Journal of Forestry, 2023, **XX**, 1–18
https://doi.org/10.1093/jofore/fvad036
Advance access publication 14 August 2023
Research Article - fire & fuels management

OXFORD

Metrics and Considerations for Evaluating How Forest Treatments Alter Wildfire Behavior and Effects

Anthony G. Vorster,[1,*] Camille Stevens-Rumann,[2] Nicholas Young,[1] Brian Woodward,[1] Christopher Tsz Hin Choi,[1] Marin E. Chambers,[2] Antony S. Cheng,[2] Michael Caggiano,[2] Courtney Schultz,[3] Matthew Thompson,[4] Michelle Greiner,[3] Greg Aplet,[5] Robert N. Addington,[6] Mike A. Battaglia,[4] Daniel Bowker,[7] Ethan Bucholz,[8] Brian Buma,[10,9] Paul Evangelista,[1] David Huffman,[11] Stephanie Mueller,[2] Charles Rhoades,[4] William H. Romme,[1] Andrew J. Sánchez Meador,[11,12] Wade T. Tinkham,[4] Matt Tuten,[13], and Amanda West (Fordham)[1,8]

[1]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA (anthony.vorster@colostate.edu).
[2]Colorado Forest Restoration Institute, Forest and Rangeland Stewardship Department, Colorado State University, Fort Collins, CO 80523, USA.
[3]Department of Forest and Rangeland Stewardship, Colorado State University, Fort Collins, CO 80523, USA.
[4]USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO 80526, USA.
[5]The Wilderness Society, Denver, CO 80202, USA.
[6]The Nature Conservancy, Colorado Field Office, Boulder, CO 80302, USA.
[7]Coalition for the Poudre River Watershed, Fort Collins, CO 80524, USA.
[8]Colorado State Forest Service, Colorado State University, Fort Collins, CO 80523, USA.
[9]University of Colorado, Denver, CO 80204, USA.
[10]Environmental Defense Fund, Boulder, CO 80302, USA.
[11]Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011, USA.
[12]School of Forestry, Northern Arizona University, Flagstaff, AZ 86011, USA.
[13]USDA Forest Service, Pagosa Springs, CO 81147, USA.

[*]Corresponding author email: anthony.vorster@colostate.edu

Abstract

The influence of forest treatments on wildfire effects is challenging to interpret. This is, in part, because the impact forest treatments have on wildfire can be slight and variable across many factors. Effectiveness of a treatment also depends on the metric considered. We present and define human–fire interaction, fire behavior, and ecological metrics of forest treatment effects on wildfire and discuss important considerations and recommendations for evaluating treatments. We demonstrate these concepts using a case study from the Cameron Peak Fire in Colorado, USA. Pre-fire forest treatments generally, but not always, experienced reduced burn severity, particularly when surface fuels were reduced. Treatments in the Cameron Peak Fire have also been documented as increasing tree survivorship, aiding suppression efforts, promoting firefighter safety, and influencing fire spread. However, the impacts of pre-fire management on primary landscape-scale objectives, like watershed protection, are unknown. Discussions about the influence of pre-fire treatments on fire effects must define the indicator(s) being assessed, as the same treatment may be considered successful under one measure but not others. Thus, it is critical to bring a common language and understanding to conversations about treatment effects and advance efforts to evaluate the range of treatment effects, thus supporting treatment planning.

Study Implications: Forest management is critical for striving to modify large, high-severity wildfires to benefit fire suppression activities, community safety, and healthy, functioning ecosystems. Interpretation of treatment effects on wildfire and what is deemed effective requires consideration of many factors such as site and treatment characteristics, burn conditions, spatiotemporal scale, and community and management values. Assessments of treatment effects on wildfire should consider multiple metrics to identify how management is affecting a range of resources and to identify management trade-offs. Explicit identification of these metrics can improve communications and community engagement by aligning manager intentions, treatment implementation, and public expectations.

Keywords: fire management, prescribed fire, treatment effectiveness, remote sensing, wildfire

As wildfires in many forested ecosystems have increased in extent, severity, and frequency in the past several decades (Abatzoglou and Williams 2016; Higuera et al. 2021; Stephens et al. 2014), they are interacting with a variety of forest management treatments and revealing the effects of fuel-reduction treatments on wildfire impacts in the Western United States. Many studies are predicting extreme wildfire conditions will continue to increase in the coming decades (Coop et al. 2022;

Received: March 9, 2023. **Accepted:** July 14, 2023.

Riley and Loehman 2016). Given this situation, managers, researchers, community members, and policy makers grapple with where, when, and under what conditions treatments moderate wildfire behavior and ameliorate outcomes and how to improve pre-fire management actions going forward. However, there is little consistency in how forest treatments are evaluated for their effects on wildfire, both within fire-affected communities and across fire research and management communities (McKinney et al. 2022). This is especially pronounced in the face of recent large wildfires burning under extreme fire weather conditions and their interaction with often much smaller treatments.

Forest treatments are developed to accomplish a wide variety of goals, and many are not specifically intended to affect wildfire behavior. Fuel treatments, which represent a subset of forest treatments, encompass mechanical, manual, and prescribed or managed fire methods intended to reduce the total quantity or alter the vertical and horizontal arrangement of flammable vegetation (Hoffman et al. 2020; Jain et al. 2012; Reinhardt et al. 2008; Stephens et al. 2021). Fuel treatments vary greatly in their goals and objectives. For example, many of the smallest treatments are intended to provide "defensible space" with the goal of providing firefighters opportunities to protect homes and structures in the event of a wildfire, especially within the Wildland Urban Interface (WUI; Syphard et al. 2014). Fuel treatments are commonly, but not always, a component of ecological restoration projects that aim to reverse forest changes associated with historical land use and fire exclusion. Mastication treatments aim to alter fire behavior by rearranging rather than removing fuels (Battaglia et al. 2010; Jain et al. 2012; Jain et al. 2018). Many forest treatments may not have explicit goals of affecting how a wildfire interacts with a landscape (e.g., regeneration or salvage cut), yet the impacts on fuels are considered (Collins et al. 2012), and these treatments may be evaluated post hoc against various fire metrics, such as rate of spread and severity. Additionally, even when objectives are explicit regarding fire behavior, treatment intensity is often designed to affect fire behavior under certain fire weather conditions (e.g., 95% fire weather), which may or may not be the burning conditions when a wildfire interacts with a treatment. Prescribed fires and management of natural fires as a treatment often have the explicit goals of moderating future fire behavior and restoring historical forest structure and composition through surface and lower-strata fuel consumption along with low-to-moderate tree mortality (North et al. 2021). Finally, a combination of these treatments may be done in a single area, resulting in a wildfire interacting with multiple treatments. The goals and conditions for which treatments are implemented and the resulting influence on wildfires varies greatly. Fuel reduction goals sometimes drive treatment design and are secondary considerations in other scenarios. Treatments also often have tradeoffs, such as balancing fuel reduction benefits with ecological outcomes and habitat conservation. Regardless of why a treatment is initially implemented, whether it be to moderate fire behavior, restore historical ecological attributes, facilitate fire management during incidents, improve wildlife habitat, regenerate a forest, or some other purpose, all treatments have the potential to burn, and thus we consider all forest treatments that remove or modify fuels in this article.

Interpretations of forest treatment effects in moderating fire impacts, and whether treatments are deemed effective, can vary widely depending on the audience. Treatment *effects* are objective measures of the influence on wildfire parameters, whereas *effectiveness* connotes a human judgment of this effect relative to a value-based goal. News media and the public often ascribe a treatment's effectiveness to a few metrics: did treatments reduce the number of homes or high-value assets lost? Did treatments contain a fire? In contrast, firefighters may be focused on effectiveness through the lens of their ability to defend structures more efficiently or engage in suppression activities that otherwise would not have occurred (Jain et al. 2021). Meanwhile, land managers might be focused on soil impacts and associated short term watershed risks (i.e., debris flows, flooding, sedimentation, threats to drinking water supplies), as well as longer term ecosystem responses to wildfires, such as forest recovery. Interpretations of effectiveness may also change over time, as different outcomes become more or less important to the management goals of a given group.

Treatments can affect wildfires in a number of ways, including changing fire behavior and intensity, fire size, or footprint, altering impacts to ecological processes, facilitating incident operations, reducing suppression costs, and affecting the number of homes and structures lost (Agee and Skinner 2005; Kalies and Kent 2016; Thompson et al. 2013; Weatherspoon and Skinner 1996). However, quantifying the effect of treatments is complicated by the potentially minor influence relative to numerous other factors driving fire behavior, such as vegetation type, fuel arrangement and load, fire weather, topography, time of day of burning, and fire suppression efforts. In studies that look at these factors combined, the dominant influences on fire severity are often temperature, wind, and vegetation cover type (Birch et al. 2015; Evers et al. 2022; Martinson and Omi 2013; Prichard et al. 2020). Another challenge of quantifying the effect of treatments is the integration of data and processes operating at multiple spatial and temporal scales. Further, the scale of intended treatment effects varies widely. For example, some treatments are designed for local effects (e.g., defensible space around a home) whereas others may be designed for landscape effects (e.g., watershed protection). Fire behavior, typically measured as fire intensity, is commonly reduced following prescribed fire and in areas with previous fuels treatments or basal area reductions (Cansler et al. 2022; Kalies and Kent 2016; Prichard et al. 2020; Ritchie et al. 2007; Symons et al. 2008). Given these interacting factors, treatment effects are hard to quantify yet critical to understand as we are faced with growing costs and losses from wildfires (Bayham et al. 2022; Peterson et al. 2021; Steel et al. 2022; Wang et al. 2021) with increasing size and severity of these fires (Abatzoglou and Williams 2016; Stephens et al. 2014).

Evaluating treatment performance relative to stated or implicit objectives and how landscapes should be managed are topics of active research and discussion (Hessburg et al. 2021; Hood et al. 2022; McKinney et al. 2022; Sánchez et al. 2019). We add to these conversations by identifying a range of metrics to measure treatment effects on wildfire outcomes and considerations, challenges, and recommendations when evaluating and communicating about treatment effects. Here, we (1) present a framework to define metrics of treatment effects on wildfires that can be used to evaluate effectiveness of forest treatments for mitigating wildfire behavior and socioeconomic and ecological outcomes and (2) discuss important considerations and recommendations for evaluating these effects of treatments on fires.

We draw on experience and literature primarily from the western United States and use the 2020 Cameron Peak Fire in Colorado, USA, as a case study to illustrate these considerations and evaluate the multiple modalities of treatment effects. Quantifying wildfire outcomes in treated areas provides better data-driven rationale for assessing effectiveness, which can aid in setting realistic expectations for how treatments will fare when confronted by extreme fire behavior and thus inform treatment prioritization and justify costs. This framework and these considerations can guide evaluations of treatment effects and assist managers, researchers, policy makers, and the general public in developing a common language for communicating about treatment effectiveness.

Cameron Peak Fire Case Study Methods

The Cameron Peak Fire burned 84,544 ha (208,913 ac) in 2020 and became the largest wildfire in Colorado's recorded history. This fire burned from August 2020 to January 2021 with vast human impacts, including the loss of 469 structures, loss of life in postfire flooding, multiple water resources compromised, and other damage to infrastructure that is currently estimated at more than $100 million in total costs, not including the $133 million in suppression costs (National Interagency Coordination Center 2021). The Cameron Peak Fire provides many examples of where wildfires interacted with a variety of forest treatment types (figures 1 and 2). Given the costly economic and ecological impacts of this fire, it provides an excellent case study to describe the complexity of wildfire-treatment interactions and to compare a range of treatment types. Here, we use treatment databases, field data, remote sensing, and other reports to evaluate multiple metrics of treatment effects on the Cameron Peak Fire and highlight challenges associated with evaluating treatment effectiveness.

