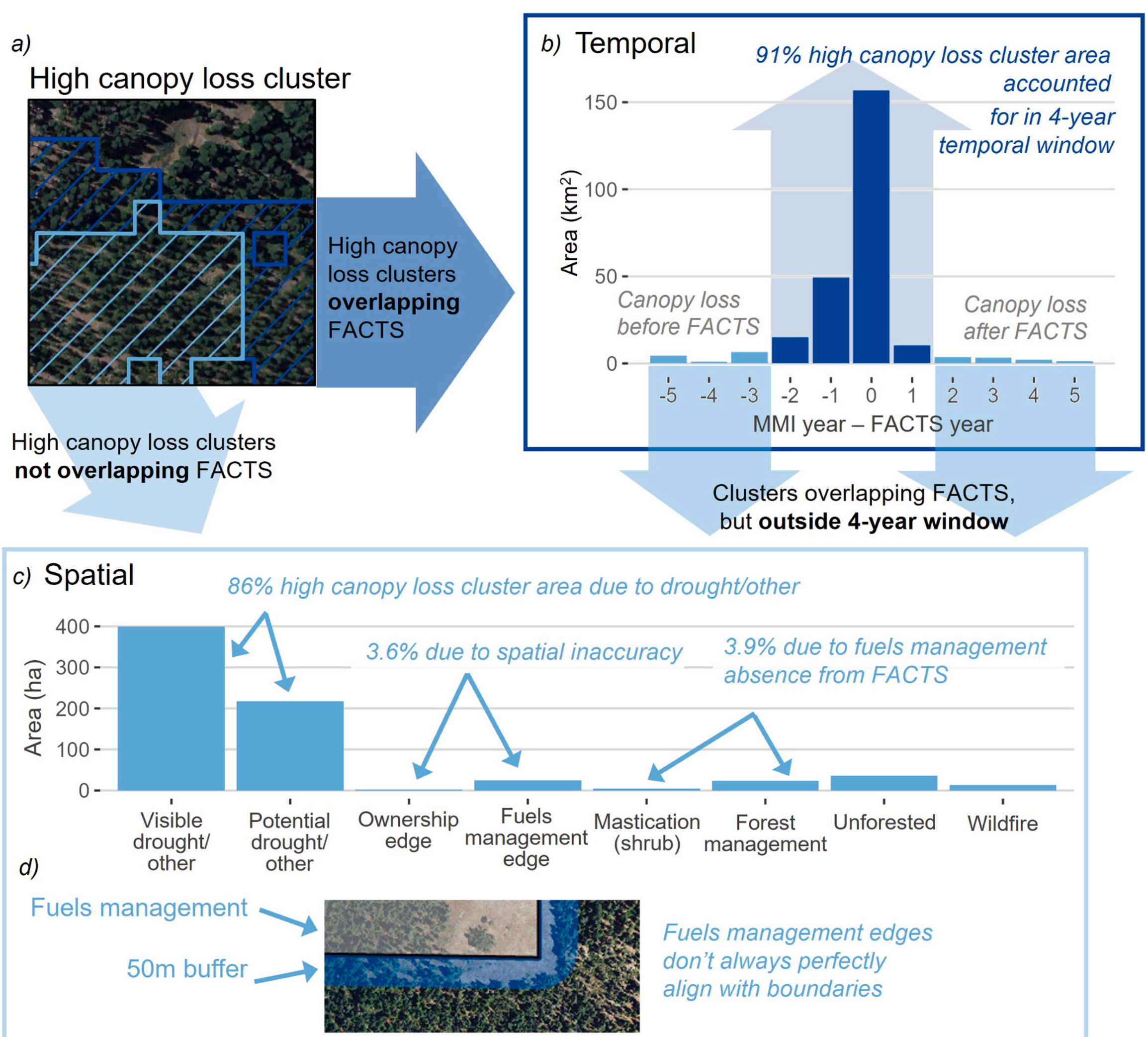


**Fig. 3.** An example of a high canopy change cluster (HCC cluster) (a) illustrates the input data used for determining the (b) distribution of annual HCC cluster area in relation to the reported date of FACTS completion. For HCC cluster area that was not within a FACTS polygon (using the 4-year temporal window shown in dark blue: two years before to one year after the completion date), we determined the cause of change by visually examining NAIP imagery, summarized in the bar graph (c). Also note that there was often minor spatial inaccuracy (d) of forest management polygons and on USFS ownership boundaries that was insufficient to create an HCC cluster (often just one or two pixels wide).

