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Effectiveness of Fuels Reduction and Restoration Treatments in Seasonally Dry Forests – Annotated Bibliography

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Introduction to this Annotated Bibliography

Forest fuels reduction treatments (fuel treatments) are generally defined as "the purposeful use of any silvicultural method, including mechanical methods, managed wildfire, prescribed fire, or a combination of approaches, to intentionally alter the fuel complex in such a way as to modify fire behavior and thereby minimize the potential negative impacts of future wildfires on ecosystem goods and services, cultural resources, and human communities" (Hoffman et al. 2018, Stephens et al. 2021). Seasonally dry forests are those pine, dry mixed conifer, moist mixed conifer, and cold forests that are available to burn most years during the wildfire season (Hessburg et al. 2021). In 2021, Hessburg et al. summarized that "A large body of work shows that fuel reduction treatments, including portions of some past wildfires, effectively mitigate subsequent fire behavior and effects...Many studies show that fuel reduction treatments are effective at moderating subsequent fire severity, even under extreme weather. Far fewer experimental or empirical studies challenge this premise" (Hessburg et al. 2021). Prichard et al. (2021) state that "there exists widespread agreement that combined effects of thinning plus prescribed burning consistently reduces the potential for severe wildfire across a broad range of forest types and conditions… [T]here is strong scientific evidence that even under extreme weather conditions, fuel treatments are effective at moderating fire severity across a range of forest types and wildfire events".

This general consensus is not new. Dow et al. (2016) note that their finding of reduced conditional burn probability across a landscape with coordinated fuel treatments is not "a new finding". In fact, in 2012, Safford et al. concluded that their results add significantly to the growing evidence that fuel treatments that include removal of surface and ladder fuels in yellow pine and mixed conifer forests are highly effective management tools for reducing fire severity and canopy tree mortality. In their opinion, "quantitative assessments of fuel treatment effects on fire severity in frequent-fire forest types hardly merit further effort" (Safford et al. 2012). Given the acceleration of climate change and extreme drought and its influences on fire regime, continued assessments of fuel treatment effects under extreme weather conditions over the last decade have been continued and have drawn the same conclusions as Safford et al. (2012).

Despite this general and well-established consensus, a minority group of counter-evidence advocates continue to question the efficacy of thinning treatments (those that reduce tree density via harvest/removal) in modifying fire behavior and resulting vegetation effects as intended. The body of science on fuels treatment effectiveness in the seasonally dry forests of the western US continues to grow, even in the face of changing climates and extreme fire weather. This bibliography is meant to gather the majority of references on the effectiveness of fuels treatments in the western seasonally dry forests into a single, easily accessible location. However, it is not an exhaustive bibliography. Further, this bibliography does *not* include the references that only examined effects of fuels treatments on fire suppression efficiency or activities, though there are many of those, and the consensus is that fuels treatments increase firefighter response efficiency and options. This bibliography does not consider references that assess fuels treatment effectiveness in only high-severity fire regime forests (aside from a couple of references that occurred lodgepole pine systems which are noted in the 'other forest types' section), as these systems are expected to respond differently than those dominated by lower severity and more frequent fire regimes. Many other pieces of literature were considered and reviewed in the development of this bibliography, but did not meet the criteria of assessing fuel treatment effectiveness in seasonally dry western forests, and were thus not included here.

Empirical effects of fuels treatments on fire behavior and effects

Studies showing treatments are effective

1. Agee, James K.; Skinner, Carl N. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management. 211: 83-96.
    a. *Location*: California, Colorado, and Washington.
    b. *Vegetation types*: Many, includes CA ponderosa
    c. Summary: In addition to reviewing key challenges and techniques for mitigating fire risk, the authors simulate (model) four fuel reduction treatments: reduction of surface fuels, increasing the height to live crown, decreasing crown density, and retaining large trees of fire-resistant species. The publication contains very straightforward figures of these results. The authors found low thinning to be more effective than crown or selection thinning, and that management of surface fuels will increase the likelihood that the stand will survive a wildfire. Fire severity decreased as wildfires progressed further into areas with more treated area. Five empirical examples of such treatment are discussed: Hayfork fires, California, 1987; Tyee fire, Washington, 1994; Megram fire, California, 1999; Hayman fire, Colorado, 2002; and the Cone fire, California,

2002. Applying treatments at an appropriate landscape scale will be critical to the success of fuel reduction treatments in reducing wildfire losses in Western forests.

d. Longevity: Tyee Fire fuelbreak created in 1970s (effective); Megram fuelbreak after 1996 (effective); Megram noted ineffective where established 10-15 yrs pre-fire; Cone (effective) 2 and 5 yrs prior to fire. Suggests fuelbreaks ineffective 10-15 yrs post-treatment, but does not directly evaluate time since treatment.

2. Arkle R. S., D. S. Pilliod, and J. L. Welty. 2012. Pattern and process of prescribed fires influence effectiveness at reducing wildfire severity in dry coniferous forests. Forest Ecology and Management 276:174–184.
   a. *Location***:** central Idaho
   b. *Vegetation types***:** mixed conifer forest
   c. Summary: The authors examined the effects of three early season (spring) prescribed fires on burn severity patterns of summer wildfires that occurred 1–3 years post-treatment in a mixed conifer forest in central Idaho. Mechanical treatments were not part of this study. They found that wildfire severity was significantly lower in treated areas than in untreated areas and significantly lower than the potential wildfire severity of the treated areas had treatments not been implemented. The authors found considerable evidence that prescribed fires have landscape-level influences within treatment boundaries; most notable was an interaction between distance from the prescribed fire perimeter and distance from treated patch edges, which explained up to 66% of the variation in wildfire severity. Early season prescribed fires may not directly target the locations most at risk of high severity wildfire, but proximity of these areas to treated patches and the discontinuity of fuels following treatment may influence wildfire severity and explain how even low severity treatments can be effective management tools in fire-prone landscapes. This study suggests that even low severity prescribed burns can be an effective approach to limiting high severity fire in dry forests.
   d. Longevity: Wildfire occurred 1-3 years post-treatment.
3. Cram, D., Baker, T., Boren, J., 2006. Wildland Fire Effects in Silviculturally Treated Vs. Untreated Stands of New Mexico and Arizona. Res. Paper. RMRS-RP-55. USDA For. Serv., Rocky Mountain Res. Sta., Fort Collins, CO.
   a. Location: Arizona and New Mexico
   b. Vegetation: Doug-fir, ponderosa, white fir, Gambel oak, spruce spp.
   c. *Summary*: The authors examined whether forest stands treated with four different silvicultural prescriptions would be (a) less susceptible to stand- replacing crown fires, and (b) more ecologically and functionally resilient compared to untreated stands following extreme wildland fire. The authors compared fire severity indices, fireline intensity (btu/ft/s), stand characteristics including canopy bulk density, and post-fire recovery indices in silviculturally treated vs. untreated forest stands in New Mexico and Arizona. Results indicated fire severity lowered when surface and aerial fuel loads were reduced. As density and basal area decreased and mean tree diameter increased, fire severity and fireline intensity decreased. The more canopy bulk density was reduced, the less susceptible forest stands were to crown fire. The authors found mechanical treatment followed by prescribed fire had the greatest impact toward mitigating fire severity and that treated stands were also more ecologically and functionally resilient than untreated forest stands following wildland fire. Succinct tables and figures illustrate the above results with data/numbers. This article is now 15 years old.
   d. *Longevity:* Time since treatment ranged from 3-4 years (Rodeo-Chediski Fire, Oso Fire) and 5-8 years (Borrego Fire); time since treated not evaluated.

4. Estes, B. L., E. E. Knapp, C. N. Skinner, and F. C. C. Uzoh. 2012. Seasonal variation in surface fuel moisture between unthinned and thinned mixed conifer forest, northern California, USA. International Journal of Wildland Fire 21:428-435.
    a. *Location***:** Goosenest Adaptive Management Area on the Klamath National Forest, southern Cascade region, northern California.
    b. *Vegetation types:* mixed-conifer forest
    c. *Summary***:** While this study did not directly measure effects of thinning on fire behavior, it did measure attributes that influence fire behavior, and is thus summarized here. The objective of this study was to determine whether woody fuel moisture differed between unthinned and thinned mixed-conifer stands. Sections of logs representing the 1000- and 10 000-h fuel sizes were placed at 72 stations within treatment units in the fall (autumn) of 2007. Following snow-melt in 2008, 10-h fuel sticks were added and all fuels were weighed every 1–2 weeks from May until October. Moisture of the 10- and 1000-h fuels did not differ between unthinned and thinned stands at any measurement time. The 10 000-h fuel moisture was significantly less in thinned than unthinned stands only in early to mid-May. Overall, even when fuel moisture varied between treatments, differences were small. The long nearly precipitation-free summers in northern California appear to have a much larger effect on fuel moisture than the amount of canopy cover. Fuel moisture differences resulting from stand thinning would therefore not be expected to substantially influence fire behavior and effects during times of highest fire danger in this environment.
    d. *Longevity:* Does not address.
5. Finney, M. A., C. W. McHugh, and I. C. Grenfell. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35:1714–1722.
    a. *Location*: Rodeo and Chediski fires, Arizona
    b. Vegetation Type: Southwestern ponderosa pine forests
    c. *Summary*: This study analyzed previous satellite imagery and prescribed fire records to assess previous prescribed burn impact on fire behavior and effects of two of Arizona's largest ever recorded wildfires that occurred in 2002. The study does not examine mechanical fuels treatments. The authors found prescribed burning in ponderosa pine forests 1–9 years before the Rodeo and Chediski fires reduced fire severity compared with untreated areas, despite the large wildfire sizes and record drought. Fire severity increased with time since treatment but decreased with unit size and number of repeated prescribed burn treatments. Fire progression captured by Landsat 7 enhanced thematic mapper plus showed the fire circumventing treatment units and protecting areas on their lee side.
    d. *Longevity:* Treatments occurred 1 to 9 years prior to the fire; study does not evaluate differences by time since treatment.
6. Graham, R.T., T.B. Jain, and M. Loseke. 2009. Fuel treatments, fire suppression, and their interaction with wildfire and its impact: The Warm Lake experience during the Cascade Complex of wildfires in central Idaho, 2007. Gen. Tech. Rep. RMRS-GTR-229. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 36 p.
    a. *Location***:** Cascade Complex fires, central Idaho
    b. *Vegetation types:* ponderosa pine, Douglas-fir, lodgepole pine
    c. *Summary***:** This report summarizes an investigation into the 2007 Cascade Complex of wildfires in central Idaho, and details the influence of fuel treatments on fire behavior, suppression actions, and structure loss. The wildfires burned through several areas previously subject to fuel treatments designed to protect many residences around Warm Lake. A total of 9,095 acres were treated between 1996 and 2006 with mechanical treatments and prescribed fire. In almost every case, mechanical treatments were followed by prescribed fire to reduce surface

fuels. The fuel treatments allowed fire crews to conduct safe burnout operations. The location of fuel treatments was used to determine placement of fire lines and the incident command post. The fuel treatments were effective in influencing fire behavior and allowing firefighters to protect the vast majority of structures in the area. In addition to modifying wildfire intensity, the burn severity to vegetation and soils within the areas where the fuels were treated was generally less compared to neighboring areas where the fuels were not treated.

d. *Longevity***:** Treatments occurred 1 to 11 years prior to the fire; study does not evaluate differences by time since treatment.

7. Hudak, A.T., Rickert, I., Morgan, P., Strand, E., Lewis, S.A., Robichaud, P.R., Hoffman, C., Holden, Z.A., 2011. Review of Fuel Treatment Effectiveness in Forests and Rangelands and a Case Study From the 2007 Megafires in Central, Idaho, USA. Gen. Tech. Rep. RMRS-GTR-252. USDA For. Serv., Rocky Mountain Res. Sta., Fort Collins, CO.
   a. *Location*: Central Idaho
   b. *Vegetation Types*: Engelmann spruce, subalpine fir and lodgepole pine
   c. *Summary*: This extremely comprehensive GTR covers a case study how fuels treatments in the WUI fared in the 2007 megafires of central Idaho, and also includes a literature review. Both the literature review and case study results support the consensus that forest thinning followed by some form of slash removal is most effective for reducing subsequent wildfire severity. Fuel treatments altered fire behavior and subsequent fire effects in multiple large fires in 2007, usually in desirable ways but not always. The results confirm the widely held notion that mechanical thinnings are the most effective fuels treatment, provided the activity fuels are treated. Prescribed burn treatments may be the most cost-effective maintenance treatments for keeping fuel accumulations in check over time and for lowering the risk of severe fires.
   d. *Longevity***:** Treatments occurred 1 to 19 years prior to the fire; study does not evaluate differences by time since treatment.
8. Johnson, M. C., and M. 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 28:216–229.
   a. *Location:* 2011 Wallow Fire (Arizona)
   b. *Vegetation Types:* mid-to-high-elevation mixed-conifer forests
   c. *Summary:* Fuel reduction treatments are designed to meet multiple management objectives, resulting in unique vegetation structures that do not conform to standard classifications and vary considerably over space and time. We evaluated how different post-treatment vegetation structures relate to patterns in wildfire severity. To reconstruct both untreated and treated pre-fire forest structure, we used post-fire stand data measured at three different fuel treatment units burned by the 2011 Wallow Fire (Arizona). We describe (1) how forest structure differs among the treatment units, both in the untreated forest and within the treated area; and (2) how those differences in forest structure explain variability in burn severity. We show that the retention of smaller trees (ladder fuels) for wildlife cover relates significantly to higher severity within one treatment unit. Further variability in within-treatment severity is explained by the severity of the wildfire in the untreated forest as the fire approached the treated area. The untreated forest structure and species composition constrain post-treatment structure and composition, which was related to within-treatment structure and post-fire composition and structure. The study design presented in this paper suggests that

evaluations of fuel treatment effectiveness can move beyond simple classifications of treatment type and fire behaviour

d. *Longevity***:** Treatments occurred 1 to 7 years prior to the fire; study does not evaluate differences by time since treatment.