Treatment information and previous wildfire footprints within the Cameron Peak Fire were aggregated from multiple agency treatment databases. These included geographic information system (GIS) data from the 2017 Colorado Forest Restoration Institute (CFRI) Fuels Treatment Library (Mueller and Caggiano 2022), Forest Activity Tracking System (FACTS; US Forest Service 2018), the 2017 Fire History Perimeters (National Wildfire Coordinating Group 2017), the Stewardship Mapping and Reporting Tool (SMART; USDA Forest Service 2020), and the 2016 LANDFIRE Remap Public Events Geodatabase (LANDFIRE 2016). We retained stand-level treatments from SMART but removed management plan–level treatments that are often mapped to the entire property boundary rather than the management footprint itself. There were twenty-six unique treatment types (although some are very similar in practice) in the combined database. We reclassified the treatment types into eight categories to simplify the database and to identify overlapping or repeat treatments more efficiently: (1) prescribed (Rx) fire, (2)

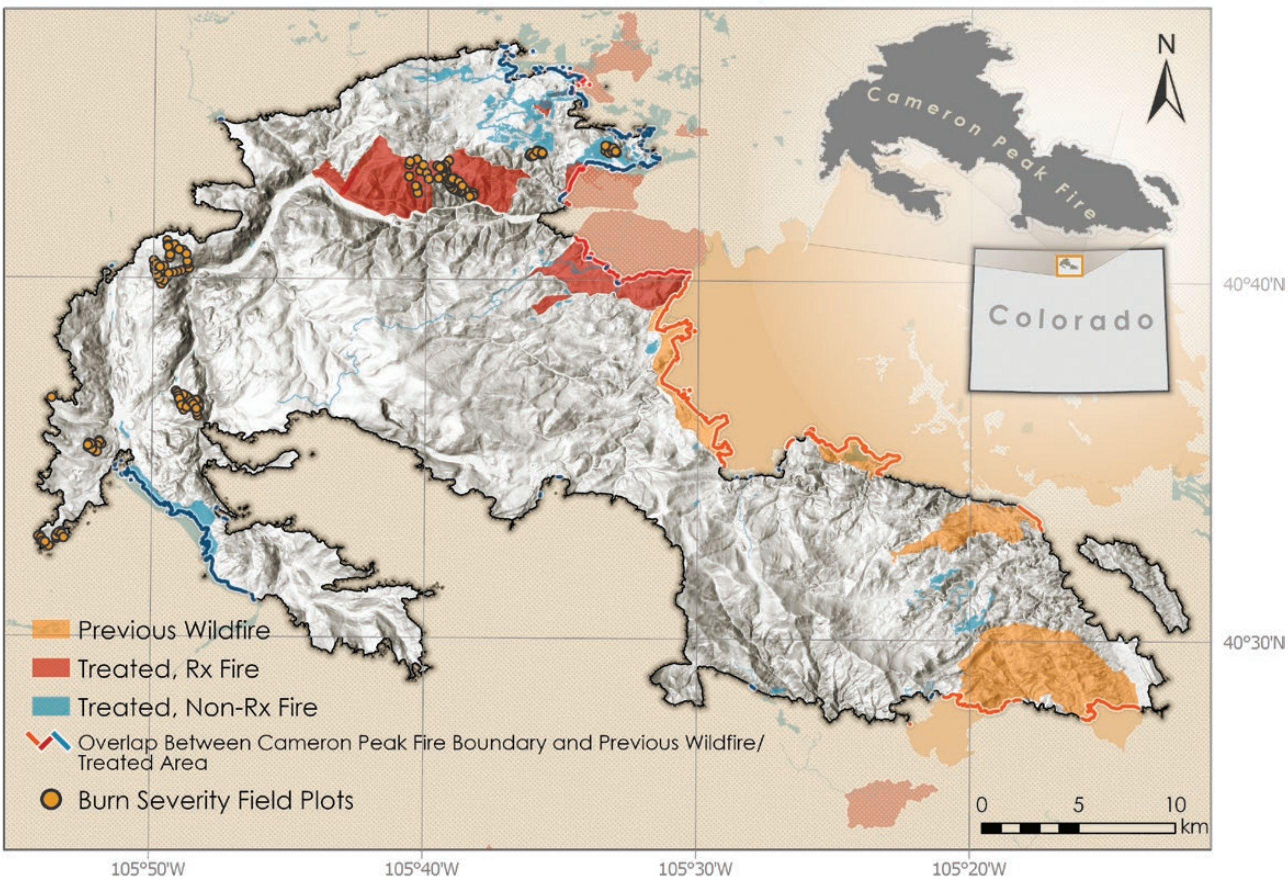

Figure 1 The 2020 Cameron Peak Fire and locations of past forest management and wildfire. A total of 6.8% of the Cameron Peak Fire footprint was recorded in the treatment database as having been managed prior to the fire. The Treated, Non-Rx Fire treatment category encompasses all treatments that were not prescribed fire for ease of visualization with figure 2 showing more detailed treatment classifications.

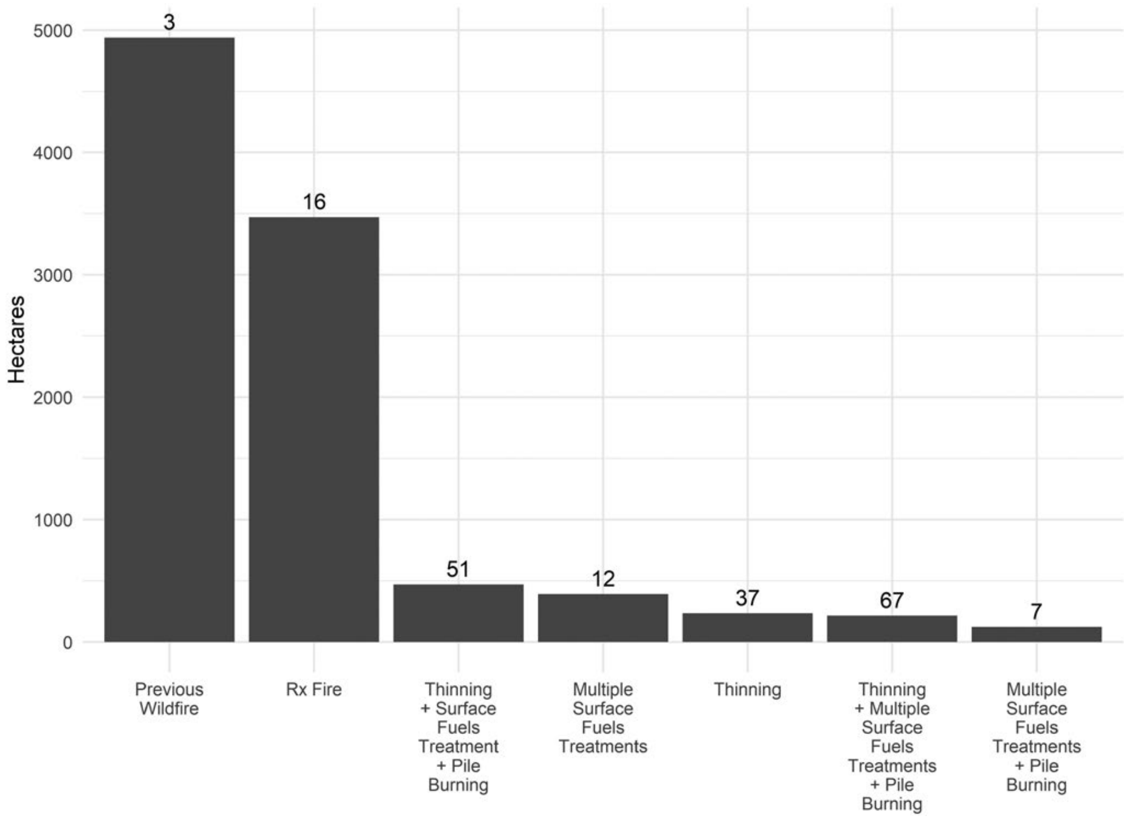

Figure 2 Area of largest treatment types (including previous wildfire) and the number of individual treatments/previous wildfires within the Cameron Peak Fire. The treated or burned area totaled about 11,000 ha (13%) of the 84,000 ha wildfire. Treatment types are only shown here that account for more than 1% of the treated area.

thinning, (3) surface fuels treatment (e.g., yarding, piling, or rearranging of fuels), (4) pile burning, (5) clearcut, (6) chipping, (7) previous wildfire, and (8) unknown (Table S1). In ArcGIS Pro v2.6.4, the intersection geoprocessing tool was used to create unique treatment polygons for spatially overlapping treatments, including repeated treatment types (Esri Inc. 2021). Overlapping treatments were joined to form treatment areas with treatment classifications that reflected the combination of treatments that occurred in those areas (e.g., Rx fire + thinning, thinning + surface fuels treatment + pile burning). Where the same treatment type was repeated in the same area, it was defined by the repeated treatment type's name preceded by "Multiple" (e.g., Multiple Surface fuel treatments). Treatments recorded in the database span from 1994 to 2020; however, fewer than ten treatments were recorded in 11 of the 13 years from 1994 to 2006, suggesting an incomplete treatment record before 2007 (Figure S1). The incomplete record before 2007 explains the seemingly illogical occurrence of some treatment types documented alone, such as pile burning (figure 3), that should only occur in this region following previous forest management. There were also very few treatments recorded in 2019 and 2020, likely because they have yet to be recorded in treatment databases. Year of treatment was missing for 19.8% of treatments, so we were unable to determine the order of implementation for overlapping treatments. The multiple types of treatments, but not the order, are retained in areas of overlapping treatment. In the Cameron Peak Fire, 6.8% of the area (5,758 ha) was documented in the treatment database as having been treated before the Cameron Peak Fire and 6.0% (5,033 ha) burned in previous wildfires from the last roughly four decades (figures 1 and 2). Prescribed fire was the most expansive pre-fire treatment (3,741 ha; figure 2).

This case study draws on field data and remotely sensed burn severity indices. We collected thirty composite burn index (CBI; Key and Benson 2006) measurements in 10 m radius plots in May and June 2021 in three focal treated and untreated paired sites to evaluate treatment effects on the Cameron Peak Fire (figure 3). Polygons were delineated in adjacent treated and untreated ponderosa pine (*Pinus ponderosa*) dominated forests with a minor component of Douglas-fir (*Pseudotsuga menziesii*), Rocky Mountain juniper (*Juniperus scopulorum*), and quaking aspen (*Populus tremuloides*). The treated and untreated polygons were created in pairs in the field, with each pair being directly adjacent to each other and having comparable slope and aspect. Locations for ten CBI plots per focal treatment (five treated and five untreated) were then randomly generated within these polygons. Treatments I and II (figure 3) were treated in 2011 as shelterwood preparatory cuts with the material yarded to the landing using a feller buncher. Treatment I has records of piles being burned in 2007, indicating that previous thinning may have also occurred on this site. Treatment III (figure 3) was thinned and slash was piled in 2009. These piles were burned in 2011.

We evaluated treatment effects on burn severity for the variety of treatments found across the Cameron Peak Fire using remote sensing. We produced maps of burn severity from a pair of sensors (Landsat 8 and Sentinel-2), testing how image dates and burn severity indices affected the agreement of these maps to the aforementioned 30 CBI plots and an

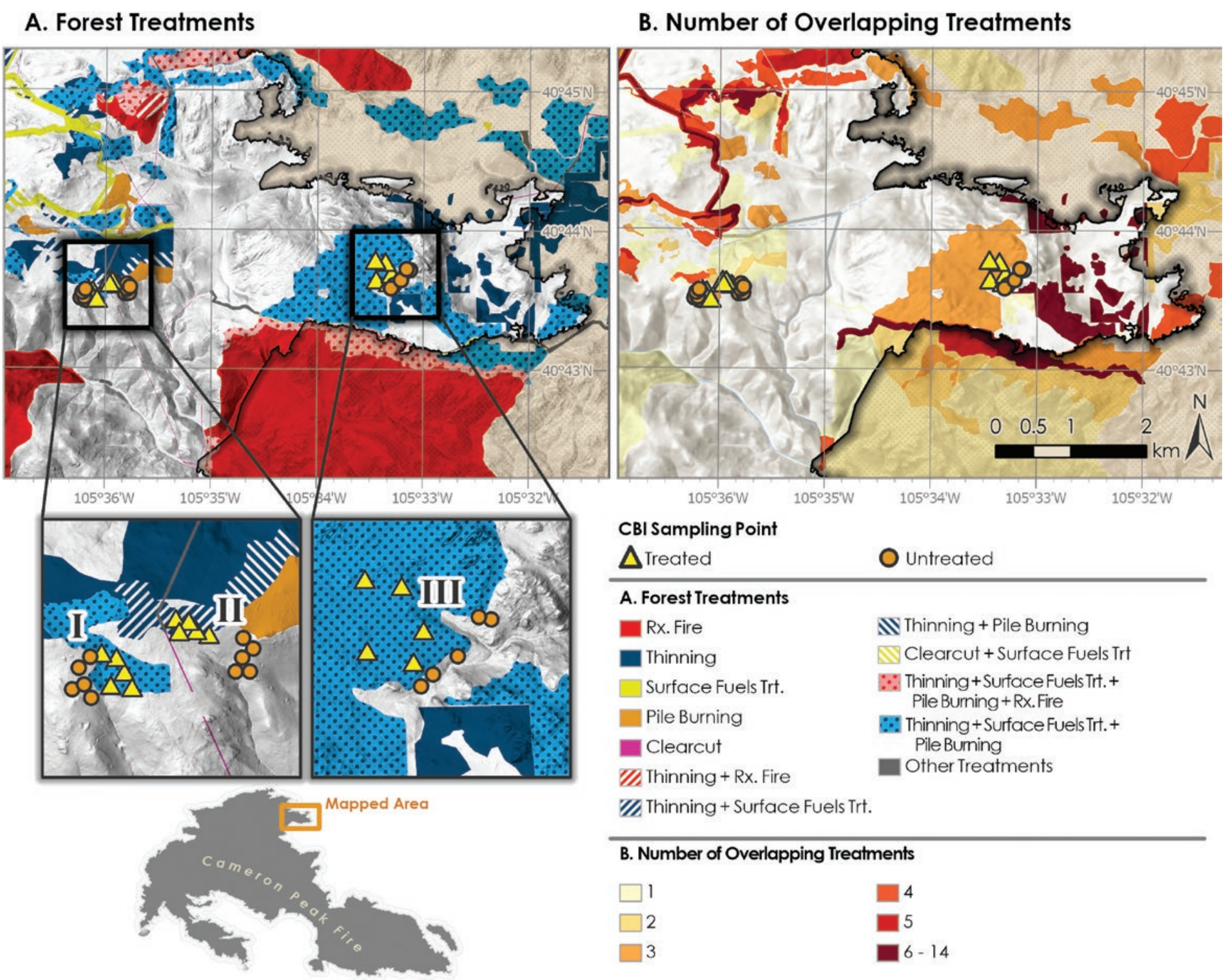

Figure 3 Past forest treatment interactions within the 2020 Cameron Peak Fire burn area. The CBI field sampling locations across focal treated (roman numerals) and untreated burned areas, which were used to assess burn severity, are also shown. A: combinations of treatments larger than 140 m^2. Each treatment type within these combinations represents either a single treatment, or repeated treatments (the same treatment occurring multiple times over the same area). B: the number of overlapping treatments, with darker areas showing the highest amount of treatment overlaps.

additional 139 CBI burn severity field plots. These additional 139 plots also had a 10 m radius and also were established during May and June 2021, but rather than being designed to compare treated and untreated areas, they were used to characterize burn severity across six focal watersheds and represent a variety of vegetation types, burn severities, and elevations (figure 1). The burn severity map with the greatest correlation to field observations, relativized burn ratio (RBR; Parks et al. 2015) generated from September 14, 2018 and September 18, 2021 Sentinel-2 MultiSpectral Instrument images, was used for analyses in this case study. The RBR and field-measured burn severity have an R^2 of 0.74.