## 3. Results

### 3.1. FACTS fuels management temporal and spatial accuracy

Across 254 $km^2$ of HCC clusters (2009–2017; Fig. 3a) that overlapped (completely or partially) FACTS fuels management polygons within five years (before or after) of the reported completion date (973 $km^2$), only 157 $km^2$ (62 %) of the changed area occurred on the same year as FACTS-reported completion (Fig. 3b). An additional 49 $km^2$ (19 %) and 15 $km^2$ (6 %) of HCC cluster area occurred one and two years before the completion year, respectively, and 10 $km^2$ (4 %) of HCC cluster area occurred in the year after the completion year. In summary, within a four-year period (from two years before to one year after the fuels management completion year), 91 % of HCC cluster area was accounted for by fuels management polygons (Fig. 3b).

Across 2013, 2015, and 2017, there were 42.9 $km^2$ of HCC cluster area total (including both HCC clusters that overlapped FACTS fuels management polygons, as well as HCC clusters that did not overlap them). Clusters that overlapped FACTS polygons using the above four-year temporal window accounted for 35.7 $km^2$ (83 %) of that total HCC cluster area. Of the remaining 7.2 $km^2$ (17 %; 156 individual HCC clusters) that did not overlap FACTS fuels management polygons, drought/other accounted for the majority (85.6 %) of unaccounted HCC cluster area (i.e., not overlapping with FACTS; Supplementary Table 2), and edge accounted for 3.6 % of HCC cluster area, including fuels management that was not fully contained by the FACTS polygon. A similarly small proportional area (3.9 %) was due to obvious fuels management activity that was not present in the FACTS dataset, although some of these were captured by FACTS fuels management polygons with dates outside the four-year span or blank completion dates. Other obvious instances of fuels management were completely absent from the FACTS dataset, although this was due to recent USFS land acquisition in at least one instance. The remaining categories also represented minimal area, with 5 % and 1.9 % of unaccounted for HCC cluster area occurring in unforested areas and mis-mapped wildfire area, respectively. In summary, across 42.9 $km^2$ of HCC cluster area, 83.2 % overlapped with FACTS fuels management, 1.3 % (0.5 $km^2$) was visually confirmed to be fuels management area not captured by our methods, 14.4 % was drought/other, and 1.1 % was misclassified for other reasons.

The omission rate for fuels management was estimated as a ratio $A_o$ / $A_{FM}$, where $A_o$ is the area (0.5 $km^2$) of HCC clusters that did not overlap with FACTS fuels management polygons within the four-year temporal window and was visually determined to be fuels management; and $A_{FM}$

