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Tamm review: A meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US

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ABSTRACT

Increased understanding of how mechanical thinning, prescribed burning, and wildfire affect subsequent wildfire severity is urgently needed as people and forests face a growing wildfire crisis. In response, we reviewed scientific literature for the US West and completed a meta-analysis that answered three questions: (1) How much do treatments reduce wildfire severity within treated areas? (2) How do the effects vary with treatment type, treatment age, and forest type? (3) How does fire weather moderate the effects of treatments? We found overwhelming evidence that mechanical thinning with prescribed burning, mechanical thinning with pile burning, and prescribed burning only are effective at reducing subsequent wildfire severity, resulting in reductions in severity between 62% and 72% relative to untreated areas. In comparison, thinning only was less effective – underscoring the importance of treating surface fuels when mitigating wildfire severity is the management goal. The efficacy of these treatments did not vary among forest types assessed in this study and was high across a range of fire weather conditions. Prior wildfire had more complex impacts on subsequent wildfire severity, which varied with forest type and initial wildfire severity. Across treatment types, we found that effectiveness of treatments declined over time, with the mean reduction in wildfire severity decreasing more than twofold when wildfire occurred greater than 10 years after initial treatment. Our meta-analysis provides up-to-date information on the extent to which active forest management reduces wildfire severity and facilitates better outcomes for people and forests during future wildfire events.

1. Introduction

High-severity wildfire (i.e., when wildfire kills the majority of overstory trees) plays an important ecological role in forests, including promoting heterogeneity across landscapes (Agee, 1998; Hessburg et al., 2019, 2016; Huffman et al., 2020) and jumpstarting tree regeneration in forest types adapted to high-severity wildfire regimes (Pausas and Vallejo, 1999; Turner et al., 2003). However, due to climate change, high fuel loads, and development in the wildland-urban interface, evidence shows that wildfire patterns are changing worldwide (United Nations Environment Programme, 2022) – including the extent of high-severity wildfire. In turn, high-severity wildfire is increasingly impacting people and forests and creating complex challenges for society.

In the western United States ("US West"), area burned has doubled in recent decades (Iglesias et al., 2022) and a growing proportion of burned areas contain high-severity wildfire (Parks et al., 2023; Parks and Abatzoglou, 2020). Consequently, high-severity wildfire is increasingly causing infrastructure loss (Higuera et al., 2023) and reducing safe access for firefighters during suppression efforts, as well as impacting air quality and human health (D'Evelyn et al., 2022; Jung et al., 2024; Liu

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et al., 2016). It is also facilitating wildfire-driven change in forests (i.e., high-severity burn areas not recovering back to forests over time or loss of critical habitats; Coop et al., 2020), with consequences for municipal watersheds (Hohner et al., 2019), recreation (Gellman et al., 2022; White et al., 2023), carbon storage (Peeler et al., 2023), and wildlife habitat (Hysen et al., 2023). With these impacts accumulating into a wildfire crisis, people are urgently looking to solutions that can protect communities from wildfire and support fire-resistant forests. One solution is using active forest management (Prichard et al., 2021) to proactively reduce subsequent wildfire severity (i.e. wildfire effects on organic matter aboveground and belowground). Hereafter referred to as treatments, several types of active forest management exist for modifying wildfire severity (Fig. 1).

