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Accurate tracking of forest activity key to multi-jurisdictional management goals: A case study in California

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ABSTRACT

An essential component of sustainable forest management is accurate monitoring of forest activities. Although monitoring efforts have generally increased for many forests throughout the world, in practice, effective monitoring is complex. Determining the magnitude and location of progress towards sustainability targets can be challenging due to diverse forest operations across multiple jurisdictions, the lack of data standardization, and discrepancies between field inspections and remotely-sensed records. In this work, we used California as a multijurisdictional case study to explore these problems and develop an approach that broadly informs forest monitoring strategies. The State of California recently entered into a shared stewardship agreement with the US Forest Service (USFS) and set a goal to jointly treat one million acres of forest and rangeland annually by 2025. Currently, however, federal and state forest management datasets are disjoint. This work addresses three barriers stymying the use of federal and state archival records to assess management goals. These barriers are: 1) current databases from different jurisdictions have not been combined due to their distinct data collection processes and internal structures; 2) datasets have not been comprehensively analyzed, despite the need to understand the extent of previous treatments as well as the rate of current activity; and 3) the spatial accuracy of archival datasets has not been evaluated against remotely-sensed data. To reduce these barriers, we first aggregated existing archival forest management records between 1984 and 2019 from the USFS′ Forest Activity Tracking System (FACTS) and the California Department of Forestry and Fire Protection (CAL FIRE) using a qualitative scalar of treatment intensity. Combined FACTS and CAL FIRE completed footprint acres – defined as unique areas of land where a treatment was completed at any time since 1984 – have decreased since a peak in 2008. At most, 300,000 footprint acres are completed each year, 30% of the million-acre goal. Prescribed fires – defined as direct burning operations – have risen over time, according to the FACTS hazardous fuels dataset but prescribed fire records in CAL FIRE's dataset have rapidly increased since 2016. We also refined the spatial and temporal detail of the aggregated management record using the Continuous Change Detection and Classification algorithm on satellite remote sensing data to produce a state-wide time series map of harvest disturbances. A comparison of the algorithm's refined data to the archival record potentially suggests over-reporting in both FACTS and CAL FIRE's archival datasets. Our integrated dataset provides a better assessment of current treatments and the path towards the 1-million-acre a year goal. The refined dataset leverages the strengths of complementary, albeit imperfect, monitoring strategies from archives and remotely-sensed detection.

1. Introduction

> *The need for timely, quality, and accessible data and statistics has never been more urgent.*
>
> The Global Forest Goals (2021)

Accurate monitoring of forest activity is a foundational component of sustainable forest management (UNFF, 2007; Marchi et al., 2018). The

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premise of sustainable forest management is that forests can be managed to provide benefits today without sacrificing long-term future benefits (*sensu* MacDicken et al., 2015). These benefits include the production of resources, the delivery of ecosystem services, and the maintenance of esthetic, recreational, and cultural uses. In fire-prone forests, managing wildfire is critical to sustainable practice (Hirsch et al., 2001).

Globally, policies related to sustainable management are in place for most forests (MacDicken, 2015). Although monitoring has increased considerably in recent years according to the Global Forest Resources Assessment (FAO, 2015), in practice, effective monitoring is complicated. For example, complications arise when a diversity of forest operations (e.g., timber harvest, salvage logging, fire-hazard reduction) are applied but inconsistently tracked by multiple landowners. The use of metrics based on different data sources, such as remote sensing and regional inventories, represents another challenge. For example, Ceccherini et al. (2020) reported abrupt increases in harvested forest area in the European Union from 2016 to 2018. The estimated increase (49%) was sufficiently large to threaten climate change mitigation goals. However, their results relied on remotely-sensed estimates of forest cover change, results that were not corroborated by field-based records collected by member nations (Sweden and Finland, Wernick et al., 2021; France, Picard et al., 2021). The Global Forest Goals (2021) posits that a paucity of standardized and comparable datasets is an ongoing challenge in many countries (United Nations Department of Economic and Social Affairs 2021). Evidence-driven assessments are acutely needed to track environmental progress towards sustainable forest management, particularly in forest ecosystems under threat from various abiotic and biotic stressors.

Many temperate forests across the world are experiencing climate-exacerbated forest disturbances that transcend administrative boundaries, pose increasing threat of forest conversion (Coop et al., 2020; Liang et al., 2017b), and threaten the feasibility of using forests as natural climate solutions (Anderegg et al., 2020). Forestlands in California are no exception. They are undergoing rapid change due to catastrophic wildfires, a warming climate, severe drought, and human population pressures (Safford and Stevens, 2017; Liang et al., 2017a, 2017b; Dass et al., 2018). Of the 33 million acres (13.5 million hectares) in California, 15 million acres of forestland need some form of restoration, particularly treatments that reduce wildfire severity and improve sustainability (Forest Climate Action Team, 2018). Recently the USDA Forest Service (USFS) and the State of California each committed to facilitating the treatment of 500,000 acres of forestland annually for a total of 1,000,000 acres per year by 2025 (USDA Forest Service and State of California 2020).

Charting progress toward meeting this 1-million-acre goal will require coordinated and coherent record-keeping of the types, timing, location, and size of treatments. Nearly 28 million acres are managed and/or regulated by either the USDA Forest Service (USFS) or the State of California (CAL FIRE 2017). Federal and state agencies acknowledge the need for consolidating data and establishing methods to monitor the agreement's goals and regional impact (USDA Forest Service and State of California 2020). Moreover, federal (National Forest Management Act of 1976) and state laws (Z'Berg-Nejedly Forest Practices Act of 1973) require reports documenting timber harvests and other forest management activities. Yet, the current databases that track treatments are disconnected and incompatible. Since the early 20th century in California, federal and state managers have deployed different systems to record silviculture treatments. The USFS, which manages 48% of California's forested lands, uses the Forest Activity Tracking System (FACTS) to document forest management activity in national forests and national management basins (Table 1) (CAL FIRE 2017). While the California Department of Forestry and Fire Protection (CAL FIRE) does not directly manage large tracts of lands, it is responsible for approving and recording forest operations that require permits on private holdings (Table 2). Corporate and non-corporate private owners own an estimated 39% of forested lands (CAL FIRE 2017). While other entities manage the remaining 13% of forests in California (e.g., the Bureau of Land Management, the National Park Service, and Native American Tribal Lands), these entities tend to be more disparate in management objectives and are not committed to the 1-million-acre goal.

Table 1
Summary of FACTS datasets. Only records from California are discussed below.

Administrative body	Dataset	No. of records	Year of earliest record	Used in this study
Federal – USFS, FACTS 1000 – Fire 2000 – Range 3000 – Cultural Resources 4000 – Timber and Silviculture 5000 – Soil/Air/Watershed 6000 – Wildlife/Fisheries 7000 – Vegetation/Restoration 8000 – Miscellaneous 9000 – Engineering	Timber harvests – 4000	74,492	1900	Yes
	Silviculture reforestation – 4000	65,982	1919	No
	Silviculture timber stand improvement – 4000	65,535	1948	No
	Hazardous Fuel Treatments – 1000, 2000, 3000, 4000, 6000, 7000, 9000	63,353	1900	Yes
	Collaborative Forest Landscape Restoration (CFLR) Program – 1000–9000	5927	2010	No
	Stewardship contracting – 1000, 2000, 4000, 5000, 6000, 8000	3748	2013	No
	Range vegetation improvement – 2000	1209	1975	No

Table 2
Summary of CAL FIRE dataset types. The number of records reflect unprocessed/uncleaned records (details about data cleaning steps are shown in Fig. 1).

Administrative body	Dataset	No. of records	Date of earliest record	Used in this study
State – CAL FIRE	Timber harvest plans (THP)	141,108	1997	Yes
	Non-industrial timber management plans (NTMP)	5618	1991	Yes
	Emergencies	334,153	2014	No
	Exemptions	8682	2011	No
	Exemptions (post-2019)	1196	2019	No
	Prescribed fire	1345	1984	Yes
	CalMAPPER treatments	5412	1992	Yes
	CalMAPPER activities	14,954	1992	Yes

In this study, we took advantage of California's pressing need to integrate its forest monitoring to inform the global challenge articulated by Picard et al. (2021) in response to the controversy generated by Ceccherini et al. (2020) – existing limitations in forest monitoring systems require the exploration of "diversified techniques" including field inspections and remote sensing. Specifically, our premise was that we could leverage the strengths of complementary, albeit imperfect, monitoring strategies to produce a hybrid dataset that provides a better understanding of historical and current forest management in California.

To test this premise, we first examined the archival management records from the USFS in California and from CAL FIRE, explaining key historical dimensions and agency-specific nuances. Next, we merged federal and state datasets by standardizing the intensity of silviculture treatments by canopy loss. These integration steps can be applied to other American states because federal forest activity tracking is consistent across the US. Third, we compared federal and state archival records of silviculture treatments, including prescribed fire, and then quantified the amount and types of treatment on different cover types. Lastly, we applied a change detection algorithm based on satellite remote sensing from California between 1984 and 2019 to identify management events. We compared the algorithm to archival datasets and presented a refined hybrid remote-archival state-wide management dataset with improved information on the timing and spatial detail of management events.

2. Methods and materials

Given the number and complexity of our datasets, we developed a flowchart to track how specific datasets from FACTS and CAL FIRE were cleaned and merged before analyses (Fig. 1, Fig. S1); additional historical information about the datasets is presented in the supplement. Cleaned and merged federal/state datasets and the refined hybrid remote-archival state-wide management dataset are available through an open-access data repository and an online mapping tool hosted by the California Center for Ecosystem Climate Solutions (https://california-ecosystem-climate.solutions/).

