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A novel methodology to assess fuel treatment effectiveness: application to California's forests

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ABSTRACT

Background. Fuel treatments are increasingly used to mitigate wildfire risks. **Aims.** Proposing a novel, scalable and transferable methodology, this study investigates which treatment is (more) effective at a regional scale. **Methods.** This research evaluates the effectiveness of fuel treatments in California forests using the Fuel Treatment Effectiveness Monitoring (FTEM) database, which provides a binary (yes/no) assessment of treatment efficacy based on a structured subjective evaluation process. Proposed methodology enables scaling up site-specific treatment outcomes to the regional level. **Key results.** 61% of treatment footprints that were intersected by a wildfire were effective at modifying fire behavior. Treatments that included wildland fire and/or fuel removal were more effective in modifying fire behavior (>70%) than those dominated by fuel rearrangement (49–54%). Even treatments with lower overall efficacy successfully modified fire behavior when applied at large scales. Fuel treatment effectiveness outcomes were robust under extreme weather conditions. **Conclusions.** Fuel treatments are an effective wildfire mitigation tool, even under a warming climate with intensified fire weather. The proposed methodology can be used to assess fuel treatment effectiveness in United States regions that do not have California's extensive case studies. **Implications.** The choice of treatment options needs to be carefully considered as their effectiveness widely varies.

Keywords: FACTS, forest, FTEM, fuel treatment, national scale fuel treatment efficacy assessment, resilience, risk mitigation, wildfire.

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Introduction

The anthropogenic modification of wildland vegetation has a long history in the fire-prone western United States (US). Native Americans modified landscapes to maintain and create open space, encourage wildlife habitat and forage, and enhance the growth of medicinal and culturally important plants (Van Wagtendonk *et al.* 2018; Roos *et al.* 2021; Knight *et al.* 2024). European settlement led to elimination of indigenous burning practices, vastly altering the biophysical settings, especially in areas of California and the greater Southwest (Minnich 2008). Extensive livestock grazing in mid- and low-elevation areas led to a depletion of grass, thus disrupting short-period burn intervals. A series of disastrous wildfires in that same period helped lead to a national policy of full wildfire suppression, although this was not universally seen as the most appropriate course of action (Stephens and Ruth 2005; Pyne 2015) and more recently has been demonstrated to have caused pattern shifts in fire regimes and ecosystem functionality (Parks and Abatzoglou 2020; Hagmann *et al.* 2021). These shifts have coincided with increases in critical fire weather metrics (e.g. temperature) (Westerling *et al.* 2006; Littell *et al.* 2009) and increases in anthropogenic ignitions (Balch *et al.* 2017), resulting in more severe and more destructive wildfires (Parks and Abatzoglou 2020; Modaresi Rad *et al.* 2023).

Wildland fuels (i.e. vegetation), weather and topography are the principal drivers of fire behavior. However, only fuels can be reasonably modified through landscape management actions. Since around the turn of the current century, there has been a marked increase by local, state and federal government entities to increase the impact and spatial scale of fuel management treatments to combat the effects of an ecologically misaligned fire suppression doctrine. These efforts tend to focus on both reducing wildfire risk to human interests and promoting resilient forests and rangelands (Forest Management Task Force 2021; USDA Forest Service and US Department of the Interior 2001; US Forest Service 2022). The four principles of fuel reduction within forests include (1) reduce surface fuels, (2) increase height to live crown, (3) decrease crown density, and (4) preserve large specimens of fire-resistant species (Agee and Skinner 2005). Treatment options for achieving fuel reduction include planned and unplanned wildland fire (i.e. prescribed fire and natural ignitions/wildfire) as well as mechanized equipment (e.g. hand tools or large machinery) (Prichard *et al.* 2021). The use of biological (e.g. grazing) and chemical applications is less prevalent (Van Wagtendonk *et al.* 2018). Fuel treatments are often referenced as 'fuel reduction'; however, in many cases, they include treatments that rearrange existing fuels without a removal component, thus, 'reduction' may be misleading.

Given the considerable cost of implementing hazardous fuel reduction treatments, there is substantial interest in examining their effectiveness. The range of fuel treatment options encompasses diverse goals, so assessment of their effectiveness must consider their original intended purpose (Vaillant and Reinhardt 2017; Lydersen *et al.* 2019). For example, ecological effectiveness evaluates immediate post-fire severity effects within the impacted treatment and will often include a focus on the recovery/resilience of the treated stand years after any wildfire interaction (Waltz *et al.* 2014; Stephens *et al.* 2020). Landscape-level effectiveness scales up stand-level ecological evaluations, more recently including the so-called 'shadow effects' of modification of fire behavior outside a treated stand (Finney *et al.* 2007). The effectiveness of fuel treatments that serve to provide societal risk reduction should be evaluated based on the reduction of real losses specifically within the built environment (Scott *et al.* 2016) as well as whether the treatment was tactically leveraged during the suppression response and management (Stephens *et al.* 2023). Many treatments have both ecological and risk reduction goals, and often more than one treatment is applied to a tract of land, adding to the complexity of the outcome analyses.

Fuel treatment effectiveness has largely been researched through individual case studies (e.g. Safford *et al.* 2009, 2024; Kennedy *et al.* 2019; Brodie *et al.* 2024) and systematic reviews (e.g. Cochrane *et al.* 2013; McKinney *et al.* 2022; Ott *et al.* 2023), generally demonstrating fuel treatments are effective at meeting their intent (Cochrane *et al.* 2013; Stevens-Rumann *et al.* 2013; Prichard *et al.* 2021; Davis *et al.* 2024). Individual case studies often benefit from a deep exploration into the detailed treatment combinations that were burned by wildfire, but as studies grow into larger geographies, the treatment history becomes obfuscated. This research contributes a novel method to retain the granularity of treatment combinations (hereafter referred to as 'treatment' regardless of the number of activities that occurred at the location) while evaluating the effectiveness of fuels treatments across a large geography – in this case, all National Forest System lands in California, with the potential for application in other US National Forest System lands. This bridges the scientific gap on how the sequence/combinations of multiple hazardous fuel treatments, rather than just the last treatment before wildfire, contribute to the treatment efficacy across large geographies. We did this by fusing the Forest Service Activity Tracking System (FACTS) data, which documents all land management activities (i.e. treatments), with the data in the interagency Fuel Treatment Effectiveness Monitoring system (FTEM) which flags the overlap of the most recent fuel treatment activity with a wildfire that intersects it. While FACTS includes all management activities, it also includes naturally caused wildfires that have been identified as 'meeting objectives': typically characterized as fires whose effects align with historical fire regimes (natural range of variability and/or historical range of variability). This fusion provided a regional data set of site-specific treatment sequences (also referred to as combinations throughout this paper) of fuel treatments for which effectiveness was determined. It is important to note that FTEM provides a binary (yes/no) assessment of fuel treatment efficacy based on the monitors subjective evaluation of whether the treatment altered fire behavior. Despite this limitation, the dataset supports large-scale analyses of fuel treatment effectiveness across the US. We used this data to test the following hypotheses:

1. Treatment combinations (including single treatments) contribute differently to fire behavior modification.
2. Effective modification of fire behavior is a function of treatment size and wildfire size.
3. Lack of modification of fire behavior within treatments is associated with higher fire danger.