9. Kennedy , M. C., and M. 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.
   a. *Location*: Arizona, 2011 Wallow Fire
   b. *Vegetation Type*: Ponderosa pine – Douglas-fir, white fir
   c. *Summary*: This study was performed after the 2011 Wallow fire in Arizona. Researchers measured 14 transects across two different fuel treatment types on three different units in the forest surrounding the wildland-urban interface. For both fuel treatment types, only ladder fuels had been removed. They found that while severity was reduced at all sites, the spatial distribution of fire severity within the treatment areas varied by treatment type and unit as well as which fire severity metric they were analyzing. They found fuel treatments reduced fire severity anywhere from -7 m to 533 m into the treatment area. The authors caution that local site conditions, topography and vegetation type will be other sources of variation in fire severity.
   d. *Longevity*: Treatments occurred 1 to 7 years prior to the fire; study does not evaluate differences by time since treatment.
10. Kobziar, L. N., J. R. McBride, and S. L. Stephens. 2009. The efficacy of fire and fuels reduction treatments in a Sierra Nevada pine plantation. International Journal of Wildland Fire 18:791- 801.
    a. *Location*: Sierra Nevada, CA
    b. *Veg Type*: Ponderosa Pine Plantations
    c. *Summary*: The authors examined the effectiveness of 4 fuels treatments in a Sierra Nevada pine plantation: mastication, mastication and burning; burning; and no treatment. They showed that mastication was affective at controlling modeled rates of spread, but was also associated with higher flame lengths that increased predicted torching within a stand. Increased torching, in turn, could relate to increased mortality. Combining mastication with prescribed burning was the most effective way of reducing fuel loads in young plantations and increasing the overall resiliency of a stand. The authors emphasized the cost-efficiency of prescribed burning in comparison to mastication.
    d. *Longevity*: Mastication occurred 1 to 2 years prior to prescribed burning.
11. Low KE, Collins BM, Bernal A, Sanders JE, Pastor D, Manley P, White AM, Stephens SL. 2021. Longer-term impacts of fuel reduction treatments on forest structure, fuels, and drought resistance in the Lake Tahoe Basin. Forest Ecology and Management 479: e118609
    a. *Location:* Lake Tahoe Basin Management Unit, West Shore
    b. *Vegetation Types:* Vegetation on these sites is characterized as upper elevation mixed- conifer forests, comprised of six dominant canopy species: red fir (*Abies magnifica*), white fir (*A. concolor*), incense-cedar (*Calocedrus decurrens*), lodgepole pine (*Pinus contorta*), Jeffrey pine (*P. jeffreyii*), and sugar pine (*P. lambertiana*).
    c. *Summary:* Long fire-excluded forests that historically experienced frequent-fire are associated with reductions in tree vigor due to increased competition. Extensive tree mortality from California's 2012–2015 drought made this reduction in vigor abundantly clear. Rising

temperatures attributed to climate change have increased the likelihood of drought events in California. It is well documented that fuels reduction treatments can reduce wildfire hazard and alleviate individual tree stress. However, direct observations that quantify the longer-term effects on forest structure and individual tree vigor are lacking. Thinning treatments effectively met and maintained overstory structural objectives and reduced downed woody fuels and snag basal area. Thinning treatments, especially those leaving lower residual basal area, improve drought resistance.

d. *Longevity*: Evaluated effects at 1 and 10 years post-treatment, found that effects persisted at 10 years post-treatment.

12. Lydersen, J.M., Collins, B.M., Brooks, M.L., Matchett, J.R., Shive, K.L., Povak, N.A., Kane, V.R. and Smith, D.F. (2017), Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecol Appl, 27: 2013-2030. https://doi.org/10.1002/eap.1586
    a. *Location*: 2013 Rim Fire, Central Sierra Nevada, CA
    b. *Vegetation Types*: Mixed-Conifer (2/3 of fire area)
    c. *Summary*: The authors assessed, at three scales, the relative influence of previous fuels treatments (including wildfire), fire weather, vegetation, and water balance on fire-severity in the Rim Fire of 2013. Fuels treatments included precommercial and commercial thinning, surface fuel treatments, prescribed and pile burning, and fires managed for resource benefit. The authors found that both fuels treatments and previous low to moderate-severity wildfire reduced the prevalence of high-severity fire. They also found that, generally, areas without recent fuels treatments and areas that previously burned at high severity tended to have a greater proportion of high-severity fire in the Rim Fire. The lowest fire severity was observed in areas that were previously treated with a combination of thinning and prescribed burning. When moderate and high-severity fire encountered a previously treated area, fire severity was significantly reduced in the treated area relative to the adjacent untreated area. These results show that fuels treatments and low to moderate severity wildfire can reduce fire severity in a subsequent wildfire, *even when burning under fire growth conditions*. These results serve as further evidence that both fuels treatments and lower severity wildfire can increase forest resilience.
    d. *Longevity*: Treatments occurred 1 to 18 years prior to the Rim Fire. Did not evaluate differences in response variables by time since treatment.
13. Lyons-Tinsley, C., and D. L. Peterson. 2012. Surface fuel treatments in young, regenerating stands affect wildfire severity in a mixed conifer forest, eastside Cascade Range, Washington, USA. Forest Ecology and Management 270:117–125.
    a. *Location: M*ature, mid-elevation forests in the Okanogan-Wenatchee National Forest (OWNF) on the eastside of the Cascade Range in Washington, USA
    b. *Vegetation Types: M*ixed-species plantations (Douglas-fir, subalpine fir, Engelmann spruce, western larch)
    c. *Summary:* In 2006, the 70,925 ha Tripod Fire burned through plantations 10-30 years old that were previously established in the surrounding lodgepole pine matrix. Some of the regeneration units were burned after the initial harvest and before trees were planted. To understand what drives fire effects in plantations, especially those that exist in spatially heterogeneous forests, we compared fire severity in plantations with and without fuels-reducing site preparation (i.e., fuel treatments), using three metrics to quantify severity:

mortality (%), exposed mineral soil (%), and char height (m). Stands that have trees closer together with crowns near the ground are more likely to have lower mortality. Overall, the results suggest that young stands in some dry mixed conifer forests can be resilient to wildfire if surface fuel loading is low upon stand establishment.

d. *Longevity*: Treatments occurred up to 30 years prior to fire but time since treatment not detailed or differentiated.

14. Martinson, Erik; Omi, Philip N.; Shepperd, Wayne. 2003. Part 3: Effects of fuel treatments on fire severity. Gen. Tech. Rep. RMRS-GTR-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 396 p.
    a. *Location*: Hayman Fire on front range of Colorado.
    b. *Vegetation Type*: Ponderosa pine forest
    c. *Summary*: The Hayman Fire encountered many types of fuel conditions. The authors classified these as natural disturbances (primarily wildfires), prescribed fires, surface fuel treatments, timber stand improvements, commercial timber harvests, and plantations. A qualitative assessment was completed within the Hayman Fire evaluating the BAER (which has limited applicability in assessing vegetation effects) fire severity maps and the treatment locations. In the summary, the authors state: "each of the different types of fuel modification encountered by the Hayman Fire had instances of success as well as failure in terms of altering fire spread or severity". The results of the quantitative assessment indicate that fuel modifications generally had little influence on the severity of the Hayman Fire during its most significant run on June 9. The most obvious effects were produced by the prescribed burns and timber harvest. Except for the Polhemus prescribed burn (2001), the Schoonover wildfire (2002), and the Platte Springs wildfire (2002), which occurred less than 1 year earlier, fuel treatments did not stop the fire but did in many cases change fire behavior and effects. Under more moderate wind and humidity conditions (June 10 through 16), recent prescribed burns appeared to have lower fire severity than older burns.
    d. *Longevity*: Differentiates between fuels modifications occurring 1 to 12 years prior to the Hayman Fire, and fuels/modifications occurring > 12 years prior to the Hayman Fire.
15. Martinson, Erik J.; Omi, Philip N. 2003. Performance of fuel treatments subjected to wildfires. In: Omi, Philip N.; Joyce, Linda A., tech. eds. Fire, fuel treatments, and ecological restoration; proceedings; 2002 April 16-18; Fort Collins, CO. Proceedings RMRS-P-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 7-13.
    a. *Location*: Western USA.
    b. *Vegetation*: Conifer forests
    c. *Summary*: Fire severity was evaluated in eight recent wildfires with standardized methods in adjacent treated and untreated stands. Sampled sites occurred in a variety of conifer forests throughout the western United States. Treatments included reduction of surface fuels and crown fuels, both in isolation and in combination. Synthesis of the results indicates that treatment effectiveness is related to differences in tree size (mean diameter) between treated and untreated stands ($p < 0.001$), as well as estimated historic fire frequency ($p < 0.1$). The results suggest that fuel treatments will be most effective when they complement ecosystem restoration objectives, such as the removal of small trees from ecosystems that historically experienced frequent fire.

   d. *Longevity*: Treatments occurred from 1 to 9 years prior to fires. Found no significant difference in fuel treatment effects by treatment age.

16. Martinson, E. J., and P. N. Omi. 2013. Fuel treatments and fire severity: a meta-analysis. Res. Pap. RMRS-RP-103www. USDA Forest Service, Fort Collins, Colorado, USA.
   a. *Location:* Northwest US, Southwest US, Eastern US
   b. *Vegetation Types:* Long needle pine forest, mixed conifer forest, woodlands and grasslands
   c. *Summary:* We employed meta-analysis and information theory to synthesize findings reported in the literature on the effects of fuel treatments on subsequent fire intensity and severity across the US. Data were compiled from 19 publications that reported observed fire responses from 62 treated versus untreated contrasts. Effect sizes varied widely and the most informative grouping of studies distinguished three vegetation types and three types of fuel treatment (canopy thinning with or without surface fuel treatment, surface fuel treatment with burning or mastication). Most studies of fuel treatment effectiveness that met our study selection criteria were conducted in conifer forests (85%), with nearly half of those in long needle pine systems. The fuel treatment studies included in our synthesis were concentrated in the western United States (79%), with these divided roughly evenly between northwest and southwest. The resultant meta-analytic model is highly significant ($p<0.001$) and explains 78% of the variability in reported observations of fuel treatment effectiveness. We found that the 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 30.5 m to 16.1 m, or an inferred reduction in flame length from 3.4 m to 2.1 m. Treatments have proved most effective in grasslands and in conifer forests that were heavily thinned and subsequently burned, while the least effective treatments have been mechanical rearrangements in woodlands. The extreme case of treatment effectiveness observed a reduction in crown volume scorch from 83% in untreated mixed conifer forest to less than 1% in an adjacent stand that was thinned and burned one year previously but our synthesis demonstrates that fuel treatments vary widely in effectiveness, which is largely explained by vegetation and treatment type. Our synthesis highlights several considerations that both support and inform the current fuels management paradigm.
   d. *Longevity*: Median treatment age 3 years, with maximum age of 20 years. Distinguished differences in fuel treatment effectiveness in conifer forests at approximately 10 years (less effective).

17. McLean, Herbert E. 1993. The Boise quickstep: [A plan to restore the health of a Idaho national forest to reduce fire losses of commercially valuable forests]. American Forests. 99(Jan/Feb): 11-14.
   a. *Location*: Boise National Forest in southern Idaho.
   b. *Vegetation Types:* Ponderosa Pine
   c. *Summary:* In August 1992, a wildfire burned more than 257,000 acres of range and forest lands near Boise, Idaho, fueled by high fuel loads, steep slopes, and low humidity. Fire suppression costs came to $16 million. However, in Tiger Creek, the crown fire skirted a particular 2,500 acre stand of ponderosa pines, leaving it the only surviving stand of trees within miles. The Tiger Creek stand had been commercially thinned, then “defueled” by the use of prescribed fire. The article discusses the implications of this for the management of other western forests. It mentions the Tiger Creek stand as an example of where thinning worked to prevent wildfire going through an area, but does not give more than a few details.

   d. *Longevity:* This study did not address fuel treatment longevity.

18. Meyer, M., A. Wuenschel, and M. Slaton. 2020. Indiana Summit Research Natural Area Post-Fire Ecological Assessment. Unpublished report. USDA Forest Service Pacific Southwest Region. Bishop, CA.
    a. *Location*: Indiana Summit Research Natural Area, Inyo National Forest, CA
    b. *Vegetation Type*: Jeffery Pine forest
    c. *Summary*: The authors assessed the ecological condition of a late-seral Jeffrey pine (Pinus jeffreyi) forest in the Indiana Summit Research Natural Area (ISRNA) on the Inyo National Forest one year before and after the 2016 Clark Fire. Our assessment included analysis of remote-sensing indicators of fire severity and ecological monitoring data collected from plots located in prescribed (Rx) burned and untreated portions of ISRNA. Forest stands in ISRNA that were treated with prescribed fire in the mid-1990s exhibited reduced fire effects within NRV during the 2016 Clark Fire. In contrast, nearby untreated stands exhibited more severe fire effects outside NRV.
    d. Longevity: Prescribed burns occurred approximately 30 years prior to the 2016 Clark Fire.
19. Murphy, K. T. Rich, and T. Sexton. 2007. **An assessment of fuel treatment effects on fire behavior, suppression effectiveness, and structure ignition on the Angora Fire**. U.S. Department of Agriculture, Forest Service, Pacific Southwest Region, R5-TP0-25. Available at http://bofdata.fire.ca.gov/board_committees/monitoring_study_group/msg_archived_documents/msg_archived_documents_/murphy_usfs_2007_a.pdf (last accessed 5/2/2018).
    a. *Study location*: Lake Tahoe, California.
    b. *Vegetation type*: Mixed conifer
    c. *Summary*: This report details an investigation of the effectiveness of fuel treatments subject to the 2007 Angora Fire near Lake Tahoe, California in terms of reduced structure loss, fire suppression effectiveness, and public safety. Investigators based their findings on ground and aerial reconnaissance, interviews with homeowners, firefighters, scientists, and fire behavior experts, and review of available video and photos. Key findings showed that most of the area fuel treatments reduced fire behavior changing it from a crown to surface fire. Fuel treatments on steep slopes and those that were adjacent to untreated units burned at higher intensity than those on flat areas and those that were surrounded by other treated units. They concluded that most fuel treatments burned with low intensity surface fire, thereby producing less smoke and fewer embers. This provided greater visibility and enhanced the ability to evacuate residents.
    d. *Longevity:* This report only highlights the age of treatments prior to the 2007 Angora Fire. These treatments spanned 1995 – 2006 and ranged from urban lot fuel treatments to USFS fuels treatments. There was no evaluation of treatment longevity.
20. Pollet, Jolie; Omi, Philip N. 1999. Effect of thinning and prescribed burning on wildfire severity in ponderosa pine forests. In: Neuenschwander, Leon F.; Ryan, Kevin C., tech. eds. Proceeding of the joint fire science conference and workshop: crossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management; 1999 June 15-17; Boise, ID. Moscow, ID: University of Idaho: 137-141.
    a. *Location*: Montana, Washington, California, and Arizona.
    b. *Vegetation Types:* Ponderosa Pine forests

c. *Summary*: This study tested whether fuel treatments affected fire severity in four wildfires burning in ponderosa pine forests in Washington (Tyee site), Montana (Webb site), Arizona (Hochderffer site), and California (Cottonwood site). In the results section, the authors state, "The treated plots in this study have lower fire severity ratings and less crown scorch than the untreated plots. From these results we infer that the types of fuel treatments studied reduce fire severity rating and crown scorch. The treated plots burned less severely in terms of below-ground fire severity. Based on the statistical results and field reconnaissance, sites with mechanical fuel treatment appear to have more dramatically reduced fire severity compared to sites with prescribed fire only. Although fire severity ratings and percent crown scorch are lower at treated plots and higher at untreated plots at all sites, the Webb site's differences were the least extreme. Apparently, mechanical fuel treatments at the Tyee, Cottonwood, and Hochderffer sites allow for more precise and controlled results compared to prescribed fire. For example, mechanical fuel treatment programs may specify the exact number of post-treatment residual trees per hectare and the treatment can be applied uniformly across the stand. By contrast, prescribed fire fuel treatment often varies across a stand and results in less precise stand structure changes.

d. *Longevity:* This study did not address fuel treatment longevity.