2.1. Data compilation

2.1.1. USFS datasets

We compiled the most complete set of archival silviculture management activities for California. Using the Enterprise Data Warehouse website (https://data.fs.usda.gov/geodata/edw/), we obtained the Timber Harvest and Hazardous Fuels datasets from the USFS's Forest Activity Tracking System (FACTS) (USDA Forest Service 2020a, 2020b). Federal FACTS data were clipped to California's boundary in QGIS (QGIS Development Team, 2020). We used the NAD83 California Albers projection for all datasets. The USFS lists silviculture treatments across several datasets; because fuel and timber removal are largely recorded in timber harvests and hazardous fuel treatments, we focused on these datasets (Table 1). These data are published as two discrete datasets, one for Timber Harvest and another for Hazardous Fuels. The datasets are delivered with two kinds of duplication – intra and inter duplication – which help the agency record sequential treatments on the same piece of land (Fig. 2). We stress that duplication is not meant as a pejorative. It is simply the best description of the dataset's replication. If replication is

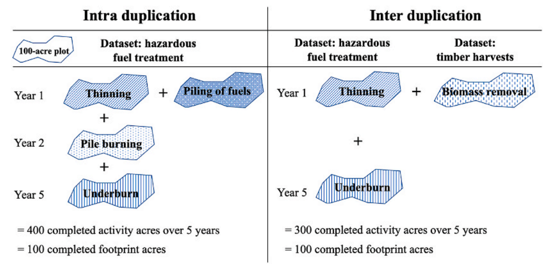

Fig. 2. Visual representation of intra and inter duplication in the US Forest Service's hazardous fuel treatment dataset and timber harvest dataset (duplication also occurred in some CAL FIRE datasets, see Fig. 1). In the left panel, a 100-acre plot has multiple treatments completed over 5 years that results in 400 completed activity acres in the hazardous fuel treatment dataset; the completed footprint of the treatments is 100 acres. In the right panel, a 100-acre plot is thinned. The commercial thinning is reported in the timber harvest dataset and reported as biomass removal in the hazardous fuel treatment dataset. In this case, there were 200 completed activity acres and 100 completed footprint acres.

not considered, it can introduce bias into analyses of progress toward statewide implementation goals. Intra duplication occurs when a sequence of activity is applied to the same area as denoted by ID number and acreage, and this sequence of activity is recorded in a single dataset. Inter duplication occurs when a sequence of activity is applied to the same area as denoted by ID number and acreage, but the different activities are recorded in different datasets (Fig. 2). We found both intra and inter duplication when FACTS′ datasets were queried on stand unit ID and acres. We recognize that tracking the sequence of activity required to complete a silvicultural prescription allows other management questions to be answered. However, we used our definitions of duplication to distinguish the unique footprint of the area treated from the sequential activities on the landscape.

Our lexicon for tallying acres is as follows. **Completed footprint acres** refers to a unique area of land where a treatment event's status equals completed at any time since 1984; intra and inter duplication have been removed such that only one defined forest management activity is counted. Because we collapse any sequential treatments to

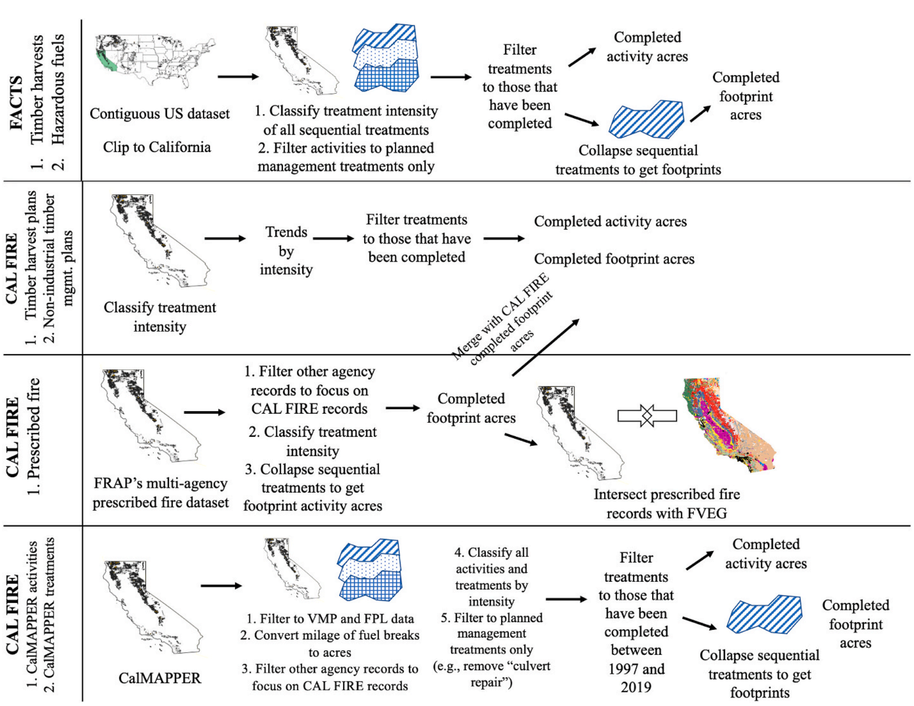

Fig. 1. Flowchart (read left to right) depicting how the archival data was cleaned, merged, and analyzed to produce the results presented in section 3. FACTS data (top panel) required cleaning steps after treatments were ranked by intensity. Non-silviculture/management related activities (such as "permanent flooding" or "administrative changes") were filtered out. Analysis of filtered activities can be found in the supplement. Duplicated records of sequential treatments on the same plot of land were collapsed (see Fig. 2 for more details) and only completed treatments were counted. CAL FIRE data (second panel) was classified by treatment intensity; there was no duplication of treatments. However, only completed treatments counted. CAL FIRE's prescribed fire data (third panel) was filtered to remove other agency data, treatments were ranked by intensity, and sequential treatments were removed. Then data were merged with CAL FIRE's harvest data to match FACTS′ grouped harvest and prescribed fire data. Additionally, CAL FIRE prescribed fire data were intersected with a state-wide spatial vegetation layer (Fveg, CAL FIRE 2015), linking treatments with vegetation type for additional analyses. Lastly, CalMAPPER's vegetation management plan and fire plan activity and treatment datasets were cleaned and incorporated into CAL FIRE other datasets (bottom panel).

achieve completed footprint acres, we refrain from discussing treatment intensities. We restrict footprint acres to completed treatments because some treatments have the status of "approved" but not completed, "withdrawn" and not completed, or "unlogged." **Completed activity acres** refers to the sum of completed treatments where intra and inter duplication is preserved. We note that any sequential treatments that are planned but not yet completed are not counted in the sum. Although we stick to completed acreage tallies in this work, we recognize the importance of planned treatments for understanding near-term management trajectories. Thus, we discuss **planned footprint acres** and **planned activity acres** in the supplement (see page 6 in the supplement, Figs. S2-S3).

Numerous activities can be found in the FACTS datasets, but we filtered our data to activities related to activity treatments that modified or manipulated vegetation and fuels. For example, activities such as patch clear cuts or commercial thins counted as treatments while activities such as "administration changes," "silviculture stand examination," or "permanent flooding" were excluded from both the FACTS timber harvest and FACTS hazardous fuels dataset. Within the FACTS hazardous fuels dataset, four wildland fire categories were also excluded: "wildfire fuels benefit", "wildfire human ignition", "wildfire natural ignition", and "wildland fire use." Although unplanned ignitions can be beneficial, we focused on intentional treatment activities. We quantify the acreage of excluded categories in Table S1.

2.1.2. CAL FIRE datasets

Several CAL FIRE datasets exist, including timber harvest data, prescribed fire data, and vegetation management activities (Table 2). For this work, we obtained Timber Harvest Plans, Non-industrial Timber Management Plans, and prescribed fire from CAL FIRE's GIS data portal (CAL FIRE 2020a, 2020b, 2020c, 2020d). Vegetation management activities recorded in CalMAPPER (discussed below) were not available for download on the agency data portal and were instead obtained from CAL FIRE's data manager (pers. comm. Mark Rosenberg).

CAL FIRE datasets were assumed to record management events on private lands; only 3% of California's forestland is owned by the state of California (USDA Forest Service, Agreement for Shared Stewardship 2020). Inter duplication was not found across CAL FIRE's Timber Harvest Plans and Non-industrial Timber Management Plans. However, there was intra duplication in the prescribed fire and CalMAPPER datasets.

CAL FIRE prescribed fire perimeter data spans from 1984 to 2019 and contains records from multiple agencies, including the USFS, the National Park Service, Bureau of Land Management, and others. We removed other agency data besides CAL FIRE and 49 instances of intra duplication in the records by querying on treatments and acres to achieve CAL FIRE's completed footprint acres using prescribed fire. For these records, the specific use of fire is denoted by a number (pers. comm., CAL FIRE data portal manager, David Passovoy): broadcast burns (3), fire use (7), hand pile burns (10), jackpot burns (11), machine pile burn (14), and NA. CAL FIRE's prescribed fire perimeters include applications in all biomes (e.g., forests, grasslands, woodlands, and agricultural lands). Given goals around conducting treatments specifically on forestlands, we classified the amount of prescribed fire that occurred on different vegetation types. In QGIS, we intersected the prescribed fire spatial data with California's Fveg data. Fveg provides the best available statewide land cover data (CAL FIRE 2015). After performing the spatial intersection, we found the proportion of prescribed fire that occurred on various cover types, as defined by California's Wildlife Habitat Relationships (California Wildlife Habitat Relationships 2020).

CalMAPPER is CAL FIRE's Management Activity Project Planning and Event Reporter (California Department of Forestry and Fire Protection Resource Management 2021a, 2021b). It is used by CAL FIRE to capture forest and fuels management projects and activities and includes the Vegetation Management Program (VMP), Fire Plans (FPL), and California Forest Improvement Program (CFIP). We focused on the VMP and FPL datasets but not the CFIP data which largely records planting and non-silviculture activity. The VMP and FPL datasets, like the FACTS data, have intra and inter duplication. They also contain data from other agencies (e.g., the Army Corps of Engineers, Bureau of Land Management, USFS) that is not comprehensive and was therefore removed. Lastly, CalMAPPER data contain events that do not modify or manipulate vegetation or fuels (e.g., culvert maintenance) that were filtered out. The CalMAPPER activities and treatments that were removed from consideration here were quantified in the supplement and amount to a total of 491,857 acres (Tables S2 and S3). CalMAPPER data were recorded in various units, including acres, hours, tons, and miles. We focused on treatments with acreage and miles. Reported mileage of fuel breaks were converted to acres by estimating a width of 300 feet; this figure was obtained from CAL FIRE's standard fuel break design (CAL FIRE 2019a, 2019b). Lastly, we note that CAL FIRE recently published a forest fuels and species conservation tool (FFSC MOU, CAL FIRE 2021a, 2021b) that provides modern inter-agency fuels data. However, this new monitoring and reporting effort does not contain the long-term records needed for this analysis.