Using R Statistical Software v4.2.1, adjacent comparable untreated areas were generated for each treated area by creating a buffer zone from 40–340 m around each treatment (R Core Team 2020; Pebesma 2018; Hijmans 2022) for comparing treated and untreated RBR values. These untreated comparison areas were generated for all treatment types that accounted for 1% or more of the Cameron Peak Fire treated area. Untreated areas were constrained to the range of existing slope and eastness and northness conditions of the corresponding treated area, with other treatments that fell in the buffer being excluded. Topographic data was derived from the Shuttle Radar Topography Mission (SRTM; NASA Jet Propulsion Laboratory 2014). Only pixels with 10% or more pre-fire canopy cover in treated and untreated areas were retained for analysis (LANDFIRE 2022). We compared RBR in treated and untreated areas with two box plots: (1) all treated and untreated pixels aggregated by treatment type and (2) the differenced mean RBR of each treatment polygon and the mean RBR of its untreated buffer, also presented by treatment type.

Interpretations of Effectiveness

Here we summarize sixteen metrics of treatment effects on wildfire that have been used in the literature or may be important during a wildfire incident itself. We have categorized the metrics into three groups: (1) human–fire interactions (Table 1), (2) fire behavior (Table 2), and (3) ecological impacts (Table 3). Tables 1–3 provide definitions, data sources, and measurements for monitoring treatment effects and example references of that metric. We selected empirical studies of treatment effects when possible rather than modeled studies.

Table 1. Human-fire interaction metrics of treatment effects on wildfire, their definition, and common measures used to evaluate the impact of treatment, and citations that use these metrics in empirical studies.

Metric	Definition	Data sources	Evaluation measurements	Citations
Human–fire interactions				
Fire suppression activities	Treatments altered firefighting actions or decisions during the wildfire event	National Incident Feature Service (NIFS) ICS-209s Fire progression maps Surveys and interviews WFDSS	Use of treatments as a control or anchor point, initial attack, structure protection opportunity, or a burn out operation Incident effectiveness and safety Incident strategy development and decision making	Kolden and Henson (2019) Bayham et al. (2020) Moghaddas and Craggs (2007) Rapp et al. (2020) Noble and Paveglio (2020) Noonan-Wright and Seielstad (2021) Greiner et al. (2022)
Fire suppression costs/ incident expenditures	Treatments changed the total cost of fire fighting activities	Suppression costs	Dollars per unit area Total costs	Belval et al. (2019) Sánchez et al. (2019)
Structure, infrastructure, and natural and cultural value damage	Treatments influenced damage to structure and infrastructure and natural and cultural values	Incident command reports Insurance assessments Community members	Number of structures lost Infrastructure damage Changes to viewsheds Recreation and cultural access closures	Sánchez et al. (2019)
Ingress and egress routes	Treatments impacted human movement during wildfire event	Surveys and interviews	Adequate evacuation, emergency services, and firefighter access	Schmidt et al. (2008) Calkin et al. (2014)

Table 2. Fire behavior metrics of treatment effects on wildfire, their definition, and common measures used to evaluate the impact of treatment, and citations that use these metrics in empirical studies.

Metric	Definition	Data sources	Evaluation measurements	Citations
Fire behavior				
Barriers, skips, and fire lines	Treatment influenced extent and/or spatial pattern of fire	Firefighter observations Remotely or aerially detected fire extent and severity	Qualitative reports Fire perimeters Remotely sensed burn severity	Parks et al. (2015) Keeley et al. (2009) Prichard et al. (2020)
Rate of spread	Treatment resulted in a localized change in fire rate of spread	Firefighter observations Remotely or aerially detected fire progression	Rate of spread Qualitative reports Ember production	Johnson and Kennedy (2019) Prichard et al. (2020) Kreye et al. (2014)
Flame length	Treatment resulted in a localized reduction in flame length	Firefighter observations Postfire tree charring	Flame height Char height	Jahdi et al. (2022) Ager et al. (2020)
Fire type	Treatment resulted in a change in dominant spread pattern (e.g., active crown fire, passive crown fire, torching, surface fire)	Firefighter observations Postfire fuel consumption and charring	Observed crown or surface fire Char height Canopy scorch Needle and branch consumption Surface fuel consumption	Safford et al. (2009) Martinson et al. (2003) Kennedy and Johnson (2014) Symons et al. (2008)

Human–fire interactions are the metrics commonly identified by news media and the public in conversations of forest treatment effects on wildfire. During and immediately postfire, the focus is often on effectiveness metrics related to lives, homes, and infrastructure lost (Table 1) with an initial focus on elements that may determine continued livelihood and resilience. Others may be primarily concerned with visual changes to the landscape and to impacts on natural and cultural values. Further, national and state policymakers query the costs of fire suppression activity, with many identifying not only the cost of suppression but the combined cost of suppression and prefire and postfire treatments and recovery efforts as being the ultimate cost (Bayham et al. 2022).

These human-fire interactions are both quantifiable values and perceptions. For example, a community may feel that a treatment improved the outcomes and protected homes, especially those on the perimeter of the fire near the final fire boundary, as was seen on the northeast corner of the Cameron Peak Fire (figure 3). Alternately, residents within the fire interior may feel like no action would have changed the outcome given the fire conditions when the fire interacted with their property. The lack of knowledge about treatments, especially on public lands, may also contribute to perceptions of a lack of forest management and thus a lack of pre-fire effort to mitigate potential community impacts. Similarly, the perceptions of high fire suppression costs, with many homes still being lost, and thus higher total costs, may correspond to

Table 3. Ecological metrics of treatment effects on wildfire, their definition, and common measures used to evaluate the impact of treatment, and citations that use these metrics in empirical studies.

Metric	Definition	Data sources	Evaluation measurements	Citations
Ecological indicators				
Soils conditions and processes	Treatment reduced soil burn severity and related impacts to soil function (e.g., water infiltration, nutrient retention, etc.)	Remote sensing and field observations of soil burn severity Biogeochemical properties Erosion Soil function Microbiome impacts	Remotely sensed burn severity Organic matter and surface fuel consumption Soil structure Soil nitrogen and carbon concentration Runoff chemistry Microbial biomass and composition Infiltration Evidence of rilling Headcutting Mass of soil eroded and accumulated	Choromanska and DeLuca (2001) Homann et al. (2011) Fultz et al. (2016)
Watershed and water impacts	Treatments altered impacts to water resources	Impacts on water quality, erosion events, hydrology, debris flows, and disruption to water supply Hillslope, stream channel, and floodplain geomorphology Riparian and wetland habitat condition	Stream channel change Streamflow amount, timing, and fluctuation Water chemistry (N, P, and metals) Sediment transport Vegetation recovery Remotely sensed burn severity of watersheds Evidence of rilling Headcutting	Jones et al. (2017) Salis et al. (2019)
Tree survival	Treatment increased tree survival	Forest inventory Remote sensing	Live trees/area Forest demographics Remotely sensed burn severity and live tree canopy	Shive et al. (2013) Agee and Skinner (2005) Stephens et al. (2012) Waltz et al. (2014) Prichard et al. (2010) Ritchie et al. (2007) Weatherspoon and Skinner (1995)
Vegetation consumption and response	Treatment impacted the amount of vegetation material consumed and its response	Remote sensing Field observations	Remotely sensed burn severity and vegetation recovery Vegetation consumption and recovery Charring Cone consumption Scorching Vegetation cover, richness, and composition	Prichard and Kennedy (2014) Springer et al. (2018) Stevens-Rumann et al. (2016)
Forest response	Treatments altered forest response or resilience	Proximity to viable seed Regeneration surveys	Distance to nearest seed source Fire severity patch metrics (size, density, shape, core) Cone consumption Seedling, sapling and sprout stems/area Cones/tree Refugia	Tubbesing et al. (2019) Roccaforte et al. (2018) Waltz et al. (2014)
Wildlife habitat	Treatment influenced how wildfire changes wildlife habitat	Wildlife census Habitat survey	Habitat suitability: food, shelter, water, space Survivorship and population connectivity	Stevens-Rumann et al. (2013)
Spatial patterns and heterogeneity	Treatments increase post-fire heterogeneity or result in landscape ecology conditions that increase resilience	Remote sensing Field observations	Patch metrics of fire severity, forest, openings, etc. (size, density, shape, core) Forest demographics Remotely sensed burn severity and vegetation recovery/structure Canopy cover and openness Snow accumulation patterns Spatial heterogeneity/homogeneity	Shive et al. (2013) Waltz et al. (2014)
Carbon storage	Treatments impacted wildfire emissions and carbon storage following wildfire	Carbon stock inventory and allocation into each pool Postfire growth rates Soil carbon loss from organic matter consumption or post-fire erosion	Biomass consumption Soil carbon Carbon stocks and their allocation into live and dead and above and belowground pools	Finkral and Evans (2008) North and Hurteau (2011) Zhang et al. (2023)

a community's sense of poor outcomes postfire (Kooistra and McCaffrey 2022).

Forest treatments can affect wildfires by facilitating incident response tactics and decision making during a fire. For instance, interviews with fire and fuel personnel revealed that existing treatments are generally used during incidents for fire assessment, staging, burnout operations, access and anchor points, and contingency plans (Greiner et al. 2022). During the Cameron Peak Fire, fuel treatments provided incident management teams greater tactical options that allowed for some improved responder safety, additional containment opportunities, and some time-saving efficiency for fire crews (Greiner et al. 2022). How treatments are incorporated into strategic and tactical decisions during fires is not well captured in databases designed to document the performance of burned treatments, such as the Fuel Treatment Effectiveness Monitoring application.

Second, treatments may affect fire behavior by altering rate of spread, increasing or decreasing flame length, and creating fire barriers or fire lines (Table 2). Influencing fire behavior is the mechanism for many of the human–fire interactions and ecological impacts. Efforts to stop, slow, and influence wildfires are often concentrated in human-inhabited areas. These treatment effects are often witnessed by firefighters, incident command teams, or may be measured postfire. For example, firefighters may observe a decrease in flame lengths or a transition from a crown fire to a surface fire as the active fire interacts with a treatment, but these could also be observed by quantifying crown scorch or bole char height once the fire is extinguished (Kennedy and Johnson 2014; Martinson and Omi 2013). Assessments of changes in fire behavior are often made using metrics of burn severity or postfire field assessments of burning conditions, as intensity during a wildfire is difficult to assess systematically in multiple locations.

Finally, we can assess treatment impacts on a number of postfire ecological metrics (Table 3). There are many time steps postfire where ecological effects can be observed and studied depending on the indicator (see Scale section). Some ecological metrics are commonly considered when evaluating treatment effects (i.e., tree survival, vegetation consumption and response), whereas others are rarely quantified empirically (soils conditions and processes, wildlife, watershed and water impacts; Kalies and Kent 2016). The tools needed to monitor certain ecological effects, such as changes to ecosystem carbon and the soil microbiome, are a challenge for current science. Further research in these fields is critical to fully understand ecological implications of treatments.