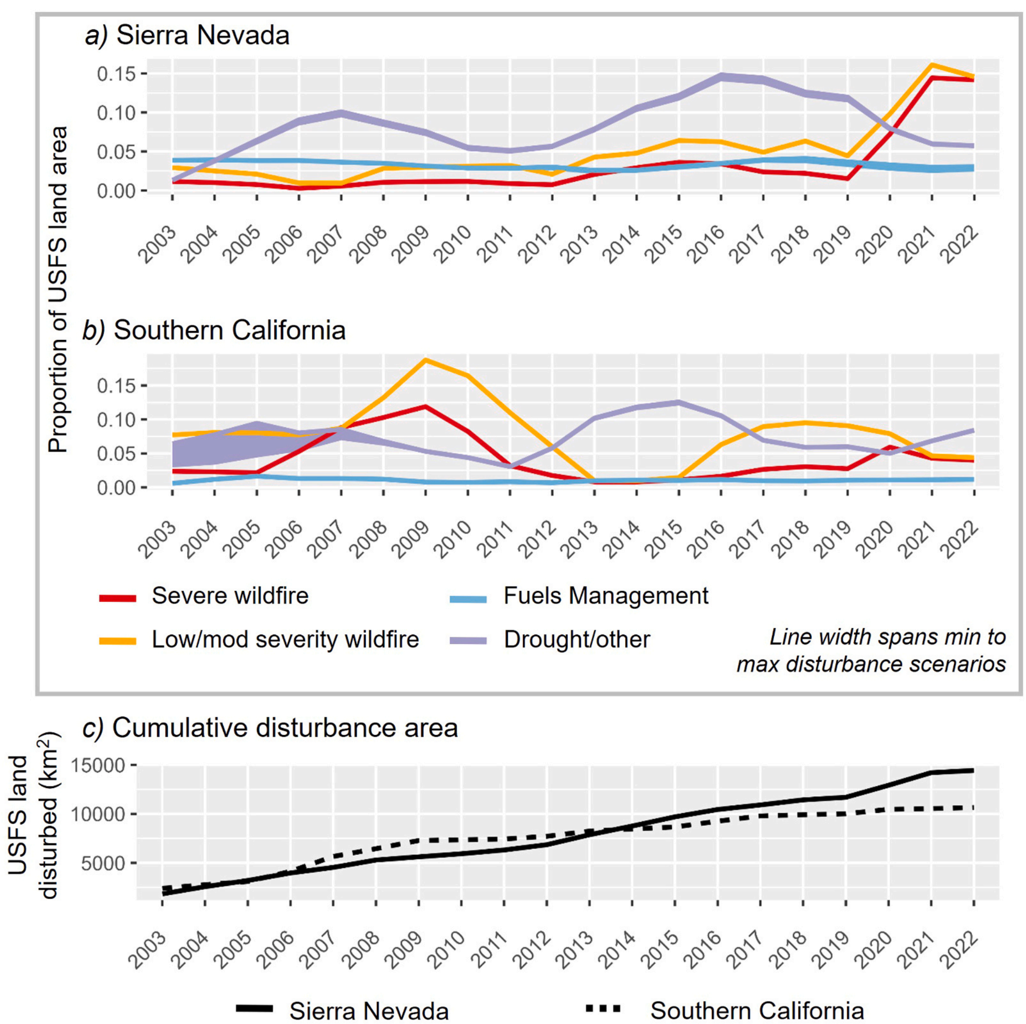


**Fig. 4.** Proportion of the USFS land in the study area affected by each disturbance type through time (2003–2022) for the Sierra Nevada (a), and Southern California (b). The line width represents the difference between the minimum (only FACTS polygons with completion dates) and maximum (incorporating FACTS polygons without completion dates based on the year they were awarded) disturbance scenarios. Note that all four disturbance types span four years, so the relative heights of the lines in relation to one another, as well as over time, should represent the overall magnitude of that disturbance type on the landscape in comparison to the other disturbance types. We also display the cumulative disturbed area on USFS land (c) in the Sierra Nevada and Southern California study areas.

is the total area of all fuels management HCC clusters in the same spatial and temporal window (0.5 $km^2$ + 35.7 $km^2$). This yielded a fuels management omission rate of 1.5 %, which represents the estimated proportion of fuels management misclassified as drought/other in the output maps.

### 3.2. Annual disturbance assessment

The annual disturbed area for each disturbance type fluctuated through time, although fuels management was consistent and low compared to fire and drought/other (Fig. 4). The difference between the maximum and minimum disturbance scenarios is represented by the line widths in Fig. 4b), which were narrow for nearly all disturbance types across both study areas, except for drought/other in Southern California between 2003 and 2008. Additional sources of model sensitivity did not substantially change the model trends or annual values (Supplementary Fig. 4). Overall temporal trends show drought/other pulses centered on 2007 and 2016 in the Sierra Nevada and 2015 in Southern California. Wildfire area also showed pronounced inter-annual differences with a marked rise in the Sierra Nevada in 2020–2022. In contrast, fuels management was relatively constant from one year to the next and the least prevalent driver of forest change overall. Fuels management varied between 2 % and 4 % of the land area each year in the Sierra Nevada and was below 2 % each year in Southern California.