Effectiveness of fuel treatments varies depending on vegetation type.

This research combines site-specific treatment monitoring history with large landscape-scale reporting, and to the best of our knowledge, is the first research that leverages a fused FACTS and FTEM databases to determine efficacy rates. The combination and sequencing of fuel treatments proposed herein closely matches site-specific research, supporting the utility of this binning methodology to allow for robust efficacy evaluations considering the critical need for governmental agencies to report fuel treatment effectiveness at the regional scale. While we focused our methodology on case studies from California, given the abundance of fuel treatment effectiveness studies in the state, the approach is applicable to other geographies.

Methodology

This research uses data from the FTEM application, which is an interagency module housed within the larger Interagency Fuel Treatment Decision Support System (iftdss.firenet.gov). FTEM data documents the perceived effectiveness of hazardous fuel treatments on wildfire behavior when the treatment is intersected by wildfire. As part of the FTEM data collection protocol, trained field observers record responses to multiple questions, including 'Did the fire behavior change as a result of the treatment?', which was used as our measure of effectiveness. To answer this question, field observers evaluate evidence of changed fire behavior (e.g. percent canopy scorch, canopy consumption, bole char height) from outside and within the treatment perimeter. This response is recorded as either 'yes' or 'no' providing a large dataset for non-parametric statistical analysis, though not offering any information on the magnitude of change in fire behavior.

We obtained FTEM monitoring results for treatments that were impacted by a wildfire between 2017 and 2022 on National Forest System Lands within California, US. Location of the samples used in this study are included in Supplementary Fig. S1. FTEM is a subset of the larger FACTS database in that it captures (1) only the most recent hazardous fuel treatment (i.e. a treatment which primary or secondary objective was to modify hazardous fuels) and (2) only treatments that have been intersected by wildfire. To gain the historical sequence of treatments, FTEM interactions were merged with the national FACTS database using the spatial unit identification (SUID) field attached to all hazardous fuel treatments occurring on a site from 1950 to 2022. FTEM is designed to only flag treatments for monitoring of potential effects if the treatment was completed within 10 years of intersection with wildfire. Thus, all treatments analyzed in this dataset had at least one hazardous fuel treatment within a decade of a wildfire intersecting with it. All treatments that were impacted by fires less than 0.01 acre (40 m^2) were eliminated from the analysis because they can be as insignificant as a campfire that has crept out of a fire ring. This analysis returned a total of 1621 treatments identified as hazardous fuel reduction that were also impacted by wildfires.

A total of 44 distinct fuel treatment sequences with confirmed wildfire interactions were identified within the data set (Fig. 1) and were initially merged into four categories that broadly explain how they impacted vegetation, thus crosswalking treatment sequences to generalized fuel arrangements:

1. **Fire**: treatments dominated by broadcast fire exclusively, taking the form of either prescribed fire or wildfire (natural ignitions) that met resource objectives. These treatments are assumed to consume more small-diameter and contiguous surface fuels than any mechanical treatments. Wildfires identified as fuels treatments are those with moderate behavior and effects, similar to prescribed fires. Wildfires with unacceptable effects (e.g. high severity and unacceptable canopy mortality) were excluded.
2. **Rearrangement**: treatments that rearrange the fuel structure but do not reduce the overall level of on-site biomass.

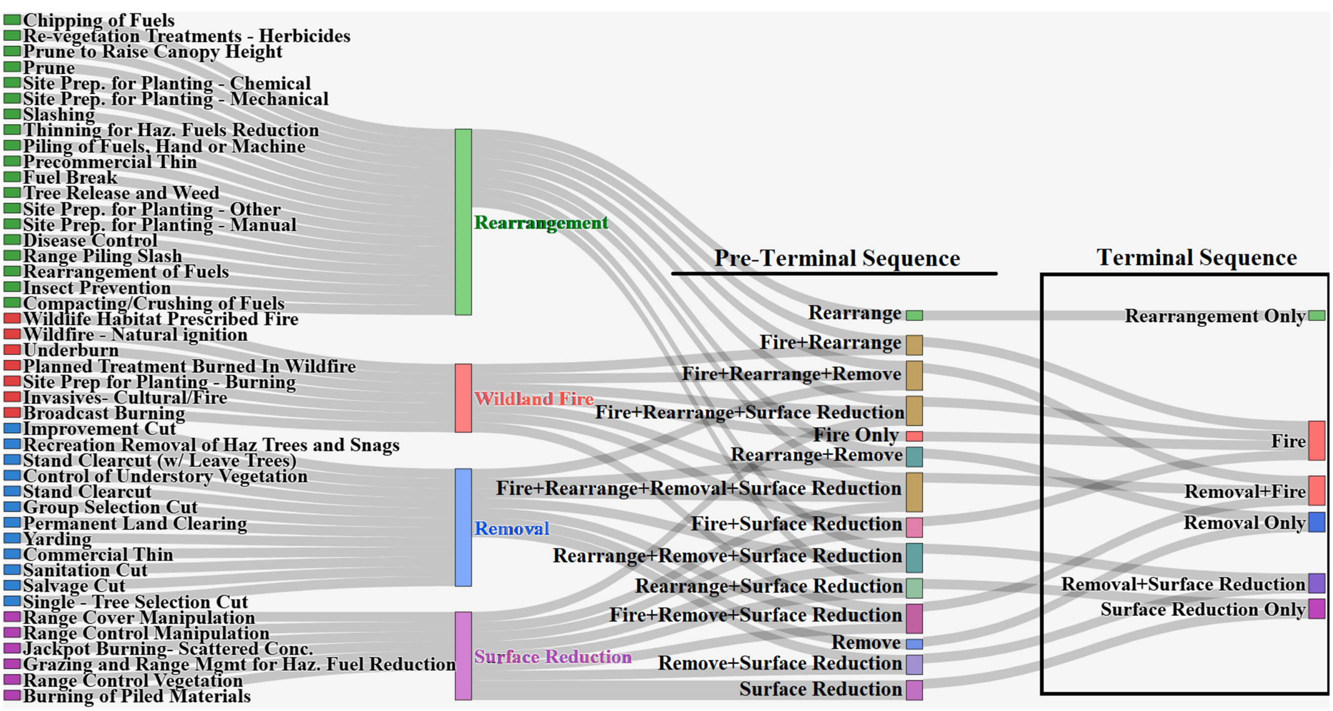

Fig. 1. Fuel treatment sequence and categorization. In a two-stem process, large number of specific treatments were categorized and combined based on their sequence, and then further combined based on the dominant characteristic of the modification of fuels.