2.2. Crosswalking intensity of silviculture treatments

Understanding the intensity of silviculture treatments is critical for comparing and crosswalking (i.e., finding equivalent elements across different datasets) management activities among agency datasets. To aid the comparison, we grouped treatments into high, medium, low, and variable low/medium/high intensities. We defined treatment intensity by the amount of basal area removed from the canopy that can be detected from above via aerial or satellite survey. We used our professional field-level expertise to categorize the intensity of forest management activities by general silvicultural and fuels management prescriptions (Table S4). This intensity categorization was also verified with remotely-sensed changes (see 3.4). For timber harvests, we ranked even-aged treatments (e.g., patch/stand clear cuts, seed tree, and shelterwood cuts) as medium to high intensity. In contrast, we ranked uneven-aged treatments like group selection, single tree selection, and special products removal as low intensity. Hazardous fuel treatments are sometimes paired with higher intensity treatments. For instance, burning of pile materials typically accompanies "thinning of hazardous fuels" (FACTS code 1160), an activity that can be high impact depending on the forest stand structure. The intensity of CAL FIRE's silviculture treatments is generally comparable to FACTS silviculture treatments, with important exceptions (Table S5). For example, group selection is classified as low intensity in FACTS but medium intensity in CAL FIRE's database; this discrepancy is due to differences in the intensity and scale of group selection harvest between federal and private lands. Additionally, under CAL FIRE, alternative prescriptions can be high or medium; sanitation salvages can be low or medium; and road right of way can be all three. CAL FIRE silviculture treatments tend to have more variability than FACTS treatments, which may be related to the how California's Forest Practice Regulations classifies silviculture choices. Within the harvest plans, each silviculture category has up to two subcategories that modify the original treatment classification. For instance, the silviculture category "special treatment area" falls under intermediate treatments or other management. Within CAL FIRE's prescribed fire and CalMAPPER datasets, we crosswalked the intensity of treatments to the USFS hazardous fuels dataset (Tables S6, S7 and S8).

2.3. CCDC algorithm and refined dataset

We compared the USFS and CAL FIRE datasets against time series remote sensing data from the Landsat series of satellites, which provides surface reflectance data at 30 m spatial resolution from 1984 to the present over all seasons. Specifically, we used dense spatiotemporal surface reflectance from the satellite data to refine the spatial representation and temporal accuracy of the archival datasets, providing an empirical check for these datasets. To develop this refinement, we used data from the Landsat 4 and 5's Thematic Mapper, Landsat 7's Enhanced Thematic Mapper+, and Landsat 8's Operational Land Imager instruments, spanning the years 1984–2019 (Wulder et al., 2012). To identify the spatial patterns and timing of potential forest management events, we applied the Continuous Change Detection and Classification (CCDC) algorithm (Zhu and Woodcock, 2014; Zhu et al., 2020) to all pixels' complete time series of surface reflectance data. Prior to the application of the change detection algorithm, all Landsat data were atmospherically corrected (Masek et al., 2006) and screened for clouds using the Fmask algorithm (Zhu et al., 2015). CCDC outputs a database of potential land disturbance as identified by statistically significant breakpoints in a series of harmonic models fit to time series of each spectral band of Landsat data. From this analysis, we generated a statewide database of the timing, location, and magnitude of potential land disturbances at a 30 m spatial grain.

We combined the archival database with the database of Landsat-based land disturbances to 'refine' each entry's spatial representation and timing. To do this, we identified all the CCDC breaks occurring within a 300 m radius of the perimeter of each forest management polygon and identified every pixel break that occurred no more than 1 year before the polygon's date (for FACTS timber harvests: DATE_AWARD, for FACTS hazardous fuels: DATE_PLANN or DATE_AWARD if planned was missing, for CAL FIRE timber harvest plans: COMP_DATE or APPR_DATE if completed date missing, for CAL FIRE non-industrial timber management plans: APPR_DATE) and no later than 7 years after the polygon's reported date. We generated spatially contiguous clusters of pixels that experienced a break within three months of each other and identified the contiguous cluster that most closely matched the reported area of forest management. We assumed that this cluster was the best remotely-sensed representation of the actual treatment. Additionally, we quantified the magnitude of the land disturbance using the pre- and post-disturbance change in the normalized burn ratio (NBR, the normalized difference of the near infrared reflectance, band 4, and the shortwave infrared reflectance, Band 7). We averaged the pixel-level differences in NBR across each refined polygon. The result is a new polygon, defined by the best-matching cluster of 30 m disturbance pixels, with improved spatial detail (e.g., accounting for spatial heterogeneity), satellite-derived timing, and average change magnitude.

To validate the performance of CCDC, we used Collect Earth Online (CEO). CEO is a free, open-source tool for landscape monitoring (Saah et al., 2019). From a random sample of known archival records in FACTS hazardous fuels and timber harvest datasets ($n = 397$) and CAL FIRE timber harvest plans dataset ($n = 393$) where disturbances were recorded, we wanted to know how many times an analyst using CEO could also identify a disturbance from 1) images in the National Agriculture Imagery Program (NAIP; US Department of Agriculture 2019a, 2019b) and 2) disturbance polygons identified by CCDC (Fig. S4). NAIP images are available on 2 to 3-year intervals between 2003 and 2019; these photos record images in red, green, and blue channels and have a spatial resolution between 0.6 and 2 m. Using a 25% cut-off, we determined how closely the two polygons matched. We defined a high degree of matching as less than or equal to 25% over/undershoot and poor matching as greater than 25% over/undershoot. We also asked whether CCDC detected a disturbance in the area delineated by the archival polygon. For archival polygons where no CCDC disturbance was detected, the analyst used NAIP imagery to describe the scene. NAIP images were also used to define the time frame when the management event occurred. This framing provided another check on the timing of treatment completion and provides some information about the relative differences between satellite-based datasets and the archival databases.

3. Results

3.1. Completed activity acres on USFS and private lands have increased over time but completed footprint acres have only recently increased

Completed activity acres for FACTS and CAL FIRE depict a generally increasing trend over time, despite some plateaus, with over 500,000 acres treated in 2019 (Fig. 3A). Note that Fig. 3A presents completed sequential treatments (intra and inter duplication preserved) with data derived from FACTS (timber harvest, hazardous fuels which includes prescribed fire) and CAL FIRE (timber harvest plans, non-industrial timber management plans, prescribed fires, and CalMAPPER data). However, the overall number of completed footprint acres on the landscape has decreased since 2008 with about 200,000 completed footprint acres/year since 2010, although 2018 and 2019 show an uptick to nearly 300,000 acres (Fig. 3B). The difference between Fig. 3A and B highlights the large number of sequential treatments occurring on the same piece of land, particularly since the mid-2000s, as opposed to the addition of new acres. The intensity of silviculture treatments has also varied over time and was different between public and private lands. About two thirds of all completed activity acres (60.3%) from FACTS and CAL FIRE datasets between 1984 and 2019 were of high and medium intensity, with medium intensity treatments dominating (Fig. 3C). High intensity treatments peaked in 2003 and have steadily decreased on public and private land; since 2002, medium intensity treatments have occurred on $>$ 100,000 acres annually (Fig. 3D). High and medium intensity treatments include clear cuts, commercial thins, and removal cuts.

3.2. FACTS trends: completed activity acres are generally increasing, medium intensity treatments dominate and have increased through time, and prescribed fire has generally increased

Before aggregating timber harvest and hazardous fuel datasets, we quantified the type and amount of duplication in the records. Given the sequential nature of many treatments (e.g., seed tree or shelterwood treatments), it was not surprising to find substantial intra and inter duplication in the FACTS datasets between 1900 and 2020 (summarized in Table 3). Completed activity acres from the hazardous fuels dataset have been increasing sharply since the mid-2000s (except 2009 and 2013) (Fig. 4A) but completed activity acres from the timber harvest dataset have remained under 50,000 acres/year since 2005 (Fig. 4A). The amount of completed footprint acres has been substantially lower than completed activity acres over time (Fig. 4B). Completed footprint acres from the hazardous fuels dataset have been about double the completed footprint acres derived from the timber harvest dataset. A total of 4.20 million activity acres have been completed between 1984 and 2019 compared to a total of 1.73 million completed footprint acres. Through time, completed activity acres have come predominantly from medium intensity treatments (48.1% of all treatment intensities) – particularly commercial thinning (46.3% of total medium intensity treatments), salvage cuts (13.6% of total medium intensity treatments), and precommercial thins (12.7% of total medium intensity treatments) (Fig. 4C).

Completed footprint acres of prescribed fires in the hazardous fuels dataset have generally risen over time and total 453,522 footprint acres since 1985 (Fig. 5). Prior to 2008, prescribed fire activities were tracked outside of the hazardous fuels database; thus, records before 2008 may be incomplete. The median treatment size of fuel reductions is 16.0 acres; broadcast burning and machine pile burns make up the vast majority (96.1%) of activity types.