When we compiled disturbance across 20 years (2003–2022) using the maximum disturbance scenario, 74 % of USFS lands were disturbed across the Sierra Nevada and Southern California (~25,000 $km^2$ total; Fig. 5a; Table 1). Broken down by each disturbance type on USFS land, wildfire burned 17,204 $km^2$ (51 % of total area and 69 % of total disturbed area; Fig. 5b; Table 1). Of that area, severe wildfire burned 7343 $km^2$ (22 % of total area and 29 % of disturbed area) and low/moderate severity wildfire burned 10,966 $km^2$ (32 % of total area and 44 % of disturbed area; Fig. 5b; Table 1). Fuels management covered 3472 $km^2$ (10 % of total area and 14 % of disturbed area; Fig. 5c; Table 1), and drought/other impacted 12,813 $km^2$ (38 % of total area and 51 % of disturbed area; Fig. 5d; Table 1). Note that a pixel could

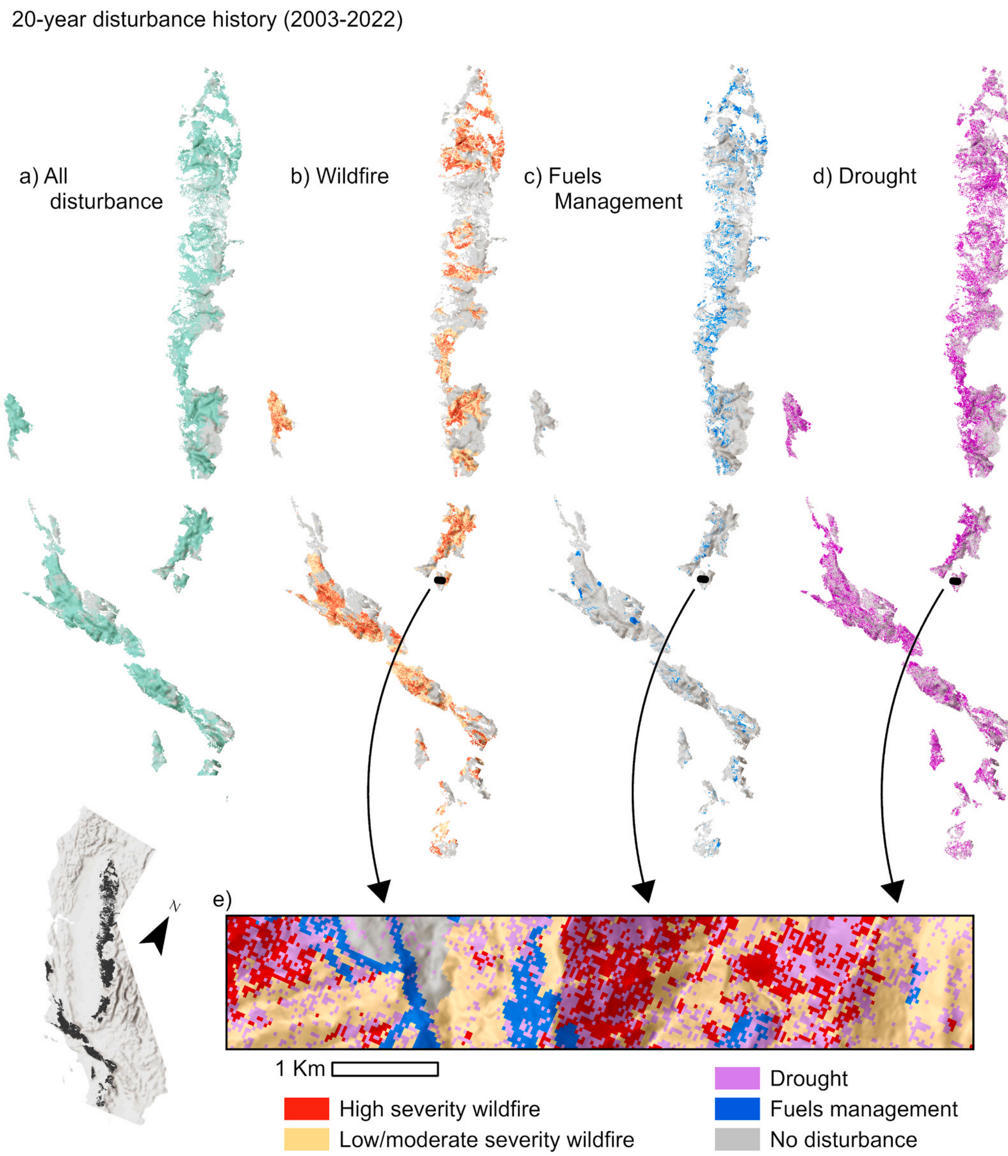


**Fig. 5.** Maps of disturbances compiled across 20 years (2003–2022) in the Sierra Nevada and Southern California study areas. We display all disturbance types together (a), as well as wildfire (b), fuels management (c), and drought/other canopy mortality (d). We also show an inset map (e) that is enlarged to show the spatial characteristics of the different disturbance types; note that for the clearest view, the layers are displayed with drought/other on top, followed by fuels management, then wildfire. We only mapped the maximum disturbance scenario (incorporating FACTS polygons without completion dates based on the year they were awarded), although the overall area and spatial pattern closely matched that of the minimum disturbance scenario. Map hillshade: Esri, USGS, NASA, NGA, and FEMA.

**Table 1**
Summary of the US Forest Service-owned land disturbed by different disturbance agents across two decades from 2003 to 2022. Note that a given pixel can be disturbed by multiple disturbance agents across this timespan, but can only count once for each disturbance type. For example, a 900 $m^2$ pixel that burned at high severity in 2005, 2010, and 2021, and at moderate severity in 2016 would count as 900 $m^2$ in the any disturbance class, 900 $m^2$ in the any wildfire class, 900 $m^2$ in the high severity class, and 900 $m^2$ in the low/moderate severity class.