21. Pollet, Jolie; Omi, Philip N. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire. 11(1): 1-10.
    a. *Location*: Montana, Washington, California, and Arizona.
    b. Vegetation types: Ponderosa pine
    c. *Summary*: Fire exclusion policies have affected stand structure and wildfire hazard in North American ponderosa pine forests. Wildfires are becoming more severe in stands where trees are densely stocked with shade-tolerant understory trees. Our research quantitatively examined fire effects in treated and untreated stands in western United States national forests. Four ponderosa pine sites in Montana, Washington, California, and Arizona were selected for study. Fuel treatments studied include: prescribed fire only, whole-tree thinning, and thinning followed by prescribed fire. On-the-ground fire effects were measured in adjacent treated and untreated forests. We developed *post facto* fire severity and stand structure measurement techniques to complete field data collection. We found that crown fire severity was mitigated in stands that had some type of fuel treatment compared to stands without any treatment. At all four of the sites, the fire severity and crown scorch were significantly lower at the treated sites. Results from this research indicate that fuel treatments, which remove small diameter trees, may be beneficial for reducing crown fire hazard in ponderosa pine sites.
    d. *Longevity:* All stands in this study were treated 15 years prior to wildfires as they assumed that any treatments greater than 15 years were outside the relatively short fire return interval. The study did not address fuel longevity directly.
22. Povak N. A., V. R. Kane, B. M. Collins, J. M. Lydersen, and J. T. Kane. 2020. Multi-scaled drivers of severity patterns vary across land ownerships for the 2013 Rim Fire, California. Landscape Ecology 35:293–318.
    a. Location: Rim Fire, 2013, Stanislaus National Forest, Central Sierra Nevada, California
    b. Vegetation Types: Mixed conifer forest
    c. Summary: The major objective of this study was to identify the biophysical and management drivers of severity patterns and their spatial variability across the 2013 Rim Fire. Mechanical

treatments showed low global importance in RF models, but local effectiveness of mechanical treatments was observed in portions of the NF. The limited area affected by management (~ 8% of Stanislaus NF within the Rim Fire extent) and even lower incidence of fuels reduction treatments may have precluded finding important effects of specific treatments on fire severity. In addition, NDVI and NDMI variables may implicitly incorporate the effect of management activities, which may better capture the vegetation response to management and remove the effect of categorical treatment variables (Parks et al. 2018b). The variable importance for mechanical treatments was higher outside of plume-dominated progression intervals suggesting that treatment effectiveness is likely greater under milder burning conditions. However, where treatment variables had high local importance, treatments within the plume were shown to have a greater relative effect at reducing fire severity compared to treated areas outside the plume-dominated spread, particularly for fire-excluded areas.

d. *Longevity:* This research does not address treatment longevity.

23. Prichard, S. J., and M. C. Kennedy. 2014. Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecological Applications. 24:571-590.
    a. *Location*: 2006 Tripod Complex fires, North Cascades range, WA
    b. *Vegetation type*: Mixed-conifer forest
    c. *Summary*: The authors evaluated relationships between fuel reduction treatments and burn severity in the 2006 Tripod Complex fires, and investigated other drivers of burn severity including landform, weather, vegetation characteristics, and a recent mountain pine beetle outbreak. Substantial portions of the landscape burned under extreme fire weather. Fuels treatments examined included clearcut only, clearcut and burn, landscape burn, thin only, and thin and burn, thin and sanitation cut, and past wildfires. The authors found that treatment type, elevation, fire weather, and vegetation characteristics were all significant predictors of fire severity. Clearcut and thin units had significantly lower burn severity than no treatment areas, and treatments that included prescribed burn had lower burn severity than treatments without prescribed fire and untreated areas, though effects of treatments varied by fire area. Higher canopy cover was also associated with higher burn severity, as was the red attack phase of a mountain pine beetle outbreak in the area. The authors conclude that, even during extreme weather, fuel conditions and landform strongly influenced patterns of burn severity. Thinning followed by prescribed burning was an effective treatment for mitigating wildfire effects under extreme weather conditions
    d. *Longevity*: Treatment age and size were only weakly correlated with burn severity and may be partly explained by the lack of treatments older than 30 years and the low rates of fuel succession in these semiarid forests. Fuel succession is slow in the represented arid landscapes, and prescribed burn treatments that were up to 20 to 30 years old still appeared effective at mitigating burn severity.
24. Prichard, S. J., D. L. Peterson, and K. Jacobson. 2010. Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. Canadian Journal of Forest Research 40:1615–1626.
    a. *Location*: 2006 Tripod Complex fires, North Cascades range, WA
    b. *Vegetation type*: Mixed-conifer forest

c. *Summary*: The authors documented the effectiveness of two types of treatments, thin only, and thin and prescribed burn, within the 2006 Tripod Complex fires. Logistic regression modeling demonstrated significant reductions in the probability of tree death under both treatments, with a much greater reduction in the thin and burn units than the thin only units. Other severity measures, including percent crown scorch and burn severity index, were lower in the thin and burn units than in the thin only and no treatment units. The authors conclude that. The authors conclude that this study provides strong quantitative evidence that thinning alone does not reduce wildfire severity but that thinning followed by prescribed burning is effective at mitigating wildfire severity in dry western forests.

d. Longevity: This study did not address treatment longevity.

25. Prichard, S. J., N. A. Povak, M. C. Kennedy, and D. W. Peterson. 2020. Fuel treatment effectiveness in the context of landform, vegetation, and large, wind-driven wildfires. Ecological Applications 30:e02104.
    a. *Location*: 2014 Carlton Complex fires, north-central WA
    b. *Vegetation type*: seasonally dry ponderosa pine and mixed-conifer forests
    c. *Summary*: This study evaluated drivers of fire severity and fuel treatment effectiveness in the 2014 Carlton Complex fires, a record-setting complex of wind-driven wildfires in north-central Washington. Treatment types included: clear-cut, clear-cut and burn, thin, thin and burn, landscape burn, and past wildfire. With the exception of the thin+pile burn treatments in the northern area (which burned under more severe weather conditions), all fuel treatments were negatively correlated with fire severity. Thin and underburn treatments were associated with lower severity than other treatments. All treatment areas burned with higher proportions of moderate and high-severity fire during early fire progressions, but thin and underburn, underburn only, and past wildfires were more effective than thin-only and thin and pile burn treatments. Treatment units had much greater percentages of unburned and low severity area in later progressions that burned under milder fire weather conditions, and differences between treatments were less pronounced. During wind-driven fire spread progressions, fuel treatments that were located on leeward slopes tended to have lower fire severity than treatments located on windward slopes. The authors conclude that thinning followed by prescribed burning was an effective treatment for mitigating wildfire effects under extreme weather conditions, and that strategic placement of fuels reduction treatments can reduce localized fire spread and severity, even during severe fire weather.
    d. *Longevity*: Included time since treatment (for prescribed fire and wildfire only) as predictive variable, but not included in final spatial autoregression models; found that effect of previous fires leveled off at 20 years in Random Forests model.
26. Raymond, C. L., and D. L. Peterson. 2005. Fuel treatment alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Canadian Journal of Forest Research 35: 2981–2995.
    a. Location: 2002 Biscuit fire, southwestern Oregon
    b. Vegetation Types: mixed-evergreen forest with a mixed-severity fire regime
    c. Summary: Modeled fire behavior showed that thinning-only treatments reduced canopy fuels, thereby decreasing the potential for crown fire spread. The potential for crown fire initiation remained fairly constant despite reductions in ladder fuels, because thinning without associated surface fuel treatments increased surface fuels, which contributed to greater surface fire intensity. Thinning followed by underburning reduced canopy, ladder, and surface

fuels, thereby decreasing surface fire intensity and crown fire potential. Crown fire is not a prerequisite for high fire severity; damage to and mortality of overstory trees in the wildfire were extensive despite the absence of crown fire. Mortality was most severe in thin-only treatments (80%–100%), moderate in untreated stands (53%–54%), and least severe in the thinned and underburned treatment (5%). Thin-only treatments had higher fine-fuel loading and more extensive crown scorch, suggesting that greater consumption of fine fuels contributed to higher tree mortality. The authors suggest that applying fuel reduction treatments simultaneously to multiple fuels strata is the most effective approach to reducing fire severity. Fire hazard treatments intended to decrease tree mortality should reduce surface fire intensity, as well as crown fire potential, in order to minimize mortality from crown scorch. The authors thus conclude that fuel treatments intended to minimize tree mortality will be most effective if both ladder and surface fuels are treated.

d. *Longevity*: Mechanical treatments occurred 6 years prior to Biscuit Fire; prescribed burning occurred 1 year prior to Biscuit Fire.

27. Ritchie, M. W., C. N. Skinner, and T. A. Hamilton. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. Forest Ecology and Management 247:200–208.
    a. *Location*: Blacks Mountains Experimental Forest, 2002 Cone Fire, Southern Cascades, Northern CA
    b. *Vegetation Type*: Ponderosa pine forest
    c. *Summary*: The authors evaluated effectiveness of thinning and prescribed fire treatments by sampling tree survival within 9 months after fire across treated and untreated areas within the Blacks Mountain Experimental Forest. They found that the probability of survival was greatest in those areas that had both thinning and prescribed fire prior to the wildfire. Survival was near zero in untreated areas. Survival in thinned-only areas was greater than untreated areas, but substantially less than areas where thinning and prescribed fire had been completed. Probability of survival was also greater for larger diameter trees, and increased as distance from the treatment boundary increased, highlighting the value of large treatment areas. The authors conclude that "Observed changes in severity were remarkable and provide strong evidence that the reduction in fuels from thinning or thinning with prescribed fire can reduce wildfire intensity and severity in interior ponderosa pine stands."
    d. *Longevity*: Treatments occurred within 6 years of the Cone Fire.
28. Rogers, G., W. Hann, C. Martin, T. Nicolet, and M. Pence. 2008. Fuel treatment effects on fire behavior, suppression, and structure ignition: Grass Valley Fire, San Bernardino National Forest. United States Department of Agriculture R5-TP-026a. 35p. Available at: https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev7_008376.pdf (last accessed 09/16/2021).
    a. *Study location*: San Bernardino National Forest, CA
    b. *Vegetation types:* Mixed-conifer forest with recent beetle outbreak mortality, some areas of big-cone Douglas fir forest, some areas of chaparral
    c. *Summary*: This report details an investigation of fuel treatment effectiveness during the 2007 Santa Ana wind driven Grass Valley Fire on the San Bernardino National Forest. Roughly half of the 1,242 acre fire had previously been subject to fuel treatments. These treatments included removal of dead and dying trees, thinning, pruning, chipping, and burning. The investigators

used ground and aerial reconnaissance, photos, videos, interviews, and review of documents to determine the effectiveness of these fuel treatments in terms of fire behavior, fire effects, structure ignition, fire suppression, public safety, and egress. The fuel treatments were effective in reducing fire intensity, which allowed firefighters to focus on structure protection and to attack the fire directly. Fire behavior in fuel treatment areas was less rapid and less intense than in adjacent untreated wildland fuel and urban structural fuel. Within the treatment areas, the fire exhibited lower flame lengths, slower rate of spread, less transition to crown fire, and less spotting than outside the treatment area. The fuel treatments also increased visibility which likely enhanced firefighter safety.

d. *Longevity*: Time since treatment not specified.

29. Safford H. D., D. A. Schmidt, and C. 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 258:773–787.
    a. *Location*: 2007 Angora Fire, Lake Tahoe Basin, CA
    b. *Vegetation Types*: Jeffery pine and mixed conifer forests
    c. *Summary*: In this study, the authors measures fire effects on vegetation in treated and adjacent untreated areas within the Angora fire perimeter, immediately after and one year after the fire. Treatments were generally all the same type, beginning with a mechanical commercial harvest, followed by a ‘‘precommercial thin’’ of smaller trees carried out by hand, and completed with hand piling and burning. Results show that fuel treatments generally performed as designed and substantially changed fire behavior and subsequent fire effects to forest vegetation. Exceptions include two treatment units where slope steepness led to lower levels of fuels removal due to local standards for erosion prevention, one of which had not yet implemented burning of piled fuels. Fire severity and tree mortality higher in untreated forest stands than in treated stands. In most cases, crown fire behavior changed to surface fire within 50 m of encountering a fuel treatment. The authors conclude that their results underline the important role that properly implemented fuel treatments can play in protecting assets, reducing fire severity, and increasing forest resilience.
    d. *Longevity*: Fuels treatments occurred 1 to 11 years prior to the Angora Fire. Effect of time since treatment not evaluated.
30. Safford, H. D., J. T. Stevens, K. Merriam, M. D. Meyer, and A. M. Latimer. 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. Forest Ecology and Management 274:17–28.
    a. *Location*: 12 fires that burned between 2005 and 2011 in eastern and southern CA
    b. *Vegetation Types*: Yellow pine and mixed conifer forests of California
    c. *Summary*: This study assessed the effectiveness of forest fuel thinning projects in reducing fire severity and tree mortality in 12 forest fires that burn in yellow pine or mixed conifer forests in eastern and southern CA between 2005 and 2011. All treatments but one were combined mechanical thinning and prescribed fire/pile burn. With few exceptions, fire severity measures (bole char height, scorch and torch height, scorch and torch percentage) and tree mortality were much lower in forest stands treated for fuels than in neighboring untreated stands. Within treatments, fire severity decreased with distance from the treatment boundary, and canopy fires were almost always reduced to surface fires within 70 m of entering the treatment. The authors note that their results add significantly to the growing evidence that

fuel treatments that include removal of surface and ladder fuels in these forest types are highly effective management tools for reducing fire severity and canopy tree mortality. In their opinion, "quantitative assessments of fuel treatment effects on fire severity in frequent-fire forest types hardly merit further effort"

d. *Longevity*: Treatments occurred from 1 to 9 years pre-fire. No effect of treatment age on fire severity or tree survival.