3. **Surface Reduction**: treatments that reduce the volume of surface fuels, primarily in the larger fuel size categories, but do not include the use of broadcast fire. This group is primarily represented by pile burning and jackpot burning, where large limbs and tree boles or entire trees are collected and burned, but residual smaller branches and twigs remain.
4. **Removal**: treatments dominated by a large wood removal component, such as entire merchantable sized trees.

Treatments often include multiple entries in a logical sequence, such as felling trees, piling or removing whole or parts of the downed trees, and/or burning. Where the FACTS data identified multiple treatments had occurred, we created 14 distinct treatment classifications ('pre-terminal sequence' in the middle column of Fig. 1) to account for both singular and combined treatments. We assumed the treatments were completed in a logical order – e.g. piling of fuels (rearrangement) would happen before the piles were burned (surface reduction). We then merged these further based on the dominant characteristic of the modification of fuels into the final six 'terminal sequence' categories (right column in Fig. 1). For example, 'Fire + Rearrangement + Surface Reduction + Removal' was distilled to 'Removal + Fire' as the impacts of rearrangement and surface reduction would be eliminated by the application of fire through the system, but the impacts of removal would remain. This effectively cross-walks treatment(s) into a coarse surface fuel model.

The FTEM database also provides the date that wildfire entered the treatment unit. A variety of meso-scale weather and fire danger indices from the location and date of first intersection between wildfire and treatment, including vapor pressure deficit (VPD), energy release component (ERC) and burning index (BI) (Bradshaw *et al.* 1984), were acquired from the gridMET dataset (Abatzoglou 2013). These data were appended to the merged FTEM and FACTS database to analyze the impact of weather-related wildfire covariates on fuel treatment effectiveness.

A proportions z-test was used to determine whether treatments had a statistically significant impact on modifying wildfire behavior. An independent T-test was used to determine if the size of wildfire and fuel treatments significantly impacted the treatment effectiveness outcome. A Mann–Whitney U test was used to assess whether the distributions of weather and fire danger indices associated with fuel treatments that modified wildfire behavior were statistically different than those that did not. Finally, the Chi-squared test was used to assess whether the outcome (i.e. effectiveness ratio) of fuel treatment sequences was similar. In all tests, a P-value of 0.05 is considered the threshold for statistical significance. Expanded explanations regarding the statistical tests used in the study are included in Supplementary Section S1.

Vegetation type data was amassed by using the fuel treatment locations from FTEM intersected with the LandFire Biophysical Settings (BpS) layer (v1.4.0, 2014). Only treatments that intersected with BpS vegetation groupings annotated as conifer, hardwood or shrubland were included and analyzed using a Chi-squared test.

Results

Treatment combinations (including single treatments) contribute differently to the fire behavior modification

Using the terminal fuel sequence classification, of the 1621 treatments in our data set, 61% were documented as having modified wildfire behavior. This was statistically significant per one-sample z-test results ($P < 0.05$). The categories 'Fire', 'Removal', 'Removal + Fire' and 'Removal + Surface Reduction' significantly contributed to a modification of fire behavior (one-sample z-test $P < 0.05$, Table 1). The categories 'Fire' and 'Removal + Fire' had the highest rates of effectiveness, with 78 and 74% of cases modifying fire behavior, respectively. However, the 'Rearrangement' and 'Surface Reduction' terminal sequences did not significantly modify fire behavior (Table 1). A Chi-squared analysis showed that the effectiveness of terminal sequences varied significantly

Table 1. Effectiveness of treatment terminal sequences in modifying wildfire behavior.

Terminal sequence	Count of treatments that did not modify fire behavior	Count of treatments that modified fire behavior	Percent effectiveness (%)
Fire	**40**	**143**	**78**
Removal	**46**	**119**	**72**
Removal + Fire	**11**	**31**	**74**
Removal + Surface Reduction	**96**	**229**	**70**
Surface Reduction	238	236	49
Rearrangement	199	233	54
Total	**630**	**991**	**61**

Categories associated with a statistically significant fuel treatment effectiveness are shown in bold font.

among categories ($P < 0.05$; Table 1). Terminal sequence effectiveness ranged from 49 to 78%.

Though the terminal sequence categories in Fig. 1 and analyzed in Table 1 were designed to represent generalized treatment-fire interactions, we also analyzed differences among the pre-terminal sequences. Table 2 shows the combinations of pre-terminal sequences with a large enough sample size to meet the assumptions of a one-sample z-test ($n > 30$). Effectiveness patterns in the terminal sequence categorization analysis (Table 1) are generally reflected in the pre-terminal sequences analysis (Table 2); however, the latter analysis clarifies the drivers of lack of fire behavior modification in the terminal sequence of 'Surface Reduction'. The two pre-terminal sequences that feed into the terminal sequence of 'Surface Reduction' are 'Rearrangement + Surface Reduction' and 'Surface Reduction (only)' (Fig. 1). Pre-terminal analysis (Table 2) shows that 'Rearrangement + Surface Reduction' did not modify fire behavior, whereas 'Surface Reduction' has a significant positive modification effect. This analysis suggests that the inefficacy of the terminal sequence 'Surface Reduction' category is explained by a lack of modification of fire behavior by treatments that combine rearrangement and surface reduction. While 'Surface Reduction' treatments are expected to significantly modify fire behavior, their benefit decreases when combined with a 'Rearrangement' treatment, which may increase the amount of surface fuels prior to the 'Surface Reduction'. Adding surface fuels from rearrangement can increase fire activity, particularly under weather conditions that increase surface fuel dryness and greater unimpeded surface winds.

Effective modification of fire behavior is a function of treatment size and wildfire size

We hypothesized that larger treatments were significantly more likely to modify fire behavior than smaller treatments. We expected the success of treatments to modify fire behavior would be greater when interacting with smaller wildfires relative to larger ones.

Treatment completion acres

Statistical analysis confirmed our hypothesis that the size of treatments would differentially modify fire behavior across treatment sequences. Using a Mann–Whitney U test ($P < 0.05$), we found significant differences in the distribution of treatment sizes that did and did not modify fire behavior in the case of 'Rearrangement', 'Removal + Fire' and 'Surface Reduction' terminal sequences (Fig. 2, Table 3). As hypothesized, larger-sized treatments afforded more fire modification than smaller treatments (Table 3). Interestingly, while 'Rearrangement' and 'Surface Reduction' had not been found to significantly modify fire behavior as evaluated in hypothesis 1, evaluation of hypothesis 2 demonstrates that larger 'Rearrangement' sizes can confer effectiveness. A distribution of the frequency of size of treatments by terminal sequence is provided (Supplementary Fig. S2).