| | Southern California | | Sierra Nevada | | Total | | |
|---|---|---|---|---|---|---|---|
| | Area $km^2$ | Proportion | Area $km^2$ | Proportion | Area $km^2$ | Proportion | Proportion of disturbed area |
| Total pixels | 14,046 | 1.000 | 19,871 | 1.000 | 33,917 | 1.000 | NA |
| Any disturbance | 10,647 | 0.758 | 14,429 | 0.726 | 25,075 | 0.739 | 1.000 |
| Any wildfire | 7891 | 0.562 | 9313 | 0.469 | 17,204 | 0.507 | 0.686 |
| Severe wildfire | 3211 | 0.229 | 4131 | 0.208 | 7343 | 0.216 | 0.293 |
| Low/moderate wildfire | 5277 | 0.376 | 5689 | 0.286 | 10,966 | 0.323 | 0.437 |
| Fuels management | 685 | 0.049 | 2787 | 0.140 | 3472 | 0.102 | 0.138 |
| Drought/other | 5395 | 0.384 | 7417 | 0.373 | 12,813 | 0.378 | 0.511 |

contribute to multiple disturbance types during area calculation; for example, a pixel burned in multiple wildfire incidents at both high and low/moderate severity, followed by fuels management five years later.

## 4. Discussion

Disturbance has occurred on 34,000 $km^2$ of USFS land in the Sierra Nevada and Southern California over the last two decades, covering 74 % of the study area, with wildfire and drought/other being the primary disturbance agents with relatively minimal fuels management. This method that combines existing data products collected by the USFS and derived from remote sensing overcomes previous challenges of vetting and parameterizing uncertainty in one of the input datasets (FACTS) and combines three major causal types of disturbance into a single product. This product offers a resource for researchers and forest managers to investigate spatial and temporal attributes of different disturbance types, including their interactions, and the relationship of reported forest management activities on detectable changes on the landscape.