Mechanical thinning and prescribed burns are common treatments in dry pine and dry to moist mixed-conifer forests to reduce the potential for high-severity wildfire. These forests historically experienced low and mixed severity wildfire regimes, but exclusion of Indigenous burning and intentional wildfire suppression in the US West caused a fire deficit that created high fuel loads during the last century (Hagmann et al., 2021; Kimmerer and Lake, 2001). Furthermore, in many areas, historical logging removed large, fire resistant trees resulting in higher densities of small-diameter and fire sensitive trees (Allen et al., 2002; Collins et al., 2017; Knapp et al., 2013). To reduce high fuel loads, mechanical thinning is used to remove ladder fuels (fuels that allow fire to move from surface fuels to canopy fuels) and small trees, while leaving behind larger, older trees to continue growing (Agee and Skinner, 2005). In turn, mechanical thinning creates lower density forests (Fulé et al., 2012) that are more aligned with conditions that would exist without a fire deficit and can improve forest resistance and resilience to wildfire, drought, insects, and disease (Bernal et al., 2023; Hood et al., 2016; Knapp et al., 2021; North et al., 2022; Steel et al., 2021; Tepley et al., 2020). Following mechanical thinning with pile burning (i.e., placing removed surface and ladder fuels into piles and burning them) or prescribed burning (i.e., intentionally reintroducing low to moderate severity fire to a predetermined area using broadcast burning) consumes surface fuels and restores natural processes associated with fire, which creates conditions less likely to support high-severity wildfire (Fig. 1; Agee and Skinner, 2005; Fulé et al., 2012). Indigenous peoples have used fire to shape landscapes for millennia (Lake and Christianson, 2020) and many older studies show that combining mechanical thinning and prescribed burning effectively reduces wildfire severity (Kalies and Yocom Kent, 2016; Martinson and Omi, 2013; Stephens et al., 2009). However, misconceptions and misinformation about these treatments and their effectiveness persist (Fulé et al., 2014; Jones et al., 2022; Peery et al., 2019; Safford et al., 2015; Spies et al., 2010).

Although combining mechanical thinning and prescribed burning is a common treatment used for mitigating wildfire severity, mechanical thinning cannot be implemented everywhere. In the US West, mountainous regions contain rugged terrain that is too steep or remote for machinery to access (Hessburg et al., 2016; North et al., 2015). Additionally, legal constraints prohibit mechanical thinning in certain land ownership types (i.e., US Forest Service wilderness areas). In areas where mechanical thinning is restricted due to steepness, remoteness, or legal constraints, using prescribed fire alone might be a primary strategy for reducing subsequent wildfire intensity or severity. But using prescribed fire without mechanical thinning is not feasible in all scenarios