Wildfire size

Mann–Whitney U-test showed that the distribution of wildfire sizes for cases that did and did not modify fire behavior was significantly different for 'Removal', 'Removal + Fire', 'Surface Reduction' and 'Removal + Surface Reduction' terminal sequences (Fig. 3). Overall, the results did not confirm our overarching hypothesis that treatments would be more effective with smaller fires (Table 4). We acknowledge that multiple treatments might occur within one megafire, and hence, samples may not be spatially independent. Additionally, wildfire size indicates only the final outcome, and wildfire behavior (e.g. growth, intensity) at the day of interaction with fuel treatment was not assessed in this analysis. We also note that the lack of impact of wildfire sizes on fuel treatment effectiveness is not entirely unexpected given the large variation in the size of fires, with significant outliers during

Table 2. Effectiveness of pre-terminal sequences of treatments in modifying wildfire behavior.

Pre-terminal sequence	Count of treatments that did not modify fire behavior	Count of treatments that modified fire behavior	Percent effectiveness (%)
Fire	**23**	**107**	**82**
Rearrangement + Removal	**19**	**62**	**77**
Rearrangement + Removal + Surface Reduction	**80**	**174**	**69**
Rearrangement + Surface Reduction	**184**	**139**	**43**
Removal	**27**	**57**	**68**
Removal + Surface Reduction	**16**	**55**	**77**
Surface Reduction	**54**	**97**	**64**
Rearrangement	199	233	54
Total	**602**	**924**	**61**

Only preterminal sequences that met the adopted threshold for statistical analysis ($n > 30$) are reported. Those with a statistically significant fuel treatment effectiveness are shown in bold font.

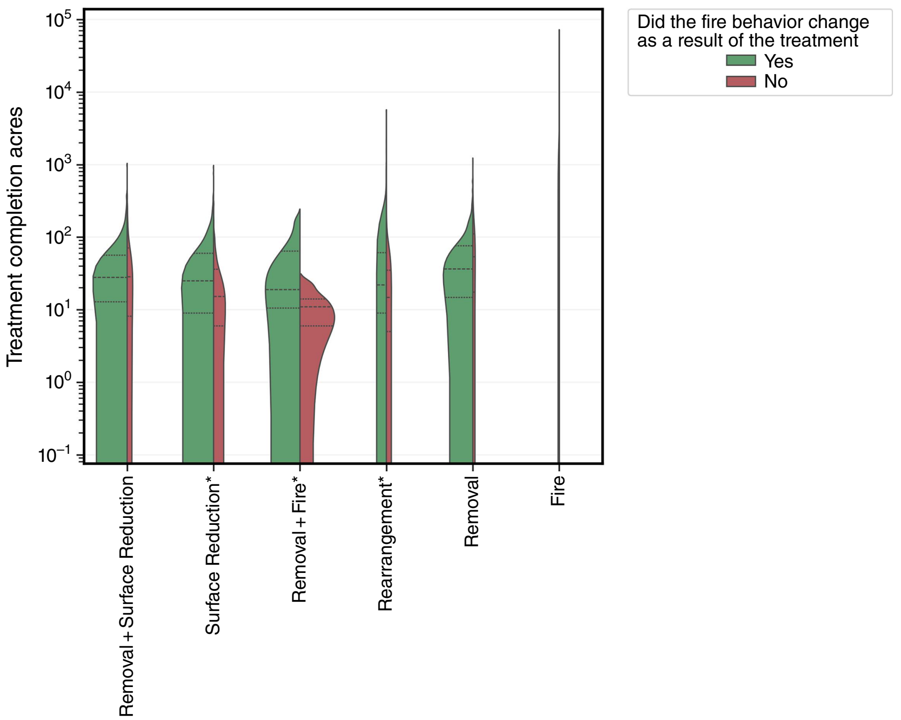

Fig. 2. Distribution of treatment sizes associated with effective (green) and ineffective (red) cases of terminal treatment sequences. Horizontal lines show median and interquartile range on each side of the violin plot. Asterisks denote significant differences in distribution. *Y*-axis is presented in log-scale.

Table 3. Mean and median treatment sizes for each terminal sequence based on treatment effectiveness.

Terminal sequence	Did treatment modify fire behavior?			
	Yes		No	
	Mean treated acres	Median treated acres	Mean treated acres	Median treated acres
Rearrangement	**97.8**	**22.0**	**47.0**	**14.8**
Removal + Fire	**48.7**	**19.0**	**11.1**	**11.0**
Surface Reduction	**53.9**	**25.0**	**29.5**	**15.3**
Fire	654.8	59.0	1851.3	55.0
Removal	63.8	36.5	105.8	53.6
Removal + Surface Reduction	53.4	28.0	56.4	28.5

Terminal sequences with significantly different distributions of acres treated are shown in bold font.

2017–2021, that could have impacted the overall analysis (see Cova *et al.* 2023).

Lack of modification of fire behavior within treatments is associated with higher fire danger days

In general, this hypothesis was not supported as results were generally mixed and did not demonstrate the expected correlation between high fire danger and lack of fuel treatment effectiveness, especially for BI and ERC (see Supplementary Section S3, Supplementary Figs S3 and S4, and Supplementary Tables S1 and S2). Distributions of VPD for cases that did (green) and did not (red) modify fire behavior were significantly different for 'Rearrangement', 'Removal + Fire', 'Removal + Surface Reduction' and 'Surface Reduction' (Fig. 4; Mann–Whitney U test $P < 0.05$). Importantly, the direction of association between fuel treatment effectiveness and extreme weather was consistent among all terminal sequences, with all ineffective cases being associated with higher mean and median VPD than effective cases (Table 5). Generally, the results of VPD were more conclusive than traditional fire danger indices of ERC and BI, implying that extreme weather might have had a fingerprint on treatments' failure to modify fire behavior, although not conclusively. Additionally, this analysis indicated that the effectiveness of 'Fire' and 'Removal' terminal sequences in modifying fire behavior was not affected by weather, and they are decisively impactful treatment choices.

Effectiveness of fuel treatments varies depending on vegetation type

Percent effectiveness was plotted as a function of general vegetation types and the terminal sequence categories (Fig. 5).