31. Skinner, C.N .. Ritchie, M.W., Hamilton. T., Symons,j., 2004. Effects of prescribed fire and thinning on wildfire severity. In: Cooper. S. (Ed.). Proceedings 25th Annual Forest. Vegetation Management Conference University of California Cooperative Extension, Redding, CA, january 20-22, 2004, pp. 80-91.
    a. *Location*: Blacks Mountains Experimental Forest, 2002 Cone Fire, Southern Cascades, Northern CA
    b. *Vegetation Type*: Ponderosa pine
    c. *Summary*: This article presents results which were later further explored and published in Ritchie et al. 2007 (see above). The study examined wildfire response to thinning treatments of either high or low structural diversity, half of each of which had also been treated with prescribed fire. For the half of the low diversity treatments that had received prescribed fire, the wildfire died out within 50 meters of entering the treatment. For the half not receiving prescribed fire, as well as both types of high diversity treatments, the wildfire continued through the unit as a low-intensity surface fire. In the case of all treatments the fire dropped quickly out of the crowns to become either a surface fire or die out upon entering the treated areas, so that treated stands experienced lower fire severity than untreated stands. Tree mortality was lower within thin-only treatments than in untreated areas, and was lower within thin-and-burn treatments than in either thin-only or untreated areas.
    d. *Longevity*: Treatments occurred within 6 years of the Cone Fire.
32. Stephens S. L., M. A. Battaglia, D. J. Churchill, B. M. Collins, M. Coppoletta, C. M. Hoffman, J. M. Lydersen, M. P. North, R. A. Parsons, S. M. Ritter, and J. T. Stevens. 2021. Forest restoration and fuels reduction: convergent or divergent? Bioscience 71:85-101.
    a. *Location*: Western US
    b. *Vegetation Types*: Historically frequent-fire coniferous forests of the western US
    c. *Summary*: While this reference is largely a synthesis of existing information, it does include an empirical case study that is summarized here. The Hartless Ridge project in the mixed conifer forests of the Sierra Nevada, CA was treated for both restoration and fuels reduction objectives. Less than five years after treatment completion, the project area was affected by a multi-year drought and the 2014 King Fire. Despite the restrictions on marking guidelines, this treatment did result in a more resilient stand structure that withstood both stressors, as is evident by the remaining mature trees in the treated area. The heterogeneity introduced by the initial treatment and subsequent disturbance-related mortality resulted in a forest structure that more closely resembles the open, heterogeneous stand conditions found in pre-Euro-American forests. However, the treated unit is embedded within an untreated forest that burned at high severity. Thus, although this unit now constitutes a refugium for live trees and seed for forest regeneration, and the stand-scale restoration work made it more resilient to the wildfire and drought, this example also highlights the need for contiguous restoration projects

at much larger scales to promote resilience to increasingly common landscape-scale disturbances occurring across the western United States.

d. *Longevity*: This study was largely a synthesis with recommendations. One case study does address treatment longevity as the Harless Ridge project was treated five years prior to the 2014 King Fire. This treatment did result in a more resilient stand structure that withstood the fire.

33. Stevens, J. T., H. D. Safford, and A. M. Latimer. 2014. Wildfire-contingent effects of fuel treatments can promote ecological resilience in seasonally dry conifer forests. Canadian Journal of Forest Research 44:843-854.
    a. *Location*: Southern and Eastern California
    b. *Vegetation Types*: Seasonally dry conifer forests
    c. *Summary*: The authors measured a suite of forest characteristics at 12 different sites in California, where wildfire burned through fuel treatments. Ordination revealed that the magnitude of ecological change attributable to wildfire is lower in treated stands than in untreated stands. The authors conclude that properly implemented treatments can promote resilience to both first-entry and subsequent wildfires.
    d. *Longevity:* This study did not address fuel treatment longevity.
34. Strom, B. A., and P. Z. Fule´. 2007. Pre-wildfire treatments affect long-term ponderosa pine forest dynamics. International Journal of Wildland Fire 16:128–138.
    a. *Location*: 2002 Rodeo-Chediski fire, East-central Arizona
    b. *Vegetation Type*: Ponderosa pine forest
    c. *Summary*: The 2002 Rodeo-Chediski fire burned over treated stands and adjacent untreated stands in the Apache-Sitgreaves National Forest. The authors developed seven pairs of treated-untreated sites, and measured characteristics two years after fire. Treatments included thinning and prescribed fire. They found that thinning was strongly associated with reduced burn severity. Treated areas had more live trees, greater survival, and reduced fire intensity as indicated by crown base height and bole char. Ponderosa pine regeneration was patchy but denser in treated areas. Differences between treated and untreated areas were projected to persist for several decades after the fire in terms of stand structure characteristics and for at least 100 years in terms of species composition, with untreated areas more apt to undergo a shift from forest to a shrubfield state. The authors conclude that even under the extreme conditions of drought and wind that characterized this fire, fuel reduction treatments that took place before the fire had a major effect in reducing fire severity and helping perpetuate ponderosa pine ecosystems. The authors also highlight the multi-century legacy of failing to conduct fuels treatments today.
    d. *Longevity:* This study did not address fuel treatment longevity.
35. Tubbesing CL, Fry DL, Roller GB, Collins BM, Fedorova VA, Stephens SL, Battles JJ. 2019. Strategically placed landscape fuel treatments decrease fire severity and promote recovery in the northern Sierra Nevada. Forest Ecology and Management 436: 45–55.
    a. *Location*: American Fire, Sierra Nevada, CA
    b. *Vegetation Type*: mixed-conifer forest
    c. *Summary*: This study takes advantage of a strategically placed landscape fuel treatment network that was implemented and monitored before being burned by a wildfire. Treatments included cable logging, whole-tree harvest, mastication, and prescribed fire, and covered 18%

of the fireshed area. The authors evaluated treatment efficacy in terms of resistance, defined here as the capacity to withstand disturbance, and recovery, defined here as regeneration following disturbance. They found that the treated landscape experienced lower fire severity than an adjacent control landscape: in the untreated control landscape, 26% of land area was burned with stand-replacing fire, while in the treated landscape only 11% burned at the same severity. This difference was despite greater pre-treatment fire risk in the treatment landscape, as indicated by FARSITE fire behavior modeling. The treatments also reduced core patch area (high severity areas more than 120 meters from the patch edge) by approximately 5.3 percent. At a more local scale, monitoring plots within the treatments themselves saw greater regeneration of conifer seedlings two years following the fire than plots outside the treatments. SPLATs moderated landscape-level fire severity, resulted in post-fire vegetation patterns that will likely improve long-term ecological integrity of the studied forest, and promoted conifer seedling regeneration in the two years following fire. The authors conclude that their results indicate that SPLATs achieved their objective of increasing forest resistance and recovery.

d. *Longevity:* This study does not address the longevity of treatment effects in cases where there is a time lag between treatments and wildfire, since the American Fire burned only one year after treatments were completed (five years after treatments began). Collins et al. (2011b) showed that treatments at Last Chance were likely to affect conditional burn probabilities for 20 years. This longevity is consistent with similar treatment networks in other locations (Finney et al., 2007), though treatments may last longer if maintenance treatments are incorporated (Collins et al., 2013). Fire severity may actually have been lower in the American Fire if it had burned a few years later because activity fuels (in cable logged areas) would have decayed and compressed over time (Collins et al., 2014).

36. Walker, R. B., J. D. Coop, S. A. Parks, and L. Trader. 2018. Fire regimes approaching historic norms reduce wildfire-facilitated conversion from forest to nonforest. Ecosphere 9:e02182.
    a. *Location*: 2011 Las Conchas fire in northern New Mexico
    b. *Vegetation Type*: Ponderosa pine and mixed-conifer forest types
    c. *Summary*: The authors compared burn severity in areas that had previously been prescribed burned, burned via wildfire, or both. Mechanical treatments were not part of this study. The authors found that Las Conchas burn severity was lowest, and tree survival was highest, in sites that had experienced both prescribed fire and prior wildfire. Sites that had experienced only prescribed or prior wildfire exhibited moderate burn severity and intermediate levels of forest retention. Burn severity was more strongly reduced within prescribed fire perimeters than those of wildfires, likely due to fuels generated by wildfires. Sites lacking any recent prior fire burned at the highest severity and were overwhelmingly converted to non-forested vegetation including grassland, oak scrub, and weedy, herbaceous-dominated types. In addition to providing general support for more use of fire to meet management objectives, the authors conclude that this study also suggests that the benefits of fire may be optimized by its sequential application, particularly the use of prescribed fire following wildfire. As shown by this study, downed and dead woody materials may rapidly accumulate post-wildfire, sometimes exceeding pre-fire loads. Strategically applying prescribed fire after wildfire can consume these accumulated fuels, thereby reducing subsequent surface fire intensity that

would occur under more extreme conditions and increasing the probability that residual live trees will survive subsequent fire events.

d. Longevity: This study did not address fuel treatment longevity.

37. Waltz, A.E.M., Stoddard, M.T., Kalies, E.L., Springer, J.D., Huffman, D.W., Sanchez Meador, A., 2014. Effectiveness of fuel reduction treatments: assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ. For. Ecol Manage. 334, 43–52.
    a. *Location*: 2011 Wallow Fire, eastern AZ
    b. *Vegetation Type*: ponderosa pine and mixed conifer forests
    c. *Summary*: This study set out to test the hypothesis that fuel reduction treatments in mixed conifer forests increased a fire-adapted system's resiliency to uncharacteristically severe wildfire. In addition, the authors tested the hypothesis that fuel reduction treatments reduced burn severity. Treatments studied included non-commercial or pre-commercial mechanical thinning followed by residual fuel removal (mechanically or broadcast burned) prior to wildfire incident. Analysis of resiliency metrics showed that: (a) treated units retained a higher proportion of large trees and had post-fire tree densities within the natural range of variability; (b) the understory herbaceous community had significantly higher cover of native grasses in the treated units, but no significant differences in nonnative cover between treated and untreated units; and (c) high severity patch sizes were significantly larger in untreated stands and covered a larger proportion of the landscape than historical reference conditions. Fire severity, as defined by overstory mortality and basal area loss, was significantly lower in treated units; on average, trees killed per hectare in untreated units was six times the number of trees killed in treated units. The authors conclude that fuel reduction treatments simultaneously reduced fire severity and enhanced short-term metrics of ecosystem resiliency to uncharacteristically severe fire.
    d. *Longevity:* This study did not address fuel treatment longevity. However, this paper shows fuel reduction treatments can additionally increase specific resiliency metrics of forested ecosystems, even within short-term timeframes.
38. Wimberly, M. C., M. A. Cochrane, A. D. Baer, and K. Pabst. 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. Ecological Applications 19: 1377–1384.
    a. *Location*: Camp 32 fire in Western Montana, School fire in southeastern Washington, and Warm fire in northern Arizona
    b. *Vegetation Type*: fire-prone ecosystems of western US
    c. *Summary*: The authors examined effects of fuel treatments on fire severity in three fires in the Western USA. Fuel treatments included, thinning, burning, and thinning plus burning. Effects of past shelterwood harvests were also assessed in one fire. Across all three fires, treatments that incorporated prescribed burning were more effective than thinning alone. For the Camp 32 fire, thinning alone increased burn severity, whereas the combination of thinning and prescribed burning decreased burn severity. For the School fire, the combination of thinning and prescribed burning resulted in lower burn severity than untreated areas, and thinning alone also decreased burn severity. The effect of prescribed burning alone was not statistically significant. For the Warm fire, prescribed burning alone and shelterwood harvesting resulted in lower burn severities than untreated areas, while thinning alone increased burn severity over untreated areas. The authors note that the situation in the thinned areas on the Camp 32 and Warm fires treatments represent a worst-case scenario in which a wildfire occurred before the

thinning treatment was completed and loadings of surface fuels were therefore particularly high. In contrast, four-year-old thinning treatments on the School fire and 14–18-year-old shelterwood harvests on the Warm fire reduced burn severity compared to untreated areas. The authors found evidence of a landscape-level treatment effect, in which the combined influences of fire interactions with the treated areas reduced burn severity even in nearby areas that were outside the treated units.

d. *Longevity*: This study did not address fuel treatment longevity. However, four-year-old thinning treatments on the School fire and 14–18-year-old shelterwood harvests on the Warm fire reduced burn severity compared to untreated areas.

39. Yocom Kent, L. L., K. L. Shive, B. A. Strom, C. H. Sieg, M. E. Hunter, C. S. Stevens-Rumann, and P. Z. Fulé. 2015. Interactions of fuel treatments, wildfire severity, and carbon dynamics in dry conifer forests. Forest Ecology and Management 349:66–72.
    a. *Location*: Rodeo-Chediski fire, AZ
    b. *Vegetation Types*: mid- and higher-elevation mixed conifer forests
    c. *Summary*: The authors examined fire severity and post-fire carbon pools in the Rodeo-Chediski Fire, which burned under extreme fire weather. Treatments included prescribed fire, thin and burn, and not treatment. The authors found that moderate- and high-severity effects were reduced from 76% in untreated areas to 57% in prescribed fire, and 38% in thin and burn treatments. Live carbon increased over time in low-severity sites but decreased over time in high-severity sites. The authors conclude that fuel treatments can significantly influence fire severity, which in turn influences carbon pools.
    d. Longevity: This study did not address fuel treatment longevity.