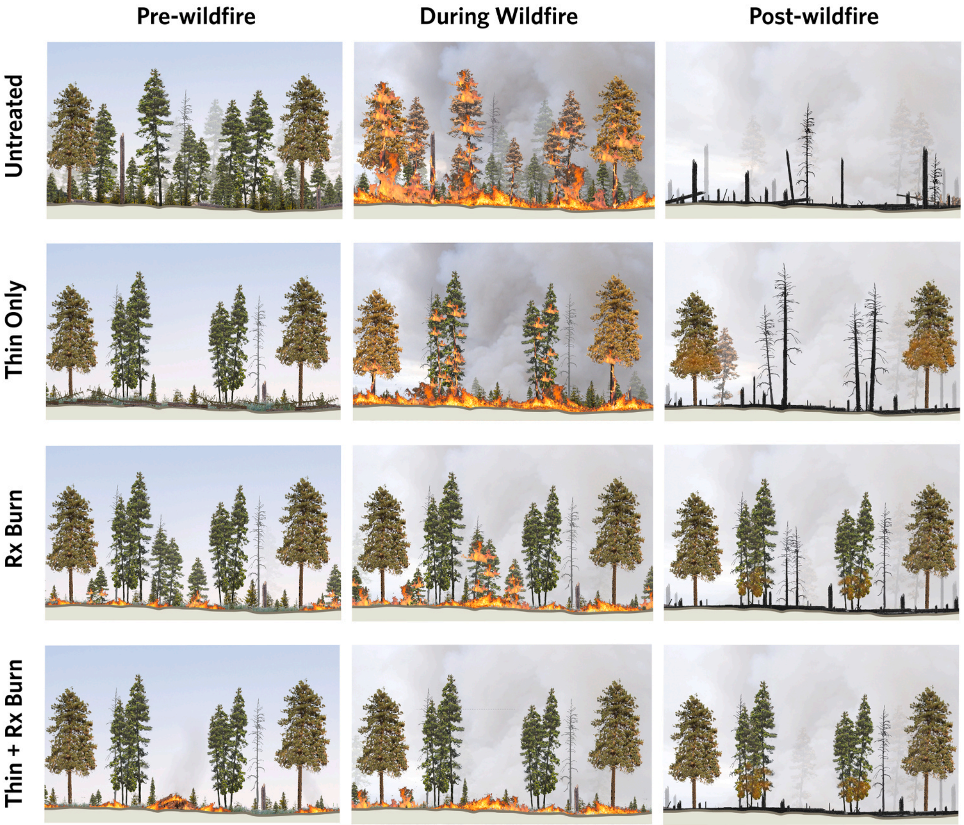

Fig. 1. Diagram demonstrating potential treatment effects on forest stand structure (pre-wildfire), fire behavior (during wildfire), and fire severity (post-wildfire). Untreated stands are often denser than treated stands with more ladder fuels which leads to higher fire intensity, increased risk of passive and active crown fire, and higher fire severity. "Thin only" stands have a lower tree density, but high surface fuel loads from slash left on site can in some cases lead to a higher likelihood of passive crown fire, more intense surface fire, and higher fire severity than other treatment types. "Rx burn" treatments often retain higher tree densities than thinned stands, but due to reductions in surface fuels can still reduce subsequent fire intensity and severity. "Thin and prescribed burn" treatments reduce tree density, ladder fuels, and surface fuels which leads to a lower likelihood of passive and active crown fire, lower fire intensity, and lower fire severity. "Thin and pile burn" would be similar to "thin and prescribed burn", but may retain higher surface fuels than areas treated with broadcast prescribed burns. Figure by Erica Sloniker.

either (Addington et al., 2020; Hessburg et al., 2016), as locations containing high fuel loads are difficult to burn safely. Consequently, mechanical thinning and prescribed fire, in combination or alone, will only be one component of a multifaceted solution for reducing subsequent wildfire severity (Prichard et al., 2021).

Given the scale of the wildfire crisis in the US West, mitigating future wildfire severity will likely require using managed wildfires over large areas. Managed wildfire, also known by other terms such as "wildland fire use" and "resource objective wildfire," is a strategy whereby fire managers use natural ignitions to allow fire to fulfill its natural role on the landscape under moderate burning conditions (Bean and Evans, 2023). This strategy has been widely used in certain National Parks and wilderness areas on National Forests (Berkey et al., 2021; Van Wagtendonk, 2007) where recurrent fires influence subsequent fire severity and extent (Collins et al., 2009; Holden et al., 2010; Parks et al., 2015, 2014) and restoring more frequent fire regimes has led to increases in landscape and species diversity, inorganic soil N availability, and soil moisture (DeLuca and Sala, 2006; Stephens et al., 2021). As area burned increases (Iglesias et al., 2022; Parks and Abatzoglou, 2020), more wildfires are intersecting the footprints of past wildfires and reburning landscapes at management-relevant timescales, even in areas where fire suppression is still the dominant paradigm (Buma et al., 2020; Prichard et al., 2017). Understanding how prior wildfire shapes subsequent wildfire severity provides important insights for managing wildfires that are not intentionally ignited. These insights are timely, given the growing interest in managing wildfires to burn when far from communities and experiencing moderate weather conditions (Huffman et al., 2020; North et al., 2021; Stephens et al., 2016). In managing certain wildfires to burn under safe conditions, managed wildfire could help expand the pace and scale of active forest management in the US West and assist with future maintenance of treatments (North et al., 2012, 2021).

