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Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review

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ABSTRACT

The prevailing paradigm in the western U.S. is that the increase in stand-replacing wildfires in historically frequent-fire dry forests is due to unnatural fuel loads that have resulted from management activities including fire suppression, logging, and grazing, combined with more severe drought conditions and increasing temperatures. To counteract unnaturally high fuel loads, fuel reduction treatments which are designed to reduce fire hazard and improve overall ecosystem functioning have been increasing over the last decade. However, until recently much of what we knew about treatment effectiveness was based on modeling and predictive studies. Now, there are many examples of wildfires burning through both treated and untreated areas, and the effectiveness of treatments versus no action can be evaluated empirically. We carried out a systematic review to address the question: Are fuel treatments effective at achieving ecological and social (saving human lives and property) objectives? We found 56 studies addressing fuel treatment effectiveness in 8 states in the western US. There was general agreement that thin + burn treatments had positive effects in terms of reducing fire severity, tree mortality, and crown scorch. In contrast, burning or thinning alone had either less of an effect or none at all, compared to untreated sites. Most studies focused on carbon storage agreed that treatments do not necessarily store more carbon after wildfire, but result in less post-wildfire emissions and less carbon loss in a wildfire due to tree mortality. Understory responses are mixed across all treatments, and the response of other ecological attributes (e.g., soil, wildlife, water, insects) to treatment post-wildfire represents an important data gap; we provide a detailed agenda for future research. Overall, evidence is strong that thin + burn treatments meet the goal of reducing fire severity, and more research is needed to augment the few studies that indicate treatments protect human lives and property.

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1. Introduction

Across dry forests of the western United States, stand-replacing forest fires are increasing in frequency and extent (Westerling et al., 2006; Miller et al., 2009). This change is occurring in historically frequent-fire forests due to unnaturally high fuel loads that have resulted from a century of fire suppression, logging, and grazing, combined with more severe drought conditions and rising temperatures (Covington, 2000; Fry and Stephens, 2006). Climate change is likely to exacerbate the situation, most likely resulting in increases in tree mortality due to competition, drought, insects and pathogens, and increases in wildfire size and severity (Garfin et al., 2013). These changes may already be occurring; several states in the western US, including Washington, New Mexico, Arizona, Utah, and California have experienced their largest wildfire in recorded history since 2000. An increase in fire severity has been documented in some regions as well (Miller et al., 2009; Poling, 2016).

Research over several decades has demonstrated heavier fuel loads present in today's forests compared to historical conditions (e.g., Covington and Moore, 1994; Taylor, 2004; Fry and Stephens, 2006). Fuel reduction treatments, including prescribed fire, mechanical thinning, and pile burning, are designed to create a more open forest structure and reduce fire hazard by removing surface fuels, increasing the height of the canopy and reducing canopy fuels, and retaining large, fire-resistant trees (Agee and Skinner, 2005; L.L. Stephens et al., 2012). These treatments also may improve overall ecosystem function, by increasing rates of decomposition and nutrient cycling, water availability, carbon storage, plant biodiversity, and populations of native wildlife species (Converse et al., 2006; Finkral and Evans, 2008; Boerner et al., 2009). Because of the potential benefits for reducing fire hazard and increasing ecosystem function, U.S. Department of the Interior land management agencies and the U.S. Forest Service spent an average of $522 million annually between 2002 and 2012 on fuel reduction treatments, and treated an average of 1.1 million hectares between 2002 and 2006 (Gorte, 2011, 2013), in the hopes of preventing catastrophic wildfires.

Despite the strong belief that fuel treatments should be effective in reducing fire risk, and their increased implementation on the landscape, firefighting costs have tripled over the last 25 years (Gorte, 2013). Thus, either treatments are not working as predicted, or they are not being implemented widely enough. Meanwhile, millions of hectares of forest containing uncharacteristically heavy and continuous fuel loads persist on the landscape (Covington, 2000), and fuel treatments are the subject of significant public and policy debate about risks, particularly in regards to prescribed fire, versus rewards (Kline, 2004; Ryan et al., 2013). It is timely to assess the current state of knowledge about fuel treatment effectiveness.

Research on fuel treatment effectiveness has been increasing in many fire-prone regions of the world. For example, prescribed fire has been implemented in Australia since the mid-1950s, and a review on the subject concluded that prescribed fires are effective in reducing fire severity, particularly <5 years post-treatment (Fernandes and Botelho, 2003). In Europe, treatments have been implemented more recently (circa 1990s) and mostly in the form of fuelbreaks; fuel reduction treatments have been limited due to high costs, minimal area where they can be implemented, and legal barriers (Xanthopoulos et al., 2006). In North America, fuel reduction treatments are widely implemented in dry forests and are thought to be a valuable land management tool (L.L. Stephens et al., 2012), but there has been no review of treatment effectiveness based on actual responses after wildfire, and modeling studies only provide predictions of fire behavior based on given forest and weather conditions, and could be misleading (Cruz and Alexander, 2010). After two decades of wide-spread treatment implementation in the U.S. and Canada, there are now many examples of wildfires burning through both treated and untreated areas, and the effectiveness of implemented treatments can be evaluated empirically. We chose to focus on western North America due to the need for synthesis and the particular forest history of the place: fire regime interruption resulting from westward expansion and settlement, and subsequent intensive livestock grazing, all temporally correlated (Fulé et al., 1997). There has also been a fairly consistent forest management response via the U.S. Forest Service (Dellasala et al., 2004). Thus, our review is directly relevant to the importance that fuel treatment effectiveness has for natural resource policy in the western U.S.

Evidence-based reviews, including systematic reviews, are being used in ecology as an objective and rigorous means of accessing and synthesizing the literature (Peppin et al., 2010; Fulé et al., 2012). The goal of a systematic review is to exhaustively search and obtain data in all relevant, peer-reviewed journal publications as well as unpublished, often not peer-reviewed, gray literature using clearly defined and replicable procedures. The final review uses criteria to rank the quality of each source of evidence, quantitatively or qualitatively summarizes the findings (using the quality of evidence as a weighting scheme), highlights areas where additional research is needed, and provides management recommendations that incorporate the quality of individual science findings (Pullin and Stewart, 2006). Systematic reviews are excellent tools for identifying the extent of research on a topic, including research gaps (Lortie, 2014). In this review, we identified studies that examined treated and untreated sites, both post-wildfire, to evaluate the current state of knowledge about whether treatments are more effective than no action, and whether certain treatments are more effective than others. Our objective was to address the question: What evidence is there that fuel treatments are effective at achieving ecological (restoring ecosystem structure, composition, and function) and social (saving human lives and property) objectives?