### *4.1. FACTS data can be a reliable fuels management data source*

This study improves our understanding of the uncertainty and limitations of the FACTS database and indicates that, depending on the type of use and processing methods, FACTS can be an effective data source for tracking fuels management. These findings align with previous research that found that disturbance was detected by remote sensing within about half of FACTS polygons across an eight-year timespan, and that the median difference in timing between the award year and the change in the remote sensing was 0 years (Knight et al., 2022). We found that the majority (62 %) of fuels management detected by remote sensing appeared to occur in the completion year (often the same as the award year). To our knowledge, no other studies have examined timing in the FACTS database in further detail (such as the temporal distribution of fuels management when it was not the same year as that reported) or exploring possible instances of fuels management beyond (> 300 m from) the borders of FACTS polygons. While there were instances of fuels management areas not represented in FACTS, these were minimal (1.5 % of HCC cluster fuels management area) when the aforementioned four-year temporal window was applied. Furthermore, although we only tested the temporal accuracy of relatively intense fuels management in the FACTS database, we have no reason to believe that FACTS reporting standards would be different between differing treatment intensities, leading us to assume that this dataset would represent both more and less intense fuels management with similar spatial and temporal accuracy. Because this disturbance dataset combines FACTS polygons with MMI data on remote-sensing-derived canopy cover change, it is able to capture both the areas undetected by remote sensing (via FACTS) and the relative fuels management intensity (via MMI).

The four-year temporal window accounted for multiple sources of mismatch between eDaRT detections and FACTS records. One source of mismatch was the temporal inaccuracy of disturbance detection and omissions by eDaRT (also present in other satellite-derived disturbance products). Naturally, delayed detection in eDaRT is much more frequent than premature detection. Indeed, the timing of a disturbance event in eDaRT is the date of the first Landsat image in which the signs of disturbance were observed. Therefore, disturbances starting after October each year may not be detected until the following year when clear-view Landsat observations became available; and any disturbance that began in December cannot be detected until the following year due to the seasonal constraints of eDaRT processing (Section 2.3). Another reason for delays may be small-magnitude activities on the ground that were detected after their completion date due to the compound effect of subsequent additional disturbance. Also, the mismatch can occur when fuels management activities span multiple calendar years, and therefore eDaRT can (correctly) detect them years before the completion date in FACTS. Finally, the mismatch can be due to an error in the FACTS dates or the polygon coverage.

Therefore, if eDaRT (or a similar remote sensing product) is being used in conjunction with FACTS, we advise users to accommodate this mismatch between the remote sensing product and FACTS by temporally buffering the data. In the case of eDaRT, we recommend 1) attributing to fuels management any disturbance detected up to a year after the fuels management completion date in FACTS, or 2) instead of utilizing just the year, as we did in this analysis, utilizing the time of year of the fuels management award and completion and also the exact date of disturbance onset detection available in eDaRT. Finally, improvements in eDaRT capabilities are underway toward version 3.0, including more accurate timing and, importantly, disturbance type classification maps, which could complement FACTS with additional remote-sensing evidence in similar future studies. Furthermore, expanded datasets that incorporate FACTS with other federal (and soon state and NGO) records of fuels management are now available and could be used to expand our disturbance product beyond USFS ownership (Call et al., 2025).

One of our aims was to extend the applicability of the work done by Knight et al. (2022) in generating a robust fuels management spatial dataset. Specifically, we completed additional spatiotemporal assessment and filtering of the FACTS data to improve its applicability and robustness as a data product, and we combined the fuels management spatial data with additional disturbances to create a broader, multi-disturbance dataset. Furthermore, the product described in this manuscript offers some additional end-user flexibility in that a scientist or manager could tailor how they use the FACTS data depending on the magnitude of the spatial and temporal error acceptable for their study design. For instance, if the objective was to isolate any area with moderate temporal resolution where canopy change could have been due to USFS fuels management (and not another disturbance agent), a four-year span (two years before to one year after the FACTS completion date) paired with a buffer around fuels management polygon boundaries would capture the majority of fuels management activity. If the objective was to identify areas where change should be attributed to drought/other, we recommend blocking out all burned areas as discussed above, as well as any canopy change that was detected by eDaRT within a buffer (of a size determined by the user) around fuels management and non-USFS ownership. Because different land change products vary significantly in their temporal and spatial resolution and because users will have a different tolerance for the errors of omission and commission that these buffers would create, we will not make any recommendations on the size of that buffer here. However, a 50 m buffer appeared to account for many of the spatial inaccuracies that we encountered in our study area (Fig. 3d) and did not substantially change the overall disturbance predictions (Fig. 4).