Understanding the effectiveness of active forest management in reducing wildfire severity is imperative to addressing the wildfire crisis in the US West. However, the most recent qualitative review of active forest management effects on wildfire severity occurred in 2016 (Kalies and Yocom Kent, 2016), while the last meta-analysis to quantify site-level effect sizes occurred in 2013 (Martinson and Omi, 2013). Since that meta-analysis, wildfires have burned under increasingly severe fire weather conditions (Abatzoglou et al., 2021; Higuera and Abatzoglou, 2021; Reilly et al., 2022) and scientists have documented new evidence in 27 studies across the US West on the effectiveness of active forest management. To incorporate this new evidence in an updated meta-analysis, we asked three research questions: (1) How much do treatments reduce wildfire severity within treated areas? (2) How do the effects vary with treatment type, treatment age, and forest type? and (3) How does fire weather moderate the effects of treatments? Our meta-analysis provides up-to-date information on scenarios where proactively applying treatments could reduce subsequent wildfire severity. In turn, strategically using treatments (e.g., Barros et al., 2019; Finney, 2001; Prichard et al., 2020; Urza et al., 2023) could facilitate better outcomes for people and forests during future wildfires, including mitigating infrastructure loss, giving firefighters safer access for wildfire response, and supporting fire-resistant forests.

2. Materials and methods

2.1. Literature search

We used Web of Science to conduct a literature search to identify peer-reviewed publications and technical reports which evaluated the effects of forest management (thinning, prescribed burning, wildfire) on subsequent wildfire severity. Our Web of Science search used the following key words: fire, burn, forest, management, severity, intensity, resource objective, restoration, fuel treatment, Indigenous, cultural, prescribed, thinning, salvage, harvest, grazing, reburn, prior fire, and previous fire. We also searched Treesearch using the same key words for technical reports that may be relevant. We then filtered results to only include publications focused on conifer-dominated forests in the western US, which resulted in 220 publications.

Of the 220 publications, 40 were found to meet four additional criteria (Appendix A Table A1). First, we only included publications whose methodology collected empirical data on wildfire severity in both treated and untreated areas (i.e., contained controls) – allowing us to estimate an effect size for subsequent statistical analysis. We did not include studies that relied on modeled output to estimate treatment effects on simulated severity. Second, wildfire had to occur after treatment was completed. Third, the variables measured after the wildfire needed to include some measure of wildfire severity, including: bole char height, crown scorch height, percent tree or basal area mortality, percent canopy cover change, percent crown scorch, percent crown consumption, wildfire severity derived from satellite imagery (RBR, dNBR, correlated CBI, or RdNBR), and percent of area burned at high severity. Bole char height and crown scorch height are also sometimes considered proxies of fire intensity, but because these are also ecological effects of wildfire, and for simplicity, we refer to reductions in these metrics as a reduction in severity as well. We did not consider treatment effects on fire spread, burn probability, or fire size. Finally, we only considered studies that included one or more of the following treatments: prescribed fire alone ("prescribed burn"), mechanical thinning alone ("thin only"), mechanical thinning in combination with slash/activity fuel removal (largely through pile burning, but at two sites slash was removed from the site; "thin and pile burn"), mechanical thinning in combination with prescribed burning ("thin and prescribed burn"), or prior wildfire (i.e., studies that examined short-interval fires). While "prior wildfire" is not a treatment per se, we studied its effect because of the large scale at which wildfires are occurring and because evidence indicates that many of the effects of wildfires may be consistent with the goal of future fire hazard reduction (e.g., Parks et al., 2014).

2.2. Treatment effects and study characteristics

We quantified how much treatments affected wildfire severity using the log response ratio between a given treatment and its control which is a commonly used metric for ecological meta-analyses (Hedges et al., 1999). This metric is also known as the log transformed ratio of means: log(treated mean/control mean); (Viechtbauer, 2010). The response ratio is log-transformed because the sampling distribution is skewed and to linearize the metric which means that the metric is then equally affected by deviations in the numerator and denominator (Hedges et al., 1999). Hereafter, we refer to the log response ratio metric as the "effect size." For ease of interpretation and visualization we back transformed the log response ratio ("lnRR") to the percent change in severity between control and treated areas with the equation: Percent change = 100*(exp(lnRR)-1) (Pustejovsky, 2018).