Studies showing treatments are not effective

1. Graham. R., M. Finney, C. McHugh, J. Cohen, D. Calkin, R. Stratton, and N. Nikolov. 2012. Fourmile Canyon Fire Findings. Gen. Tech Rep. RMRS-GTR-289, Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 110p.
    a. *Location*: 2010 Fourmile Canyon Fire, Colorado Front Range
    b. *Vegetation types***:** ponderosa pine, Douglas-fir, lodgepole pine
    c. *Summary***:** This report summarizes an investigation of the 2010 Fourmile Canyon Fire in Colorado, which burned 6,181 acres and 162 structures. The investigators assessed the effectiveness of fuel treatments and suppression actions during this fire by conducting interviews with federal, state, and local agency representatives and examining home loss in relation to burn severity and fuel treatments. Within the fire perimeter, 600 acres had previously been subject to fuel treatments, representing 9.7% of the burned area. These treatments were primarily near structures and designed to create defensible space. Treatments consisted of thinning in conjunction with piling, chipping or mastication of surface fuels. Treatments were not followed-up with prescription burning to reduce surface fuel loading. Likely because surface fuels were not reduced, there was no evidence that the fuel treatments modified fire behavior or provided protection to structures.
    d. Longevity: This study did not address fuel treatment longevity.

Modeled/Simulated effects of treatment on fire behavior and effects

Numerous modelling/simulation studies indicating that fuel treatments reduce fire intensity and effects in dry conifer forests, even under dry fuels and high wind speeds.

Studies showing treatments are effective

1. Agee, JK, Lolley, M.R. 2006. Thinning and prescribed fire effects on fuels and potential fire behavior in an eastern Cascade forest, Washington, USA. Fire Ecology 2(2), 3–19.
    a. *Location*: eastern Washington Cascades
    b. *Vegetation Types*: dry forests dominated by ponderosa pine and douglas-fir
    c. *Summary*: Fire behavior was estimated in the study area using NEXUS with 80 and 97 percentile weather values. Treatments included controls, thin-only, burn only, and thin and burn in low intensity spring burn. Burn coverage was spotty and 'considered ineffective in reducing fuels by management and research personnel". Potential flame lengths predicted after treatment under 80 percentile weather did not differ between treatments. Thinning increased potential surface fire flame length under the 97th percentile weather. Active crown fire potential was significantly lower on thinned units. Basal area survival did not significantly differ between treatments.
    d. *Longevity:* This study did not address fuel treatment longevity.
2. Ager, A., A. J. McMahan, J. J. Barrett, and C. W. McHugh. 2007. A simulation study of thinning and fuel treatments on a wildland–urban interface in eastern Oregon, USA. Landscape and Urban Planning 80:292–300.
    a. *Location*: Blue Mountains, eastern Oregon
    b. *Vegetation Types*: dry forests of ponderosa pine, cold forests dominated by subalpine-fir and Engelmann spruce, and a transition zone containing grand fir, Douglas fir, and western larch forest
    c. *Summary*: The authors simulated forest management scenarios in the wildland-urban interface near La Grande, Oregon. Potential fire effects were simulated using the FVS FFE. The thinning treatments had a marked effect on the stand characteristics that determine wildfire behavior. Potential tree mortality from wildfire increased over time in the no treatment scenario, and steadily declined through time for the thin and thin-and-burn scenarios. Crowning index, which estimates the windspeed required to sustain an active crown fire was substantially higher in the thin and thin-and-burn scenarios than the no treatment scenario, and steadily increased over time. Overall, the simulations indicated that thinning to meet stand density goals would reduce stand-level potential for crown fire behavior and associated mortality.
    d. *Longevity:* This study did not address fuel treatment longevity.
3. Bigelow, S. W., and M. P. North. 2012. Microclimate effects of fuels-reduction and group-selection silviculture: Implications for fire behavior in Sierran mixed-conifer forests. Forest Ecology and Management 264:51–59.
    a. *Location*: Meadow Valley area, Plumas National Forest, northern California
    b. *Vegetation types*: Sierran mixed-conifer
    c. *Summary*: This study measured fire-related microclimate variables for two years before and after experimental, operational-scale application of fuels-reduction thinning and group selection treatments in a Sierra Nevada mixed-conifer forest. Authors then simulated fire spread with FMAPlus. Measurements included air speed, temperature, and relative humidity; soil temperature and moisture; and dead fuel moisture. Wind gust speed increased moderately

(average 0.7 m s1 or 31% increase) in thinned forest and sharply (average 2.5 m s1 or 128% increase) in group-selection openings. Treatments did not affect air temperature or humidity. Soil temperatures increased by a mean of 4 C in group openings but did not increase in thinned stands. Duff moisture in group selection openings was 72% of that in the control stands, but there were no effects on moisture in other fuel particle size classes, or in thinned stands. Soil moisture increased in group-selection openings at depths down to 0.7 m but did not change in thinned stands. Fire spread simulation modeling with FMAPlus indicated that elevated wind speeds could increase the fire rate of spread, but that increases are moderate and largely linear rather than exponential across the observed range of wind gust speeds. The authors conclude that their results suggest that group selection openings placed in high canopy cover, Sierran mixed-conifer forests are distinct microclimatic environments that will have slightly different fire behavior than the surrounding matrix due to higher surface temperatures and faster wind speeds. On the other hand, current fuels-reduction thinning practices in dry western forests, will have minimal microclimatic-mediated influence on wildfire behavior, and there is little cause for concern about a faster rate of fire spread or drier fuels in such stands.

d. *Longevity:* This study did not address fuel treatment longevity.

4. Cochrane, M.A., Moran, C.J., Wimberly, M.C., Baer, A.D., Finney, M.A., Beckendorf, K.L., Eidenshink, J., Zhu, Z., 2012. Estimation of wildfire size and risk changes due to fuels treatments. Int. J. Wildland Fire 21, 357–367.
   a. *Location*: 14 large fires in nine states, USA
   b. *Vegetation Types*: Not reported, but likely many and variable
   c. *Summary*: In this study, the authors used FARSITE to examine the landscape effects of more than 72 000 ha of wildland fuel treatments involved in 14 large wildfires that burned 314 000 ha of forests in nine US states between 2002 and 2010. Analysis of simulation results from the 14 wildfires indicated that fuels treatments reduced the average size of any given wildfire by an estimated 7.2%, with amount of change correlated with the proportion of the landscape treated, though results were highly variable. Large landscape regions experienced both increased and decreased risks of fire spread foreach fire event as a function of fuels treatment presence. The authors conclude that fuels treatments effectively redistribute fire risk on the landscape, but caution that treatment effectiveness varies by ecosystem type, treatment intensity, size, age and distribution on the landscape as well as the weather conditions at the time of a wildfire.
   d. *Longevity:* This study did not address fuel treatment longevity.
5. Collins, B. M., H. A. Kramer, K. Menning, C. Dillingham, D. Saah, P. A. Stine, and S. L. Stephens. 2013. Modeling hazardous fire potential within a completed fuel treatment network in the northern Sierra Nevada. Forest Ecology and Management 310:156–166.
   a. *Location*: Northern Sierra Nevada, CA
   b. *Vegetation Types*: Sierran mixed-conifer forest
   c. *Summary*: This study aimed to: (1) model hazardous fire potential with and without the treatment network, (2) project hazardous fire potential over several decades to assess fuel treatment network longevity, and (3) assess fuel treatment effectiveness and longevity over a range of two critical fire modeling inputs: surface fuel models and canopy base height. Treatments covered approximately 20% of the landscape, were included five types: hand-thin and pile burn, masticate, prescribed burn, mechanically-thin and prescribed burn, and group selection harvest. Fire behavior was modeled using FlamMap. Modeling results demonstrate

reductions in the hazardous fire potential across much of the treated landscape, relative to the untreated condition. These reductions persisted throughout the modeling duration, 2010–2050. However, there was a strong effect of varying ingrowth levels, which were manipulated to generate different estimates of canopy base height over time, on hazardous fire potential over time. The effect of varying fuel models in treated areas had much less impact on hazardous fire potential, indicating a robust treatment effect. The authors note that while reductions in hazardous fire potential are evident throughout the study area following treatment implementation, the effects are more pronounced on the leeward side of the relatively linear treatment blocks. Based on their results, the authors conclude that a coordinated fuel treatment network that incorporates local knowledge of fire weather and likely fire behavior patterns can have a substantial impact on reducing hazardous fire potential. However, they note that, even with planned maintenance of the treatment network, hazard grows in untreated areas over time, resulting in an increase in overall fire hazard. This suggests additional treatments, would be necessary to maintain low hazardous fire potential over time. This study built on previous work by Moghaddas et al. (2010) who investigated the effectiveness of this same fuel treatment and group selection network at reducing modeled landscape-level fire behavior. Moghaddas et al. (2010) found that overall conditional burn probability was lower for the post-treatment landscape relative to pre-treatment. They also demonstrated that fire size under a modeled ‘‘problem fire’’ scenario was reduced by one-third for the post-treatment landscape.

   d. *Longevity:* This study did show that after 20 years (from 2030 through 2050) hazardous fire potential did increase for the treated landscape however average burn probabilities for the treated landscape were well below that for the untreated landscape and high ingrowth levels), particularly in 2050 (Fig. 4). These large differences between the treated and untreated landscapes in 2050, along with the fact that burn probabilities for the treated landscape are lower in 2050 than the initial untreated condition (2010), suggest considerable longevity for the fuel treatment network.

6. Collins, B.M., Stephens, S.L., Roller, G.B., Battles, J.J., 2011. Simulating fire and forest dynamics for a landscape fuel treatment project in the Sierra Nevada. For. Sci. 57, 77–88.
   a. *Location*: northern Sierra Nevada, CA
   b. *Vegetation Type*: Mixed conifer forest
   c. *Summary*: This study evaluated a landscape fuel treatment project that was designed by local US Forest Service managers in the northern Sierra Nevada. The authors modeled (using FVS FFE and FlamMap) the effects of the project on reducing landscape-level fire behavior at multiple time steps, up to nearly 30 years beyond treatment implementation. Simulated treatments included thinning from below at various diameter limits, mastication, and prescribed burn. The planned fuel treatments reduced modeled conditional burn probabilities substantially across the landscape, not just within the treatment areas, relative to those for a scenario with no simulated treatments. This reduction relative to that for the no treatment landscape was evident approximately 20 years after simulated treatment implementation. The authors note that because the analysis incorporates variable wind directions and speeds, one of the dominant drivers of fire spread, they believe these results reflect a realistic assessment of treatment effectiveness and not simply results driven by a few key modeling assumptions. However, they continue, it is worth noting that this modeling may under represent crown fire

propagation and spotting and thus may not be able to capture differences in reduction of crown fire potential among thinning scenarios.

d. *Longevity:* This study suggests landscape-level treatment longevity of approximately 20 years based on a single-entry treatment. Although we do not model it, maintenance treatments (e.g., prescribed fire) would probably extend this longevity across the landscape.

7. Dow, C.B., Collins, B.M., Stephens, S.L., 2016. Incorporating resource protection constraints in an analysis of landscape fuel-treatment effectiveness in the northern Sierra Nevada, CA, USA. Environ. Manage. 57, 516–530. https://doi.org/10.1007/s00267- 015-0632-8.
   a. *Location*: northern Sierra Nevada, CA
   b. *Vegetation Type*: Mixed Conifer forest
   c. *Summary*: In this study, the authors examined alternative approaches to landscape-scale fuel treatment design for the same landscape, including three active treatment scenarios and one no treatment scenario. The active approaches assessed included: the actual implemented treatments, a restricted scenario that avoided treatment in certain land allocations while optimizing treatment locations, and an unrestricted scenario to optimize effects to fire behavior. Treatments included thinning from below, followed by grapple piling, hand piling, pile burning, and underburning; mastication; group selection harvest; and prescription burns were also included. Fire behavior was modeled with FlamMap. Results demonstrate that in all the three active treatment scenarios, hazardous fire potential, fire area, and emissions were reduced by approximately 50 % relative to the untreated condition. While all treatment scenarios resulted in reductions in mean conditional burn probability when compared to the untreated scenario, the restricted-tom treatment had the greatest calculated reduction in burn probability across the core study area, likely due to the greater aggregation and continuity of fuel treatments. The reduction in fire area was also the greatest in the restricted-tom treatment, with a mean fire area of nearly half that of the untreated scenario.
   d. *Longevity:* This study did not address fuel treatment longevity.
8. Ex SA, Ziegler JP, Tinkham WT, Hoffman CM. 2019. Long-term impacts of fuel treatment placement with respect to forest cover type on potential fire behavior across a mountainous landscape. Forests 10: 438.
   a. *Location*: 48 km2 in Colorado
   b. *Vegetation Type*: ponderosa-dominated and Doug-fir-dominated forest types
   c. *Summary*: This article modeled how the placement of fuels treatments with respect to forest cover type affected the rate of spread, size, and prevalence of different fire types for simulated wildfires for 50 years after treatment. The authors used Forest Inventory and Analysis (FIA) data, FVS-FFE to simulate fuels reduction treatments and WFDS (based on Fire Dynamics simulator) to model fire behavior. Although post-treatment metrics of stand-level fuel hazard were similar among treatment scenarios, only the south treatment reduced rates of fire spread and fire size relative to no treatment. Differences in modeled fire behavior between treatment scenarios disappeared after two decades, despite greater rates of stand-level fuel hazard development post-treatment for the north treatment, highlighting the importance of aspect.
   d. *Longevity:* In this study, we set out to understand specifically how treatment placement within different forest cover types impacted the initial effectiveness and longevity of fuel treatments to modify potential fire behavior. Most differences in modeled fire behavior between treatment scenarios disappeared after two decades, despite persistently greater rates of stand-level fuel hazard development post-treatment for the north treatment. For all scenarios, the

overall trajectory was of shrinking fires and less crown fire behavior over time, owing to crown recession in untreated stands.