2. Methods

We searched Web of Science and Google Scholar databases for papers published prior to January 2016. We used the keywords "WILDFIRE and EFFECTS and TREATMENT," and selected studies that met these 4 criteria:

1. Subject: western U.S. and Canada coniferous forests dominated by (1) ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*), (2) pines mixed with oak (*Quercus* spp.), or (3) dry mixed conifer forests dominated by one of these pine species but also could contain true firs (*Abies* spp.), Douglas-fir (*Pseudotsuga menziesii*), other pine species (e.g., *Pinus lambertiana*, *Pinus coulteri*) and/or quaking aspen (*Populus tremuloides*).
2. Intervention: fuel treatments including thin, burn, or thin + burn; in all cases, later burned by wildfire.
3. Comparator: untreated forest stands or sites; in all cases, later burned by wildfire.

4. Outcome: any ecosystem or human response variable, including but not limited to fire behavior, acres burned, property lost, carbon stored/lost, wildlife habitat, etc.

We extracted data from each relevant paper, and summarized the results in tabular form (Table 1). Parameters noted included: source of the paper, location of the study, forest type, the number of fires included in the study, and time since fire, in addition to a qualitative summary of results. Whenever possible, we noted results by treatment type (thin, burn, thin + burn) although some studies simply referred to "fuel reduction treatments." Because this is strictly a systematic review and not a meta-analysis, we did not record effect size.

We assessed "quality of evidence" in each paper based on experimental design (empirical, modeling, or anecdotal), whether or not the paper was peer-reviewed, and the number of fires considered in the paper (Table 2). We omitted modeling studies that predicted fire severity, but included modeling studies that examined carbon or wildlife habitat, because these variables are otherwise difficult to evaluate. Empirical, peer-reviewed papers that included data from multiple fires were assigned as the "highest" quality evidence, while anecdotal reports, not peer-reviewed, and based on one fire were assigned to the "lowest" quality category.

3. Results

We found 56 papers over a variety of response variables (Table 1). The majority of papers (79%) were published since 2007. Study sites range over 8 states in the western U.S. (Fig. 1). Nineteen fires were studied in California, 6 in AZ, 5 each in Oregon and Washington, 3 in New Mexico, and 2 each in Colorado, Idaho, and Montana. Some fires were included in multiple papers. 66% of papers included one fire and 34% included two or more fires (Fig. 2); modeling studies are not included in these statistics, as they typically do not model specific fires. Almost half of the papers (43%) were focused on mixed-conifer forests, 25% were on pine only, 2 papers (4%) were focused on pine-oak forests, and the rest included a combination of mixed-conifer, pine, and pine-oak forests. Of the papers in which time between the fire and effectiveness of fuel treatments was reported (43), more than half (22) measured effectiveness the same year or 1 year post-fire. Thirteen measured effectiveness 2–10 years post-fire, and only 2 measured differences between treated and untreated sites >10 years post fire.

There is a range of quality of papers (Fig. 3) due to the different methods used (71% empirical, 21% modeling, and 9% anecdotal), the different sources of information (71% peer-reviewed and 29% gray literature), and the number of fires included in each study. Including papers of all quality levels helps to reduce bias (e.g., by including data unpublished due to lack of significant results). We presented every response variable that was reported in the studies that met our criteria, and then grouped them in a logical fashion into the following categories: fire behavior/overstory structure, soil, understory vegetation, carbon storage, wildlife, and human values (property saved or safety improved). Any response variable not discussed (e.g., hydrological, invertebrate, or economic responses to treatment and wildfire) represents a data gap.

We attempted further synthesis of our results by considering the sample size for each response variable; however, most variables had a sample size <13 (e.g., carbon). Although 39 papers are listed under "fire behavior/overstory structure," they report a wide range of response variables, most not of an adequate sample size for meta-analysis. Variables related to fire severity (canopy volume scorch and scorch height percent crown scorch) had an adequate sample size, but a meta-analysis was recently conducted using 19 of these studies (Martinson and Omi, 2013) and thus we do not recreate their work. We also do not attempt to summarize the results via "vote-counting" whereby we simple tally the number of significant positive and negative, and non-significant results. This practice has been thoroughly debunked in the literature (Hedges and Olkin, 1985; Koricheva et al., 2013; Lortie, 2014) because it ignores quality of evidence (e.g., sample size, variance) and has poor statistical power; in fact, the larger the pool of studies, the more difficult it becomes to detect an effect. Thus, our results and discussion focus on a qualitative synthesis, as well as identification of data gaps, in order to provide an agenda for future research.

3.1. Evidence for fuel treatment effectiveness in terms of ecological attributes

3.1.1. Fire behavior and overstory structure

The majority of papers (39) included results on the effects of fuel treatments post-wildfire on various aspects of fire behavior and the direct effects of fire on overstory structure, including assessments of burn severity, crown and bole scorch and char, and tree mortality. Most papers were in the highest (6) or high (26) quality categories, with 2 in each of the medium, low, and lowest quality categories. Studies included fires in 8 western states, and all forest types we considered for this review (pine, pine-oak, and mixed-conifer) were represented. Papers included results on fire behavior, fire severity, crown torch and scorch, canopy consumption, char height and bole scorch, overstory mortality/survivorship, live basal area, tree density, canopy cover and closure, live tree cover, and regeneration. All studies found a positive effect of at least one treatment. Several studies found that thin + burn treatments had the greatest positive effects, while burning or thinning alone had either less of an effect or none at all (Omi et al., 2006; Harbert et al., 2007; Ritchie et al., 2007; Hudak et al., 2011; Prichard and Kennedy, 2012; Cram et al., 2015). In at least two cases, thinning alone actually increased burn severity compared to untreated sites (Raymond and Peterson, 2005; Wimberly et al., 2009). In three studies, time since treatment (>5–19 years) was associated with a decrease in positive effects (Foxx, 1996; Finney et al., 2005; Omi et al., 2006), and treatment size (roughly >4 km^2) was associated with an increase in positive effects in one study (Finney et al., 2005). Three studies found that distance from the edge of a treatment was important, with treatment benefits higher farther into fuel treatments (Symons et al., 2008; Safford et al., 2009; Kennedy and Johnson, 2014).