Where possible, we extracted the mean, standard deviation, and sample size directly from the article text, tables, or supplementary material. The means were used to calculate the effect size and the standard deviations and sample sizes were used to calculate the sampling variances to include in the meta-analytic models. For studies that presented data as figures only, we used a web plot digitizer (https://apps.automeris.io/wpd) to extract data values. When necessary, we converted reported standard error metrics to standard deviation by multiplying the standard error by the square root of the sample size. For studies that reported medians and interquartile ranges, we estimated means and standard deviations using the method for unknown non-normal distributions (MLN) in the estmeansd R package (McGrath et al., 2023). In the case that the first quartile was < 0 (2.6% of observations), we used the estimator for the mean from Luo et al. (2018) and the estimator for the standard deviation from Wan et al. (2014) because the MLN method requires positive values. For observations that did not include the standard deviation, standard error, and/or sample size for the reported means, we used a multiple imputation method to impute the standard deviation and/or sample size with predictive mean matching for 100 imputations in the MICE package (Van Buuren and Groothuis-Oudshoorn, 2011). Multiple imputation can reduce bias in meta-analyses compared with completely removing the cases without information on variance or sample sizes (Ellington et al., 2015; Kambach et al., 2020). We imputed 31% of sample sizes and 35% of variances, which is within the range shown to result in unbiased estimates of the grand mean and approximated confidence intervals (Kambach et al., 2020).

To investigate how treatment efficacy varies with forest type and treatment age, we extracted information from each study about the forest type and the age of treatments when exposed to wildfire (Table 1). We grouped selected studies into five broad forest types, based on site descriptions in the studies: California mixed conifer, interior mixed conifer, lodgepole pine, ponderosa/Jeffrey pine, and subalpine (Fig. 2). California mixed conifer (CA mixed conifer) included sites dominated by some combination of ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*P. jeffreyi*), white fir (*Abies concolor*), red fir (*A. magnifica*), incense cedar (*Calocedrus decurrens*), sugar pine (*P. lambertiana*), black oak (*Quercus kelloggii*), and Douglas-fir (*Pseudotsuga menziesii*). This forest type was found across the Sierra Nevada and Klamath ecoregions, and not all species were present at all sites. Interior mixed conifer forests included sites dominated by ponderosa pine and Douglas-fir, with additional components of lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), grand fir (*A. grandis*), white fir, southwestern white pine (*Pinus strobiformis*), blue spruce (*Picea pungens*), and/or Engelmann spruce (*Picea engelmannii*) depending on geographical location. This forest type spanned the interior Northwest through the Rocky Mountains and Southwest. We did not have enough data to split this group by ecoregion. The lodgepole pine type only included forests that were dominated primarily by lodgepole pine (rather than sites that included lodgepole as a component of mixed conifer or subalpine forests). These sites were constrained to the Klamath ecoregion but were not combined with CA mixed conifer due to the different historical fire regimes and tree species traits associated with these two forest types. Ponderosa/Jeffrey pine forests included sites with almost pure ponderosa or Jeffrey pine forests, with only occasional components of other species such as Gambel's oak (*Quercus gambelii*), Douglas-fir, or incense cedar. These sites were broadly distributed including in the interior Northwest, Sierra Nevada and Southwest. Finally, subalpine sites were dominated by subalpine fir (*A. lasiocarpa*), Engelmann spruce, and lodgepole pine and were located in the Middle Rockies – Blue Mountains, Okanagan, and UT-WY Rockies ecoregions.

Table 1
Predictor variables used in the mixed effect models of reduction in wildfire severity.