Considerations When Evaluating Treatment Effects

The current discussions and research about treatment effectiveness underscore that measuring, interpreting, and communicating treatment effects on goals and wildfire outcomes is challenging due to the many nuanced contextual factors at play during a wildfire (Hood et al., 2022; Jain et al. 2021; Kalies and Kent 2016; McKinney et al. 2022; Sánchez et al. 2019). The effect of treatment is difficult to disentangle from the many other factors influencing fire behavior (e.g., Prichard et al. 2020). Further, the challenges of evaluating treatment effects propagate into additional challenges communicating within and between groups such as forest managers, the general public, researchers, and policymakers. Below, we summarize considerations when evaluating treatment effectiveness and demonstrate these with Cameron Peak Fire examples to improve applied research and communications. Acknowledging and addressing these considerations can improve the design and implementation of forest treatments, advance forest science, inform forest policy, and promote public understanding and support.

There are limitations regarding how and under what conditions a treatment can modify fire behavior, especially in the most extreme fire weather conditions. For example, treatments designed to reduce crown fire under 95th percentile fire weather conditions may not be deemed a failure for carrying crown fire during 99th percentile conditions. These conditions can change from day to day and hour to hour, and thus vary even within a single fire footprint. Several studies have found treatments to be the most effective in moderating fire behavior on the flanks of a fire or during days of less fire spread and mild to moderate fire weather (Davim et al. 2021; Prichard et al. 2020). Rain and snow during the Cameron Peak Fire enhanced the mitigation effects of a previous wildfire (the 2012 High Park Fire), which moderated fire behavior and allowed for more effective suppression efforts (Caggiano et al. 2021). On the other hand, mechanical treatments that burned under extreme weather conditions and that were oriented parallel to the direction of fire spread were unable to contain the fire (Caggiano et al. 2021). As burning conditions become more extreme under an increasingly favorable climate for fire (Coop et al. 2022; Taylor et al. 2022), more treatments may experience fire weather conditions beyond the thresholds for which they were designed, in turn leading to reduced effectiveness or perceptions thereof.

Site and Treatment Characteristics

The metrics of treatment effects on wildfire (Tables 1–3) can be applied across diverse contexts, but the determination of what is and is not considered effective requires an understanding of site-specific criteria, such as forest type and treatment type. Forest type and the associated disturbance and utilization regimes inform treatment need and design and influences interpretations of treatment effectiveness. For example, many treatments in the western United States have focused on frequent fire forests with fire resistant traits, such as the ponderosa pine forests at the lower elevations of the Cameron Peak Fire (Kalies and Kent 2016). Thus, the goal in these forests is often persistence of forest cover resulting in treatments aimed to promote tree survivorship and spatial heterogeneity by reducing fuel loads and ladder fuels and retaining the most fire-resistant individuals in patches of varying sizes. Alternatively, complete overstory mortality may be acceptable in some forest types even within treatments. This was the case in the Cameron Peak Fire with resprouting species like quaking aspen or semi-serotinous species like lodgepole pine (*Pinus contorta*) as long as viable root or seed source remains to regenerate the site. Further, treatment type (i.e., thinning, mastication, prescribed fire) and surface fuel loading or management method (i.e., lop and scatter, whole tree harvest, fall or spring burns) and their interaction with forest types can alter effectiveness. Finally, the treatment objectives need to be considered when evaluating the effectiveness of a treatment. Although most forest treatments modify fuels, not all these treatments have fuel reduction as an objective.

There is considerable heterogeneity in stand structure and fuel loading across treatments, within treatment types, and with various times since treatment. Johnson and Kennedy (2019) demonstrated this with findings showing substantial variability in stand structures, and thus fire interactions, between the same broad treatment type, in this case "thinning" (figure 4). Treatment type and implementation interact with site factors to influence the timeframe that treatments can be expected to mitigate fire effects (Skinner 2005; Stephens et al. 2012; Tinkham et al. 2016). Treatments differ in terms of their size, intensity, location on the landscape relative to topographic features and other treatments, and degree of fuel removal (i.e., mastication and chipping generally redistribute fuel, whereas whole tree logging and prescribed fire both remove and redistribute fuels). Prescribed fire is another treatment that results in a wide range of fuel and structure conditions within a single treatment type. Hunter and Robles (2020) provide a recent review on prescribed fire effectiveness and variability. Even treatments with specific goals of mitigating fire behavior may have additional goals, such as improving wildlife habitat, resulting in retention of some understory and ladder fuels (Knapp et al. 2009). Further, all treatments are constrained by pretreatment forest structure, thus dictating the range of posttreatment conditions that can be created. For example, whereas a thinning treatment in primary forests has the luxury of retaining large fire-resistant trees, a thinning in secondary forests may not have this option and thus may only retain smaller trees more sensitive to fire (Symons et al. 2008). These site and treatment characteristics influence treatment effects on wildfire and interpretations of what is considered effective, yet information about these details is difficult to locate and often absent from treatment databases (more on this in the Attribution of Treatment Effect and Data Complexity section). Previous wildfire can moderate fire behavior, as exemplified by the 2012 High Park Fire during the Cameron Peak Fire (Caggiano et al. 2021). However, in other contexts, previous wildfires can readily reburn, with severity patterns echoing previous burn severities and varying by vegetation type and time since fire (Taylor et al. 2021; Taylor et al. 2022).

Scale

Scale is central to evaluations of treatment effects on wildfire. Metrics are assessed at different spatial and temporal scales, and many metrics can be assessed at multiple scales. For example, analyses of soil conditions and processes may be necessary immediately postfire as managers grapple with the need to conduct hillslope stabilization efforts; however, understanding long-term sediment loads and impacts of biogeochemical processes and the microbiome may be necessary at the decadal scale. Similarly, numerous studies across the western United States demonstrate that treatments that include fire as a component, either previous wildfires, prescribed fire, or thinning and burning, are effective at decreasing remotely sensed burn severity, and these data are available in the months following a wildfire (Hessburg et al. 2015; Kalies and Kent 2016; Martinson and Omi 2013; Prichard et al. 2010; Prichard et al. 2020; Stephens et al. 2012). Although some metrics of vegetation community response may be evident in the years immediately following fire (e.g., tree survival), vegetation response in some contexts may only be available on the order of decades or centuries postfire, depending on the life history traits of the species making up a forest, and may vary from initial measures of severity depending on fire adaptation traits. Attributing vegetation community response to pre-fire treatments is further complicated by the influence of postfire management, climate, and subsequent disturbances. Human-fire and ecological metrics of effectiveness continue to change years after a fire (Roccaforte et al. 2018).

The success of a treatment is also dependent on spatial scale. The scale of treatment impact should be reported relative to the broader landscape or burned area. Some groups, such as homeowners whose houses were spared by the fire, may consider localized treatment impacts effective. Others may define success as having desirable impacts on a landscape scale. Certain metrics are naturally assessed at broader scales, like an entire fire (e.g., suppression costs), or smaller scales (e.g., flame length). Further, treatment effects can be evaluated within (e.g., increasing tree survival within the treatment) or beyond the boundary of an actual treatment (e.g., protecting structures adjacent to treatments). Evaluating these treatment effects at landscape scales becomes increasingly difficult and often requires simulation models (Hood et al. 2022; Jain et al. 2021).

Watershed and water impact metrics illustrate challenges associated with scale and evaluation of landscape-scale treatment effects. As is commonly the case in the western United States, watershed and water supply protection were a motivation for many treatments in the Cameron Peak Fire. Monitoring and research are underway to understand impacts of the fire on watersheds and water quality and quantity. But teasing out the role of pre-fire treatments in

Figure 4 Three thinning treatments resulting in a variety of forest structures, but that all receive the same classification in most treatment databases. Photos taken by Mike Battaglia.

the postfire water response is another challenge altogether. Treatment effects are commonly measured on the treated hillslopes, whereas watershed impacts are often measured in streams draining much larger areas that may only have a fraction of the watershed treated. The effectiveness of a treatment for mitigating fire effects on water also depends on other postfire processes operating at different spatial and temporal scales like vegetation recovery and weather. Although treatments may be deemed effective at mitigating postfire watershed impacts after moderate intensity rainfall, these same treatments may not protect water values under a more severe rainfall event.

Considering Multiple Metrics

Assessing multiple modalities of treatment effects is complicated because the metrics are often assessed at different spatial and temporal scales and require different expertise and study designs. Considering multiple treatment effects that are related is more common than studies that cross-cut human–fire interactions, fire behavior, and ecological metrics. Furthermore, treatment effects are heterogeneous between and within treatments, making it challenging to label treatments simply as effective or ineffective for a given metric. Rather, the range of treatment outcomes must be characterized and associated with other driving factors (e.g., weather, topography, proximity to natural fuel breaks) to identify under which conditions treatments were effective. The influence of treatment may be obvious in some locations and for some metrics of effectiveness, nonexistent in others, and more nuanced in other cases. For example, several thinning and pile burn treatments on the northeast edge of the Cameron Peak Fire coincided with the perimeter of the fire (figure 3; immediately northeast of 40°44' N, 105°32' W). These treatments were implemented with the objectives of creating a shaded fuel break to provide opportunity for firefighters to engage a fire and to reduce the movement of fire through the canopy. The weather conditions were less extreme and the treatment accomplished its objective of allowing firefighters to establish fire lines in these treatments. This combination of conditions resulted in the treatments being effective under the lens of multiple metrics: serving as a location for suppression activities and as a barrier. Another thinning treatment (figure 3; focal treatment III) lies just west of the fire perimeter where the fire burned through these treatments. They did not serve as a barrier but may have contributed to the fire behavior conditions that allowed construction of a fire line nearby and, based on field measurements, these treatments did reduce tree mortality and burn severity (figure 5) compared with adjacent untreated areas. This example illustrates the importance of interactions with suppression activities, weather context, and potential treatment effects in aggregate.

Attribution of Treatment Effect and Data Complexity

Attributing the role of treatments on wildfire behavior and effects requires diverse data sources, and the needed information is often incomplete or unavailable. This challenge is demonstrated by questions regarding the extent to which pre-fire treatments helped contain the Cameron Peak Fire. Although only 3% of the Cameron Peak Fire area received treatments other than prescribed fire, 8% of the fire perimeter overlapped with these treatments (Table 4). This suggests that these treatments may have been effective as fire barriers. However, as is commonly the case, these treatments tend to fall along roads, which makes it challenging to determine post hoc the relative importance of treatment, road, fire suppression, or other factors in containing the fire without eyewitness accounts.

Attribution of treatment effect is typically addressed for fire behavior and ecological metrics of effectiveness by pairing nearby treated and untreated sites that ideally only differ in their treatment history. This approach has the advantage of being able to directly compare many metrics of effectiveness but often uses time-intensive field measurements. Locating neighboring suitable comparisons of treated and untreated forest can be prone to bias and difficult, as treatment boundaries often coincide with changes in topography, forest structure, or land ownership. Similarly, treated versus nontreated areas may experience the wildfire at different times and thus different burning conditions.

Another approach to evaluating treatment effectiveness is by examining effects across many treatments and including other influential variables. This is typically done with GIS and geospatial analyses (Prichard and Kennedy 2014; Stevens-Rumann et al. 2016), which allow efficient analyses across large areas and a range of treatment, forest, and fire conditions. In the Cameron Peak Fire, comparing remotely sensed burn severities (RBR) across treatment types shows treatments that included fire (prescribed fire or pile burning) or surface fuels management tended to have greater reductions in burn severity than comparable untreated areas (figure 6). Although thinning alone sometimes had higher burn severity and sometimes had lower burn severity than untreated areas, the median response was slightly reduced burn severity. Previously burned areas had the lowest burn severity and showed the greatest reduction in burn severity when compared with nearby untreated areas (figure 6).

However, the remotely sensed burn severity images central to these analyses introduce uncertainties of their own. In one case on a different wildfire, we observed treatment differences in burn severity that were exaggerated by remote sensing, likely because the pre-fire spectral values differ between treated and untreated areas and because of differences in the timing of data collection between remotely sensed and field measured burn severity (Vorster et al., unpublished data). In the Cameron Peak Fire, the thinned plots we sampled burned at lower severity than neighboring untreated sites according to both field and remote sensing data (figure 5; Table S4). Each treatment analyzed individually also shows a significant reduction in CBI severity relative to the untreated plots (Table S4). The magnitude of treatment effect and severity of treated sites does, however, differ depending on whether field or remotely sensed data are used. For example, within treated plots, field-based burn severity measures showed higher severity and were much more variable compared with the same plots measured via remote sensing.