A meta-analysis by Martinson and Omi (2013) summarized canopy volume scorch and scorch height percent crown scorch in treated versus untreated sites burned by wildfire in 19 studies. They found that overall mean effect of fuel treatments on fire responses in the 19 studies was large and significant, equating to a reduction in canopy volume scorch from 100% in an untreated stand to 40% in a treated stand, and a reduction in scorch height from 30 m to 16 m. The effect was greater with increased thinning intensity, a result also found by Cram et al. (2006). In addition, treatment age was important, with treatments <10 years old more effective.

Three studies examined tree regeneration post-wildfire. Stevens et al. (2014) found that tree seedlings were more abundant in treated areas after wildfire across 12 sites in California. Strom and Fulé (2007) found that ponderosa pine regeneration was patchy, but denser in treated areas. Shive et al. (2013b) found that 8 years after fire, there was higher pine regeneration frequency in thin + burn sites versus untreated sites, and this effect increased with fire severity. The authors hypothesized that this was because high severity fire patches were smaller in the treated areas, resulting in less distance from a seed source.

Table 1

Citation, location/forest type, time since fire, quality of evidence category, and outcome of each study that met search criteria; studies are arranged by response variable, then from highest to lowest quality, and then alphabetically.

Authors	Source[a]	Location	Forest type[b]	Time since fire (years)	Quality of evidence[c]	Outcome
Fire behavior/overstory structure						
Arkle et al. (2012)	Forest Ecology and Management	Central ID	MC	1	Highest	Treatments (burn) resulted in significantly reduced wildfire severity compared to untreated buffers
Cram et al. (2015)	Forest Science	3 sites in AZ and NM	MC, PO	2–10	Highest	Mixed results; thin treatments were not effective in reducing overstory mortality, but thin + burn treatments reduced mortality
Pollet and Omi (2002)	International Journal of Wildland Fire	4 sites in MT, WA, CA, AZ	PINE	1–2	Highest	Fire severity and crown scorch were significantly lower at the treated (thin, burn, thin + burn) sites
Safford et al. (2012)	Forest Ecology and Management	12 sites in CA	MC, PINE	0–5	Highest	Char height, height and percent of crown torch and scorch, and adult tree survivorship were all increased in treated areas compared with untreated areas in almost all fires
Stevens et al. (2014)	Canadian Journal of Forest Research	12 sites in CA	MC, PINE	2, 3, or 5	Highest	Treatments (thin, thin + burn) resulted in higher live basal area, live tree density, canopy closure and live tree cover than untreated sites after wildfire
Wimberly et al. (2009)	Ecological Applications	3 sites in MT, WA, and AZ	MC, PINE	Short-term but yrs not specified	Highest	Thin + burn treatments reduced fire severity on 2 of the fires; recent thinning alone increased burn severity on 2 of the fires but in two cases where the treatments were older thinning alone resulted in decreased burn severity
Cram et al. (2006)	USFS RMRS-RP-55	5 sites in AZ and NM	PINE	0, 1, 4	High	Determined a canopy fuel consumption threshold that consisted of canopy bulk density of 0.047 kg/m^3; stands that underwent surface fuel treatments (thin or thin + burn) with canopy bulk density below this threshold showed no evidence of canopy fuel consumption
Foxx (1996)	USFS RM-GTR-286	Northern NM	PINE	0, 1, 8, 15, 16	High	Areas burned 1 and 17 years before the wildfire suffered less damage to crowns than areas that had been burned 40 and 84 years before
Hudak et al. (2011)	USFS RMRS-GTR-252	Central ID	MC	1	High	Thin + burn treatments reduced crown and overstory char and scorch; no effect of thinning alone
Kennedy and Johnson (2014)	Forest Ecology and Management	Eastern AZ	MC	0	High	Treated areas (thin + pile burn) showed evidence of reduced fire severity compared to untreated areas; severity was further reduced farther into fuel treatments
Lyons-Tinsley and Peterson (2012)	Forest Ecology and Management	Northern WA	MC	Short-term but yrs not specified	High	Treated areas (broadcast burn after harvest) in young plantations had less severe fire effects as measured by tree mortality
Martinson and Omi (2003)	USFS RMRS-P-29	8 sites across the western US	MC, PINE	1–10	High	Crown volume scorch averaged 38% in treated (thin, burn, thin + burn) areas versus 84.5% in untreated areas
Martinson et al. (2003)	USFS RMRS-GTR-114	Central CO	MC, PINE	0	High	Extreme weather conditions and other abiotic factors made most pre-wildfire stand treatments ineffective, but there were examples in which prescribed fires, old burns, thinning treatments, and timber harvests mitigated wildfire burn severity by changing fire behavior from crown to surface fire
Moghaddas and Craggs (2007)	International Journal of Wildland Fire	Northern CA	MC	0	High	Lower fire severity in treated sites (thin + biomass removal)
Martinson and Omi (2013)	RMRS-RP-103WWW	US	MC, PINE, PO	NA	High	Meta-analysis found that overall mean effect of fuel treatments on fire responses is large and significant, equating to a reduction in canopy volume scorch from 100% in an untreated stand to 40% in a treated stand, a reduction in scorch height from 30 m to 16 m, or an inferred reduction in flame length from 3.4 m to 2.1 m; heavier thinning has greater effect
Omi and Martinson (2002)	JFSP Final Report	3 sites in CA, CO, and NM	MC, PINE	0, 1	High	Wildfire severity (scorch height, crown volume scorch, stand damage, and depth of char) was lower in treated areas (thin, burn, thin + burn) compared to untreated areas
Omi et al. (2006)	JFSP Project 03-2-1-07	5 sites across the western US	MC, PINE	1	High	Fire severity was reduced in recent treatments (<10 yr), with thin + burn having the greatest effect (versus thin, burn, untreated)
Prichard and Kennedy (2012)	International Journal of Wildland Fire	Northern WA	MC	1–3	High	Higher tree mortality in control and thin only compared to thin + burn treatments
Prichard and Kennedy (2014)	Ecological Applications	Northern WA	MC	1	High	Treatments (thin, thin + burn) resulted in lower burn severity than untreated areas
Prichard et al. (2010)	Canadian Journal of Forest Research	Northern WA	MC	1–3	High	Total tree mortality, large tree mortality, percent crown scorch, and burn severity index, are significantly lower in thin + burn units, higher in thin, and highest in control units
Raymond and Peterson (2005)	Canadian Journal of Forest Research	Southwestern OR	MC	1–2	High	Tree mortality was most severe in thinned treatments (80–100%), moderate in untreated stands (53–54%), and least severe in the thinned and burned treatment (5%)
Ritchie et al. (2007)	Forest Ecology and Management	Northeastern CA	PINE	1	High	Probability of survival was greatest in those areas that had both thinning and prescribed fire prior to the wildfire event; less in thinned-only areas; near zero for the untreated areas