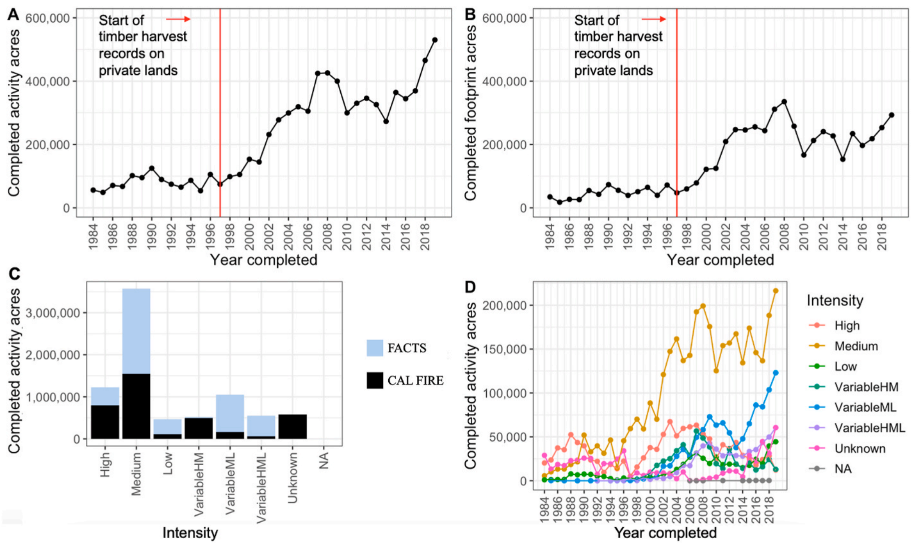

Fig. 3. For all graphs, FACTS (timber harvest, hazardous fuels which includes prescribed fire) and CAL FIRE (timber harvest plans, non-industrial timber management plans, prescribed fires, and CalMAPPER data) are shown. In **(A)**, completed activity acres are shown at year completed; in **(B)**, completed footprint acres in are shown at year completed; red lines at 1997 indicate the start of timber harvest and non-industrial timber management plans records into CAL FIRE databases (note that CAL FIRE's prescribed fire dataset starts in 1984). In **(C)**, the intensity variation in completed activity acres is depicted across FACTS datasets (blue) and CAL FIRE datasets (black) between 1984 and 2019. In **(D)**, treatment intensity variation in completed activity acres at year completed is shown for both FACTS and CAL FIRE datasets; colors correspond to treatment intensities. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Summary of the completed activity acres across USFS datasets compared to the number of completed footprint acres across all years in the dataset (1900–2020). In **(A)**, completed activity acres were summed for the timber harvest and hazardous fuel data sets. In **(B)**, completed footprint acres where duplication from within a single dataset was removed, e.g., duplication from within the hazardous fuels dataset (called intra duplication). In combined dataset **(C)**, intra duplication and inter duplication were removed to achieve completed footprint acres across both data sets.

US Forest Service dataset	A	B	C	% change		
	Data	Data with no intra duplication	Combined data with no intra or inter duplication	A to B	B to C	A to C
	Completed activity acres	Completed footprint acres	Completed footprint acres			
Timber Harvests[a]	1,977,240	1,636,295	–	−17.2	–	–
Hazardous Fuel Treatments[a]	2,672,668	1,438,613	–	−46.2	–	–
Totals	4,649,908	3,074,908	1,854,336	−33.9	−39.7	−60.1

[a] Calculations performed on all years between 1900 and 2020.

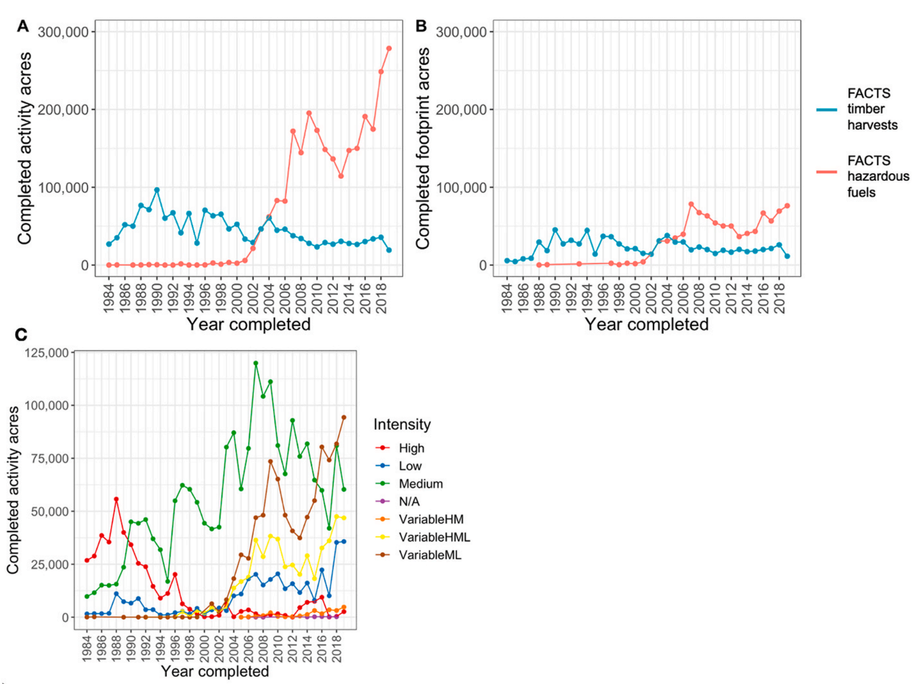

Fig. 4. In **(A)**, the completed activity acres in both FACTS data sets since 1984 where timber harvest data are shown in blue and hazardous fuel data are shown in orange. In **(B)**, the completed footprint acres in both FACTS data sets since 1984 where timber harvest data are shown in blue and hazardous fuel data are shown in orange. In **(C)**, completed activity acres for timber harvest and hazardous fuel datasets are broken down by treatment intensity (colors for intensities are shown on the right). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

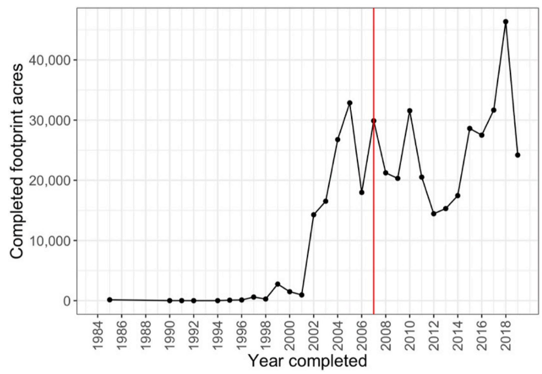

Fig. 5. Variation in the amount of footprint acres accomplished by planned prescribed fire methods between 1985 and 2019 according to the US Forest Service's hazardous fuel treatments dataset. Note hazardous fuel treatments, such as prescribed fire, were not reliably reported in this dataset prior to 2007 (red line) and thus the dataset is incomplete (Vaillant and Reinhardt, 2017). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.3. CAL FIRE trends: completed footprint acres are decreasing, medium intensity treatments dominate but decrease through time, and prescribed fire has rapidly increased in the last five years

Some 3.31 million footprint acres have been completed on private land since 1997 of which 2.78 million acres were commercial timber operations beginning in 1997, plus 239,772 footprint acres from prescribed fire (since 1997), plus 284,288 footprint acres from CalMAPPER that includes VMPs and FPLs. The amount of completed footprint acres peaked in 2008 and the record has since ranged between 100,000 and 200,000 footprint acres (Fig. 6A); we note that timber harvests were much greater in the past (Marcille et al., 2020). Treatments in the medium intensity category, particularly selection and group selection, made up the dominant intensity classification (Fig. 6B). Of the 2.78 million acres of completed treatments from timber operations (not prescribed fire), 65% have occurred in the Cascade region of California since 1997 and the majority were medium intensity (Fig. S5). Some 26% of treatments occurred on the Coast, followed by 8% in the Sierra, and 0.03% in the South. Treatment intensity is predominantly high or medium intensity across all regions.

In contrast to federal prescribed fire treatments, state prescribed fire has not steadily increased over time. Instead, prescribed fire was generally higher in the 1990s, lower in the 2000s, and has increased dramatically since 2016 (Fig. 7A). Between 1984 and 2019, most prescribed burns occurred on hardwood forests (45.1%), followed by shrubs (17.7%), mixed conifer and hardwood forest (14.9%), conifer forests (11.2%), herbaceous cover (6.3%), and other (4.9%) that includes barren land, agriculture, urban, and water (Fig. 7B and C). Lastly, the prescribed fire dataset was broken down by vegetation type as defined by the California Wildlife Habitat Relationship System (CWHR, California Department of Fish and Wildlife (2020)). Montane hardwood, blue oak woodland, and mixed chaparral were the top three treated types by acreage (Fig. 8). The first conifer CWHR type ranked 8th by acreage and was Sierran Mixed Conifer.

3.4. CCDC-refined polygons validate intensity classification and tend to indicate smaller treatment areas than reported in agency datasets

We assessed the ability of CCDC to capture harvest disturbances by comparing polygons outputs from CCDC to documented treatments from FACTS (Table S9) and CAL FIRE (Table S10) and NAIP images between 2003 and 2019 using CEO's crowd-sourcing platform. Analysts visually assessed NAIP imagery overlain with FACTS polygons and CCDC polygons and ranked the degree of matching between the archival and algorithm polygons. Like Olofsson et al. (2016), we used a small (n = 4) research team over the course of a year to look at images. Having a small well-trained team reduces variance and increases reproducibility. Results show that about half (54.4%) of the time, CCDC detected a disturbance where there was a FACTS archival event (Table S9). Of this fraction, analysts found close matching 78.9% of the time between CCDC and FACTS polygons. For the 45.6% when there was a FACTS polygon but no CCDC-detected disturbance, the main cause was a lack of obvious disturbance in the NAIP imagery, suggesting no actual disturbance happened. For all events, analysts selected the polygon they thought best captured the extent of the disturbance. Analysts found both FACTS and CCDC had roughly equally accurate polygons 20.7% of the time. For 22.4% of all events, they ranked CCDC as more accurate than FACTS's polygons (Table S9).

Analysts repeated this procedure for CAL FIRE and CCDC polygons. The CCDC algorithm detected a disturbance a large majority (80.4%) of the time when there was a known CAL FIRE archival event (Table S10). Of this fraction, analysts found close matching between 78.1% of the CCDC and CAL FIRE polygons. For the 19.6% when there was a CAL FIRE polygon but no CCDC-detected disturbance, the main cause was a lack of obvious disturbance event in the NAIP imagery. When analysts selected the polygon they thought best captured the extent of the disturbance, they selected CCDC's polygon more than CAL FIRE's (35.4% versus 15.8%).