Evaluations of treatment effects are sensitive to analytical approach and the measurement used. For example, conclusions about the effect of the treatment classes "thinning" and "multiple surface fuel treatments" on burn severity differ depending on whether treated and untreated areas are aggregated and then compared (treated areas tending to have higher RBR; figure 6A) or whether treatments are compared directly to their untreated analog (treated areas tending to have lower RBR; figure 6B). The example above of the three

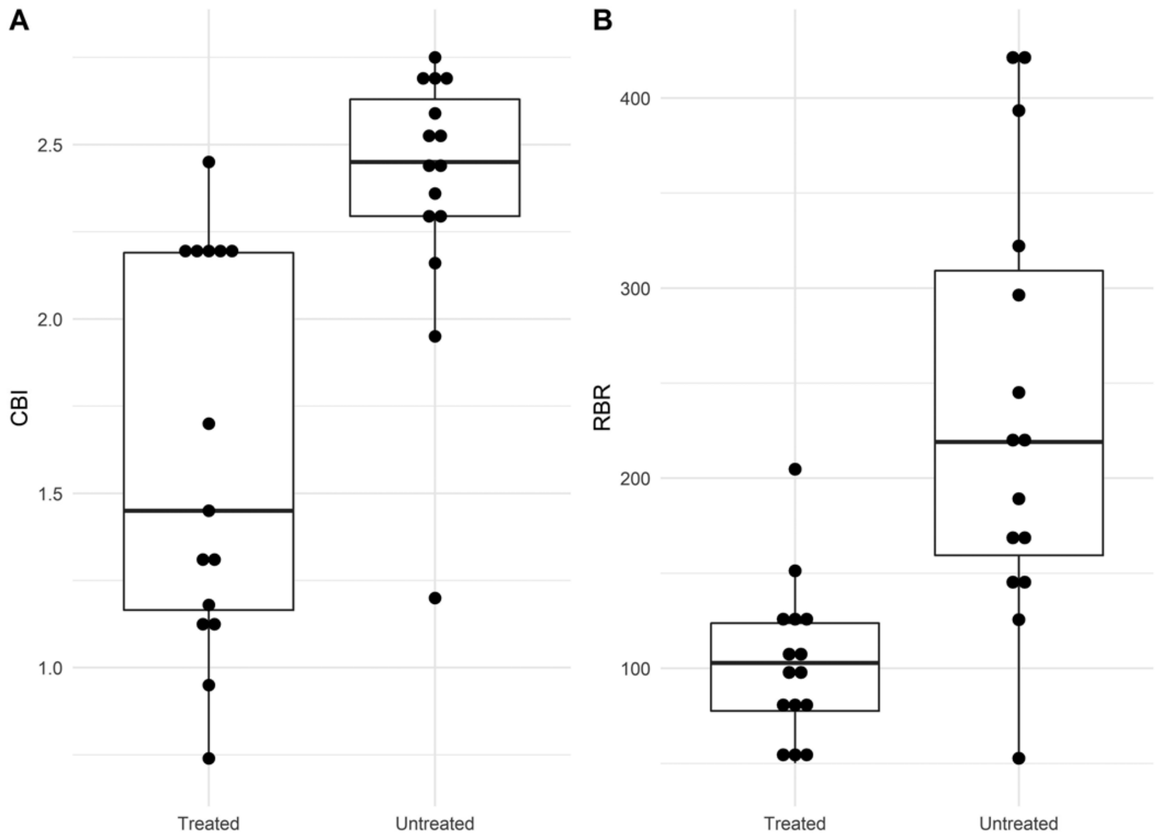

Figure 5 Field measured burn severity as measured by (A) the CBI and (B) remotely sensed burn severity as measured by the RBR. Values are shown for the thirty field plot locations across three focal treated and untreated pairings of the Cameron Peak Fire.

Table 4. The area and perimeter overlap between previous wildfire, prescribed (Rx) fire, and treatments other than prescribed fire with the Cameron Peak Fire.

	Area (ha)	Percent of Area	Perimeter length (km)	Percent of perimeter
Cameron Peak Fire	84,482	100	524	100
Previous wildfire	5,033	6	47	9
Rx fire	3,741	4	19	4
All treatments other than Rx fire	2,287	3	44	8

focal treatments shows how using different measurements (RBR and CBI) did not change the overall conclusion about treatments reducing burn severity but changed the magnitude of that difference and the burn severity distributions. These are just two examples of many methodological decisions that influence findings about fuel treatment effects.

Both the RBR analysis across the Cameron Peak Fire and the field plot and RBR analysis of three focal treatments show that treated areas generally had reduced burn severity relative to comparable untreated sites. This case study demonstrates some important considerations about treatment effect and effectiveness. The overall treatment effect on RBR was consistent, with all treatment types having a median effect of reduced burn severity. This effect was also variable. Individual treatments of each treatment type could be found that had higher burn severity than untreated comparisons (figure 6). This serves as a cautionary reminder to evaluate as many treatments as possible to capture the range of fire effects. The magnitude of treatment effect should be reported when possible (Tables S2–S4) because ultimately it is this magnitude placed in the context of human values and costs or risks associated with treatment that determines effectiveness.

Evaluating treatment effectiveness is further complicated by the complexity in the data used. Treatment databases provide valuable documentation of treatment location, implementation year, the general prescription, and equipment used. These databases are intended for activity reporting, not research, and thus often lack the detail needed for rigorous evaluations of treatment effects. Treatments recorded in treatment databases can lack spatial fidelity of treatment locations and treatment information, treatments of different types and ages often overlap in space, and different databases exist across agencies and vary in their reporting detail, terminology, and years (see USDA Forest Service Activity Tracking System 2018 for an example of complexity). Critical details, such as year of treatment, treatment type, forest structure, amount of material removed, equipment used, and residue management are important variables for evaluating effectiveness but may not be included in databases. As an example, nearly 20% of treatments in the Cameron Peak Fire did not have a year documented. Even the perimeter of treatments shown in these databases may not meet research-level needs as some treatments are assigned to property boundaries rather than the specific location of management activities. Furthermore, treatment databases give a partial historical record because tracking treatment activities in GIS has only become commonplace in the last few decades. Remote sensing of forest treatments offers opportunity for supplementing information in treatment databases and thus supporting evaluations of treatment effect by providing improved information on treatment year, extent, and the resulting forest structure (Coops et al. 2022; Keay et al. 2022; Woodward et al. 2017). The utility of remote sensing for treatment tracking is greatest for high-intensity treatments and data-rich areas that have recent or repeat high-resolution imagery or airborne lidar collections.

Another missing component to many of these databases is what the original goals and objectives were for the treatment. As discussed above, these are important details both when monitoring effects and determining effectiveness. And although many of these databases were not set up with the intention of being used to evaluate treatment effects post-wildfire, they commonly are the only information post hoc. When combining treatment databases from multiple sources and agencies for the Cameron Peak Fire, we encountered myriad treatment types (Table S1). Treatment type descriptions ranged from sufficient (e.g., “precommercial thin,” “clearcut”) to ambiguous (e.g., “Broadcast Burning - Covers a majority of the unit,” “silviculture”). Furthermore, treatment polygons overlap, forming a complex management history on the landscape, making it difficult to ascertain which management actions and which combinations were effective (figure 3).

Evaluating treatment effects requires integration of data from many sources with a range of resolution and accuracy. Remote sensing offers critical data for assessing treatment effects but often has varying spatial and temporal resolutions. For example, 30 m resolution is common for remote sensing burn severity when using Landsat-derived data, whereas during an incident, daily fire progression maps often have coarser resolution and field measurements may be at a much finer scale. Similarly, weather data is derived at different scales and often interpolated from sparsely located weather stations and are often difficult to match with progression maps of variable time windows. Further, repeated measures study designs that allow focused understanding of both treatment and wildfire impacts provide the most robust field-based understanding; however, these data are rarely available, as we cannot predict the location of future wildfires and field-based monitoring of treatments is variable across agencies, property owners, and implementers.

Interaction with Wildfire Planning and Response

Tables 1 and 2 highlight the importance of firefighter observations for evaluating treatment effects. However, collating information from firefighter observations can be difficult because these resources often disperse after the fire. Managers and researchers could benefit from knowing what happened during a fire, as these observations are easy to conceptualize but are the most difficult to acquire (Moriarty et al. 2019). Incident response data are challenging to acquire and apply, which severely limits our ability to understand how and whether forest treatments benefitted response efforts in any measurable way outside of anecdote and recollection (Gannon et al. 2020; Plucinski 2019; Simpson et al. 2021; Thompson et al. 2018).

There is an advantage to using landscape strategies in fire management, such as those developed in the 1990s to early 2000s like the Fireshed Assessment (Bahro et al. 2007), or more recently, Potential Operational Delineations (PODs; Thompson et al. 2016). Prior to the Cameron Peak Fire, treatments were integrated into strategic pre-fire planning through the PODs process initiated by the Arapaho and Roosevelt National Forests and Pawnee National Grasslands (Caggiano et al. 2021). The boundaries identified for potential engagement during a wildfire are often aligned with key topographic features, roads, previous wildfire perimeters, and forest treatments. Some treatments that aligned with PODs boundaries influenced suppression tactics and were reinforced during the fire. Local managers and incident management members credit the PODs strategic planning and forest management completed before and during the fire with improving the outcomes of the Cameron Peak Fire (Caggiano et al. 2021).

Similarly, firefighters would benefit from improved pre-fire treatment documentation (Greiner et al. 2022). Incident management teams and firefighters may make firefighting decisions because of forest conditions at a certain site without the knowledge of previous treatment. These decisions and changes in suppression activities are often made without treatment boundary or type of treatment details (Kolden and Henson 2019). Even with treatment databases to reference, critical treatment details that influence firefighter decision-making may be missing from treatment databases, such as the treatment of thinning residues. Furthermore, treatment effects important to firefighting decisions can be inversely related. The reduced surface fuel loads in thinned areas may lower flame length or fireline intensity but can also increase rate of spread due to a potential increase in fine fuels and higher windspeeds due to reduced canopy cover. Incident command team culture and experience level in the local fuel type can also influence how treatments are utilized during a fire (Greiner et al. 2022). Thus, interpretations of treatment effectiveness may vary with the particular incident command strategic priorities and firefighter backgrounds.

Conclusion

We describe a range of metrics of forest treatment effects on wildfire and highlight key considerations and challenges for evaluating wildfire treatment effects. Our aims are to advise careful consideration when evaluating treatment effectiveness and to inform ongoing research and critical discussions on the topic. The treatment effects on wildfire metrics (Tables 1–3) fit into frameworks for characterizing cross-scale cumulative forest treatment impacts, such as the fuel management regime presented by Hood et al. (2022). Conversations about treatment effectiveness are prone to oversimplification and bias by highlighting certain cases to demonstrate a point while ignoring counterfactual evidence. A risk of having so many metrics of effects (Tables 1–3) is that every treatment can be deemed effective or ineffective post hoc by some metric rather than matching postfire metrics with pre-fire intentions for that treatment. We provide the following recommendations for advancing evaluations of treatment effects on wildfire:

- Consider multiple treatment effects metrics and consider local context to give a more holistic view of treatment interactions with wildfire and to account for regional differences such as vegetation types, fire regimes, and management practices. Although it is important to align these metrics with the treatment objectives, additional metrics may reveal unintended consequences of treatments and can be just as valuable to adapting treatment methods.