(*continued on next page*)

Table 1 (*continued*)

Authors	Source[a]	Location	Forest type[b]	Time since fire (years)	Quality of evidence[c]	Outcome
Safford et al. (2009)	Forest Ecology and Management	Northern CA	MC	0–1	High	Bole char height and fire effects to the forest canopy (measured by crown scorching and torching) were significantly lower, and tree survival significantly higher, within sampled treatments (thin + burn) than outside them; in most cases, crown fire behavior changed to surface fire within 50 m of encountering a fuel treatment
Shive et al. (2013a,b)	Forest Ecology and Management	East–central AZ	PINE	8	High	8 years post-fire, significantly higher pine regeneration frequency in thin + burn sites versus untreated sites, and this effect increased with fire severity
Stevens-Rumann et al. (2013)	International Journal of Wildland Fire	East-central AZ	PO	2 and 9	High	Canopy cover and live basal area were higher in treated (thin + burn) sites than untreated sites 2 and 9 years after wildfire
Strom and Fulé (2007)	International Journal of Wildland Fire	East-central AZ	PINE	2	High	Treated (thinned) areas had more live trees and survival, and reduced fire intensity as indicated by crown base height and bole char. Ponderosa pine regeneration was patchy but more dense in treated areas. Differences were projected to persist for several decades (stand structure characteristics) up to at least 100 years (species composition)
Symons et al. (2008)	The California Geographer	Northeastern CA	MC	Short-term but yrs not specified	High	Reduced overstory tree mortality, bole scorch, and crown scorch in treated areas (thin, thin + burn). Distance from edge was important, with reductions in bole scorch and crown scorch higher farther into treated areas
van Leeuwen (2008)	Sensors	East-central AZ	PINE	0, 1, 3, 5	High	Prescribed fire fuel treatments were largely unburned or impacted by low-severity fire in the Rodeo-Chediski fire
Wagle and Eakle (1979)	Forest Science	East-central AZ	PINE	1	High	Treatment (burn) resulted in lower tree mortality
Waltz et al. (2014)	Forest Ecology and Management	Eastern AZ	MC	1	High	High-severity fire patches were smaller in treated (thin, thin + burn, or thin + fuel removal) areas compared to untreated areas, and overstory mortality was less in treated areas compared to untreated
Yocom Kent et al. (2015)	Forest Ecology and Management	East-central AZ	PINE	2 and 8	High	High and moderate-severity fire was reduced from 76% in untreated areas to 57% in burn treatments and 38% in thin + burn treatments
Finney et al. (2005)	Canadian Journal of Forest Research	East–central AZ	PINE	0	High	Fire severity increased with time since treatment (prescribed burn only) but decreased with unit size and number of repeated treatments
Dailey et al. (2008)	USFS Unpublished report	Northern CA	MC	0	Medium	Treated (thin, thin + burn) areas had significantly lower levels of tree crown consumption than untreated areas
Fites et al. (2007)	USFS Unpublished report	Northern CA	MC	0	Medium	Significantly greater proportion of plots showed high-severity impacts on trees in untreated areas compared to treated (thin, burn, thin + burn) areas
Harbert et al. (2007)	USFS & BLM Unpublished report	Central OR	MC, PINE, PO	0	Low	Mixed results; thin only treatments were less effective than thin + burn in reducing tree mortality and fire severity
Graham et al. (2009)	USFS RMRS-GTR-229	Central ID	MC	0	Low	Treatments (thin, burn, thin + burn) modified wildfire intensity; burn severity to vegetation and soils within the areas where the fuels were treated was generally less than untreated
Bostwick et al. (2011)	USFS Unpublished report	Eastern AZ	MC, PINE	0	Lowest	Fuel treatments resulted in less severe fire
Murphy et al. (2007)	USFS R5-TP-025	Northern CA	MC	0	Lowest	Treatments (thin + pile burning) reduced fire behavior from a crown fire to a surface fire
Rogers et al. (2008)	USFS R5-TP-026a	Southern CA	PO	0	Lowest	Treatments (thin, thin + burn) decreased fire severity
Soil						
Stevens et al. (2014)	Canadian Journal of Forest Research	12 sites in CA	MC, PINE	2, 3, or 5	Highest	Treatments (thin, thin + burn) resulted in deeper litter, less bare ground, and lower soil moisture than untreated sites after wildfire
Choromanska and DeLuca (2001)	Soil Science Society of America Journal	Southwestern MT	MC	0–2	High	Compared to untreated sites burned by wildfire, treated (burn only) sites had decreased rates of net nitrogen mineralization, increased levels of potentially mineralizable nitrogen and biomass carbon, and faster rates of microbial recovery
Homann et al. (2011)	Soil Science Society of America Journal	Southwestern OR	MC	1	High	Nitrogen loss was twice as high in treated (thinned) sites compared to untreated sites
Wagle and Eakle (1979)	Forest Science	East-central AZ	PINE	1	High	Treatment (burn) resulted in less available soil nutrients
Dailey et al. (2008)	USFS Unpublished report	Northern CA	MC	0	Medium	Areas with treatments (thin, thin + burn) had significantly lower levels of soil burn severity than untreated