CCDC analysis produced four "refined" polygon datasets: refined FACTS hazardous fuels, refined FACTS timber harvests, refined CAL

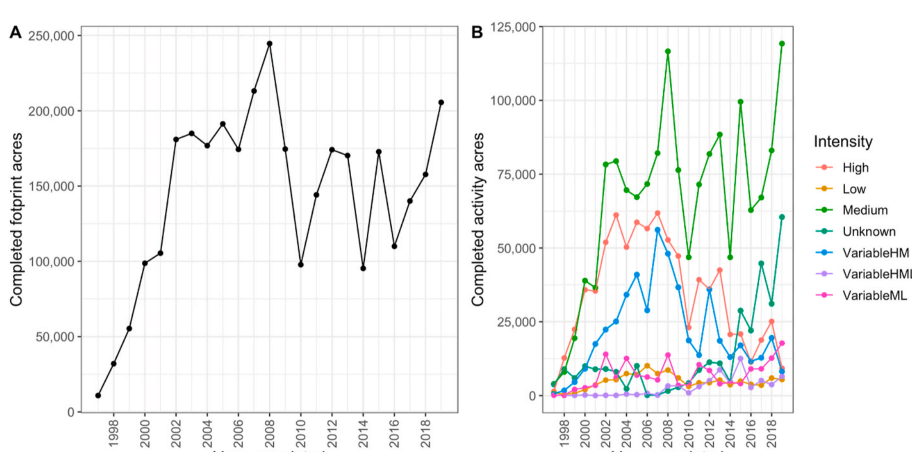

Fig. 6. In **(A)**, completed footprint acres recorded in CAL FIRE's timber harvest plans, non-industrial timber management plans, prescribed fires, and CalMAPPER data) are shown between 1997 (the beginning of timber harvest records) and 2019. In **(B)** acres are broken down by treatment intensity between 1997 and 2019.

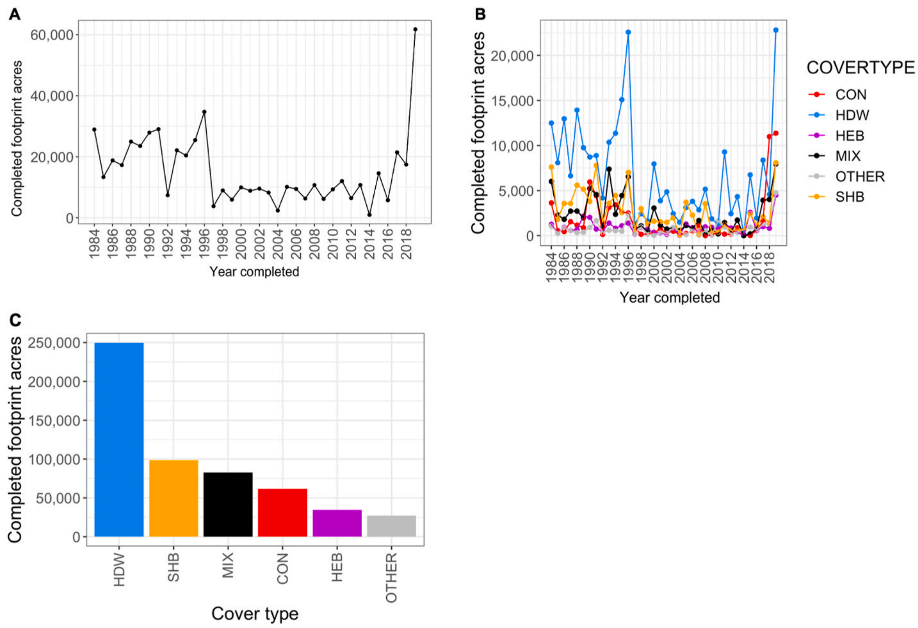

Fig. 7. Completed footprint acres of prescribed fire treatments recorded by CAL FIRE between 1984 and 2019 on **(A)** all cover types combined and **(B)** classified by cover types where CON is conifer forest (red), HDW is hardwood forest (blue), HEB is herbaceous (purple), MIX is mixed conifer and hardwood forest (black), SHB is shrub (orange), OTHER is a combined category of agriculture, water, urban, and barren (grey). **(C)** Completed footprint acres of prescribed fire carried out by CAL FIRE between 1984 and 2019 sorted by cover type; colors match **(B)**. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

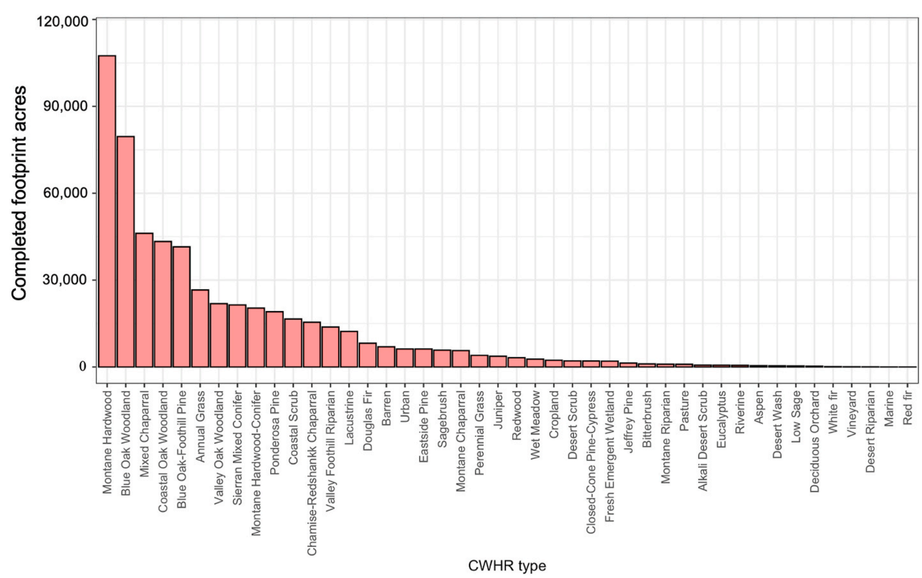

Fig. 8. The acreage of prescribed fire treatments across CWHR types from CAL FIRE's prescribed fire dataset between 1984 and 2019.

FIRE timber harvest plans, and refined CAL FIRE non-industrial timber management plans. First, we evaluated our intensity categorization using the refined CCDC data. We found areas with large remotely-sensed changes (i.e., large change magnitude in CCDC defined as greater than 0.5 reduction in NBR) were associated with high intensity treatments such as stand clear cuts, thinning, and salvages. Across all four refined datasets, the CCDC algorithm did not always detect change in areas with documented treatments in the archival data. We expected low intensity treatments (e.g., single-tree selection, fuel hazard reductions) to be more difficult to detect remotely, as CCDC is most sensitive to land disturbances that result in significant canopy removals (Wang et al. 2020, 2021). Therefore, we focused on the refinements with both an archival record and where CCDC detected a disturbance, particularly the change in polygon size (area of treatment) and the change in treatment year (treatment date).

The total treatment area of archival polygons was generally larger than CCDC-refined polygons when averaging across all years (Fig. 9A–D). However, the inter-annual variation was large. For example, the median percent change of the area refinement for FACTS polygons in the hazardous fuel dataset was −22.4%, indicating that archival polygons were larger, on average, than CCDC polygons. The first and third quartiles of percent change were −56.2% and +11.6% and shows that some years the archival and CCDC polygons matched more closely. Similarly, the area refinement for CAL FIRE's timber harvest plans was large: a median −43.8% change (Q1: 54.6% and Q3: 15.5%), depicting consistently larger archival polygon size compared to CCDC polygons. Total acreage of archival and CCDC polygons between 1997 and 2019 also indicates consistently larger archival polygons (Table 4). Lastly, the treatment date refinement was small for both FACTS and CAL FIRE data. For FACTS, the median change between the archival year and the CCDC detection year was zero years. For CAL FIRE, the median year change was +1, meaning that CCDC detection was a year before the archival year.

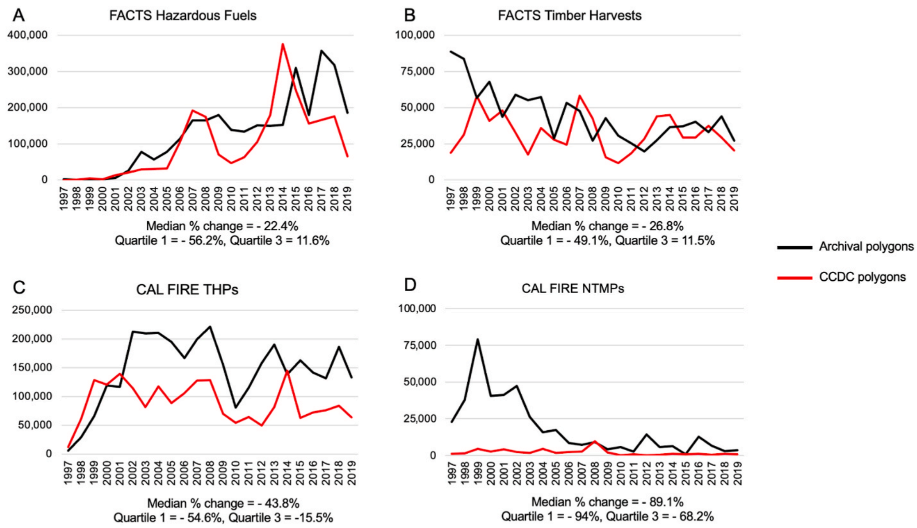

Fig. 9. Plots (A–D) show the acreage of original archival polygons (black line) and the acreage of CCDC-refined polygons (red line) between 1997 and 2019. The median percent change over each year's total acreage (i.e., the percent change between the archival area and the refined area for each year), as well as the first and third quartile, are shown below each graph. Note that 1) y-axes change, and 2) archival polygons **not** detected by CCDC were removed before plotting, thus acreage cannot be directly compared to graphs in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Quantifying the total difference in acreage of original archival polygons and the acreage of CCDC-refined polygons between 1997 and 2019. Refinements of polygon size were restricted to those events with both an archival record and where CCDC detected a disturbance.

Dataset	Archival acreage (acres)	CCDC-refined acreage (acres)	Percent change (%)
FACTS hazardous fuels	3,028,007	2,420,616	−20
FACTS timber harvests	2,088,271	1,373,857	−34
CAL FIRE timber harvest plans	3,346,645	2,212,863	−34
CAL FIRE non-industrial timber management plans	516,704	62,362	−88

4. Discussion

Keeping track of forest activity is a necessary component of effectively monitoring progress toward sustainable forest management, but activity tracking is challenging to implement across treatments and jurisdictions. In this work, we used California as a case study to understand how increased data coordination across federal and state jurisdictions can facilitate increased capacity of sustainable forest management. Specifically, this research provides an integrated dataset about silviculture, hazardous fuel reduction, and prescribed fire treatments so that California can track its progress on an ambitious joint federal-state stewardship agreement to treat one million acres annually by 2025. Integrated and refined datasets analyzed herein are publicly available on a data repository and on a forthcoming mapping tool from the California Center for Ecosystem Climate Solutions.