9. Finkral, A.j. Evans, A.M . 2008. The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest. For. Ecol. Manage. 255. 2743-2750.
    a. *Location*: Arizona
    b. *Vegetation Type*: Ponderosa pine
    c. *Summary*: This study examined the effect of a restoration thinning treatment on the carbon stock of a ponderosa pine forest. The authors used the Central Rockies variant of the forest vegetation simulator with the fire and fuels extension to model differences in fire effects between the pre- and post-treatment stands. They found that thinning treatments reduced carbon stocks but would result in the release of significantly less carbon in a fire than in untreated areas. They found that by increasing the crowning index the treatment moved the stand from moderate to low fire hazard. The authors note that the thinning treatment resulted in stand structural changes that make the stand less likely to support a crown fire and therefore more likely to avoid the carbon releases associated with crown fires, even under extreme fire conditions.
    d. Longevity: This study did not address fuel treatment longevity.
10. Finney, M.A., Seli, R.C., Mchugh, C.W., Ager, A.A., Bahro, B., Agee, J.K., 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. Int. J. Wildl. Fire 16, 712–727. https://doi.org/10.1071/WF06064
    a. Location: Sanders County in western Montana, central Sierra Nevada in California, and Blue mountains in south-eastern Washington.
    b. *Vegetation Types*: A wide variety of fuel and forest types, including ponderosa pine, western red cedar, lodgepole pine, whitebark pine, oak woodlands, mixed conifer, red fir, subalpine fir, and Engelmann spruce.
    c. *Summary*: In this study, a simulation system was developed to explore how fuel treatments placed in topologically random and optimal spatial patterns affect the growth and behavior of large fires when implemented at different rates over the course of five decades. The system consisted of a forest and fuel dynamics simulation module (Forest Vegetation Simulator, FVS), logic for deriving fuel model dynamics from FVS output, a spatial fuel treatment optimization program, and a spatial fire growth and behavior model to evaluate the performance of the treatments in modifying large fire growth. Simulations were performed for three study areas: Sanders County in western Montana, the Stanislaus National Forest in California, and the Blue Mountains in south-eastern Washington. For different spatial treatment strategies, the results illustrated that the rate of fuel treatment (percentage of land area treated per decade) competes against the rates of fuel recovery to determine how fuel treatments contribute to multidecade cumulative impacts on the response variables. Using fuel treatment prescriptions that simulate thinning and prescribed burning, fuel treatment arrangements that are optimal in disrupting the growth of large fires require at least 1 to 2%of the landscape to be treated each year. Randomly arranged units with the same treatment prescriptions require about twice that rate to produce the same fire growth reduction. The results also show that the topological fuel treatment optimization tends to balance maintenance of previous units with treatment of new units. For example, with 2% landscape treatment annually, fewer than 5% of the units received

three or more treatments in five decades with most being treated only once or twice and ~35% remaining untreated after five decades.

d. *Longevity:* The simulations for the four study sites consistently suggested that all treatment rates (1 to 5% per year) accumulated benefits to reduced fire spread rate, wildfire sizes, and burn probability out to about two decades. Beyond that point in time, additional treatment produced little marginal reduction in the landscape fire metrics but continued treatment would be required to maintain these benefits. Additionally, treatment rates beyond~2% per year in optimal patterns produced little added benefit for the study areas. This is probably a result of the inherent fuel accumulation and decomposition rates, which determine longevity of individual treatments.

11. Fulé P. Z., A. E. Waltz, W. W. Covington, and T. A. Heinlein. 2001. Measuring forest restoration effectiveness in reducing hazardous fuels. Journal of Forestry 11:24-29.
    a. *Location***:** northwest Arizona
    b. *Vegetation types:* ponderosa pine
    c. *Summary***:** This study modeled fire under extreme weather conditions based on treatments conducted in northwestern Arizona that included thinning of small trees and prescribed burning. Forest restoration treatments of thinning young trees followed by prescribed burning in led to significantly lower stand density, lower crown fuel load, and higher crown base height than untreated stands. Simulated fire under extreme weather conditions caused 48 percent more canopy burning and higher flame lengths, heat/area, and rate of spread in untreated stands. Wind speeds required for passive crown fire (torching) were twice as high in treated stands. Treated stands were highly heterogeneous, but restoration treatments clearly enhanced crown-fire resistance.
    d. *Longevity:* This study did not address fuel treatment longevity.
12. Hurteau MD, Koch GW, Hungate BA. 2008. Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. Front Ecol Environ 6:493–98. Hurteau, M., and M. North. 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. Frontiers in Ecology and the Environment 7:409- 414.
    a. *Location***:** California (including the Sierra Nevada), Colorado, Oregon & Arizona
    b. *Vegetation types***:** a variety of forest types
    c. *Summary***:** In this study, the authors utilized models from Agee and Skinner 2005 and Kaye et al. 2005 to account for impacts of treatment on post fire Carbon. Examining four of the largest wildfires in the US in 2002, the authors found that, for forest land that experienced catastrophic stand-replacing fire, prior thinning would have reduced CO2 release from live tree biomass by as much as 98%. The study notes that fuel reduction treatments can decrease the odds of stand replacing wildfire therefore lessening the chances of carbon loss. Prescribed thinning or prescribed fire do lessen the total carbon, but they increase carbon stability (i.e. decrease the odds of stand replacing fire).
    d. *Longevity:* This study did not address fuel treatment longevity.
13. Hurteau, M.D., North, M. 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. Front. Ecol. Environ. 7, 409-414.
    a. *Location*: Teakettle Experimental Forest, Sierra Nevada, California
    b. *Vegetation Type*: Sierra Mixed Conifer
    c. *Summary:* The authors modeled the effects of eight different fuel treatments (control, burn only, understory thin, understory thin and burn, restoration thin, restoration thin and burn, 1865 reconstruction, and 1865 reconstruction and burn) on tree-based C storage and release

over a century, with and without wildfire. Model runs show that, after a century of growth without wildfire, the control stored the most C. However, when wildfire was included in the model, the control had the largest total C emission and largest reduction in live-tree-based C stocks. In model runs including wildfire, the final amount of tree-based C sequestered was most affected by the stand structure initially produced by the different fuel treatments. In wildfire-prone forests, tree-based C stocks were best protected by fuel treatments that produced a low-density stand structure dominated by large, fire-resistant pines.

d. Longevity: This study did not address fuel treatment longevity.

14. Jain T. B., J. S. Fried, and S. M. Loreno. 2020. Simulating the effectiveness of improvement cuts and commercial thinning to enhance fire resistance in west coast dry mixed conifer forests. Forest Science 66:157-177.
    a. *Location***:** Sierra Nevada, California, eastern Oregon and Washington
    b. *Vegetation types***:** dry mixed-conifer forests
    c. *Summary*: In this study, nine multipurpose silvicultural treatments, formulated as a synthesis of recently implemented prescriptions offered by forest managers, were simulated to evaluate their effectiveness at enhancing fire resistance. The Forest Vegetation Simulator was applied, within the BioSum Framework, on over 3,000 Forest Inventory and Analysis plots representing 5 million hectares of dry mixed conifer forests in eastern Washington and Oregon and California's Sierra Nevada Mountains. The authors developed a composite fire resistance score based on four fuel modification principals and metrics: fuel strata gap, canopy bulk density, proportion of basal area in resistant species, and predicted tree survival. The trajectories of stands with and without treatment were compared to evaluate effectiveness immediately post-treatment, and over the three decades that followed. The authors found that seventy percent of these forests could be effectively treated in the short term by at least one prescription. Pretreatment forest condition, particularly fire-resistant species abundance, strongly influenced short-term treatment success, and the post-treatment stand dynamics that limit treatment longevity. Stands where 25-75% of the basal area is in fire-resistant species benefit most from treatment, in particular where smaller, fire-vulnerable species can be removed.
    d. *Longevity:* Treatment effectiveness endured 10 or 20 years, depending on fire-resistant species abundance, owing to growing space for crown expansion generated by treatment plus regeneration and release and growth of understory tree strata.
15. Johnson, M. C., M. C. Kennedy, and D. L. Peterson. 2011. Simulating fuel treatment effects in dry forests of the western United States: testing the principles of a fire-safe forest. Canadian Journal of Forest Research 41:1018–1030.
    a. *Location*: Western US
    b. *Vegetation Type*: low- to mid-elevation dry forests of the western US (e.g. ponderosa pine and Douglas fir)
    c. *Summary*: In this study, the authors used the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) to simulate fuel treatment effects on stands in low- to mid-elevation dry forests (e.g., ponderosa pine and Douglas-fir) of the western United States. They evaluated treatment effects on predicted post-treatment fIre behavior (fire type) and fire hazard (torching index). FFE-FVS predicted that thinning and surface fuel treatments reduced crown fIre behavior relative to no treatment; a large proportion of stands were predicted to transition from active crown fire pre-treatment to surface fIre post-treatment. Intense thinning treatments were predicted to be more effective than light thinning treatments. Prescribed fire was predicted to be the most effective surface fuel treatment. The inability of the model to

discriminate the effects of certain fuel treatments illuminates the consequence of a documented limitation in how FFE-FVS incorporates fuel models and the authors suggest improvements. The authors suggest that concurrence of results from modeling and empirical studies provides quantitative support for "fire-safe" principles of forest fuel.

d. *Longevity:* This study did not address fuel treatment longevity.

16. Johnston, J.D., J.H. Olszewski, B.A. Miller, M.R. Schmidt, M.J. Vernon, L.M. Ellsworth. 2021. Mechanical thinning without prescribed fire moderates wildfire behavior in an Eastern Oregon, USA ponderosa pine forest. Forest Ecology and Management, 501: 119674.
    a. *Location*: Blue Mountains, Eastern OR
    b. *Vegetation Type:* Ponderosa pine forest
    c. *Summary*: In this study, the authors assess the effects of mechanical thinning and standard post-thinning fuels management without prescribed fire on modeled fire behavior and changes in fuel loading over time in a ponderosa pine forest in Eastern Oregon. They modeled fire behavior using the Fuel Characteristic Classification System. They found that thinning without prescribed fire significantly reduced potential crown fire immediately following thinning and also moderated surface modeled fire behavior beginning 2–3 years following thinning. Although small (<7.6 cm diameter) woody surface fuel loading increased following thinning, other ground and surface fuels (i.e., litter and duff) declined substantially, which the authors attribute to surface disturbance from ground-based logging, decreased deposition of litter, and increased decomposition. By four years after thinning was completed, rate of spread, flame length, and reaction intensity were 43%, 26%, and 14% greater respectively in unthinned controls than in thinned stands. By two years post-thinning, crown initiation potential was 16% less than before thinning began and remained 16–20% lower than pre-thinning crown initiation potential three years later. The authors conclude that fuel reduction and fire risk management objectives can be met with mechanical thinning alone for a number of years.
    d. *Longevity:* It is likely that the observed trend of significantly declining surface fuel loading and significantly moderated modeled fire behavior will continue for a number of years as fine woody fuel particles decompose. Although we show that thinning in the absence of prescribed fire moderates modeled fire behavior for a number of years, prescribed fire is still an important tool for accomplishing fuel reduction and fire management objectives in ponderosa pine forests of the southern Blue Mountains and elsewhere effective at extending the longevity of treatments in thinned stands at some point in the future when the trend towards decreasing surface fuel loading is reversed and surface fuel loading begins to exceed desired thresholds.
17. Krofcheck DJ, Hurteau MD, Scheller RM, and Loudermilk EL. 2018. Prioritizing forest fuels treatments based on the probability of high-severity fire restores adaptive capacity in Sierran forests. Glob Change Biol 24: 729–37.
    a. *Location*: Dinkey Creek watershed, southern Sierra Nevada, California
    b. *Vegetation Types*: Mixture of oak and shrub to ponderosa pine and mixed-conifer, to subalpine forest.
    c. *Summary*: In this study, the authors developed two treatment placement strategies: the naive strategy, based on treating all operationally available area and the optimized strategy, which only treated areas where crown-killing fires were most probable. Both management scenarios employed combinations of mechanical thinning and prescribed burning They ran forecast simulations using projected climate data through 2100 to determine how the treatments

differed in terms of C sequestration, fire severity, and C emissions relative to a no-management scenario. They found that in both the short and long term, both management scenarios increased C stability, reduced burn severity, and consequently emitted less C as a result of wildfires than no-management. Across all metrics, both scenarios performed the same, but the optimized treatment required significantly less C removal to achieve the same treatment efficacy. The authors suggest that, given the extent of western forests in need of fire restoration, efficiently allocating treatments is a critical task if we are going to restore adaptive capacity in frequent-fire forests.

d. Longevity: This study did not address fuel treatment longevity.

18. Liang S., M. D. Hurteau, and A. L. Westerling. 2018. Large-scale restoration increases carbon stability under projected climate and wildfire regimes. Frontiers in Ecology and the Environment 16:207–212.
    a. *Location*: Sierra Nevada, CA
    b. *Vegetation Types*: low and mid-elevation forests
    c. *Summary*: Using model simulations, the study authors quantified how large-scale restoration treatments in frequent-fire forest types would influence C outcomes in the Sierra Nevada mountain range under projected climate–wildfire interactions. The study used the Leaf Biomass Harvest extension to simulate not only thinning from below but also prescribed fire treatments that are commonly practiced in low-and mid-elevation forests to reduce fire hazard in the Sierra Nevada. The thinning and prescribed fire treatments were designed to remove a greater proportion of the youngest cohorts and shift the age distribution toward older cohorts. Across the landscape, treatments were implemented in fire-prone forests that currently have a greater risk of high-severity fire. Stands with higher fire hazard were treated first. Following each thinning treatment, prescribed fire treatments were successively applied on a 10–30-year return interval as a function of elevation band. While cumulative area burned by wildfire was consistent across treatment scenarios, widespread application of restoration treatments gradually reduced the proportion of landscape burned by high-severity wildfires, with an increasingly greater proportion of the landscape burned by low-severity surface fires relative to the control. Although C loss was initially higher in the restoration treatments, treatment effects on fire severity led to an immediate reduction in wildfire emissions and lowered cumulative C emissions and losses. These results indicate that large-scale restoration treatments are an effective means of reducing fire hazard and increasing C storage and stability under future climate and wildfire conditions.
    d. Longevity: This study did not address fuel treatment longevity.
19. Mitchell SR, Harmon ME, O'Connell KE. 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecol Appl 19:643–55.
    a. *Location*: Pacific Northwest, Cascade Head, H.J. Andrews, Pringle Falls
    b. *Vegetation Type*s: Eastern Cascades Forest – ponderosa pine; Western Cascade Forests - western hemlock, Douglas-fir, Coast Range Forests – western hemlock, Douglas-fir, Sitka spruce
    c. *Summary*: This paper employed simulations using STANDCARB and generally indicates that fuel reduction treatments in the target ecosystems consistently reduced fire severity. Reductions in the amount of C lost in a wildfire, depending on treatment type and frequency, were as much as 50% in the east Cascades, 57% in the west Cascades, and 50% in the Coast Range. In the east Cascades simulations, amounts lost in wildfires were inversely related to the amounts of C removed in an average fire return interval for each ecosystem. Simulations in this fire regime revealed a slightly increasing amount of C lost in wildfires with increasing amounts removed,

though amounts removed were nonetheless larger than the amounts lost in a typical wildfire. However, fuel removal almost always reduces C storage more than the additional C that a stand is able to store when made more resistant to wildfire.

d. Longevity: This study did not address fuel treatment longevity.