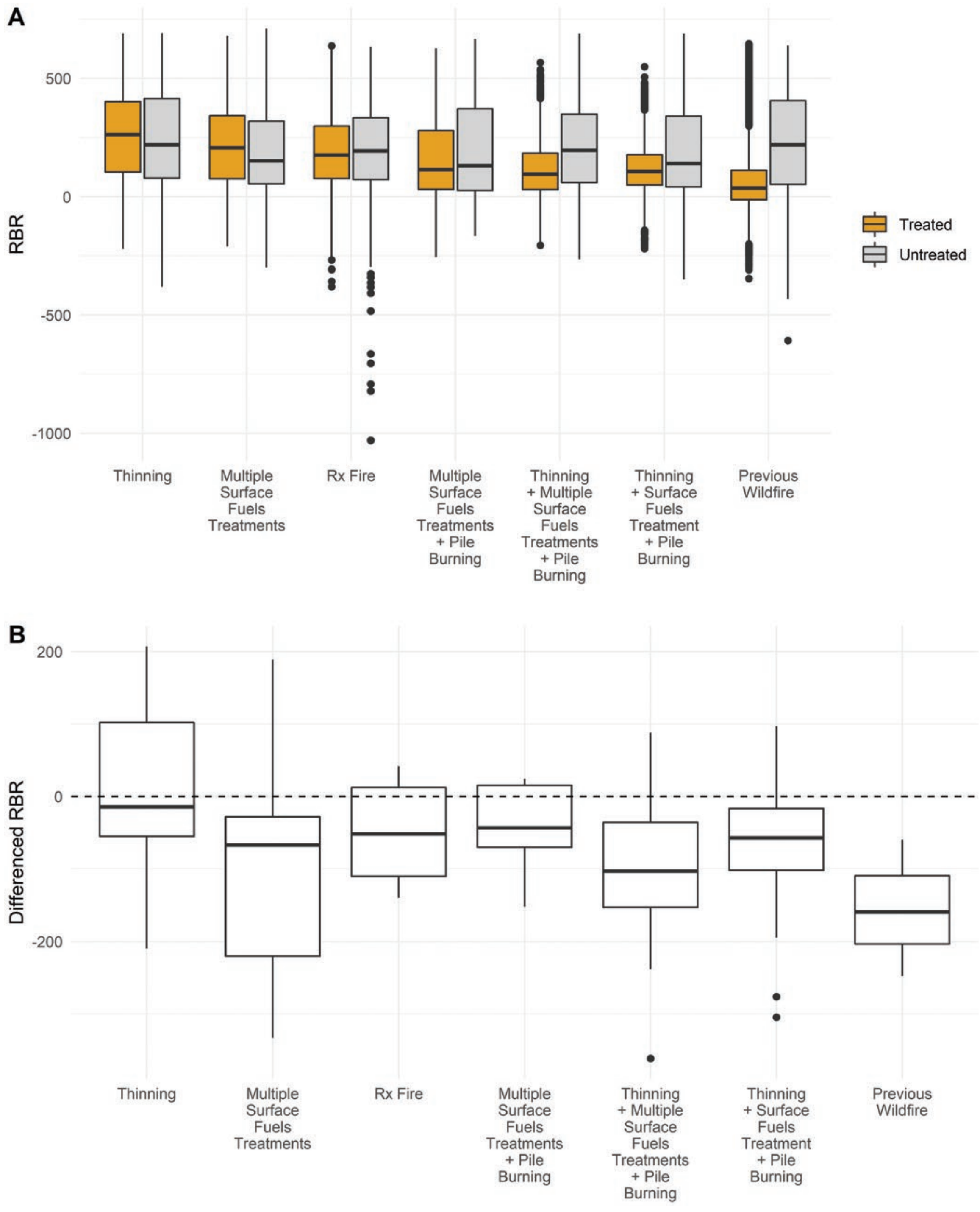

Figure 6 Boxplots comparing remotely sensed burn severity (RBR) by treatment type of (A) all pixels in treated and comparable untreated sites and (B) differenced RBR mean values of each treated and untreated pair across the most common treatment types and combinations (including wildfire). The untreated areas are a buffer of 40–340 m around each treatment of comparable slope and aspect and excludes any nonforested area or other treated areas overlapping this buffer. Negative values in (B) indicate a lower RBR in treated areas than comparable untreated areas. See Table S2 for summary statistics for (A) and Table S3 for summary statistics for (B).

- Explore and communicate the range of treatment effect outcomes across burn conditions, treatment characteristics, spatial and temporal scales, and treatment effects metrics.
- Improve documentation of suppression activities and firefighter observations, as they are critical for assessing many of the metrics and for attributing the effect of treatment or other drivers of fire behavior.
- Improve treatment databases by providing more details and complete attribution of treatment prescriptions, adding historical treatments, providing regular updates, and working towards standardization across agencies so that data can be more readily used during wildfires by incident management teams and firefighters and so effects can be more accurately and efficiently measured.

- Advance capabilities to evaluate treatment effects by improving methods for evaluating landscape-scale treatment effects, integrating diverse data streams, and targeting effects that have been difficult to quantify (e.g., watershed impacts, wildlife impacts, fire suppression and postfire recovery costs).

These recommendations can help to better characterize and communicate treatment effects on wildfire, but determining what is effective incorporates additional considerations, such as value systems, management goals, and treatment costs.

We share examples of treatments in the Cameron Peak Fire that both successfully and unsuccessfully mitigated human-fire interaction, fire behavior, and ecological metrics of treatment effects. We show areas treated with a variety of methods generally had reduced remotely sensed burn severity, reflecting less-severe wildfire impacts to soils and vegetation relative to untreated sites (figure 6). Previous wildfire and treatments that addressed surface fuel by burning or other methods tended to have the greatest reductions in burn severity. Thinning without pile or prescribed burning or surface fuel treatment experienced a wide range of outcomes, sometimes reducing and sometimes increasing burn severity relative to comparable untreated areas (figure 6). Using remotely sensed burn severity allowed for comparisons across different burn conditions and treatment types. Lessons about other metrics that rely on more intensive data collection (e.g., plot data) or opportunistic observations (e.g., firefighter observations) were more limited. Treatments were documented in these ways to increase tree survivorship, aid suppression efforts, reduce burn severity, promote firefighter safety, protect structures, and control fire spread. However, treatments were ineffective under severe weather conditions by other metrics, like containing the fire (Caggiano et al. 2021). Other metrics remain difficult to quantify and require further research. The implications of pre-fire management on postfire critical watershed and ecosystem responses and on suppression efforts and costs remain unknown. Because these are often primary objectives for forest management in these and many areas, more work is needed to gauge how management affects a broader set of resources.

Emphasis on increasing the scale of forest management to mitigate the potential for large, high-severity wildfires that affect human communities is growing. Understanding how wildfires interact with treatments and how various treatments affect wildfire outcomes is key to improving landscape management (Jain et al. 2021). Communication is also critical; providing context for what a treatment is designed to do and the limits of its potential effectiveness for moderating wildfire behavior and mitigating undesirable outcomes is important for both manager and community support. Wildfires will continue to shape our forests and landscapes in the years to come but continuing to strive for modification of large, high-severity events is important for future fire suppression actions, community safety, and healthy, functioning ecosystems.

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

Acknowledgements

We are grateful to the many organizations and individuals who made this work possible. We appreciate those that collected field data for this work: Daniel Dominguez, Elizabeth Madura, Miles Innes, and CFRI field crews. Thanks to the NASA DEVELOP team that helped to organize treatment data: Jorune Klisauskaite, Neal Swayze, and Garrett Knowlton.

Funding

This research was funded by the National Institute of Food and Agriculture (NIFA) of the USDA [grant number 2019-67019-29469], Colorado Forest Restoration Institute (CFRI) Appropriations funding, and the National Science Foundation [NSF-EAR 2101068]. This research was supported by the Forest Service, Rocky Mountain Research Station. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or US Government determination or policy.

Literature Cited

Abatzoglou, John T., and A. Park Williams. 2016. "Impact of Anthropogenic Climate Change on Wildfire Across Western US Forests." *Proceedings of the National Academy of Sciences* 113 (42): 11770–11775. https://doi.org/10.1073/pnas.1607171113.

Agee, James K., and Carl N. Skinner. 2005. "Basic Principles of Forest Fuel Reduction Treatments." *Forest Ecology and Management* 211 (1–2): 83–96. https://doi.org/10.1016/j.foreco.2005.01.034.

Ager, Alan A., Ana M.G. Barros, Rachel Houtman, Rob Seli, and Michelle A. Day. 2020. "Modelling the Effect of Accelerated Forest Management on Long-Term Wildfire Activity." *Ecological Modelling* 421: 108962. https://doi.org/10.1016/j.ecolmodel.2020.108962.

Bahro, Bernhard, Klaus H. Barber, Joseph W. Sherlock, and Donald A. Yasuda. 2007. "Stewardship and Fireshed Assessment: a Process for Designing a Landscape Fuel Treatment Strategy." In *Restoring Fire-adapted Ecosystems: Proceedings of the 2005 National Silviculture Workshop*: 41–54. USDA Forest Service Pacific Southwest Research Station, General Technical Report PSW-GTR-203.

Battaglia, Mike A., Monique E. Rocca, Charles C. Rhoades, and Michael G. Ryan. 2010. "Surface Fuel Loadings within Mulching Treatments in Colorado Coniferous Forests." *Forest Ecology and Management* 260 (9): 1557–1566. https://doi.org/10.1016/j.foreco.2010.08.004.

Bayham, Jude, Erin J. Belval, Matthew P. Thompson, Christopher Dunn, Crystal S. Stonesifer, and David E. Calkin. 2020. "Weather, Risk, and Resource Orders on Large Wildland Fires in the Western US." *Forests* 11 (2): 169. https://doi.org/10.3390/f11020169.

Bayham, Jude, Jonathan K. Yoder, Patricia A. Champ, and David E. Calkin. 2022. "The Economics of Wildfire in the United States." *Annual Review of Resource Economics* 14 (1): 379–401. https://doi.org/10.1146/annurev-resource-111920-014804.

Belval, Erin J., Christopher D. O'Connor, Matthew P. Thompson, and Michael S. Hand. 2019. "The Role of Previous Fires in the Management and Expenditures of Subsequent Large Wildfires." *Fire* 2 (4): 57. https://doi.org/10.3390/fire2040057.

Birch, Donovan S., Penelope Morgan, Crystal A. Kolden, John T. Abatzoglou, Gregory K. Dillon, Andrew T. Hudak, and Alistair M.S. Smith. 2015. "Vegetation, Topography and Daily Weather Influenced Burn Severity in Central Idaho and Western Montana Forests." *Ecosphere* 6 (1): 1–23. https://doi.org/10.1890/ES14-00213.1.

Caggiano, Michael D., Tyler A. Beeton, Benjamin M. Gannon, and James White. 2021. "The Cameron Peak Fire: Use of Potential

Operational Delineations and Risk Management Assistance Products." *Colorado Forest Restoration Institute, CFRI-2106*. https://cfri.colostate.edu/wp-content/uploads/sites/22/2021/06/Cameron-PeakFirePODsReport.pdf.

Calkin, David E., Jack D. Cohen, Mark A. Finney, and Matthew P. Thompson. 2014. "How Risk Management can Prevent Future Wildfire Disasters in the Wildland-Urban Interface." *Proceedings of the National Academy of Sciences* 111 (2): 746–751. https://doi.org/10.1073/pnas.1315088111.

Cansler, C. Alina, Van R. Kane, Paul F. Hessburg, Jonathan T. Kane, Sean M.A. Jeronimo, James A. Lutz, and Nicholas A. Povak, et al. 2022. "Previous Wildfires and Management Treatments Moderate Subsequent Fire Severity." *Forest Ecology and Management* 504: 119764. https://doi.org/10.1016/j.foreco.2021.119764.

Choromanska, U., and T.H. DeLuca. 2001. "Prescribed Fire Alters the Impact of Wildfire on Soil Biochemical Properties in a Ponderosa Pine Forest." *Soil Science Society of America Journal* 65 (1): 232–238. https://doi.org/10.2136/sssaj2001.651232x.

Collins, B.J., C.C. Rhoades, M.A. Battaglia, and R.M. Hubbard. 2012. "The Effects of Bark Beetle Outbreaks on Forest Development, Fuel Loads and Potential Fire Behavior in Salvage Logged and Untreated Lodgepole Pine Forests." *Forest Ecology and Management* 284: 260–268. https://doi.org/10.1016/j.foreco.2012.07.027.

Coop, Jonathan D., Sean A. Parks, Camille S. Stevens-Rumann, Scott M. Ritter, Chad M. Hoffman, and J. Morgan Varner. 2022. "Extreme Fire Spread Events and Area Burned Under Recent and Future Climate in the Western USA." *Global Ecology and Biogeography* 31 (10): 1949–1959. https://doi.org/10.1111/geb.13496.

Coops, Nicholas C., Piotr Tompalski, Tristan R.H. Goodbody, Alexis Achim, and Christopher Mulverhill. 2022. "Framework for Near Real-time Forest Inventory Using Multi source Remote Sensing Data." *Forestry: An International Journal of Forest Research* 96: (1): 1–19. https://doi.org/10.1093/forestry/cpac015.

Davim, David A., Carlos G. Rossa, and Paulo M. Fernandes. 2021. "Survival of Prescribed Burning Treatments to Wildfire in Portugal." *Forest Ecology and Management* 493: 119250. https://doi.org/10.1016/j.foreco.2021.119250.

Esri Inc. 2021. *ArcGIS Pro (version 2.6.4)*. Software. Redlands: Esri Inc.

Evers, Cody, Andrés Holz, Sebastian Busby, and Max Nielsen-Pincus. 2022. "Extreme Winds Alter Influence of Fuels and Topography on Megafire Burn Severity in Seasonal Temperate Rainforests under Record Fuel Aridity." *Fire* 5 (2): 41. https://doi.org/10.3390/fire5020041.

Finkral, A.J., and A.M. Evans. 2008. "The Effects of a Thinning Treatment on Carbon Stocks in a Northern Arizona Ponderosa Pine Forest." *Forest Ecology and Management* 255 (7): 2743–2750. https://doi.org/10.1016/j.foreco.2008.01.041.

Fultz, Lisa M., Jennifer Moore-Kucera, Josefine Dathe, Marko Davinic, Gad Perry, David Wester, Dylan W. Schwilk, et al. 2016. "Forest Wildfire and Grassland Prescribed Fire Effects on Soil Biogeochemical Processes and Microbial Communities: Two Case Studies in the Semi-Arid Southwest." *Applied Soil Ecology* 99: 118–128. https://doi.org/10.1016/j.apsoil.2015.10.023.

Gannon, Benjamin M., Matthew P. Thompson, Kira Z. Deming, Jude Bayham, Yu Wei, and Christopher D. O'Connor. 2020. "A Geospatial Framework to Assess Fireline Effectiveness for Large Wildfires in the Western USA." *Fire* 3 (3): 43. https://doi.org/10.3390/fire3030043.

Greiner, Michelle, Katie McGrath Novak, and Courtney Schultz. 2022. *Assessing How Fuel Treatments Are Considered During Incident Response: An Interim Report*. Public Lands Policy Group Practitioner Paper no. 13, Fort Collins: Public Lands Policy Group, Colorado State University.