4.1. Quantified agency activities demonstrates the challenge posed by the 1-million acre goal

Specific advantages of our integrated database include a crosswalk of FACTS to CAL FIRE activities standardized by treatments intensity with intensity defined in terms of canopy loss. The systematic delineation between activity acres and footprint acres further enhances the interoperability of the integrated database. While retaining the ability to address agency-specific demands, it also provides for "apples-to-apples" comparisons in charting forest treatments.

A key insight from our standardization is that combined FACTS and CAL FIRE footprint acres have ranged between 175,000 and 300,000 acres completed per year since a peak in 2008 when approximately 325,000 acres were completed (Fig. 3B). This rate is, at most, 30% of the annual million-acres target for joint management if completed footprint acres are the priority. Whether or not the state will meet its forest management goal partly depends on how activities are counted, but nonetheless harmonized, comprehensive datasets will be required to evaluate progress.

Recent rates of completed footprint acres in FACTS and CAL FIRE have not surpassed the peak in 2008. However, some records in the FACTS and CAL FIRE datasets have been planned but not yet completed. These planned treatments are important to consider because they allow managers to evaluate whether enough activities are in the pipeline to meet goals. To account for planned activities, we defined **planned footprint acres** as unique areas of land where an activity has been planned (approved) anytime between 2014 and 2019 but has not yet been carried out (see supplement). We found 150,000 planned footprint acres in 2018 from both FACTS and CAL FIRE (Fig. 10); the addition of these planned acres to the completed acres is still far below the target 1-million-acre per year goal.

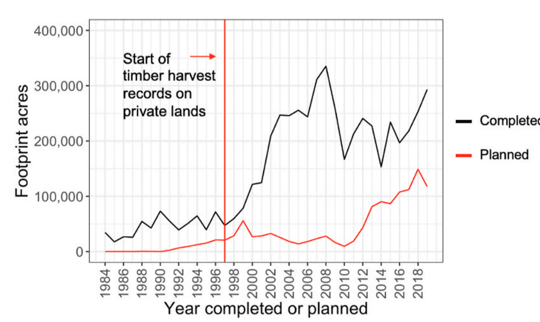

Fig. 10. The black line represents completed footprint acres from FACTS (timber harvest, hazardous fuels which includes prescribed fire) and CAL FIRE (timber harvest plans, non-industrial timber management plans, prescribed fires, and CalMAPPER data) at year completed. Note this curve is identical to Fig. 3B. The red line represented planned but not yet completed footprint acres from the aforementioned datasets, except for CalMAPPER acres which are not reported for active (i.e., planned but not completed) treatments. The red vertical line at 1997 indicates the start of timber harvest and non-industrial timber management plans records into CAL FIRE databases. Note that CAL FIRE's prescribed fire dataset dates back to 1984. Thus, the data before 1997 includes: CAL FIRE prescribed fire and FACTS data. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.2. Comparing public and private lands across treatment types, particularly prescribed burns

Treatment intensity varied between public and private lands. In general, private lands tended to implement more high and medium intensity harvests than federal forest management. This disparity may be due to several factors. First, there are distinct differences in forest policy between the state and federal regulatory frameworks. Second, economic considerations for private forest land managers may constrain implementation of low intensity harvests that provide limited financial returns. Third, national forests have dedicated fire organizations that are funded through federal appropriations to implement low intensity fuel management treatments such as prescribed fire. Medium, low, and variable intensity treatments have increased since 2003, which may reflect fuel management and uneven-aged forest management objectives on federal lands. While these medium, low, or variable treatments may meet fuel reduction objectives, they may also have shorter treatment longevity or not fully meet forest structure restoration goals thereby necessitating follow-up treatments (Fulé et al., 2006; Stephens et al., 2021).

Our tracking of prescribed fire in FACTS hazardous fuels treatments and CAL FIRE prescribed fire datasets illustrated three main points. First, almost a million footprint acres of unplanned ignitions and non-management related activities have been recorded in FACTS since 1984. Some 967,156 acres came from unplanned ignitions in four wildfire categories (wildfire fuels benefits, wildfire human ignition, wildfire natural ignition, and wildland fire use) (Table S1). The exclusion of these 967,156 unplanned ignitions acres allowed the tracking of intentional prescribed fire activities (Fig. 5). Second, CAL FIRE's prescribed fire dataset has redundancy across agencies and shows that hardwood forests and shrubs make up a large proportion of vegetation alliances treated in prescribed burns (Fig. 7B) despite increases in overall acres treated by prescribed fire (Fig. 7A). The Sierran Mixed Conifer alliance type is 8th on the rankings of treated vegetation types, behind four oak woodland alliance types and annual grassland (Fig. 8). Thus, range management settings where the primary fuel is grassland with an oak woodland overstory comprise a large amount of prescribed fire acreage. This insight is critical because the ability to maintain fire behavior and effects within a desired range differs across vegetation types. The longevity of prescribed fire is 1–2 years in grasslands and 10 years in mixed conifer and yellow pine forests because surface fuels in conifer forests (i.e., dead leaves and branches) take longer to accumulate post-fire than surface fuels in grasslands (i.e., dead grasses, Stephens et al., 2012). In general, the application of prescribed fire in conifer forests compared to grasslands is more complex, requires longer control periods, and requires more sustained personnel and resources, but is considered a high priority for forest restoration efforts (Prichard et al. In press). Third, this work also highlights the importance of prescribed fire as a growing silviculture practice. Of the total 2,345,708 footprint acres completed in FACTS and CAL FIRE between 2008 and 2019, 10.4% were prescribed fire treatments such as under burning or broadcast burning.

4.3. The influence of forest policy and historic treatments

Trends over time in the combined silviculture datasets reveal the influence of policy on forest management. For example, more timber harvests took place on private lands compared to public lands during the 2000s. This shift may be mostly due to federal efforts, such as the Northwest Forest Plan, to protect wildlife habitat of sensitive species as well as shifts in data reporting. For example, between 1997 and 2001 (Fig. 4A), there was a sustained decrease in treated acres by the USFS which coincides with policy changes to protect California's spotted owl in the early 1990s with the Northwest Forest Plan (US Fish and Wildlife 1992), as well as the formalization of new policies with the Sierra Nevada region wide planning effort following the 2001 Sierra Nevada Framework Plan Amendment (US Department of Agriculture, Forest Service, 2001). While treatments of all intensities decreased from 1990 to 1995, medium and variable high-medium-low treatment types generally increased after 2003 (Fig. 4B). This trend coincides with policy changes on national forests in the Sierra Nevada when the 2004 Record of Decision (ROD) replaced the January 2001 ROD for the Sierra Nevada Forest Plan Amendment under the rationale that the new rules allowed for higher intensity treatments to meet forest management objectives (US Department of Agriculture, Forest Service, 2004). Specifically, the 2004 decision prioritized a vegetation management strategy that was aggressive enough to reduce the risk of wildfire. Thus, there was an emphasis on installing treatments that reduced hazardous fuel conditions and limited wildfire spread (US Department of Agriculture, Forest Service, 2004).

4.4. Strengths and limitations of hybrid aerial-archival datasets: a path forward

Time series satellite remote sensing and the CCDC algorithm provide an opportunity to validate and revise archival records, as well as provide maps in areas beyond those captured by the archival databases. Analysts compared NAIP images with known archival records from FACTS and CAL FIRE and CCDC polygons. Most of the time (80.4%), CAL FIRE archival records were detected by CCDC and there was a high degree of matching among the archival polygon, the CCDC polygon, and the underlying NAIP image. In contrast, only about half (54.4%) of the FACTS archival records were detected by CCDC. There are a couple explanations for this large discrepancy. First, NAIP images are not continuous and thus not all management events were detectable from the underlying image. Analysts were also instructed to rank the accuracy of the polygons using the NAIP images as the "ground truth," but there may be errors or discontinuities in the NAIP imagery. Most crucially, CCDC may not pick up subtle disturbances on the landscape, particularly those focused on understory manipulation with minor impacts on canopy structure. Of the documented treatments that tended to not be detected by CCDC, the majority consisted of selection harvests, rehabilitation of understocked stands, machine pile burns, and commercial thinning harvests.

With the refined dataset, we examined the congruence of FACTS and CAL-FIRE records with the CCDC algorithm for two parameters: treatment date and treatment area. There was close agreement between treatment dates for both FACTS and CAL FIRE. In contrast, CCDC treatment area estimates did not match closely with FACTS or CAL FIRE archival polygons. The treatment area reported by archival records was greater than the remotely sensed areas. This divergence could be due to systemic over-estimates of treatment area in both agency's archives. Over-reporting may have occurred when uneven-aged silviculture treatments were mapped such that they filled the entire treatment footprint when in fact only a relatively small portion of the footprint was treated. The satellite-based method of identifying management area circumvents this assumption of spatial homogeneity within treatment footprints by accounting for pixel-specific disturbance histories at a 30 m spatial grain. It is therefore expected that CCDC, which is sensitive to changes on the landscape at high spatial resolution, should estimate lower total areas of management compared to FACTS or CAL FIRE.

We recognize that this discrepancy may reflect differences in the definition of what "treated acres" mean. The details of the treatment, especially with respect to whether or not surface fuels were reduced as part of the treatment (Agee and Skinner, 2005), are important. For example, an uneven-aged harvest may occur over several hundred acres, yet only a fraction of the treatment area may also receive a surface fuel reduction treatment such as pile and burn. The rest of the "treated" area may have a higher probability of high severity fire compared to before the harvest, depending on the details of how operations were conducted (Stephens and Moghaddas, 2005). To measure progress going forward, a consistent set of accounting standards along with detailed information on the location of activities is needed.