20. Parsons, R.A., Pimont, F., Wells, L., Cohn, G., Jolly, W.M., de Coligny, F., Linn, R.R., 2018. Modeling thinning effects on fire behavior with STANDFIRE. Annals of Forest Science 75 (1), 7.
    a. *Location*: Western Montana, Lubrecht, Tenderfoot
    b. *Vegetation Types*: Dry-mesic montane mixed conifer forest, in ponderosa pine/Douglas-fir forest and in lodgepole pine forest
    c. *Summary*: The authors set out to use STANDIRE to model fire behavior effects of thinning treatments, and compare results to other modeling techniques. STANDFIRE consistently predicted faster surface fires and somewhat increased surface fuel heat transfer in thinned stands, due to reduced canopy drag effects. It also predicted greatly reduced canopy fuel consumption, canopy fuel heat transfer, and tree mortality following thinning. Forest Vegetation Simulator (FVS) results predicted that thinned areas had lower Torching Index values, indicating increased potential for torching. Conversely, Crowning Index values increased with thinning, indicating decreased potential for crown fire spread. FVS predicted that flame length increased following thinning in all three sites, likely from decreases in stand level canopy cover and corresponding increases in effective wind speed. The authors suggest that by modeling trees as individual entities in space and having fire calculations that account for fuel geometry and spatial relationships, STANDFIRE provides a basis which leads away from single stand values and which embraces the complexity of wildland fuels and their intrinsic heterogeneity.
    d. *Longevity:* Does not address treatment longevity.
21. Reinhardt, E., Holsinger, L., 2010. Effects of fuel treatments on carbon-disturbance relationships in forests of the northern Rocky mountains. For. Ecol. Manage. 259, 1427-1435.
    a. *Location*: northern Rocky Mountains
    b. *Vegetation Types*: seven major habitat type groups of northern Rocky Mountains
    c. *Summary*: In this study, authors simulated effects of fuel treatments on 140 stands representing seven major habitat type groups of the northern Rocky Mountains using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). Changes in forest carbon due to mechanical fuel treatment (thinning from below to reduce ladder fuels) and prescribed fire were explored, as well as changes in expected fire behavior and effects of subsequent wildfire. Results indicated that fuel treatments decreased fire severity and crown fire occurrence and reduced subsequent wildfire emissions, but did not increase post-wildfire carbon stored on-site. The authors found that crown fire behavior was substantially reduced by prescribed fire and almost eliminated by mechanical fuel treatments. Wildfire flame length was also reduced by treatments. Fire-caused tree mortality was reduced for all forest types, in some cases dramatically, because the thinning from below and prescribed fire selectively removed the smallest and most vulnerable trees. Untreated stands had greater wildfire emissions but stored more carbon, particularly in dead vegetation.
    d. Longevity: This study did not address fuel treatment longevity.

22. Schmidt, D.A., Taylor, A.H., Skinner, C.N., 2008. The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range, California. Forest Ecology and Management 255, 3170–3184.
    a. *Location*: Goosenest Adaptive Management Area, southern Cascades, California
    b. *Vegetation Type*: mixed-conifer forest
    c. *Summary:* This study analyzes the response of several key fire behavior variables to variation in the type, amount, and spatial arrangement of fuel treatments for simulated wildfires in mixed-conifer forests of the southern Cascades in the Goosenest Adaptive Management Area (GAMA). NEXUS and BehavePlus were used to simulate pre- and post-treatment stand-level fire behavior. Fire area simulator (FARSITE) was used to simulate landscape-level wildfire behavior in both untreated and treated forest landscapes. In the forest landscape, treatment areas were placed in the landscape according to two strategically designed arrangements and one random treatment arrangement. Treatments included thinning by prescribed burning (burn-only), mechanical thinning (mechanical-only), mechanical thinning followed by burning (mechanical-burn), and no treatment (control). At the stand level, the mechanical-burn treatment most effectively reduced both surface fire (e.g., decreased flame length) and crown fire behavior (e.g., torching index). At the landscape level, treatment type, amount, and arrangement had important effects on both fire spread and fire intensity. In this landscape the most effective treatment arrangement was Finney's optimal SPLATs design. This study shows that there is potential to efficiently reduce high-intensity fire behavior while treating less area by relying on strategically placed treatments.
    d. *Longevity:* Treatment longevity is an important management consideration in planning and implementing fuel treatments. The mechanical plus burn treatments will likely last much longer than burn alone treatment. The canopy density has been reduced and the smaller trees have been removed in the mechanical thinning operations so they are not available to be killed and become additional surface fuel following the prescribed burns.
23. Stephens S. L., M. A. Battaglia, D. J. Churchill, B. M. Collins, M. Coppoletta, C. M. Hoffman, J. M. Lydersen, M. P. North, R. A. Parsons, S. M. Ritter, and J. T. Stevens. 2021. Forest restoration and fuels reduction: convergent or divergent? Bioscience 71:85-101.
    a. *Location*: Western US
    b. *Vegetation Types*: Historically frequent-fire coniferous forests of the western US
    c. *Summary*: While this reference is largely a synthesis of existing information, it does include an important case study (Box 2) of a fire simulation, which is summarized here. Fire simulations demonstrate an increase in the mid-flame wind speed associated with treatments, with the restoration treatment producing more variability in wind speed compared to fuel treatments. Surface fire rate of spread increased after restoration and fuel treatments relative to the untreated stand. This increased fire rate of spread following both treatment types is due to a combination of higher mid-flame wind speeds and a greater proportion of grass fuels, which result from reductions to canopy cover. Differences in sinuosity in the simulation are a reflection of heterogeneous surface fuel and mid-flame wind speeds (as well as more complex fire–atmosphere interactions because of small groups of trees torching that create updrafts which influence local wind velocities driving fire spread). But, importantly, crown consumption, a proxy for crown fire activity, was far lower for both the fuel (10%) and restoration (13%) treatments relative to the pretreatment conditions (85%). Overall, these simulations suggest

that both treatment types can be effective in reducing potential crown fire behavior, and therefore mitigate potential negative effects on vegetation.

d. *Longevity*: This study was largely a synthesis with recommendations. One case study does address treatment longevity as the Harless Ridge project was treated five years prior to the 2014 King Fire. This treatment did result in a more resilient stand structure that withstood the fire.

24. Stephens, S.L., B.M. Collins and G. Roller. 2012. Fuel treatment longevity in a Sierra Nevada mixed conifer forest. Forest Ecology and Management 285: 204-212.
    a. *Location:* Sierra Nevada
    b. *Vegetation Types*: Mixed conifer forest
    c. *Summary:* Understanding the longevity of fuel treatments in terms of their ability to maintain fire behavior and effects within a desired range is an important question. The objective of this study was to determine how fuels, forest structure, and predicted fire behavior changed 7-years after initial treatments. Three different treatments: mechanical only, mechanical plus fire, and prescribed fire only, as well as untreated control, were each randomly applied to 3 of 12 experimental units. Many aspects of the initial fuel treatments changed in 7 years. The overall hazard of the control units increased significantly indicating continued passive management has further increased already high fire hazards. Mechanical only fire hazard decreased after 7 years and are now similar to the two fire treatments, which both maintained low hazards throughout the study. Tree density declined significantly 7 years after the initial fire only treatments, while basal area in both fire treatments was unchanged relative to immediate post-treatment conditions. Our findings indicating reduced fire hazard over time in mechanical only treatments might provide an opportunity for a staggered treatment schedule that included prescribed fire which could increase overall treatment longevity to approximately 20 years. Changes in our mixed conifer forests after fuel treatment were generally larger than those reported from ponderosa pine forests in the Rocky Mountains.
    d. *Longevity*: This study looked directly at modeled treatment effects after seven years.
25. Stephens, S. L., J. J. Moghaddas, C. Edminster, C. E. Fiedler, S. Haase, M. Harrington, J. E. Keeley, E. E. Knapp, J. D. McIver, K. Metlen, and others. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. Ecological Applications 19:305–320.
    a. *Location*: Western US
    b. *Vegetation Type*: seasonally dry, low and mid-elevation coniferous forests of the western US that once experienced frequent, low to moderate intensity, fire regimes
    c. *Summary*: In this paper, the authors report the effects of Fire and Fire Surrogate (FFS) forest stand treatments on fuel load profiles, potential fire behavior, and fire severity under three weather scenarios from six western U.S. FFS sites. Site level treatments included an unmanipulated control, prescribed fire only, mechanical treatment only, and a mechanical plus prescribed fire treatment. Fire behavior and effects were simulated for each FFS site under upper 80th (moderate), 90th (high), and 97.5th (extreme) percentile fire weather conditions based on archived remote access weather station (RAWS) data. The mechanical treatment alone had a variable effect on torching index, with three of the five sites where these treatments were implemented showing large increases in torching index (representing lower likelihood of passive crown fire). For the combined treatment of mechanical plus fire, all five FFS sites with this treatment had a substantially lower likelihood of passive crown fire as

indicated by the very high torching indices. When mechanical treatments were followed by prescribed burning or pile burning, they were the most effective treatment for reducing crown fire potential and predicted tree mortality because of low surface fuel loads and increased vertical and horizontal canopy separation. Across all FFS sites using mechanical treatments, the relative potential for active crown fire was lowest in mechanical plus fire treatments, followed by the mechanical-only treatments, closely followed by fire-only treatments, and highest in the controls. These results indicate that mechanical plus fire, fire-only, and mechanical-only treatments using whole-tree harvest systems were all effective at reducing potential fire severity under severe fire weather conditions. Retaining the largest trees within stands also increased fire resistance.

d. *Longevity:* This study did not address fuel treatment longevity.

26. Stephens, S. L., and J. J. Moghaddas. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management 215:21–36.
    a. *Location*: north-central Sierra Nevada, California
    b. *Vegetation type*: mixed conifer forest
    c. *Summary*: This paper presents information from a replicated, stand level experiment from mixed conifer forests in the north-central Sierra Nevada that investigated how control, mechanical (crown thinning, thinning from below followed, rotary mastication), prescribed fire, and mechanical followed by prescribed fire treatments affected fuels, forest structure, potential fire behavior, and modeled tree mortality at 80th, 90th, and 97.5th percentile fire weather conditions. Fuels Management Analyst was used to model fire behavior and tree mortality. Thinning and mastication each reduced crown bulk density by approximately 19% in mechanical only and mechanical plus fire treatments. Prescribed burning significantly reduced the total combined fuel load by as much as 90%. This reduction significantly altered modeled fire behavior in both mechanical plus fire and fire only treatments in terms of fireline intensity and predicted mortality. The prescribed fire only and mechanical followed by prescribed fire treatments resulted in the lowest average fireline intensities, rate of spread, and predicted mortality. The control treatment resulted in the most severe modeled fire behavior and tree mortality. Mechanical only treatments were an improvement over controls but still resulted in tree mortality at severe fire weather when compared with the treatments that included prescribed fire.
    d. *Longevity:* This study did not address fuel treatment longevity.
27. Stevens J. T., B. M. Collins, J. W. Long, M. P. North, S. J. Prichard, L. W. Tarnay, and A. M. White. 2016. Evaluating potential trade-offs among fuel treatment strategies in mixed-conifer forests of the Sierra Nevada. Ecosphere 7:e01445
    a. *Location*: Lake Tahoe Basin, Sierra Nevada, CA
    b. *Vegetation Type*: White fir and Sierra mixed-conifer forests
    c. *Summary*: The authors simulated different treatment strategies representing a combination of different prescriptions, placements, and extents and modeled their effects on subsequent fire behavior, smoke production, and wildlife habitat. They quantified the effects of the different treatment strategies on potential fire severity in the study area using the Random-Ignitions module (RandIg) of the fire simulation software FlamMap. For each strategy, they evaluated how well it met its stated objective(s) in comparison with other strategies, by evaluating the

proportional change in the relevant variables. The main objective of the fire hazard reduction (FHR) treatment strategy was to maximally reduce potential fire severity across the entire landscape, in order to promote low-severity fire effects. All treatment placements, but particularly the FHR and WUI strategies, resulted in substantial treatment area being placed in zones with heavy fuel models and high potential flame lengths, leading to 13–44% reductions in the area prone to high-severity fire across the landscape. However, for all treatment strategies, the authors considered the magnitude of impacts at the landscape scale tended to be fairly small, relative to other studies in similar forest types.

d. Longevity: This study did not address fuel treatment longevity.

28. Vaillant, N. M., J. A. Fites-Kaufman, and S. L. Stephens. 2009. Effectiveness of prescribed fire as a fuel treatment in Californian coniferous forests. International Journal of Wildland Fire 18:165–175.
    a. *Location*: eight National Forests in California
    b. *Vegetation Type*: yellow pine and mixed-conifer forests
    c. *Summary*: This study investigates how prescribed fire affects fuel loads, forest structure, potential fire behavior, and modeled tree mortality at 80th, 90th, and 97.5th percentile fire weather conditions on eight National Forests in California. Potential fire behavior and effects were modeled using Fuel Management Analyst. Prescription burning did not significantly change forest structure at most sites. Total fuel loads were reduced by 23 to 78 percent across the sites. This reduction in fuels altered potential fi re behavior by reducing rate of spread, flame length, and fireline intensity. Increased torching index values coupled with decreased fuel loads reduced crown fire potential post-treatment in some stands. Predicted tree mortality decreased post-treatment as an effect of reduced potential fi re behavior and fuel loads.
    d. Longevity: This study did not address fuel treatment longevity.

Other forest types in the Western US

Prichard et al. (2021) note that in forests characterized by moderate- and high-severity fire regimes, a limited number of studies suggest that fuel reduction treatments are ineffective at reducing fire behavior and effects, particularly under extreme weather conditions. However some studies, noted below, as suggest that fuel reduction treatments can be effective, even in high severity fire regime forests.