Fites et al. (2007)	USFS Unpublished report	Northern CA	MC	0	Medium	Significantly greater proportion of high severity burned soil occurred in untreated areas compared to treated (thin, burn, thin + burn) areas
Understory vegetation						
Cram et al. (2015)	Forest Science	3 sites in AZ and NM	MC, PO	2–10	Highest	More bare soil in untreated stands, but no difference in understory biomass between treated (thin, thin + burn) and untreated sites
Hunter et al. (2006)	International Journal of Wildland Fire	3 sites in CO and NM	MC, PINE	1, 2	Highest	Treated areas (thin, burn, thin + burn) had a positive but non-significant relationship with exotic species at one of the three fires
Stevens et al. (2014)	Canadian Journal of Forest Science	12 sites in CA	MC, PINE	2, 3, or 5	Highest	Treatments (thin, thin + burn) resulted in more tree seedlings, less shrub seedlings, and less shrub cover than untreated sites after wildfire
Hudak et al. (2011)	USFS RMRS-GTR-252	Central ID	MC	1	High	Thin + burn treatments had no effect on understory
Kuenzi et al. (2008)	Forest Ecology and Management	East–central AZ	PINE	2–3	High	Cover was low at <3% across all years, severities, and treatments (thin + burn); no significant differences in exotic species cover between treated and untreated areas
Omi et al. (2006)	JFSP Project 03-2-1-07	5 sites across the western US	MC, PINE	1	High	Some evidence in increased plant cover but also non-natives in recent treatments (thin, burn, thin + burn; <10 yr)
Shive et al. (2013a,b)	Forest Ecology and Management	East–central AZ	PINE	8	High	8 years post-fire, higher total understory plant cover at the low-severity treated (thin + burn) sites but high-severity untreated sites (high shrub cover); no significant differences in exotic species cover between treated and untreated areas
Shive et al. (2013a,b)	Applied Vegetation Science	East-central AZ	PINE	2, 3, 9	High	Understory plant cover was higher in untreated sites than in treated sites (thin + pile burn) at 2, 3, and 9 years post-fire. Plant communities were distinct between treated and untreated sites 2 and 3 years post-fire, but were converging by 11 years post-fire
Wagle and Eakle (1979)	Forest Science	East-central AZ	PINE	1	High	Treatment (burn) resulted in more vegetation ground cover
Waltz et al. (2014)	Forest Ecology and Management	Eastern AZ	MC	1	High	Total herbaceous understory plant cover was 1.5 times higher in treated (thin, thin + burn, or thin + fuel removal) vs. untreated areas 1 year after fire
Foxx (1996)	USFS RM-GTR-286	Northern NM	PINE	0, 1, 8, 15, 16	Medium	Areas burned 1 and 17 years before the wildfire had more vegetation cover than areas that had been burned 40 and 84 years before
Carbon storage						
North and Hurteau (2011)	Forest Ecology and Management	12 sites in CA	MC	Short-term but yrs not specified	Highest	Treatment (thin + fuel removal) reduced tree mortality and retained large tree C stocks; control continued to store the most carbon after wildfire but was mostly stored in dead trees, and had the greatest wildfire emissions
Homann et al. (2011)	Soil Science Society of America Journal	Southwestern OR	MC	1	High	Carbon loss was twice as high in treated (thinned) sites compared to untreated sites
Yocom Kent et al. (2015)	Forest Ecology and Management	East-central AZ	PINE	2 and 8	High	Treatments (thin, thin + burn) significantly influenced fire severity, which in turn influenced carbon: 8 years post-fire, high-severity burned areas held 58% of total carbon and 3% of live tree biomass as compared to low-severity areas
Ager et al. (2010)	Natural Hazards and Earth System Sciences	Southeastern OR	MC, PINE	Immediately after fuel treatments (modeled)	Medium	Fuel treatments reduced carbon stored more than expected carbon benefits from reducing fire risk and fire severity
Finkral and Evans (2008)	Forest Ecology and Management	Northern AZ	PINE	Unspecified (modeled)	Medium	Treated stands store less carbon, but treated stands would release less C in a stand-replacing wildfire
Hurteau and North (2008)	Frontiers in Ecology and the Environment	Central CA	MC	100 (modeled)	Medium	Control and burn stored the most C post-wildfire compared to thin and thin + burn, but C loss due to tree mortality was lowest in the thin + burn and burn, followed by thin, then control (which also had the highest emissions)
Mitchell et al. (2009)	Ecological Applications	Central WA	PINE	Unspecified (modeled)	Medium	More carbon was lost through most fuel treatments than through wildfires in this simulation study, although some understory removal treatments did result in overall increased carbon storage on the landscape through the reduction in fire severity
Reinhardt and Holsinger (2010)	Forest Ecology and Management	Northern ID and western MT	MC, PINE	95 (modeled)	Medium	Treatments (thin, thin + burn) decreased fire severity and reduced subsequent wildfire emissions, but did not increase post-wildfire C storage; untreated stands had greater wildfire emissions but stored more C
S.L. Stephens et al. (2012), includes data from Stephens et al. (2009)	Ecosphere	6 sites in CA, OR, MT, AZ	MC, PINE	1 or 2	Medium	Live tree C pool in untreated forest and thin only treatments had the highest chance of being killed in a wildfire and highest projected emissions; in contrast, burn and then thin + burn had lower vulnerability to C loss and lower emissions
Chiono et al. (2015)	California Energy Commission report	Northern CA	MC	Unspecified (modeled)	Low	Carbon emissions were lowest in no-treatment scenarios with wildfire, compared to scenarios combining prescribed burns and subsequent wildfires

(*continued on next page*)

Table 1 (*continued*)

Authors	Source[a]	Location	Forest type[b]	Time since fire (years)	Quality of evidence[c]	Outcome
Dicus and Osborne (2015)	Proceedings of the large wildland fires conference	Northern CA	MC	5, 50 years (modeled)	Low	Carbon dynamics depended on treatment type, spatial arrangement, and proportion of the landscape treated. Short-term, thin + burn treatments resulted in the greatest carbon losses from both treatments and wildfire. Long-term, burn only treatments resulted in the greatest on-site carbon storage
Wildlife						
Ager et al. (2007)	Forest Ecology and Management	Central OR	MC, PINE	0	Medium	A non-linear decrease in the probability of habitat loss with increasing treatment (thin + burn) area
Scheller et al. (2011)	Landscape Ecology	Central CA	MC, PINE, PO	60 (modeled)	Medium	Treatments (thin, burn, thin + burn) had indirect, positive effects on fisher population sizes, by reducing the probability of large wildfires that can damage and fragment habitat over larger areas
Tempel et al. (2015)	Ecosphere	Northern CA	MC	0, 10, 20, 30	Medium	In the absence of wildfire, treatments (thin, burn, mastication) had a slightly negative effect on California spotted owl habitat and demographics, but with modeled wildfire, treatments had a slightly positive effect on habitat and demographics up to 30 years after the wildfire
Chiono et al. (2015)	California Energy Commission report	Northern CA	MC	Unspecified (modeled)	Low	Fire intensity and burn probability were reduced in California spotted owl habitat when the habitat area was treated and also when surrounding (non-habitat) forest was treated (thin + burn or pile burn)
Entomology/forest health						
Prichard and Kennedy (2012)	International Journal of Wildland Fire	Northern WA	MC	1–3	High	Higher tree mortality in control and thin only compared to thin + burn treatments; bark beetles attacks on surviving trees were highest in the thin-only treatments and lowest in the thin + burn treatments
Human values: Property saved or safety improved						
Moghaddas and Craggs (2007)	International Journal of Wildland Fire	Northern CA	MC	0	High	Treated sites (thin + biomass removal) resulted in increased penetration of retardant to surface fuels; improved visual contact between fire crews and the Incident Commander; safe access to the main fire; and quick suppression of spot fires
Fites et al. (2007)	USFS Unpublished report	Northern CA	MC	0	Medium	Firefighters were better able to use treated (thin, burn, thin + burn) areas
Harbert et al. (2007)	USFS & BLM Unpublished report	Central OR	MC, PINE, PO	0	Low	Treatments (thin, thin + burn) helped increase suppression effectiveness
Bostwick et al. (2011)	USFS Unpublished report	Eastern AZ	MC	0	Lowest	Fuel treatments resulted in fewer homes destroyed and better ability to fight fire
Murphy et al. (2007)	USFS R5-TP-025	Northern CA	MC	0	Lowest	Treatments (thin + pile burning) reduced heat and smoke allowing firefighters to be more effective
Rogers et al. (2008)	USFS R5-TP-026a	Southern CA	PO	0	Lowest	Treatments (thin, thin + burn) increased visibility during firefighting, and helped speed up evacuation