Hessburg, Paul F., Derek J. Churchill, Andrew J. Larson, Ryan D. Haugo, Carol Miller, Thomas A. Spies, Malcolm P. North, et al. 2015. "Restoring Fire-Prone Inland Pacific Landscapes: Seven Core Principles." *Landscape Ecology* 30 (10): 1805–1835. https://doi.org/10.1007/s10980-015-0218-0.

Hessburg, Paul F., Susan J. Prichard, R. Keala Hagmann, Nicholas A. Povak, and Frank K. Lake. 2021. "Wildfire and Climate Change Adaptation of Western North American Forests: A Case for Intentional Management." *Ecological Applications* 31 (8): e02432. https://doi.org/10.1002/eap.2432.

Higuera, Philip E., Bryan N. Shuman, and Kyra D. Wolf. 2021. "Rocky Mountain subalpine forests now burning more than any time in recent millennia." *Proceedings of the National Academy of Sciences* 118 (25): e2103135118. https://doi.org/10.1073/pnas.2103135118.

Hijmans, Robert J. 2022. "terra: Spatial Data Analysis." R package version 1.5-21. https://CRAN.R-project.org/package=terra.

Hoffman, Chad M., Brandon Collins, and Mike Battaglia. 2020. "Wildland Fuel Treatments." In *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires*, edited by Samuel L. Manzello, 1160–1166. Cham, Switzerland: Springer International Publishing.

Homann, Peter S., Bernard T. Bormann, Robyn L. Darbyshire, and Brett A. Morrissette. 2011. "Forest Soil Carbon and Nitrogen Losses Associated with Wildfire and Prescribed Fire." *Soil Science Society of America Journal* 75 (5): 1926–1934. https://doi.org/10.2136/sssaj2010-0429.

Hood, Sharon M., J. Morgan Varner, Theresa B. Jain, and Jeffrey M. Kane. 2022. "A Framework for Quantifying Forest Wildfire Hazard and Fuel Treatment Effectiveness from Stands to Landscapes." *Fire Ecology* 18 (1): 1–12. https://doi.org/10.1186/s42408-022-00157-0.

Hunter, Molly E., and Marcos D. Robles. 2020. "Tamm Review: The Effects of Prescribed Fire on Wildfire Regimes and Impacts: A Framework for Comparison." *Forest Ecology and Management* 475: 118435. https://doi.org/10.1016/j.foreco.2020.118435.

Jahdi, Roghayeh, Liliana Del Giudice, Massimo Melis, Raffaella Lovreglio, Michele Salis, Bachisio Arca, and Pierpaolo Duce. 2022. "Assessing the Effects of Alternative Fuel Treatments to Reduce Wildfire Exposure." *Journal of Forestry Research* 34: 1–14. https://doi.org/10.1007/s11676-022-01504-2.

Jain, Theresa, Pamela Sikkink, Robert Keefe, and John Byrne. 2018. To Masticate or Not: Useful Tips for Treating Forest, Woodland, and Shrubland Vegetation. *USDA Forest Service General Technical Report RMRS-GTR-381*, 55 p. Fort Collins: Rocky Mountain Research Station.

Jain, Theresa B., Ilana Abrahamson, Nate Anderson, Sharon Hood, Brice Hanberry, Francis Kilkenny, Shawn McKinney et al. 2021. Effectiveness of Fuel Treatments at the Landscape Scale: State of Understanding and Key Research Gaps. *JFSP PROJECT ID: 19-S-01-2*, Boise: Joint Fire Sciences Program.

Jain, Theresa B., Mike A. Battaglia, Han-Sup Han, Russell T. Graham, Christopher R. Keyes, Jeremy S. Fried, and Johnathan E. Sandquist. 2012. A Comprehensive Guide to Fuel Management Practices for Dry Mixed Conifer Forests in the Northwestern United States. *USDA Forest Service General Technical Report RMRS-GTR-292*, 331 p. Fort Collins: Rocky Mountain Research Station.

Johnson, Morris C., and Maureen C. Kennedy. 2019. "Altered Vegetation Structure from Mechanical Thinning Treatments Changed Wildfire Behaviour in the Wildland–Urban Interface on the 2011 Wallow Fire, Arizona, USA." *International Journal of Wildland Fire* 28 (3): 216–229. https://doi.org/10.1071/WF18062.

Jones, Kelly W., Jeffery B. Cannon, Freddy A. Saavedra, Stephanie K. Kampf, Robert N. Addington, Antony S. Cheng, Lee H. MacDonald, et al. 2017. "Return on Investment from Fuel Treatments to Reduce Severe Wildfire and Erosion in a Watershed Investment Program in Colorado." *Journal of Environmental Management* 198 (2): 66–77. https://doi.org/10.1016/j.jenvman.2017.05.023.

Kalies, Elizabeth L., and Larissa L. Yocom Kent. 2016. "Tamm Review: Are Fuel Treatments Effective at Achieving Ecological and Social Objectives? A Systematic Review." *Forest Ecology and Management* 375: 84–95. https://doi.org/10.1016/j.foreco.2016.05.021.

Keay, Levi, Christopher Mulverhill, Nicholas C. Coops, and Grant McCartney. 2022. "Automated Forest Harvest Detection With a Normalized PlanetScope Imagery Time Series." *Canadian Journal of Remote Sensing* 49 (1): 1–15. https://doi.org/10.1080/07038992.2022.2154598.

Keeley, Jon E., Hugh Safford, C.J. Fotheringham, Janet Franklin, and Max Moritz. 2009. "The 2007 southern California wildfires: lessons in complexity." *Journal of Forestry* 107 (6): 287–296.

Kennedy, Maureen C., and Morris C. Johnson. 2014. "Fuel Treatment Prescriptions Alter Spatial Patterns of Fire Severity Around the Wildland–Urban Interface During the Wallow Fire, Arizona, USA." *Forest Ecology and Management* 318: 122–132. https://doi.org/10.1016/j.foreco.2014.01.014.

Key, Carl H., and Nathan C. Benson. 2006. Landscape Assessment (LA). *In FIREMON: Fire effects monitoring and inventory system*, edited by Duncan C. Lutes, Robert E. Keane, John F. Caratti, Carl H. Key, Nathan C. Benson, Steve Sutherland, Larry J. Gangi, General Technical Report RMRS-GTR-164-CD, LA-1–55. Fort Collins: USDA Forest Service, Rocky Mountain Research Station.

Knapp, Eric E., Becky L. Estes, and Carl N. Skinner. 2009. Ecological Effects of Prescribed Fire Season: a Literature Review and Synthesis for Managers. *USDA Forest Service General Technical Report PSW-GTR-224*. Albany: Pacific Southwest Research Station.

Kolden, Crystal A., and Carol Henson. 2019. "A Socio-Ecological Approach to Mitigating Wildfire Vulnerability in the Wildland Urban Interface: A Case Study from the 2017 Thomas Fire." *Fire* 2 (1): 9. https://doi.org/10.3390/fire2010009.

Kooistra, Chad, and Sarah McCaffrey. 2022. "Residents' Perspectives on Colorado's 2020 Cameron Peak Fire." Coalition for the Poudre River Watershed. https://sites.warnercnr.colostate.edu/courtney-schultz/cameron-peak-fire/.

Kreye, Jesse K., Nolan W. Brewer, Penelope Morgan, J. Morgan Varner, Alistair M.S. Smith, Chad M. Hoffman, and Roger D. Ottmar. 2014. "Fire Behavior in Masticated Fuels: A Review." *Forest Ecology and Management* 314: 193–207. https://doi.org/10.1016/j.foreco.2013.11.035.

LANDFIRE. 2016. "Public Events Geodatabase Model Ready Events." LANDFIRE 2.0.0. Distributed by LANDFIRE, Earth Resources Observation and Science Center (EROS), and US Geological Survey. https://landfire.gov/publicevents.php.

LANDFIRE. 2022. "Existing Vegetation Cover (EVC) CONUS 2022 Capable." LANDFIRE 2.2.0. Distributed by LANDFIRE, Earth Resources Observation and Science Center (EROS), and US Geological Survey. https://landfire.gov/metadata/lf2020/CONUS/LC22_EVC_220.html.

Martinson, Erik, Phillip N. Omi, and Wayne Shepperd. 2003. "Part 3: Effects of Fuel Treatments on Fire Severity." In *Hayman Fire Case Study*, edited by R.T. Graham (technical editor), USDA Forest Service General Technical Report RMRS-GTR-114. 96–126. Ogden: Rocky Mountain Research Station.

Martinson, Erik J., and Philip N. Omi. 2013. Fuel Treatments and Fire Severity: A Meta-Analysis. *USDA Forest Service Research Paper RMRS-RP-103WWW*. Fort Collins: Rocky Mountain Research Station.

McKinney, Shawn T., Ilana Abrahamson, Theresa Jain, and Nathaniel Anderson. 2022. "A Systematic Review of Empirical Evidence for Landscape-Level Fuel Treatment Effectiveness." *Fire Ecology* 18 (1): 1–16. https://doi.org/10.1186/s42408-022-00146-3.

Moghaddas, Jason J., and Larry Craggs. 2007. "A Fuel Treatment Reduces Fire Severity and Increases Suppression Efficiency in a Mixed Conifer Forest." *International Journal of Wildland Fire* 16 (6): 673–678. https://doi.org/10.1071/WF06066.

Moriarty, Kevin, Antony S. Cheng, Chad M. Hoffman, Stuart P. Cottrell, and Martin E. Alexander. 2019. "Firefighter Observations of 'Surprising' Fire Behavior in Mountain Pine Beetle-Attacked Lodgepole Pine Forests." *Fire* 2 (2): 34. https://doi.org/10.3390/fire2020034.

Mueller, Stephanie E., and Michael D. Caggiano. 2022. "Colorado Interagency Fuel Treatment Database." Distributed by Colorado Forest Restoration Institute. https://cfri.colostate.edu/wp-content/uploads/sites/22/2022/02/Interagency_GDB_Report.pdf.

NASA Jet Propulsion Laboratory. 2014. "NASA Shuttle Radar Topography Mission Combined Image Data Set." Distributed by NASA Earth Observing System Data and Information System Land Processes Distributed Active Archive Center. https://doi.org/10.5067/MEaSUREs/SRTM/SRTMIMGM.003.

National Wildfire Coordinating Group. 2017. "Wildland Fire Perimeters." Distributed by the National Interagency Fire Center. https://www.nwcg.gov/publications/pms936/nifs/public-distribution.

National Interagency Coordination Center. 2021. "Wildland Fire Summary and Statistics: 2020 Annual Report." https://www.nifc.gov/sites/default/files/NICC/2-Predictive%20Services/Intelligence/Annual%20Reports/2022/annual_report.2.pdf.

Noble, Peter, and Travis B. Paveglio. 2020. "Exploring Adoption of the Wildland Fire Decision Support System: End User Perspectives." *Journal of Forestry* 118 (2): 154–171. https://doi.org/10.1093/jofore/fvz070.

Noonan-Wright, Erin, and Carl A. Seielstad. 2021. "Patterns of Wildfire Risk in the United States from Systematic Operational Risk Assessments: How Risk is Characterised by Land Managers." *International Journal of Wildland Fire* 30 (8): 569–584. https://doi.org/10.1071/WF21020.

North, Malcolm P., and Matthew D. Hurteau. 2011. "High-Severity Wildfire Effects on Carbon Stocks and Emissions in Fuels Treated and Untreated Forest." *Forest Ecology and Management* 261 (6): 1115–1120. https://doi.org/10.1016/j.foreco.2010.12.039.

North, M.P., R.A. York, B.M. Collins, M.D. Hurteau, G.M. Jones, E.E. Knapp, L. Kobziar, et al. 2021. "Pyrosilviculture Needed for Landscape Resilience of Dry Western United States Forests." *Journal of Forestry* 119 (5): 520–544. https://doi.org/10.1093/jofore/fvab026.

Parks, Sean A., Lisa M. Holsinger, Carol Miller, and Cara R. Nelson. 2015. "Wildland Fire as a Self-Regulating Mechanism: the Role of Previous Burns and Weather in Limiting Fire Progression." *Ecological Applications* 25 (6): 1478–1492. https://doi.org/10.1890/14-1430.1.

Pebesma, Edzer J. 2018. "Simple Features for R: Standardized Support for Spatial Vector Data." *The R Journal* 10 (1): 439–446. https://doi.org/10.32614/RJ-2018-009.

Peterson, Geoffrey Colin L., Steven E. Prince, and Ana G. Rappold. 2021. "Trends in Fire Danger and Population Exposure along the Wildland–Urban Interface." *Environmental Science & Technology* 55 (23): 16257–16265. https://doi.org/10.1021/acs.est.1c03835.

Plucinski, Matt P. 2019. "Fighting Flames and Forging Firelines: Wildfire Suppression Effectiveness at the Fire Edge." *Current Forestry Reports* 5 (1): 1–19. https://doi.org/10.1007/s40725-019-00084-5.