Estimating forest management areas using satellite data has advantages – for example, self-consistency across regions, precise timing based on repeat observations, and a high level of spatial detail – as well as limitations. Because remote sensing data are collected from above the trees, they are most sensitive to changes in the canopy cover and relatively insensitive to changes occurring in the understory that can be obscured by taller trees. Thus, remote sensing alone cannot account for lower intensity activities such as fuel hazard treatments that focus on reducing ladder and surface fuels. Remote sensing can improve, but not replace, the information provided by archival databases. Thus, this research demonstrates the power of multiple integrated datasets that provide complementary information.

5. Conclusion

To improve the sustainability of forests, we need to gauge the effectiveness of management interventions. Thus, environmental monitoring is fundamental to evidence-based decision-making (Noss, 1999). We used California as a case study in part because the state has detailed forest activity records from different sources (federal, state, and remotely sensed), allowing the demonstration of integrated data types that has so far been difficult in other locations (see Ceccherini et al., 2020).

We found that the integration of several databases provided a more complete accounting of efforts to reduce wildfire hazards and improve forest health. Our approach successfully leveraged the unique strengths of both remotely-sensed observations and archival datasets by producing a refined dataset. And yet these reporting efforts, even at their best, still lack essential information. Going forward, we must endeavor to avoid the "data-rich but information-poor" syndrome (Ward et al., 1986) that plagues too many monitoring programs (Lindenmayer and Likens, 2010). Additionally, this work concerning California's multi-jurisdictional forests allowed us to illustrate how disjoint datasets can be constructively compared such that pressing management questions can be answered (i.e., the 1-million-acre goal). Our work has national applications because forest activity tracking is consistent across the US, as well as international applications because combining remotely-sensed and archival data is a challenging area of active research (Ceccherini et al., 2020; Wernick et al., 2021; Picard et al., 2021).

Climate change is increasing the frequency and severity of forest disturbances like wildfire (Miller and Safford, 2012), drought (Goulden and Bales, 2019), and tree mortality (Fettig et al., 2019). This altered disturbance regime perpetuates fire management challenges for land managers in California (Stephens et al., 2018). These trends are similar to those experienced across Mediterranean vegetation types globally (Pausas and Fernández-Muñoz, 2012; Ruffault et al., 2018). Stephens et al. (2020) assert that conservation of seasonally dry forests with active fire regimes is possible if forest management activities, such as thinning and prescribed fire, are implemented at meaningful pace and scale. Consequently, robust and cross administrative boundary tracking forest management activities designed to address landscape level wildfire and drought is critical to evaluating the success of the "Shared Stewardship" approach to forest management in California. This approach may inform similar international efforts to manage Mediterranean ecosystems faced with the 21st century threat of increasing drought and wildfire interactions (Ruffault et al., 2020).

The 1-million-acre goal set by the joint federal-state stewardship agreement grew out of the widely acknowledged need to increase the pace and scale of forest restoration (Forest Management Task Force, 2021). But footprint acres treated is only a proxy for the relevant measure, namely the extent of forest area where wildfire hazard and forest resilience have been improved. The challenge is that the impacts of treatments are spatially contingent and temporally dependent. For example, fuel treatments distributed through a fraction of the forest landscape can modify fire behavior across the landscape even in areas with no treatment (Finney, 2001; Moghaddas et al., 2010; Tubbesing et al., 2019). Thus the "impact acres" can be larger than the footprint acres. Furthermore, the effect of treatments changes as the vegetation regrows and fuel loads recovers. Typically fuel treatments lose their effectiveness over time (Finney et al., 2007; Collins et al., 2011). An ideal metric of progress toward forest sustainability should be based on impact acres, but as is apparent from our example, measuring the impact is a more complex undertaking than recording acres treated. Developing monitoring frameworks that can incorporate these complexities should be a priority for future research. In the meantime, a robust and consistent account of footprint acres treated provides a straightforward means to assess contributions toward shared forest management goals.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.114083.

Credit author statement

CK: Conceptualization, Methodology, data collection/curation, performed analyses, wrote original draft and edited, made all figures/tables. RET: Methodology, wrote original draft and edited, Supervision. RY: Methodology, wrote original draft and edited. JAW: Methodology, contributed data, Validation. MG: project design/administration, provision of resources. JJB: Conceptualization, project design, edited drafts, Supervision

References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manag. 211, 83–96.

Anderegg, W.R., Trugman, A.T., Badgley, G., Anderson, C.M., Bartuska, A., Ciais, P., Cullenward, D., Field, C.B., Freeman, J., Goetz, S.J., Hicke, J.A., Huntzinger, D., Jackson, R.B., Nickerson, J., Pacala, S., Randerson, J.T., 2020. Climate-driven risks to the climate mitigation potential of forests. Science 368 (6497).

California Department of Forestry and Fire Protection Resource Management, 2021a. CalMAPPER Data. Visual access at: https://www.arcgis.com/home/webmap/viewer.html?url=https%3A%2F%2Fegis.fire.ca.gov%2Farcgis%2Frest%2Fservices%2FCalMapper%2FCalMAPPER_Public%2FFeatureServer&source=sd.

California Department of Forestry and Fire Protection Resource Management, 2021b. CA Forest Fuels and Species Conservation (FFSC MOU). Accessible at: https://egis.fire.ca.gov/portal/apps/webappviewer/index.html?id=bdc0b304b27c4d5b86fb7cbd79fa90f4.

California Department of Forestry and Fire Protection Resource Management, 2020c. Fire Perimeter Data. Accessed at: https://frap.fire.ca.gov/mapping/gis-data/.

California Department of Forestry and Fire Protection Resource Management, Forest Practice Program, 2020d. California Forest Practice Rules.

California Department of Forestry and Fire Protection, 2020a. Timber Harvest Plans. Accessed at: https://gis.data.ca.gov/datasets/d0ca5308e1e94f64b25a011c5d212cef_0.