There is a significant relationship between the effectiveness of the treatment type as it relates to the vegetation type ($P < 0.05$). Sample sizes (i.e. monitored interactions) that fall below a threshold for statistical analysis ($n < 30$) have been omitted. In conifer vegetation, where all terminal

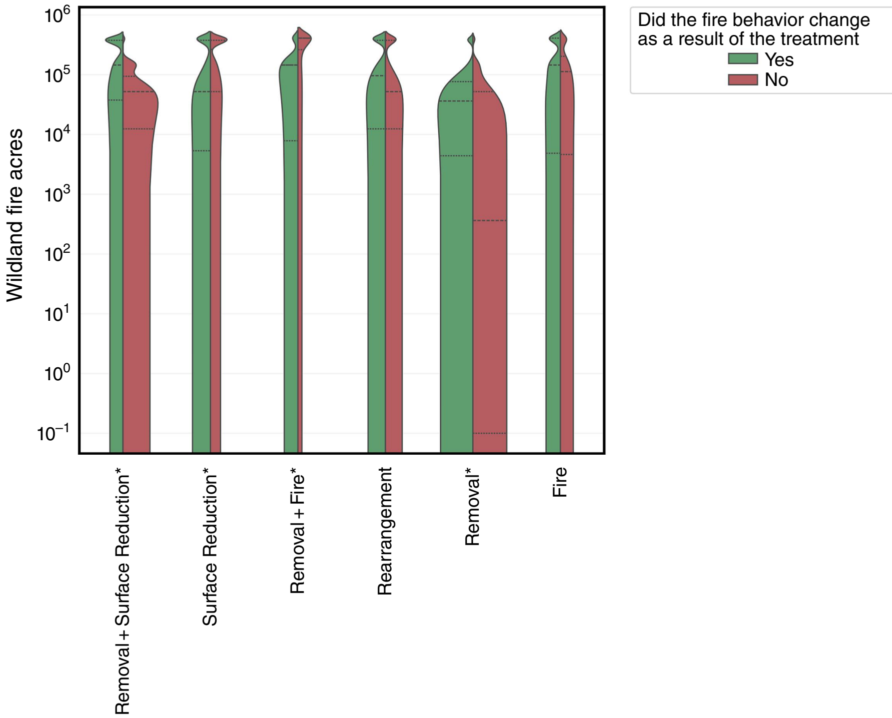

Fig. 3. Distribution of wildland fire sizes associated with effective and ineffective cases of terminal treatment sequences. Horizontal lines show median and interquartile range on each side of the violin plot. Asterisks denote significant differences in distribution. *Y*-axis is presented in log-scale.

Table 4. Mean and median wildfire sizes for each terminal sequence based on treatment effectiveness.

Terminal sequence	Did treatment modify fire behavior?			
	Yes		No	
	Mean wildfire size (acre)	Median wildfire size (acre)	Mean wildfire size (acre)	Median wildfire size (acre)
Removal	**71,086**	**36,450**	**44,437**	**366**
Removal + Fire	**136,210**	**145,632**	**310,247**	**410,203**
Surface Reduction	**174,160**	**52,498**	**225,827**	**26,7824**
Removal + Surface Reduction	**204,501**	**145,632**	**67,230**	**52,498**
Fire	172,630	145,632	140,907	113,246
Rearrangement	164,403	96,901	158,464	52,498

Terminal sequences with significantly different distributions of associated wildfires are shown in bold.

sequences are well represented, rearrangement and surface reduction treatments yield the lowest level of effectiveness of the six terminal sequences. Though lower in their representation of treatments, all terminal sequences in shrublands did effectively connote a modification of fire behavior, with 'Removal + Surface Reduction' showing the lowest effectiveness. However, results from 'Removal + Surface Reduction' and 'Removal' are influenced by a smaller sample size. While results for the hardwood vegetation show that treatments are not yielding effective modification of fire behavior, they are likely affected by small sample sizes. In line with the trends of the previous analysis, 'Rearrangement' and 'Surface Reduction' continue to demonstrate lower effectiveness rates, except in shrublands.

Discussion

Fuel treatments are designed to modify undesired fire behavior primarily to reduce risk to values and enhance fire management operational effectiveness (Moghaddas and Craggs 2007; Parks *et al.* 2015); this effort often also coincides with enhancement of ecological resilience (Finney 2001; North *et al.* 2021; Baijnath-Rodino *et al.* 2023; Wright *et al.* 2023). While previous studies on the effectiveness of fuel treatments have relied heavily on individual case studies that looked at the single most recent fire treatment or computational simulations, our approach summarizes all instances of monitored interactions across over 20 million acres of National Forest System lands in California. Conclusions were derived using a

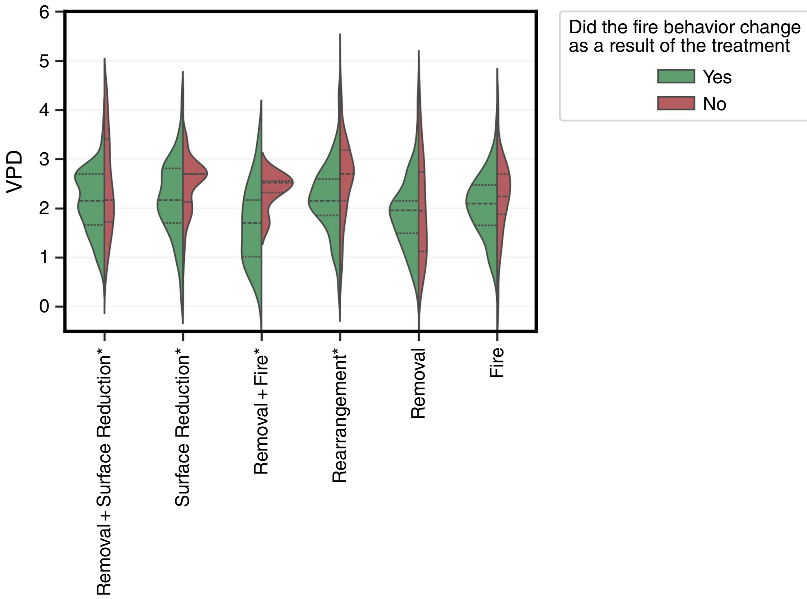

Fig. 4. Distribution of Vapor Pressure Deficit (VPD) associated with cases that did and did not modify wildfire behavior for various terminal treatment sequences. Horizontal lines show median and interquartile range on each side of the violin plot. Asterisks denote significant differences in distribution.

Table 5. Mean and median Vapor Pressure Deficit (VPD) associated with wildfires that impacted fuel treatments, categorized based on effectiveness of terminal treatment sequences.