### *4.2. Disturbance trends on USFS lands over two decades*

The compilation of disturbances showed that 74 % of USFS land area in the Sierra Nevada and Southern California experienced wildfire, fuels management, drought/other, or a combination of these disturbances across 20 years. Additionally, trends between the different disturbance types across time emerged, including an oscillating pattern of drought/other and wildfire. While this broad pattern is not surprising, these data could facilitate analyses that examine more complex relationships between the spatial and temporal patterns of disturbance and their relationship to the flora and fauna of different landscapes. An examination of the 26 % of the landscape that was not disturbed during this timeframe would also be insightful, revealing either potential disturbance refugia or areas that have sufficient fuel accumulation to be at higher risk of disturbance in the coming years.

In order to improve the utility of this product and workflow, we provide code to generate the disturbance layers, as well as the annual disturbance rasters for the Sierra Nevada and Southern California (https://github.com/peerylab/Disturbance_raster_maker). Base data needed to generate these disturbance layers are available for the state of California though eDaRT products, including the canopy cover loss maps, but do not extend to other states at this time. Also note that while MMI has been validated and has shown consistent accuracy in space and time, its accuracy varies significantly with forest type (e.g., hardwood vs. conifers; see Slaton et al. (2025), for details). As part of the code, we embedded the MMI value representing the canopy cover loss associated with each disturbance type for each pixel for each year, which could allow a user to estimate the disturbance intensity. While we did not directly evaluate MMI accuracy in measuring either fuels management or drought/other intensity, greater vegetation canopy cover loss associated with these disturbance types tends to correspond to greater values of MMI. For instance, a preliminary investigation indicated higher MMI in treatment activity types that had more intense fuel reduction, including group selection and commercial thin activities (Supplementary Fig. 5). These findings suggest that relative intensity of fuels management or drought/other disturbances could be determined from this dataset, although additional testing in this area would help to clarify their relationship. This dataset also incorporates salvage logging as a disturbance type.

### *4.3. Alignment with other research*

While not strictly comparable, 10,000 km$^2$ of California forests experienced severe canopy water loss during the 2012–2015 drought (Asner et al., 2015), which is similar to the estimate derived here of 12,813 km$^2$ of substantial canopy loss due to drought and other factors from 2003 to 2022 in the Sierra Nevada and Southern California. This recent drought killed a higher proportion of large trees that are important for both wildlife habitat and future wildfire resilience, and the effects of drought may be accelerating a species type conversion (Fettig et al., 2019).

Unsurprisingly, the predicted extent of severe wildfire was similar between this and previous studies, including larger wildfires overall (Westerling et al., 2006; Cova et al., 2023) and a high proportion of severely burned area on USFS land (Stevens et al., 2017) compared to the area burned at low or moderate severity. These findings were also similar to those that found drought and fire covered greater extents than mechanically treated area (Steel et al., 2023). Burned area is predicted to continue to increase in the coming decades, with fire effects potentially amplified by drought through feedback loops (Abatzoglou et al., 2021). These findings corroborate the arguments of many that the pace and scale of fuels management is slow and insufficient to prevent the loss of forest ecosystems in the face of climate change (North et al., 2015; Stephens et al., 2020). Part of the challenge of implementing fuels management has been uncertainty as to how these management actions, as well as in combination with other disturbance types, will affect native species and these ecosystems overall.