[a] USFS = United States Forest Service, JFSP = Joint Fire Science Program, BLM = Bureau of Land Management.

[b] MC = mixed conifer, PINE = pine-dominated, PO = pine-oak; see Section 2 for detailed description of forest types.

[c] See Table 2 for criteria for quality of evidence categories.

Table 2
Criteria used in rating quality of evidence available in literature reviewed, and categories assigned.

Criteria	Quality of evidence
Empirical, peer-reviewed, multiple fires	Highest
Empirical, not peer-reviewed, multiple fires OR empirical, peer-reviewed, one fire	High
Empirical, not peer-reviewed, one fire OR modeled, peer-reviewed	Medium
Modeled, not peer-reviewed OR anecdotal, multiple fires	Low
Anecdotal, one fire	Lowest

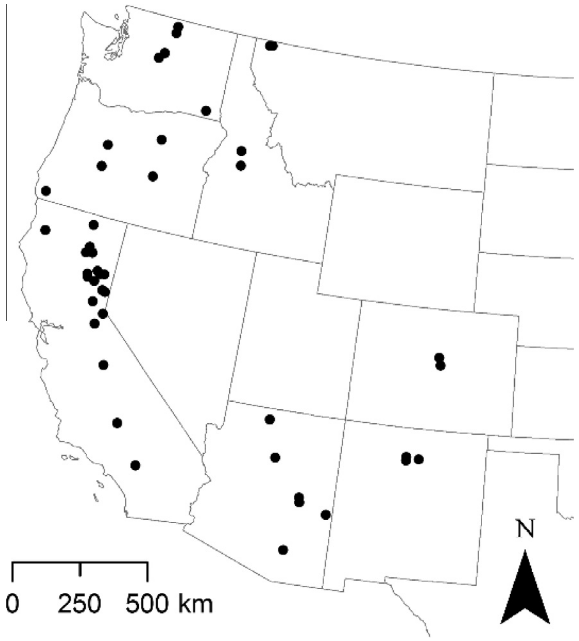

Fig. 1. Approximate locations of fires studied in papers included in this review.

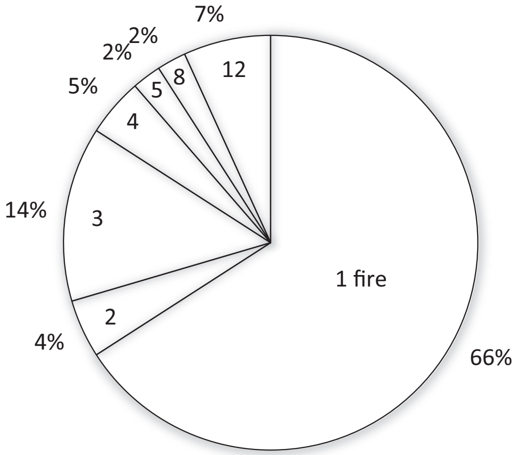

Fig. 2. Proportion of 44 papers in this review including 1 or more fires in their analysis.

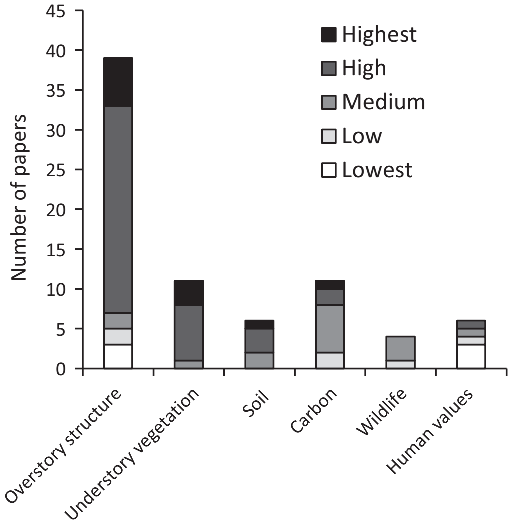

Fig. 3. Number and quality of papers identified for each response variable.

3.1.2. Understory vegetation

Eleven studies examined the effects of treatment on understory vegetation, post-wildfire. Ten papers were rated highest or high quality. Papers presented data from fires in 7 states, and included pine, pine-oak, and mixed-conifer forests. More so than for other response variables, effects of treatments on understory vegetation were mixed. A few studies found treated areas had higher plant cover (Wagle and Eakle, 1979; Omi et al., 2006; Shive et al., 2013b; Waltz et al., 2014), while others found no effect of treatment on plant cover or richness (Kuenzi et al., 2008; Hudak et al., 2011; Cram et al., 2015). Shive et al. (2013a) found that understory plant cover was higher in untreated sites compared to treated sites 2, 3, and 9 years post-fire. Omi et al. (2006) and Hunter et al. (2006) found increased non-native plant species cover associated with treatments, while Kuenzi et al. (2008) and Shive et al. (2013b) found no effect of treatment on exotics.