Terminal sequence	Did treatment modify fire behavior?			
	Yes		No	
	Mean wildfire size	Median wildfire size	Mean wildfire size	Median wildfire size
Rearrangement	**2.2**	**2.2**	**2.6**	**2.7**
Removal + Fire	**1.69**	**1.7**	**2.3**	**2.5**
Removal + Surface Reduction	**2.1**	**2.2**	**2.4**	**2.2**
Surface Reduction	**2.2**	**2.2**	**2.5**	**2.7**
Fire	2.03	2.1	2.2	2.2
Removal	1.9	2.0	2.0	2.0

Terminal sequences with significantly different distributions of VPD (kPa) between effective and ineffective treatments are shown in bold font.

count of local observations of treatment success, then organized based on treatment sequence as opposed to the last, or nonspecifically referenced, treatment before wildfire. This methodology is transferable and can provide insight into fuel treatment success in regions or other large geographies that do not have as extensive a set of case studies as California.

Treatment combinations (including single treatments) contribute differently to fire behavior modification

Sixty-one percent of all treatments, regardless of type (i.e. terminal sequence category), modified fire behavior. While impressive, this value is likely an underestimation since field observers tend to have high visual expectations of fire behavior modification. Experienced observers have noted that field crews generally expect a fuel treatment to have residual green postfire or induce a dramatic change from crown fire to low severity ground fire (K. Fallon, K. Osborne, J. Fallon, pers. obs. and pers. comm.). However, subtle differences such as scorched foliage remaining on trees within the treated stand is indicative of a change in wildfire behavior (i.e. the transition from canopy to surface fire) and may be missed by novice monitors. The expectation of more visually impactful change may lead to an underreporting of effectiveness within the FTEM module. Preliminary research utilizing the terminal sequence categorization in concert with remotely sensed burn severity and FTEM monitoring data for 28 large fires across 11 states in the western US yielded a 62% effectiveness in modification of fire behavior. The agreement of the research presented in this manuscript to site-specific case studies within California and further alignment of percent effectiveness beyond California substantiates the terminal sequence categorization as a robust method for distilling treatments while retaining legacy treatment impacts.

The significant modification of fire behavior by the terminal sequences that include modification of fuels either by fire or mechanical methods (i.e. 'Fire', 'Removal', 'Removal + Fire' and 'Removal + Surface Reduction') is in alignment with the greater body of site-specific case study literature on fuel treatment effectiveness (Martinson and Omi 2003; Stephens *et al.* 2012; Parks *et al.* 2015; Kalies and Yocom Kent 2016). In a large meta-analysis, Davis *et al.* (2024) reported that prescribed fire and pile burning 'effectively reduced fire severity by 60%', which is strikingly similar to the 63% effectiveness of the 'Fire' and 'Surface Reduction' (Table 1) reported in our results. The 'Removal' terminal

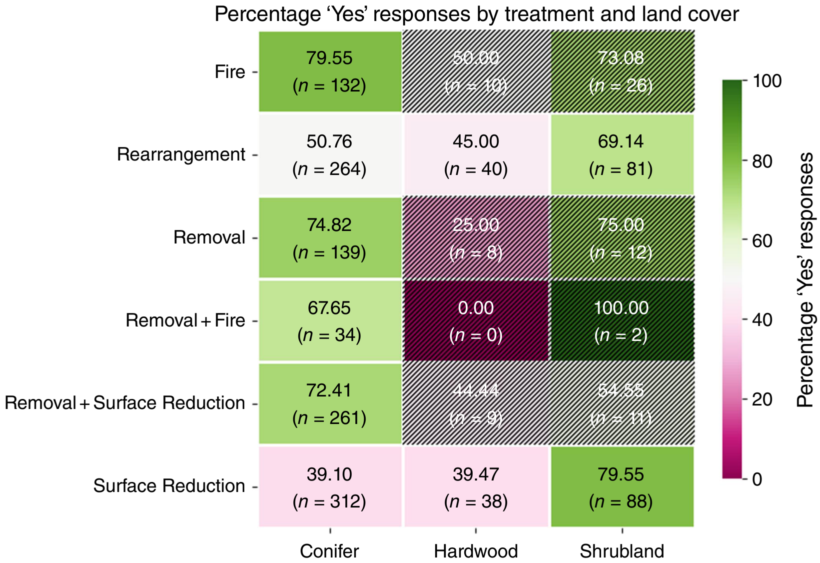

Fig. 5. Effectiveness of various terminal sequences of fuel treatment in different vegetation classes. Numbers in each cell indicate the percent 'Yes' responses to the question of whether treatment modified fire behavior with n = number of samples. Hatch denote samples where $n < 30$ and removed from statistical analyses.

sequence contains treatments that reduce fuels, but their effectiveness is dependent on the 'Removal' type (Agee and Skinner 2005). Residual activity fuels from 'Removal' projects have been shown to decrease treatment effectiveness if not followed by surface reduction treatments or prescribed burn (Raymond and Peterson 2005; Stephens and Moghaddas 2005; Fulé *et al.* 2012). Our reported efficacy of the 'Removal' terminal sequence is likely a result of the split categorization of thinning treatments between 'Rearrangement' (precommercial thinning and thinning for hazardous fuels reduction) and 'Removal' (larger wood removal projects with associated canopy reduction). This explains the seemingly contrary findings of our analysis as compared to those in the literature with respect to the efficacy of 'Removal' treatments (see Brodie *et al.* 2024; Davis *et al.* 2024). Nevertheless, the effectiveness of the 'Removal' treatment is supported through the tenets of Van Wagner principles of fire behavior (Van Wagner 1977), which suggest that the reduction of canopy fuels will reduce crown fire behavior.

Removal with subsequent prescribed fire is continually touted as one of the most effective methods for modifying fire behavior (Raymond and Peterson 2005; Prichard *et al.* 2020; Cansler *et al.* 2022; Stephens *et al.* 2024). The elevated effectiveness of 'Removal + Fire' (74%) in our study aligns with the literature; 'thin and prescribed burn' was reported to have 72% reduction of extreme fire behavior in Davis *et al.* (2024) and was found the most effective treatment combination in Brodie *et al.* (2024). 'Removal + Surface Reduction' terminal sequence had the lowest significant effectiveness in our analysis, which may be explained by the residual activity fuels (sub-merchantable trees and branches) left onsite that can carry and propagate fire. This difference between the terminal sequences of 'Removal + Fire' and 'Removal + Surface Reduction' further supports the need to evaluate 'Fire' and 'Surface Reduction' as separate treatment types and not assume surface reduction treatments (i.e. pile burning) have the same result as broadcast application of fire (Fornwalt and Rhoades 2011; Prichard *et al.* 2020). These findings highlight the need to balance finishing treatments with the increase in the pace and scale of first-entry treatments (Prichard and Kennedy 2014; Safford *et al.* 2024).