Prichard, Susan J., and Maureen C. Kennedy. 2014. "Fuel Treatments and Landform Modify Landscape Patterns of Burn Severity in an Extreme Fire Event." *Ecological Applications* 24 (3): 571–590. https://doi.org/10.1890/13-0343.1.

Prichard, Susan J., David L. Peterson, and Kyle Jacobson. 2010. "Fuel Treatments Reduce the Severity of Wildfire Effects in Dry Mixed Conifer Forest, Washington, USA." *Canadian Journal of Forest Research* 40 (8): 1615–1626. https://doi.org/10.1139/X10-109.

Prichard, Susan J., Nicholas A. Povak, Maureen C. Kennedy, and David W. Peterson. 2020. "Fuel Treatment Effectiveness in the Context of Landform, Vegetation, and Large, Wind-Driven Wildfires." *Ecological Applications* 30 (5): e02104. https://doi.org/10.1002/eap.2104.

R Core Team. 2020. "R: A Language and Environment for Statistical Computing." Software. Vienna: R Foundation for Statistical Computing. https://www.R-project.org/.

Rapp, Claire, Emily Rabung, Robyn Wilson, and Eric Toman. 2020. "Wildfire Decision Support Tools: An Exploratory Study of Use in the United States." *International Journal of Wildland Fire* 29 (7): 581–594. https://doi.org/10.1071/WF19131.

Reinhardt, Elizabeth D., Robert E. Keane, David E. Calkin, and Jack D. Cohen. 2008. "Objectives and Considerations for Wildland Fuel Treatment in Forested Ecosystems of the Interior Western United

States." *Forest Ecology and Management* 256 (12): 1997–2006. https://doi.org/10.1016/j.foreco.2008.09.016.

Riley, Karin L., and Rachel A. Loehman. 2016. "Mid-21st-Century Climate Changes Increase Predicted Fire Occurrence and Fire Season Length, Northern Rocky Mountains, United States." *Ecosphere* 7 (11): e01543. https://doi.org/10.1002/ecs2.1543.

Ritchie, M.W., C.N. Skinner, and T.A. Hamilton. 2007. "Probability of Wildfire-Induced Tree Mortality in an Interior Pine Forest: Effects of Thinning and Prescribed Fire." *Forest Ecology and Management* 247 (1–3): 200–208. https://doi.org/10.1016/j.foreco.2007.04.044.

Roccaforte, John P., Andrew Sánchez Meador, Amy E.M. Waltz, Monica L. Gaylord, Michael T. Stoddard, and David W. Huffman. 2018. "Delayed Tree Mortality, Bark Beetle Activity, and Regeneration Dynamics Five Years Following the Wallow Fire, Arizona, USA: Assessing Trajectories Towards Resiliency." *Forest Ecology and Management* 428: 20–26. https://doi.org/10.1016/j.foreco.2018.06.012.

Safford, Hugh D., David A. Schmidt, and Chris H. Carlson. 2009. "Effects of Fuel Treatments on Fire Severity in an Area of Wildland–Urban Interface, Angora Fire, Lake Tahoe Basin, California." *Forest Ecology and Management* 258 (5): 773–787. https://doi.org/10.1016/j.foreco.2009.05.024.

Salis, Michele, Liliana Del Giudice, Peter R. Robichaud, Alan A. Ager, Annalisa Canu, Pierpaolo Duce, Grazia Pellizzaro, et al. 2019. "Coupling Wildfire Spread and Erosion Models to Quantify Post-Fire Erosion Before and After Fuel Treatments." *International Journal of Wildland Fire* 28 (9): 687–703. https://doi.org/10.1071/WF19034.

Sánchez, José J., John Loomis, Armando González-Cabán, Douglas Rideout, and Robin Reich. 2019. "Do Fuel Treatments in US National Forests Reduce Wildfire Suppression Costs and Property Damage?." *Journal of Natural Resources Policy Research* 9 (1): 42–73. https://doi.org/10.5325/naturesopolirese.9.1.0042.

Schmidt, David A., Alan H. Taylor, and Carl N. Skinner. 2008. "The Influence of Fuels Treatment and Landscape Arrangement on Simulated Fire Behavior, Southern Cascade Range, California." *Forest Ecology and Management* 255 (8-9): 3170–3184. https://doi.org/10.1016/j.foreco.2008.01.023.

Shive, Kristen L., Carolyn H. Sieg, and Peter Z. Fulé. 2013. "Pre-Wildfire Management Treatments Interact with Fire Severity to have Lasting Effects on Post-Wildfire Vegetation Response." *Forest Ecology and Management* 297: 75–83. https://doi.org/10.1016/j.foreco.2013.02.021.

Simpson, Heather, Ross Bradstock, and Owen Price. 2021. "Quantifying the Prevalence and Practice of Suppression Firing with Operational Data from Large Fires in Victoria, Australia." *Fire* 4 (4): 63. https://doi.org/10.3390/fire4040063.

Skinner, Carl N. 2005. "Reintroducing Fire into the Blacks Mountain Research Natural Area: Effects on Fire Hazard." In *Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management*, edited by Martin W. Ritchie, Douglas A. Maguire, and Andrew Youngblood, technical coordinators. General Technical Report PSW-GTR-198: 245–257. Albany: USDA Forest Service, Pacific Southwest Research Station.

Springer, Judith D., David W. Huffman, Michael T. Stoddard, Andrew J. Sánchez Meador, and Amy E.M. Waltz. 2018. "Plant Community Dynamics Following Hazardous Fuel Treatments and Mega-Wildfire in a Warm-Dry Mixed-Conifer Forest of the USA." *Forest Ecology and Management* 429: 278–286. https://doi.org/10.1016/j.foreco.2018.06.022.

Steel, Zachary L., Gavin M. Jones, Brandon M. Collins, Rebecca Green, Alexander Koltunov, Kathryn L. Purcell, Sarah C. Sawyer, et al. 2022. "Mega-Disturbances Cause Rapid Decline of Mature Conifer Forest Habitat in California." *Ecological Applications* 33 (2): e2763. https://doi.org/10.1002/eap.2763.

Stephens, Scott L., Mike A. Battaglia, Derek J. Churchill, Brandon M. Collins, Michelle Coppoletta, Chad M. Hoffman, Jamie M. Lydersen, et al. 2021. "Forest Restoration and Fuels Reduction: Convergent or Divergent?." *Bioscience* 71 (1): 85–101. https://doi.org/10.1093/biosci/biaa134.

Stephens, Scott L., Neil Burrows, Alexander Buyantuyev, Robert W. Gray, Robert E. Keane, Rick Kubian, Shirong Liu, et al. 2014. "Temperate and Boreal Forest Mega-Fires: Characteristics and Challenges." *Frontiers in Ecology and the Environment* 12 (2): 115–122. https://doi.org/10.1890/120332.

Stephens, Scott L., Brandon M. Collins, and Gary Roller. 2012. "Fuel Treatment Longevity in a Sierra Nevada Mixed Conifer Forest." *Forest Ecology and Management* 285: 204–212. https://doi.org/10.1016/j.foreco.2012.08.030.

Stevens-Rumann, Camille, Susan J. Prichard, Eva K. Strand, and Penelope Morgan. 2016. "Prior Wildfires Influence Burn Severity of Subsequent Large Fires." *Canadian Journal of Forest Research* 46 (11): 1375–1385. https://doi.org/10.1139/cjfr-2016-0185.

Stevens-Rumann, Camille, Kristen Shive, Peter Fulé, and Carolyn H. Sieg. 2013. "Pre-Wildfire Fuel Reduction Treatments Result in More Resilient Forest Structure a Decade After Wildfire." *International Journal of Wildland Fire* 22 (8): 1108–1117. https://doi.org/10.1071/WF12216.

Symons, Julie N., Dean H.K. Fairbanks, and C.N. Skinner. 2008. "Influences of Stand Structure and Fuel Treatments on Wildfire Severity at Blacks Mountain Experimental Forest, Northeastern California." *The California Geographer* 48 (1): 61–82.

Syphard, Alexandra D., Teresa J. Brennan, and Jon E. Keeley. 2014. "The Role of Defensible Space for Residential Structure Protection During Wildfires." *International Journal of Wildland Fire* 23 (8): 1165–1175. https://doi.org/10.1071/WF13158.

Taylor, Alan H., Lucas B. Harris, and Stacy A. Drury. 2021. "Drivers of Fire Severity Shift as Landscapes Transition to an Active Fire Regime, Klamath Mountains, USA." *Ecosphere* 12 (9): e03734. https://doi.org/10.1002/ecs2.3734.

Taylor, Alan H., Lucas B. Harris, and Carl N. Skinner. 2022. "Severity Patterns of the 2021 Dixie Fire Exemplify the Need to Increase Low-Severity Fire Treatments in California's Forests." *Environmental Research Letters* 17 (7): 071002. https://doi.org/10.1088/1748-9326/ac7735.

Thompson, Matthew P., Phil Bowden, April Brough, Joe H. Scott, Julie Gilbertson-Day, Alan Taylor, Jennifer Anderson, et al. 2016. "Application of Wildfire Risk Assessment Results to Wildfire Response Planning in the Southern Sierra Nevada, California, USA." *Forests* 7 (3): 64. https://doi.org/10.3390/f7030064.

Thompson, Matthew P., Christopher J. Lauer, David E. Calkin, Jon D. Rieck, Crystal S. Stonesifer, and Michael S. Hand. 2018. "Wildfire Response Performance Measurement: Current and Future Directions." *Fire* 1 (2): 21. https://doi.org/10.3390/fire1020021.

Thompson, Matthew P., Nicole M. Vaillant, Jessica R. Haas, Krista M. Gebert, and Keith D. Stockmann. 2013. "Quantifying the Potential Impacts of Fuel Treatments on Wildfire Suppression Costs." *Journal of Forestry* 111 (1): 49–58. https://doi.org/10.5849/jof.12-027.

Tinkham, Wade T., Chad M. Hoffman, Seth A. Ex, Michael A. Battaglia, and Jarred D. Saralecos. 2016. "Ponderosa Pine Forest Restoration Treatment Longevity: Implications of Regeneration on Fire Hazard." *Forests* 7 (7): 137. https://doi.org/10.3390/f7070137.

Tubbesing, Carmen L., Danny L. Fry, Gary B. Roller, Brandon M. Collins, Varvara A. Fedorova, Scott L. Stephens, and John J. Battles. 2019. "Strategically Placed Landscape Fuel Treatments Decrease Fire Severity and Promote Recovery in the Northern Sierra Nevada." *Forest Ecology and Management* 436: 45–55. https://doi.org/10.1016/j.foreco.2019.01.010.

USDA Forest Service Activity Tracking System. 2018. "Hazardous Fuel Treatment Reduction: Polygon." Distributed by the USDA Forest Service. https://data.fs.usda.gov/geodata/edw/datasets.php?dsetParent=Activities.

USDA Forest Service. 2020. "The Stewardship Mapping and Reporting Tool (SMART)." Accessed January 4, 2021.

Waltz, Amy E.M., Michael T. Stoddard, Elizabeth L. Kalies, Judith D. Springer, David W. Huffman, and Andrew Sánchez Meador. 2014. "Effectiveness of Fuel Reduction Treatments: Assessing Metrics of Forest Resiliency and Wildfire Severity After the Wallow Fire, AZ." *Forest Ecology and Management* 334: 43–52. https://doi.org/10.1016/j.foreco.2014.08.026.

Wang, Daoping, Dabo Guan, Shupeng Zhu, Michael Mac Kinnon, Guannan Geng, Qiang Zhang, Heran Zheng, et al. 2021. "Economic Footprint of California Wildfires in 2018." *Nature Sustainability* 4 (3): 252–260. https://doi.org/10.1038/s41893-020-00646-7.

Weatherspoon, C. Phillip, and Carl N. Skinner. 1995. "An Assessment of Factors Associated with Damage to Tree Crowns from the 1987 Wildfires in Northern California." *Forest Science* 41 (3): 430–451.

Weatherspoon, C. Phillip, and Carl N. Skinner. 1996. "Landscape-Level Strategies for Forest Fuel Management." In Sierra Nevada Ecosystem Project: Final Report to Congress, *Assessments and Scientific Basis for Management Options* 2: 1471–1492. Wildland Resources Center Report No. 37. Davis: Centers for Water and Wildland Resources, University of California, Davis.

Woodward, Brian, Peder Engelstad, Anthony Vorster, Christopher Beddow, Stephanie Krail, Amandeep Vashisht, and Paul Evangelista. 2017. "Forest Harvest Dataset for Northern Colorado Rocky Mountains (1984–2015) Generated from a Landsat Time Series and Existing Forest Harvest Records." *Data in Brief* 15: 724–727. https://doi.org/10.1016/j.dib.2017.10.030.

Zhang, Jianwei, Matt Busse, Silong Wang, Dave Young, and Kim Mattson. 2023. "Wildfire Loss of Forest Soil C and N: Do Pre-Fire Treatments Make a Difference?." *Science of the Total Environment* 854: 158742. https://doi.org/10.1016/j.scitotenv.2022.158742.