California Department of Forestry and Fire Protection, 2020b. Non-industrial Timber Management Plans. Accessed at: https://gis.data.ca.gov/datasets/dac468487820415f82d43831ed74c1e6_0.
California Department of Forestry and Fire Protection, 2019a. CAL FIRE Fuel Breaks and Use during Fire Suppression. Fuel break design, construction, environmental protection and case studies in community protection. Accessed at: https://www.fire.ca.gov/media/5585/fuel_break_case_studies_03212019.pdf.
California Department of Forestry and Fire Protection, 2019b. California Land Ownership Dataset. Accessed at: https://gis.data.ca.gov/datasets/f73858e200634ca888b19ca8c78e3aed_0/data?geometry=-149.790%2C31.071%2C-88.750%2C43.277.
California Department of Forestry and Fire Protection, 2017. California's Forests and Rangelands: 2017 Assessment. https://frap.fire.ca.gov/media/3180/assessment2017.pdf.
California Department of Forestry and Fire Protection, 2015. Vegetation (Fveg) - CALFIRE FRAP [ds1327]. https://map.dfg.ca.gov/metadata/ds1327.html.
California Department of Fish and Wildlife, 2020. Wildlife Habitats - California Wildlife Habitat Relationships System. https://wildlife.ca.gov/Data/CWHR/Wildlife-Habitats.
Ceccherini, G., Duveiller, G., Grassi, G., Lemoine, G., Avitabile, V., Pilli, R., Cescatti, A., 2020. Abrupt increase in harvested forest area over Europe after 2015. Nature 583, 72–95.
Collins, B.M., Everett, R.G., Stephens, S.L., 2011. Impacts of fire exclusion and managed fire on forest structure in an old growth Sierra Nevada mixed-conifer forest. Ecosphere 2 article51.
Coop, J.D., Parks, S.A., Stevens-Rumann, C.S., Crausbay, S.D., Higuera, P.E., Hurteau, M.D., Tepley, A., Whitman, E., Assal, T., Collins, B.M., Davis, K.T., Dobrowski, S., Falk, D.A., Fornwalt, P.J., Fulé, P.Z., Harvey, B.J., Kane, V.R., Littlefield, C.E., Margolis, E.Q., North, M., Parisien, M.-A., Prichard, S., Rodman, K.C., 2020. Wildfire-driven forest conversion in western North American landscapes. Bioscience 70, 659–673.
Dass, P., Houlton, B.Z., Wang, Y., Warlind, D., 2018. Grasslands may be more reliable carbon sinks than forests in California. Environ. Res. Lett. 13, 074027.
FAO, 2015. Food and Agriculture Organization. Global Forest Resources Assessment 2015: How Have the World's Forests Changed? Rome, Italy. http://www.fao.org/forest-resources-assessment/past-assessments/fra-2015/en/.
Fettig, C.J., Mortenson, L.A., Bulaon, B.M., Foulk, P.B., 2019. Tree mortality following drought in the central and southern Sierra Nevada, California, US. For. Ecol. Manag. 432, 164–178.
Finney, M.A., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For. Sci. 47, 219–228.
Finney, M.A., Selia, R.C., McHugh, C.W., Ager, A.A., Bahro, B., Agee, J.K., 2007. Simulation of long-term landscape-level fuel treatment effects of large wildfires. Int. J. Wildland Fire 16, 712–727.
Forest Climate Action Team, 2018. California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate. Forest Climate Action Team, Sacramento, California, USA.
Forest Management Task Force, 2021. California's Wildfire and Forest Resilience Action Plan. https://fmtf.fire.ca.gov/media/cjwfpckz/californiawildfireandforestresilienceactionplan.pdf.
Fulé, P.Z., Covington, W.W., Stoddard, M.T., Bertolette, D., 2006. "Minimal-Impact" restoration treatments have limited effects on forest structure and fuels at Grand Canyon, USA. Restor. Ecol. 14, 357–368.
Goulden, M.L., Bales, R.C., 2019. California forest die-off linked to multi-year deep soil drying in 2012–2015 drought. Nat. Geosci. 12 (8), 632–637.
Hirsch, K., Kafka, V., Tymstra, C., McAlpine, R., Hawkes, B., Stegehuis, H., Quintilio, S., Gauthier, S., Peck, K., 2001. Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. For. Chron. 77, 357–363.
Liang, S., Hurteau, M.D., Westerling, A.L., 2017a. Potential decline in carbon carrying capacity under projected climate-wildfire interactions in the Sierra Nevada. Sci. Rep. 7.
Liang, S., Hurteau, M.D., Westerling, A.L., 2017b. Response of Sierra Nevada forests to projected climate–wildfire interactions. Global Change Biol. 23, 2016–2030.
Lindenmayer, D.B., Likens, G.E., 2010. The science and application of ecological monitoring. Biol. Conserv. 143 (6), 1317–1328.
MacDicken, K.G., 2015. Global forest resources assessment 2015: what, why and how? For. Ecol. Manag. 352, 3–8.
MacDicken, K.G., Sola, P., Hall, J.E., Sabogal, C., Tadoum, M., de Wasseige, C., 2015. Global progress toward sustainable forest management. For. Ecol. Manag. 352, 47–56.
Marchi, E., Chung, W., Visser, R., Abbas, D., Nordfjell, T., Mederski, P.S., McEwan, A., Brink, M., Laschi, A., 2018. Sustainable Forest Operations (SFO): a new paradigm in a changing world and climate. Sci. Total Environ. 634, 1385–1397.
Marcille, K.C., Morgan, T.A., McIver, C.P., Christensen, G.A., 2020. California's Forest Products Industry and Timber Harvest, 2016. Gen. Tech. Rep. PNW-GTR-994. U.S. Department of Agriculture, Forest Service, Portland, OR, p. 58. Pacific Northwest Research Station.
Masek, J.G., Vermote, E.F., Saleous, N.E., Wolfe, R., Hall, F.G., Huemmrich, K.F., Gao, F., Kutler, J., Lim, T.-K., 2006. A Landsat surface reflectance dataset for North America, 1990–2000. Geosci. Rem. Sens. Lett. IEEE 3, 68–72.
Miller, J.D., Safford, H., 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc plateau, and southern Cascades, California, USA. Fire Ecology 8, 41–57.
Moghaddas, J.J., Collins, B.M., Menning, K., Moghaddas, E.E.Y., Stephens, S.L., 2010. Fuel treatment effects on modeled landscape-level fire behavior in the northern Sierra Nevada. Can. J. For. Res. 1346, 1751–1765.
Noss, R.F., 1999. Assessing and monitoring forest biodiversity: a suggested framework and indicators. For. Ecol. Manag. 115, 135–146.
Olofsson, P., Holden, C.E., Bullock, E.L., Woodcock, C.E., 2016. Time series analysis of satellite data reveals continuous deforestation of New England since the 1980s. Environ. Res. Lett. 11 (6), 064002.
Pausas, J.G., Fernández-Muñoz, S., 2012. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. Climatic Change 110 (1), 215–226.
Picard, N., Leban, J.-M., Guehl, J.-M., Dreyer, E., Bouriaud, O., Bontemps, J.-D., Landmann, G., Colin, An, Peyron, J.-L., Marty, P., 2021. Recent increase in European forest harvests as based on area estimates not confirmed in the French case. Ann. For. Sci. 78, 9.
Prichard SJ, Hessburg PF, Hagmann K, Churchill DJ, Dobrowski S, Gray RW, Huffman D, et al. (in press). Adapting western U.S. forest to wildfires and climate change: ten misconceptions. Ecol. Appl..
QGIS Development Team, 2020. QGIS Geographic Information System. Open-Source Geospatial Foundation. Accessed in January 2020: http://qgis.org.
Ruffault, J., Curt, T., Martin-St Paul, N.K., Moron, V., Trigo, R.M., 2018. Extreme wildfire events are linked to global-change-type droughts in the northern Mediterranean. Nat. Hazards Earth Syst. Sci. 18 (3), 847–856.
Ruffault, J., Curt, T., Moron, V., Trigo, R.M., Mouillot, F., Koutsias, N., Pimont, F., Martin-StPaul, N., Barbero, R., Dupuy, J.-L., Russo, A., Belhadj-Khedher, C., 2020. Increased likelihood of heat-induced large wildfires in the Mediterranean Basin. Sci. Rep. 10 (1), 1–9.
Saah, D., Johnson, G., Ashmall, B., Tondapu, G., Tenneson, K., Patterson, M., Poortinga, A., Markert, K., Quyen, N.H., Aung, K.S., Schlichting, L., Matin, M., Uddin, K., Aryal, R.R., Dilger, J., Ellenburg, W.L., Flores-Anderson, A.I., Wiell, D., Lindquist, E., Goldstein, J., Clinton, N., Chishtie, F., 2019. Collect Earth: an online tool for systematic reference data collection in land cover and use applications. Environ. Model. Software 118, 166–171.
Safford, H.D., Stevens, J.T., 2017. Natural Range of Variation for Yellow Pine and Mixed-Conifer Forests in the Sierra Nevada, Southern Cascades, and Modoc and Inyo National Forests, California, USA. Gen. Tech. Rep. PSW- GTR-256. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, p. 229.
Stephens, S.L., Moghaddas, J.J., 2005. Silvicultural and reserve impacts on potential fire behavior and forest conservation: twenty-five years of experience from Sierra Nevada mixed conifer forests. Biol. Conserv. 125, 369–379.
Stephens, S.L., Collins, B.M., Roller, G., 2012. Fuel treatment longevity in a Sierra Nevada mixed conifer forest. For. Ecol. Manag. 285, 204–212.
Stephens, S.L., Collins, B.M., Fettig, C.J., Finney, M.A., Hoffman, C.M., Knapp, E.E., North, M.P., Safford, H., Wayman, R.B., 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. Bioscience 68 (2), 77–88.
Stephens, S.L., Westerling, A.L., Hurteau, M.D., Peery, M.Z., Schultz, C.A., Thompson, S., 2020. Fire and climate change: conserving seasonally dry forests is still possible. Front. Ecol. Environ. 18 (6), 354–360.
Stephens, S.L., Battaglia, M.A., Churchill, D.J., Collins, B.M., Coppoletta, M., Hoffman, C.M., Lydersen, J.M., North, M.P., Parsons, R.A., Ritter, S.M., Stevens, J.T., 2021. Forest restoration and fuels reduction: convergent or divergent? Bioscience 71, 85–101.
Tubbesing, C.L., Fry, D.L., Roller, G.B., Collins, B.M., Fedorova, V.A., Stephens, S.L., Battles, J.J., 2019. Strategically placed landscape fuel treatments decrease fire severity and promote recovery in the northern Sierra Nevada. For. Ecol. Manag. 436, 45–55.
UNFF, 2007. Highlights from Enabling Sustainable Forest Management: Strategies for Equitable Development, for Forests, for People. United Nations Forum on Forests. (2007). United Nations New York. http://www.un.org/esa/forests/pdf/publications/Enabling_SFM_highlights.pdf.
United Nations Department of Economic and Social Affairs, United Nations Forum on Forests Secretariat, 2021. The Global Forest Goals Report 2021: an Overview of Progress.
US Department of Agriculture, Forest Service, 2001. Sierra Nevada Framework Plan Amendment Final Environmental Impact Statement and Record of Decision. US Forest Service, Pacific Southwest Region. Vallejo, CA, USA.
US Department of Agriculture, Forest Service, 2004. Sierra Nevada Framework Plan Amendment Final Environmental Impact Statement and Record of Decision. US Forest Service, Pacific Southwest Region. Vallejo, CA, USA.
US Department of Agriculture, Forest Service, 2019a. FACTS User Guide Appendix B: Activity Codes.
United Nations Department of Economic and Social Affairs, United Nations Forum on Forests Secretariat, 2021. The Global Forest Goals Report 2021.
US Department of Agriculture, Aerial Photography Field Office, 2019b. NAIP Imagery. Accessed at: https://catalog.data.gov/dataset/national-agriculture-imagery-program-naip.
US Department of Agriculture, Forest Service, 2020a. S_USA.Activity_TimberHarvest. Accessed at: http://data.fs.usda.gov/geodata/edw/datasets.php.
US Department of Agriculture, Forest Service, 2020b. S_USA.Activity_HazFuelTrt_PL. Accessed at: http://data.fs.usda.gov/geodata/edw/datasets.php.
US Department of Agriculture, Forest Service and State of California, 2020. Agreement for Shared Stewardship of California's Forests and Rangelands.
US Fish and Wildlife Service, 1992. Final Draft Recovery Plan for the Northern Spotted Owl. USFWS, Portland, Oregon.

Vaillant, N.M., Reinhardt, E.D., 2017. An evaluation of the Forest Service Hazardous Fuels Treatment Program—are we treating enough to promote resiliency or reduce hazard? J. For. 115, 300–308.
Wang, J.A., Knight, C.A., Battles, J.J., Goulden, M., Randerson, J.T., 2020. Trends and Interactions in Land Disturbance across California from 1984-2019 from Time Series Remote Sensing. AGU Abstract.
Wang, J.A., Randerson, J.T., Goulden, M., Knight, C.A., Battles, J.J., 2021. Net Declines in California Tree Canopy Coverage Driven by Increasing Wildfire and Climate Stress submitted for publication).
Ward, R.C., Loftis, J.C., McBride, G.B., 1986. The "data-rich but information-poor" syndrome in water quality monitoring. Environ. Manag. 10, 291–297.
Wernick, I.K., Ciais, P., Fridman, J., Hogberg, P., Korhonen, K.T., Nordin, A., Kauppi, P. E., 2021. Quantifying forest change in the European Union. Nature 592, E13.
Wulder, M.A., Masek, J.G., Cohen, W.B., Loveland, T.R., Woodcock, C.E., 2012. Opening the archive: how free data has enabled the science and monitoring promise of Landsat. Rem. Sens. Environ. 122, 2–10.
Zhu, Z., Woodcock, C.E., 2014. Continuous change detection and classification of land cover using all available Landsat data. Rem. Sens. Environ. 144, 152–171.
Zhu, Z., Wang, S., Woodcock, C.E., 2015. Improvement and expansion of the Fmask algorithm: cloud, cloud shadow, and snow detection for Landsats 4–7, 8, and Sentinel 2 images. Rem. Sens. Environ. 159, 269–277.
Zhu, Z., Zhang, J., Yang, Z., Aljaddani, A.H., Cohen, W.B., Qiu, S., Zhou, C., 2020. Continuous monitoring of land disturbance based on Landsat time series. Rem. Sens. Environ. 238, 111–116.