Our findings indicate that different treatment combinations have various levels of effectiveness. Analysis of the pre-terminal sequence (Fig. 1) explains some of the patterns found in the terminal sequence classification schema and elucidates the interesting impacts of rearrangement treatments. For example, in the terminal sequence classification, 'Surface Reduction Only' combines the pre-terminal sequence 'Surface Reduction' and 'Rearrangement + Surface Reduction'. 'Surface Reduction' was found to effectively modify fire behavior, but this result is muted when terminally lumped with 'Rearrangement + Surface Reduction'. Rearrangement treatments increase surface fuels and, in turn, decrease treatment effectiveness. In fact, the pre-terminal sequence 'Rearrangement' does not show effectiveness in modifying fire behavior when used alone, agreeing with a large body of research that suggests that wildfire severity may increase in areas where piles have not been burned (Safford *et al.* 2009, 2024; Hudak *et al.* 2011, however, also see Cochrane *et al.* 2013) or where mastication treatments have not been subsequently treated with fire (Knapp *et al.* 2011; Reiner *et al.* 2012; Cochrane *et al.* 2013). Additionally, our research indicates that pile burning can decrease fire behavior, agreeing with other studies (Safford *et al.* 2024).

Nevertheless, 'Rearrangement' treatments should not be discounted when combined with other treatments. As our analysis demonstrated, 'Removal' and 'Removal + Surface Reduction' do effectively modify fire behavior and offset the assumed surface fuel increase due to rearrangement. These treatments are valuable for active offensive suppression operations (Agee *et al.* 2000; Moghaddas and Craggs 2007), and masticated areas can allow for safer operational space for heavy machinery and can provide anchor points for the initiation of firing operations (Stephens *et al.* 2023). Thus, their application in and around wildland urban interfaces (WUI) should continue to be utilized as they are safe and effective operational zones for suppression resources ingress/egress and action (Cochrane *et al.* 2013).

Effective modification of fire behavior is a function of treatment size and wildfire size

Significant differences in the size distributions of effective versus ineffective treatments were observed for 'Rearrangement', 'Removal + Fire' and 'Surface Reduction' terminal sequences, but not for others. This was unexpected at first glance, as 'Rearrangement' and 'Surface Reduction' were not found to be effective in the first hypothesis, but further analysis showed that their lack of effectiveness was due to small treatment size overwhelming the statistical analysis. Effective 'Rearrangement' and 'Surface Reduction' treatments were almost twice the size of ineffective ones, suggesting that these treatments may also be effective, provided they are large enough. The size of treatments in our study was smaller than in comparative studies; for example, Prichard and Kennedy (2014) found a threshold of approximately 200 ha to lower burn severity in the 2006 Tripod Fire Complex in north-central Washington State, US. Our analysis suggests that the size of the treatment is not critical for modification of fire behavior for 'Fire', 'Removal' and 'Removal + Surface Reduction' terminal sequences; these treatments are effective regardless of their size. This contradicts findings from Jones *et al.* (2023) in chaparral systems, where the average size of the treatment was 0.11 ha and was assumed to be too small to influence fire behavior and effects. Most of our treatments were forested systems (not shrublands), and our studied treatments were, on average, an order of magnitude larger.

Anecdotal observations of large wildfires have provided evidence of both blowing through treatments and laying down when intersected with treatments. Our results were also conflicting. While 'Removal,' 'Surface Reduction,' and 'Removal + Surface Reduction' were labeled effective in larger fires, they showed a lack of effectiveness with smaller fires, counter to expected outcomes. 'Removal + Fire,' which has been established as one of the most effective treatment combinations (Stephens *et al.* 2009), did follow expectations of being effective with wildfires less than 1500 acres, but lost effectiveness in wildfires >30,000 acres. It is cautioned against taking these outcomes at face value but presented as consideration for future research avenues.

Lack of modification of fire behavior within treatments is associated with higher fire danger

Contrary to expectation, there was no discernible change in treatment effectiveness as ERC and BI increased. In fact, some treatments that failed to modify fire behavior had lower fire danger levels than the treatments that did modify fire behavior. VPD; however, was consistently and significantly higher for cases that failed to modify fire behavior as compared to the cases that did moderate fire behavior for four of the six terminal sequences. Specifically, 'Rearrangement' and 'Surface Reduction' terminal sequences failed to modify fire behavior when VPD was significantly higher, which might have impacted the analysis of hypothesis 1, which did not find these treatments to be effective.

There are likely a few contributing factors to the lack of impact of fire weather indices on fuel treatment effectiveness. Weather data were obtained from the date that the fire started, which may not be indicative of the weather at the time wildfire intersected the treatment. This can be particularly problematic for fires that had extreme growth days after the initial start; however, we chose to move forward with this analysis, understanding that many fires, particularly the bulk of the small ones, are engaged within a few operational shifts of detection. Milder fire weather indices likely afford greater success at keeping fires small, whereas fires that escape initial attack and get large often do so when initial attack fails, both of which would be during the time in which the weather metrics were obtained. Additionally, the scale of the weather data, 4 km, is too coarse for accurate attribution to fuel treatments, which can be more than an order of magnitude smaller (tens of acres) and may occur in microclimates in regions of complex terrain that are not captured by coarser-scale weather datasets. Another equally plausible consideration is that weather variables do not factor as heavily into treatment outcomes as other drivers (e.g. size of treatment, style of treatment, residual fuel loading) (Prichard and Kennedy 2014). Though speculative, the lack of correlation in fuel treatment effectiveness and fire danger may suggest that even under climate scenarios that predict an increase in extreme fire weather, treated areas may not be subjected to a corresponding increase in failure rates. This notion is also supported by other studies which show treatment robustness and efficacy in the face of high fire weather or no relationship to standard fire weather indices (Stevens-Rumann *et al.* 2013; Povak *et al.* 2020; Prichard *et al.* 2020; Brodie *et al.* 2024; Davis *et al.* 2024; however, also see Lydersen *et al.* 2017; Jones *et al.* 2023).

Effectiveness of fuel treatments varies depending on vegetation type

The relationship between vegetation types and anticipated fire behavior is well described in the literature (Miller *et al.* 2012; Keeley and Syphard 2017; Singleton *et al.* 2019; Stephens *et al.* 2022), and there is abundant case study research into the effectiveness of fuel treatments in different vegetation types. The terminal sequence methodology introduced in this research affords a broader synthesis of the effectiveness of treatment types in different vegetation types, and identifies vegetation type and treatment combinations that should be more critically evaluated prior to implementation. While we found that 'Surface Reduction' terminal treatments consistently had low effectiveness, when we accounted for vegetation classification, it became clear that the lack of effectiveness might be driven by failures within conifer and hardwood systems. 'Surface Reduction' was substantially more effective within shrubland systems. A similar pattern is found with 'Rearrangement' treatments, which appear to afford much greater effectiveness within shrubland systems as compared to conifer and hardwood systems. Our results, shadowed by a small sample size, pointed to a lack of effectiveness of all terminal treatment categories across the hardwood cover types. Research to explain this result was sparse due to the preponderance of treatment effectiveness research focused on shrubland and conifer systems. Given the societal and ecological benefits of hardwood systems (Allen-Diaz *et al.* 2007), and impacts of future climate scenarios (Kueppers and Harte 2005), we propose that research into treatments that can enhance resilience of these systems is warranted. We present these initial findings to provide fodder for more in-depth studies on the relationship between vegetation cover type and fuel treatment effectiveness so as to identify land cover appropriate treatment combinations that can be implemented efficiently.