1. Hirsch, Kelvin; Pengelly, Ian. 1999. Fuel reduction in lodgepole pine stands in Banff National Park. In: Neuenschwander, Leon F.; Ryan, Kevin C., tech. eds. Proceeding of the joint fire science conference and workshop: crossing the millennium: integrating spatial technologies and ecological principles for a new age in fire management; 1999 June 15-17; Boise, ID. Moscow, ID: University of Idaho. 6 p.
    a. *Location:* Banff National Park, Canada.
    b. *Vegetation Types:* lodgepole pine
    c. *Abstract:* Over the last decade fire managers in Banff National Park have embarked on a comprehensive fuels management program of which one aspect has been fuel reduction treatments near structures or facilities (for example, homes, campground, hotels). These treatments included the reduction of dead and down woody surface material (for example, logs, branches, twigs), removal of coniferous understory trees, pruning, and overstory thinning. Detailed measurements of all flammable material above mineral soil were made at four plots within the treated areas and four plots in stands immediately adjacent to the

treatments. The fuel treatments resulted in a 3-, 4-, and 6-fold decrease in crown bulk density, stand density, and dead and down woody material, respectively. The change in surface fuel loading caused a 50 percent reduction in the potential surface fire intensity. Based on Van Wagner's theories, the likelihood of crown fire initiation was significantly reduced and the rate of spread required to sustain continuous crowning rose almost 4 times.

   d. *Longevity:* This study did not address fuel treatment longevity.

2. Kalabokidis, Kostas D.; Omi, Philip N. 1998. Reduction of fire hazard through thinning/residue disposal in the urban interface. International Journal of Wildland Fire. 8(1): 29-35. Groups: fire behavior and fuel reduction-fire behavior; fire behavior and fuel reduction-fuel levels.
   a. *Location*: near Rocky Mountain National Park in Colorado.
   b. *Vegetation type*: lodgepole pine
   c. *Abstract*: Alternative fire hazard reduction techniques are needed for managing fuel profiles in forest ecosystems located within the so-called wildland-urban interface. The present study includes experimental fuel manipulations initiated along the Rocky Mountain National Park interface with residential areas in Colorado, USA. Three thinning/slash disposal treatments were applied on two lodgepole pine (Pinus contorta) stands: thinning with whole-tree removal; thinning with stem removal—lopping and scattering; and thinning with stem removal—hand piling and burning. Results indicate that treatments reduced surface fire behavior parameters, bringing them down and closer to limits of direct attack methods. Crown fire potential was decreased not only because of canopy removal, but also as a result of potential reduction in heat generated by surface fuels. Projected fire behavior for the thinning-without-slash-removal scenario indicates the possibility of serious control problems with major fire runs and crown fires given an outbreak. URL: http://www.publish.csiro.au/?nid=114 ((Note: This link is valid with a subscription, which may be provided by many agencies/universities. Private users may not have access.)
   d. *Longevity:* This study did not address fuel treatment longevity.

Studies showing treatments are not effective

None assessed to date

Literature Reviews and Meta-analyses on fuel treatment effectiveness:

1. Fernandes, P. M., and H. S. Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire 12:117–128.
2. Fulé P. Z., J. E. Crouse, J. P. Roccaforte, and E. L. Kalies. 2012. Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? Forest Ecology and Management 269:68–81.
   a. *Location*: Western US
   b. *Vegetation types*: dry forests with ponderosa or Jeffrey pine component
   c. *Summary*: This is a systematic review and meta-analysis of the effects of forest thinning and burning treatments on restoring fire behavior attributes in western USA pine forests. Using a systematic review methodology, the authors found 54 studies with quantitative data suitable for meta-analysis. They found that combined treatments (thinning + burning) tended to have the greatest effect on reducing surface fuels and stand density, and raising modeled crowning

and torching indices, as compared to burning or thinning alone. However, changes in canopy base height and canopy bulk density were not consistently related to treatment intensity, as measured by basal area reduction. Results differed very little between region (e.g. southwest vs northwest, etc.), with treatments dictating results rather than local geography. Overall, meta-analysis of the literature to date strongly indicates that thinning and/or burning treatments do have effects consistent with the restoration of low-severity fire behavior.

3. Hessburg, P. F., S. J. Prichard, R. K. Hagmann, N. A. Povak, and F. K. Lake. 2021. Wildfire and climate change adaptation of western North American forests: a case for intentional management. Ecological Applications 00(00):e02432. 10.1002/eap.2432
    a. *Location*: western North America
    b. *Vegetation types*: forests of western North America
    c. *Summary*: The authors summarize existing science on fire and climate adaptation in western North American forests. They conclude that management capacity to influence how much area burns will be somewhat limited, but fuel reduction treatments, including prescribed burning, coupled forest thinning and prescribed burning, and managed wildfires, are proven methods to influence the ecological impacts of wildfire, and mitigate impacts of extreme fire events on social systems. Scaling-up a broad variety of fuel reduction treatments can tip landscape dynamics in favor of more benign fire behavior and effects. The authors note that Coupled thinning and prescribed burning treatments are proven approaches to mitigating wildfire severity in many seasonally dry forests, but they are not appropriate to all forest types, land allocations, and conditions. Further, they conclude that many studies show that fuel reduction treatments are effective at moderating subsequent fire severity, even under extreme weather and that far fewer experimental or empirical studies challenge this premise. The authors further note that science-based strategies for forest and fuel management are well known, but lack of social license and sufficient financial and personnel resources currently limit fuel reduction programs to a small percentage of wNA forestlands.
4. Kalies E. L., and 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
    a. *Location*: Western US
    b. *Vegetation types*: various
    c. *Summary*: This review represents a systematic review to address the question: Are fuel treatments effective at achieving ecological and social (saving human lives and property) objectives? The authors 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 pro-vide 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.

5. Prichard, Susan, J., Paul F. Hessburg, R. Keala Hagmann, Nicholas A. Povak, Solomon Z. Dobrowski, Matthew D. Hurteau, Van R. Kane, Robert E. Keane, Leda N. Kobziar, Crystal A. Kolden, Malcolm North, Sean A. Parks, Hugh D. Safford, Jens T. Stevens, Larissa L. Yocom, Derek J. Churchill, Robert W. Gray, David W. Huffman, Frank K. Lake, and Pratima Khatri-Chhetri. 2021. Adapting western North American forests to climate change and wildfires: ten common questions. Ecological Applications
    a. *Location*: western North America
    b. *Vegetation types*: forests of western North America
    c. *Summary*: The authors evaluate the strength of evidence in the existing scientific literature concerning 10 topical questions: (1) Are the effects of fire exclusion overstated? If so, are treatments unwarranted and even counterproductive? (2) Is forest thinning alone sufficient to mitigate wildfire hazard? (3) Can forest thinning and prescribed burning solve the problem? (4) Should active forest management, including forest thinning, be concentrated in the wildland urban interface (WUI)? (5) Can wildfires on their own do the work of fuel treatments? (6) Is the primary objective of fuel reduction treatments to assist in future firefighting response and containment? (7) Do fuel treatments work under extreme fire weather? (8) Is the scale of the problem too great – can we ever catch up? (9) Will planting more trees mitigate climate change in wNA forests? and (10) Is post-fire management needed or even ecologically justified? The authors show that: (1) Support for the suggestion that ecological departures associated with fire exclusion are overestimated has repeatedly failed independent validation by multiple research groups; (2) Some studies show that thinning alone can mitigate wildfire severity, but across a wide range of sites, thin and prescribed burn treatments are most effective at reducing fire severity. There exists widespread agreement that combined effects of thinning plus prescribed burning consistently reduces the potential for severe wildfire across a broad range of forest types and conditions. (3) Although the use of prescribed burning, often in combination with mechanical thinning, has been shown to be highly effective at mitigating wildfire severity and increasing forest resilience to drought, insects and disease, these treatments alone cannot address forest management challenges across western North America; (4) prioritizing the WUI-only for fuel reduction treatments is often too narrow in scope to address broader landscape-scale objectives. Further, there is increasing evidence that treating fuels across larger spatial extents in strategically planned wildland locations, rather than immediately adjacent to WUI, can indirectly reduce risk to communities. (5) Relying solely on managed wildfires to achieve management objectives is not possible due to a number of factors that include current restrictions on the use of managed wildfire in the WUI or near other infrastructure, limited burn windows with moderate fire weather, and the potential negative consequences of allowing fire spread into nearby fire-excluded areas with elevated fuel loads; (6) Under adaptive management, fuel treatments are not designed to prevent or stop fires but to moderate fire behavior when fire inevitably returns; (7) Although extreme fire behavior including strong winds and column-driven fire spread can overwhelm individual treatments, there is strong scientific evidence that even under extreme weather conditions, fuel treatments are effective at moderating fire severity across a range of forest types and wildfire events; (8) Evidence supports increasing the pace of treatments to significantly reduce the area impacted by uncharacteristic wildfire, even under a changing climate; (9) Alternatives to traditional plantations are emerging that are designed to

promote resilience to future fire and drought from the beginning of the planting process; and (10) opost-fire landscapes are not necessarily on resilient trajectories.

6. Prichard, S. J., C. S. Stevens-Rumann, and P. F. Hessburg. 2017. Tamm Review: Shifting global fire regimes: Lessons from reburns and research needs. Forest Ecology and Management 396:217–233.
   a. *Location*: Global, only information from the 'semi-arid forests of western North America' is summarized here
   b. *Vegetation type*: only information from the mixed conifer forests is summarized here
   c. *Summary*: The authors review published empirical studies of reburns in fire-adapted ecosystems with a legacy of 20th century fire exclusion. The authors note that numerous studies have established that strategically placed prescribed burns can reduce subsequent wildfire severity.
7. Reinhardt, E. D., R. E. Keane, D. E. Calkin, and J. D. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management 256:1997–2006.,
   a. *Location*: Western United States
   b. *Vegetation Types*: forested ecosystems
   c. *Summary*: In this paper, the authors summarize objectives and considerations for fuels treatments. They note that in western seasonally dry forests, fire occurrence is inevitable, and fuel treatments should not aim at reducing fire occurrence, size, or rate of spread, but instead strive to create conditions where fire can occur without the need for suppression. The authors suggest that while general wildfire control efforts may not benefit from fuel treatments during extreme fire behavior, fuel modifications can significantly change outcome of a wildfire within a treatment area. The authors conclude "We suggest that, while the potential of fuel treatment to reduce wildfire occurrence or enhance suppression capability is uncertain, it has an important role in mitigating negative wildfire effects, increasing ecosystem resilience and making wildfire more acceptable." The fundamental goal of fuel treatment is not to reduce rate of spread, but to reduce burn severity. The authors also note that the most appropriate fuel treatment methods vary with forest type and spatial context—there is no such thing as a ''one size fits all'' fuel treatment design. Tree removal can play an important role in treating fuels, especially removal of small understory trees that can provide a ladder into the forest canopy. However, thinning alone does not typically constitute an effective fuel treatment, but instead must be combined with treatment of surface fuels. The authors suggest that fuels treatments are even more important in the face of climate change, as wildland ecosystems require treatment to buffer the effects of the rapidly changing environment. If future fires tend to be larger and more severe, active fuel management will be needed to minimize adverse effects of high severities and ensure post-fire landscapes contain ecologically viable patterns and composition.
8. Schoennagel, T., T. T. Veblen, and W. H. Romme. 2004. The interaction of fire, fuels, and climate across rocky mountain forests. Bioscience 54:661–676.
   a. *Location*: Rocky Mountains
   b. *Vegetation Types*: Many, separated into high severity (e.g., Engelmann spruce), low severity (e.g., low elevation ponderosa pine), and mixed severity (e.g., mixed conifer that includes ponderosa pine, Douglas fir, grand fir, and western Larch) fire regime classes

   c. *Summary*: The authors separate vegetation types into their fire regime categories: high severity fire regimes (e.g. lodgepole pine, subalpine fir, and Engelmann spruce), low-severity fire regimes (e.g. ponderosa pine), and mixed-severity fire regimes (mixed conifer that includes ponderosa pine, Douglas fir, grand fir, and western Larch). They note that for high-severity fire regimes: Fire suppression has had minimal influence on the size, severity, and frequency of high-elevation fires; mechanical fuel reduction in subalpine forests would not represent a restoration treatment but rather a departure from the natural range of variability in stand structure; and given the behavior of fire in Yellowstone in 1988, fuel reduction projects probably will not substantially reduce the frequency, size, or severity of wildfires under extreme weather conditions. For low-severity fire regime forests, the authors note: Fire suppression has significantly increased tree densities and ladder fuels in low-elevation ponderosa pine forests; As a consequence of this change in stand structure, unprecedented high-severity fires now occur; and Fuel-reduction treatments involving mechanical thinning and prescribed fire are likely to be effective in mitigating extreme fire behavior and restoring this forest type to the historical fire regime. For mixed-severity fire regime forests, they note: The occurrence of high-severity crown fires is not outside the historical range of variability, although their size and frequency may be increasing, extreme climate and weather conditions can override the influence of stand structure and fuels on fire behavior; fuel-reduction treatments (mechanical thinning and prescribed burning) may effectively reduce fire severity under moderate weather conditions, but these treatments may not effectively mitigate fire behavior under extreme weather conditions and may not restore the natural complexity of historical stand and landscape structure.

9. Stephens SL, McIver JD, Boerner REJ, et al. 2012. The effects of forest fuel-reduction treatments in the United States. BioScience 62:549–60.
   a. *Location*: Seasonally dry, historically frequent fire, forests in western, eastern, and southern US
   b. *Vegetation Type*: seasonally dry forests in the US
   c. *Summary*: The authors note that their analysis supports the assertion that a lack of treatment or passive management perpetuates the potential for extensive high fire severity in forests that once burned frequently with low- to moderate-intensity fire regimes. The potential for passive crown fires (initiated by the torching of a small group of trees) is reduced most efficiently by the reduction of surface fuels followed by a reduction of ladder fuels. Reducing surface fuels by prescribed fire is a very effective treatment for reducing the potential for passive crown fires. The potential for active crown fires (fire spreading in crown and surface fuels simultaneously) is reduced most effectively by a combination of mechanical and prescribed-fire treatments, because these treatments can target ladder and surface fuels and intermediate-size trees. The effectiveness of mechanical thinning for reducing passive and active crown fire potential is largely dependent on the type of harvest system used—particularly, whether the harvest system leaves logging debris within treated stands. The authors conclude that, when they are applied, both prescribed fire and its mechanical surrogates are generally successful in meeting short-term fuel-reduction objectives and in changing stand structure and fuel beds such that treated stands are more resistant and resilient to high-intensity wildfire. They recommend that a full suite of alternative fuel treatments be implemented in appropriate forests, including prescribed fire, mechanical

thinning, and combined mechanical and prescribed fire treatments, and also support the expanded use of managed wildfire to meet management objectives.