3.1.3. Soils

We identified six studies that examined the post-wildfire effects of treatments on soil properties. One was highest quality, three were high quality, and two were medium quality. Fires from 4 states were included in these studies, and pine and mixed-conifer forest types were represented. A high quality study found that prescribed fire prior to wildfire attenuated the effects of wildfire on soil by lessening the loss of labile carbon and nitrogen and improving resistance to fire of the soil microbial community (Choromanska and DeLuca, 2001), and a highest quality study reported deeper litter and less bare ground in treated sites (Stevens et al., 2014). However, a high quality study found that prescribed fire resulted in lower soil nutrient availability (Wagle and Eakle, 1979), and another high quality study found that nitrogen loss was twice as high in treated sites compared to untreated sites (Homann et al., 2011). Two additional studies found that soil burn severity, based on visual estimates according to the U.S.D.I. National Park Service (2003) protocol, was higher in the untreated versus treated sites (Fites et al., 2007; Dailey et al., 2008).

3.1.4. Carbon storage

Eleven studies examined the effects of treatment and wildfire on carbon storage and emissions. One was highest quality, 2 were high quality, 6 were medium quality, and 2 were low quality. Fires from 6 states were described, and pine and mixed-conifer forests were represented in the papers. Compared to untreated wildfire-burned sites, treated areas had lower carbon losses in wildfire in several studies (Finkral and Evans, 2008; Hurteau and North, 2008; Reinhardt and Holsinger, 2010; North and Hurteau, 2011; S.L. Stephens et al., 2012). On the other hand, several studies also found that the control continued to store the most carbon after wildfire compared to treatments (Finkral and Evans, 2008; Hurteau and North, 2008; Reinhardt and Holsinger, 2010; North and Hurteau, 2011), or that more carbon was lost through treatments than through carbon benefits from reduced fire risk or fire severity (Mitchell et al., 2009; Ager et al., 2010; Homann et al., 2011; Chiono et al., 2015). However, in one of those cases, North and Hurteau (2011) determined that the carbon was mostly stored in dead trees, and projected that the untreated sites will become long-term carbon sources. Yocom Kent et al. (2015) found similar results; treatments significantly affected fire severity, which in turn influenced carbon storage. Eight years post-fire, areas burned at high severity held 58% of total carbon and 3% of live tree biomass as compared to low-severity burned areas.

Hurteau and North (2008) also found that initial stand conditions greatly affected carbon storage, and that a low-density forest dominated by large, fire resistant pines may best protect tree-based carbon stocks. S.L. Stephens et al. (2012) and Hurteau and North (2008) found that the projected C loss due to tree mortality in a wildfire was lowest in thin + burn and burn treatments, compared to the control; C loss in the thin only was comparable or even higher than the control. Results also may depend on the time frame of the study; Dicus and Osborne (2015) found that short-term, thin + burn treatments resulted in the greatest carbon losses, but long-term, burn-only treatments resulted in the greatest on-site carbon storage. Treatment effects on carbon lost in wildfire are reviewed in Restaino and Peterson (2013) as well as Campbell et al. (2011).

3.1.5. Wildlife

No empirical studies were found on wildlife occurrence, density, or fitness in treated versus untreated sites post-wildfire. Only 4 modeling papers were found describing treatment effectiveness for wildlife parameters, and they were all rated as medium or low quality of evidence due to the modeled results. The species involved and the geographic scope of papers in this category are limited. Three papers were on spotted owls (*Strix occidentalis caurina* and *Strix occidentalis occidentalis*) and one was on fishers (*Martes pennanti*). Three papers were based in California and one in Oregon. Modeling studies on spotted owls showed a non-linear decrease in the probability of habitat loss post-wildfire with increasing treatment area (Ager et al., 2007), reduced fire intensity and burn probability in spotted owl habitat in treated areas and also when surrounding (non-habitat) area was treated (Chiono et al., 2015), and a slightly positive effect on habitat and demographics up to 30 years post-wildfire in treated forests (Tempel et al., 2015). A modeling study of fishers (*M. pennanti*) determined that, post-wildfire, there was an overall positive effect of treatments due to reduced habitat fragmentation, compared to untreated areas lacking fire breaks (Scheller et al., 2011).

3.1.6. Entomology/forest health

One paper found that bark beetle attacks on surviving trees after treatment and wildfire were highest in the thin-only treatments and lowest in the thin + burn treatments (Prichard and Kennedy, 2012).

3.2. Evidence for fuel treatment effectiveness in terms of human values

Six papers reported on fuel treatment effectiveness in terms of human values such as firefighter safety, suppression factors, homes burned, heat and smoke, and visibility. Only one of these papers was in the high quality category; 4 were rated low or lowest because they were unpublished and/or anecdotal reports. Four included information about fires in California, 1 was about a fire in Arizona, and 1 included a fire in Oregon. Firefighting effectiveness was reportedly increased by treatments, due to increased visibility in treated areas and decreased heat and smoke (Fites et al., 2007; Harbert et al., 2007; Murphy et al., 2007; Rogers et al., 2008; Bostwick et al., 2011). However, these studies were anecdotal and not peer-reviewed. Moghaddas and Craggs (2007), the high quality paper, reported similar results with treatments resulting in increased penetration of retardant to surface fuels, improved visibility between fire crew members, safe access to the fire, and quick suppression of spot fires. We found one paper on homes saved in treated versus untreated areas post-wildfire; however, this study was anecdotal, based mostly on testimonials from fire fighters and home owners (Bostwick et al., 2011). Another paper mentions that treatments increased the speed of evacuations (Rogers et al., 2008), which may have helped save human lives.

4. Discussion

Measuring fuel treatment effectiveness is difficult because it is impossible to know exactly where and when a wildfire will burn, so researchers cannot measure pre-fire fuel and forest conditions in expectation of an imminent wildfire. In addition, detailed information about treatments is usually not available and cannot be measured after a wildfire has burned through. However, despite these challenges, a body of literature is emerging on fuel treatment effectiveness across the western US, empirically comparing treated and untreated forested areas after wildfire. We found that this body of literature is fairly robust in outlining treatment effectiveness in terms of overstory structure and fire behavior attributes. However, there are important data gaps in documenting fuel treatment effectiveness in terms of other ecological and human values (Table 3).