Much research has examined how these disturbance types individually affect rare species or species communities, but few studies have considered multiple disturbance types as a complex spatiotemporal mosaic, perhaps in part due to the absence of a comprehensive data source. For instance, the effects of fire (severity, spatial configuration, and patch size) on California spotted owls (*Strix occidentalis occidentalis*) have been thoroughly studied, with findings indicating that these owls avoid large, severely burned patches for many years after fire, yet they don't avoid smaller high severity patches or low and moderate severity fire (Roberts et al., 2011; Kramer et al., 2021; Jones et al., 2021). Drought had differing effects on the avian community, dependent on species (Roberts et al., 2019), and while fuels management had minimal effects on many animal species, California spotted owl occupancy declined (Stephens et al., 2014). Pyrodiversity is a metric that captures the spatiotemporal aspects of fire and is linked to biodiversity, yet no such metric currently exists for disturbance overall (Tingley et al., 2016). Steel et al. (2023) attributed declines in canopy cover and tall trees in Southern California to different disturbance agents and predicted that more homogeneous disturbances, combined with the mortality of larger trees, would negatively impact habitat for old-forest specialists like the California spotted owl and fisher (*Pekania pennanti*), yet they did not have data on the movement or occupancy of these species to test this prediction. As such, the comprehensive dataset that we developed here, combined with species distribution and movement information, can facilitate more nuanced investigations of the effects of these disturbances on biodiversity.

### *4.4. Management implications*

Our findings will facilitate forest management and science in at least two important ways: (1) by combining the results from our first two research questions, demonstrating how the FACTS database can be integrated with remotely sensed data to accurately map fuels management history and the drivers of forest disturbance, and (2) via our compilation of common disturbances into a fine-scale (30 m) series of annual rasters that we created to answer our third research question. The FACTS database holds vast and detailed data on USFS activities, yet it has been underutilized within and outside the agency due to uncertainties around its accuracy, how to appropriately incorporate this uncertainty into analyses, and the unwieldy size of the dataset. Here, we suggest ways to organize, filter, and buffer the data based on a potential user's objectives. Beyond FACTS, the disturbance rasters we compiled have a fine spatial (30 m) and temporal (annual, starting in 2003) scale, and could be utilized for numerous purposes. Some potential uses include 1) monitoring change across time in a given area (as we did here), 2) modeling how different disturbances (including salvage logging and disturbance intensity) influence forest structure or wildlife occupancy or habitat, and 3) planning study designs or reserves based on different disturbance histories or spatial patterns. For instance, these data are already being used to model how spotted owl occupancy is affected by different disturbance types and intensities (Ng et al., In Review), attributing changes in spotted owl habitat to each disturbance type in Southern California (Barry et al., In Press), and weighing the slight decline in habitat after intense fuels management against the gains in forest resilience in the face of wildfire when fuels management precedes wildfire, both in general and in the context of the spotted owl (McGinn et al., In Press).

In summary, these ecosystems, as well as many areas around the globe, are changing in multifaceted ways and at an accelerating pace. Many have argued that the pace and scale of restoration efforts are too slow, and that we risk losing some of these species and ecosystems if we continue the status quo (North et al., 2015; Stephens et al., 2020). The slow speed of restoration is due, in part, to a lack of research on the effects of these disturbances on these systems and species, but in order to accomplish this, scientists first need a comprehensive dataset that captures the facets of those disturbances, and we hope that this dataset can serve that purpose.

## CRediT authorship contribution statement

**Slaton Michèle R:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Alexander Koltunov:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Jones Gavin M:** Writing – review & editing, Writing – original draft, Methodology. **M. Zachariah Peery:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **H. Anu Kramer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Winiarski Jason M:** Writing – review & editing, Methodology. **Ng Elizabeth M:** Writing – review & editing, Methodology, Conceptualization.

## Declaration of Competing Interest

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

## Acknowledgements

Many thanks to Stephanie Coppeto and TJ Moore for their help deciphering the intricacies of the FACTS database. We also thank Craig Thompson, Sarah Sawyer, Josh Barry, Connor Wood, and Spencer Keyser for their valuable input at various stages of our analyses. We gratefully acknowledge funding from Region 5 of the USFS for supporting this work.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123385.

## Data availability

I have shared the link to my data and code at the attach file step Disturbance_raster_maker (Github)

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