Limitations

The FTEM data, which is a subset of the US Forest Service authoritative data set (FACTS) for treatments, is a qualitative evaluation of effectiveness given that trained observers are limited to the binary selection of 'yes' the fire behavior was modified, or 'no' it was not. Classifying a continuous response variable in this binary manner has limitations. However, our construction of questions and appropriate statistical analyses were designed to work within the limited inferences that can be made with such data. We are encouraged that the qualitatively derived results and crosswalk of fuel treatment sequences to coarse fuel model types align with quantitative studies, thus opening the door to linking quantified data sets (e.g. light detection and ranging (LiDAR) or remotely sensed data) with the qualitative data outputs.

We also acknowledge the limitations of our day-of-start derived weather indices knowing that larger fires can span multiple weeks before spread is contained. Ideally, perimeter growth maps would be used to refine this analysis. However, those maps are generally only available for large fires that have aerial support, which would be a small fraction of the fires included in this data set. Given that a substantial proportion of monitored wildfires are between 10 and 100 acres (Li and Banerjee 2021), wildfire interactions with the fuel treatments would be dominated by fires that were effectively suppressed during the first few operational shifts. Hence, weather conditions during the time of the interaction with treatment are accurately captured by the fire weather indices adopted in this study. Further, large fires are typically the product of suppression failure within the first few operational shifts, with significant growth during their initial establishment; thus, we offer that the adopted fire weather indices sufficiently represent the weather under which the monitored interactions between wildfire and fuel treatments likely occurred. While this assumption is expected to impose additional uncertainty on our analyses, the agreement of our results with site-specific case studies gives us confidence that our assumption was reasonable. Lastly, due to the limitations of FTEM data collection methodology, these results are specific to project-level analysis and are inappropriate for evaluating ecological effectiveness or risk reduction. However, the alignment of the fuels categorization schema (Fig. 1) may afford a path forward to evaluate metrics of effectiveness that were out of the scope of the current study.

It is important to consider that the treatments which comprise the 'Rearrangement' and 'Surface Reduction' (e.g. piling and burning, chipping/mastication, precommercial thinning and thinning for hazardous fuels reduction) are common treatments around WUI, and therefore may have benefitted through the addition of suppression resources that leveraged the favorable fuel conditions during initial attack. These results underscore the confounding variable of management/suppression action on the outcome and evaluation of fuel treatment effectiveness. The analysis and evaluation of the effectiveness of fuel treatments based on size is not necessarily a straightforward question based on the data used in this analysis alone. Small treatments may be entered within FTEM, as effective in smaller fires if they are aggressively and successfully suppressed; however, these same smaller treatments will likely not modify fire behavior where intersected by larger fires. Research relating treatment size to outcome should be vigilant regarding the contribution of firing operations or reinforcement by aerial support. Additionally, our research did not assess daily fire behavior impacts on fuel treatment effectiveness, as information regarding the day-to-day firing operations and locations is scant and difficult to collect from Incident Action Plans (e.g. Incident 209 forms; see Gannon *et al.* 2023). Furthermore, our analysis is blind to how active suppression tactics and incident management decisions were implemented, putting an increased burden on the treatments to be effective as stand alone. It is well established that treatments that are leveraged during suppression operations for firing or holding are more successful than treatments that are not (Green 1977; Reinhardt *et al.* 2008). Lastly, due to the overwhelming amount of small fires as compared to larger incidents, future research may benefit through the lumping of fire size categories in analysis.

Conclusion

This research offers a novel approach by blending historical fuels treatment data (FACTS) into a logical treatment categorization schema to evaluate fuel treatment effectiveness at the regional scale using monitoring information found within the FTEM database. Our methodology presents a novel and statistically substantiated crosswalk between myriad fuel treatment methods and coarse fuel models that can be used for determining treatment effectiveness. By successfully testing our methodology in California, which has a rich case study history, we showed that this methodology may apply to large geographic regions that do not have the benefit of multiple robust case studies. Our findings indicated that most fuel treatment sequences were effective in modifying fire behavior, although mere rearrangement or surface reduction treatments were less effective. Further analysis indicated that although the footprint of treatment size and wildfire size on the effectiveness of fuel treatments was minimal, larger applications of even less effective treatments can enhance treatment efficacy. Additionally, the analysis of the fire weather relationship with fuel treatment effectiveness returned inconclusive results but generally indicated a lack of impact of fire weather on fuel treatment effectiveness. These results cast optimism that regardless of wildfire size or intensification of fire weather, fuel treatments are an important management tool for increasing the resilience of landscapes in the face of an anticipated increase in wildfire activity. Future research can further refine our analyses through leveraging wildfire progression maps (see Brodie *et al.* 2024) to acquire weather and wildfire behavior data coincident with the dates that wildfires intersected with treatments. Future research may also investigate whether treatments restore historical normal fuel loads at the treated site, and also the age of treatment when intersected by wildfires, to better capture the nuances of fuel treatment effectiveness. We also suggest evaluation of other fire regime metrics that may better describe fuel treatment effectiveness, most notably high severity patch size. Finally, we quality-controlled the raw data from FACTS, specifically for coordinates of fuel treatments, but note that future quality control of this invaluable data source is warranted.

The management implications of this research are far-reaching and highlight the need for removing residual activity fuel (most effectively using fire) and focus on treatment completion through the burning of rearrangement treatments (i.e. burning piles instead of turning them into jackpots of fuel). Continued research on evaluating the vulnerabilities of rearrangement treatments, which are often the interim stage of a multi-treatment plan, would provide value to management. Further study of the dissection of data by vegetation types could also provide additional valuable information for managers to consider during the planning and implementation of fuel treatments. The analytical results presented here should be considered as one facet of the wildfire management decision space. This contribution of which fuel treatments and under what conditions, demonstrates the highest effectiveness in modifying fire behavior, is part of many considerations, including social acceptance and the cost of implementation.

Supplementary material

Supplementary material is available online.

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Data availability. FTEM and FACTS data can be accessed through: https://iftdss.firenet.gov/iftdss2/#/landing IFTDSS-Landing (Accessed 30 June 2025). GridMET is available at: https://www.climatologylab.org/gridmet.html. LandFire data are available at: https://landfire.gov/. A preprint of this paper is available on ESS Open Archive at: https://doi.org/10.22541/essoar.172590227.72370322/v1.

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