The consensus of our qualitative review is that fuel treatments reduce fire severity, crown and bole scorch, and tree mortality compared to untreated forests, post-wildfire; however, this finding is most consistent for thin + burn treatments. This conclusion is based on mostly high quality studies, and corroborated by a meta-analysis on the same topic (Martinson and Omi, 2013), which found that treatment effects are overall large and significant, but vary in effectiveness due to treatment type (thin, burn, or thin + burn) and vegetation (treatments are more effective in conifer forests and less so in woodlands). A systematic review by Fulé et al. (2012) did not meet our criteria for inclusion, as they used a predictive approach to evaluate the effects of treatments; however, they found similar results, where thin + burn treatments tended to have the greatest effect on reducing surface fuels and stand density, and reduced the modeled probability of crowning and torching, as compared to burning or thinning alone. Increased treatment size and intensity (e.g., number of trees removed) can increase effectiveness.

Although fire behavior is generally reported to be reduced by fuel treatments, it is less clear how fuel reduction treatments are affecting other ecological attributes. The overstory has greater survival and regeneration in response to treatments, particularly in thin + burn treatments, with more mixed results in thin and burn only. This difference in outcomes between treatment types is likely because different methods treat different aspects of the fuels complex. Thin + burn treatments remove surface, ladder, and canopy fuels, whereas burn only may not remove ladder fuels, and thinning without follow-up burning may just move fuels from the ladder and canopy to the surface (Brown et al., 2004). With currently 13 studies that examine treatment effectiveness in terms of tree survival, a meta-analysis on this response variable may be timely with the publication of a handful of additional studies. Understory responses are mixed across all treatments, and since the results are reported in high quality studies, the results may be due to the effect of other variables such as soil type, treatment intensity, fire

Table 3
Data gaps in the fuel treatment effectiveness literature.

Areas for future research	Existing evidence on this topic
Overstory • Tree regeneration • Overstory structure (e.g., tree mortality) • Other fire-adapted forest types (e.g., pine-oak)	Strong- focused on fire severity/behavior
Carbon • Other fire-adapted forest types (e.g., pine-oak)	Moderate- good consensus on western conifer forests
Understory • Mixed results of treatments; need to sort out effects of covariates (soil, fire severity, time, etc.) • Other response variables such as species diversity, invasive species	Moderate- mixed results
Soils • Fuel (duff, litter, soil) • Soil physical properties: nutrient cycling, soil moisture, soil pH, etc. • Microbial communities	Weak- fire severity only
Wildlife • Diversity, occurrence, fitness (reproduction and survival) • Other key species need attention besides spotted owl	Weak- only modeling studies focused on habitat
Entomology • Pests/pathogens • Pollinators • Insect diversity	Non-existent
Hydrology • Water yield • Water quality (sedimentation, nutrients)	Non-existent
Human lives and property ($) • Speed of evacuation • Number of homes lost/saved	Weak
Firefighting safety/$ • Heat • Smoke • Visibility	Weak
Forest uses ($) • Timber, recreation, hunting, fishing • Scenic beauty	Non-existent
Rehabilitation effort ($) • Types of treatments needed- seeding, erosion control structures, planting, etc.	Non-existent

Note: “$” indicates variables that may be best assessed via an economic analysis.

severity, or time since fire. Most studies focused on carbon storage were of high or medium quality, and agreed that treatments do not necessarily store more carbon after wildfire because carbon is removed during the treatments themselves, but result in less post-wildfire emissions and less carbon loss in a wildfire due to tree mortality.

Soil and wildlife data are too sparse to draw conclusions. Soil studies focus mostly on fire severity, and more information is needed on fuels, biological and physical properties of soil, and microbial communities. Only 4 wildlife studies exist and none are empirical; all use modeling and focus on habitat as a proxy for wildlife occurrence. Data on wildlife occurrences and diversity, density, reproduction, and survival are needed, but these types of studies are challenging because in addition to establishing a control and treatment, reference conditions are needed as a benchmark to define “desired” species or numbers. Such reference conditions often do not exist for wildlife populations.

Additional ecological data gaps (Table 3), almost entirely unaddressed in the literature, include hydrological (water quality/quantity) and entomological (pests as well as pollinators). More information is needed about treatment design, in terms of the effectiveness of different sizes or intensities (i.e., level of thinning, or frequency of burning) of treatment. This review did not attempt to examine the effectiveness of spatial scale, size, or arrangement of treatments (e.g., fuelbreaks) because we focused at the within-treatment scale, but this may be another topic for synthesis. In addition, the current body of treatment effectiveness literature is geared heavily toward conifer forests, and virtually no information exists on other fire-adapted forest types such as oak forests. In addition, there is a lack of understanding of the long-term effectiveness of treatments (see Yocom, 2013 for a summary). Fuel treatment longevity represents a data gap that needs attention via research and monitoring. With the likely prospect of different climate scenarios and the corresponding increases in wildfire size and severity (Westerling et al., 2006; Miller et al., 2009), research opportunities on post-wildfire effectiveness are increasing and likely to continue to grow.

Several studies reported that treatments were effective in achieving human objectives, including property saved and safety improved; however, reports are only anecdotal and generally of low quality. Data are needed on social variables including lives/property, firefighting effort and safety, human uses of forests (timber, recreation, etc.), and rehabilitation effort and cost (Table 3). This represents a large and important data gap: do fuel treatments make a difference in firefighter or homeowner outcomes when a wildfire comes through? There is a need for high-quality studies evaluating the safety of life and property in treated and untreated areas, and especially for converting such response variables into economic terms, to provide better cost-benefit analysis against costs of suppression versus restoration. Once again, the theory that restoration is more cost-effective than suppression is established in the literature (Snider et al., 2006), but empirical evidence is needed.

5. Management implications

Despite the millions of dollars spent annually on fuel treatments, and despite the general consensus that fuel treatments are indeed effective, there is surprisingly little data on fuel treatment effectiveness in North America, especially as it relates to outcomes other than overstory and fire behavior. What studies exist, however, support the notion that thinning and burning treatments are likely to be most effective because they remove both canopy and surface fuels. We also know that there are limitations to the effectiveness of fuel treatments; extreme weather conditions can overwhelm fuel conditions, and other variables likely cofound results of treatment-control studies (e.g., soil type, forest type, time since treatment, etc.). In addition, fuel treatment effectiveness likely decays over time, and so a fuel treatment plan must include a long-term strategy rather than a one-time effort. Most importantly, as treatments are implemented and wildfires burn, managers and researchers need to rigorously monitor and study treatment effectiveness to fill the many data gaps in our knowledge.

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