Predictor	Categories	Description
Treatment type	Thin + prescribed burn	Mechanical thinning treatment and a prescribed fire/broadcast burn following the thinning
	Thin + pile burn	Mechanical thinning treatment and activity fuels/slash were either piled and burned or removed from the site
	Thin only	Mechanical thinning treatment and activity fuels/slash were left on the site
	Prescribed burn	Prescribed fire/broadcast burn without prior mechanical thinning
	Wildfire	Area burned in a prior wildfire
Forest type	CA mixed conifer	Ponderosa pine, Jeffrey pine, white fir, red fir, incense cedar, sugar pine, and/or Douglas-fir
	Interior mixed conifer	Ponderosa pine and Douglas-fir, with components of lodgepole pine, western larch, grand fir, white fir, southwestern white pine, blue spruce, and/or Engelmann spruce
	Lodgepole pine	Lodgepole pine
	Ponderosa/ Jeffrey pine	Ponderosa or Jeffrey pine with small amounts of Gambel's oak, incense cedar, and/or Douglas-fir
	Subalpine	Subalpine fir, Engelmann spruce, and lodgepole pine
Treatment age	≤10 years, >10 years	Years between treatment and wildfire occurrence
Prior fire severity	Low, moderate, high	Fire severity of the initial wildfire
Minimum relative humidity	Continuous variable	Minimum relative humidity as reported in the initial study
Maximum temperature	Continuous variable	Maximum temperature as reported in the initial study
Maximum wind speed	Continuous variable	Maximum wind speed as reported in the initial study
Energy release component	Continuous variable	Energy release component as reported in the initial study
10-hr fuel moisture	Continuous variable	10-hr fuel moisture as reported in the initial study
Measure of wildfire severity	Crown scorch and torch	Percent crown volume scorched or torched (consumed)
	Char and scorch height	Bole char height or scorch height
	Percent high severity	Percent area that burned at high severity (based on satellite-derived severity metrics)
	Satellite severity	Satellite-derived (e.g., Landsat) fire severity measured as RBR, dNBR, CBI (modelled from RdNBR), or RdNBR
	Tree mortality	Percent tree mortality or tree basal area loss

We categorized the age of treatments at the time of wildfire into two groups (≤ 10 years, > 10 years) because precise annual information was not available for all studies, 10 years was the most commonly used cutoff in studies that grouped treatment ages above and below a certain threshold, and this threshold is supported by prior work (Martinson and Omi, 2013). For observations that grouped treatments that occurred in multiple years, the oldest treatment was used to categorize the observation. For example, if some of the treated area was completed 12 years before affected by wildfire and some was treated 7 years before the wildfire, we would categorize that observation as ">10." Thus the ≤10-year category indicates that all treatments were no older than 10 years when they burned, whereas the >10-year category includes any studies that combined younger and older treatments. Therefore, we may overestimate the effectiveness of treatments in the >10-year category due to the effect of some studies combining older and younger treatments. We also included eight observations (3%) in the >10-year category that did not specify the age of the treatments at the time that they burned.

To assess how fire weather moderates treatment efficacy, we extracted information on fire weather when provided including: minimum relative humidity, maximum temperature, maximum wind speed, energy release component, and/or 10-hour fuel moisture. These variables were either reported for the day the treatment burned or for a range of days to weeks before and/or after the treatment burned. When a range of values was reported, we choose the value that corresponded to more severe fire weather conditions (i.e., lower RH and 10-hr fuel moisture, higher maximum temperature, wind speed, and ERC).

Finally, to account for potential differences in effect size arising from the different ways wildfire severity was measured, we categorized the metric used to measure wildfire severity into five groups (Table 1).

2.3. Statistical analysis

All statistical analyses were conducted in R Statistical Software version 4.3.1 (R Core Team, 2023). Data visualizations drew on code from the orchaRd 2.0 R package (Nakagawa et al., 2023). We conducted statistical analyses separately for forest types that historically experienced frequent to moderately frequent low- or mixed-severity fire (CA mixed conifer, interior mixed conifer, ponderosa/Jeffrey pine) and those

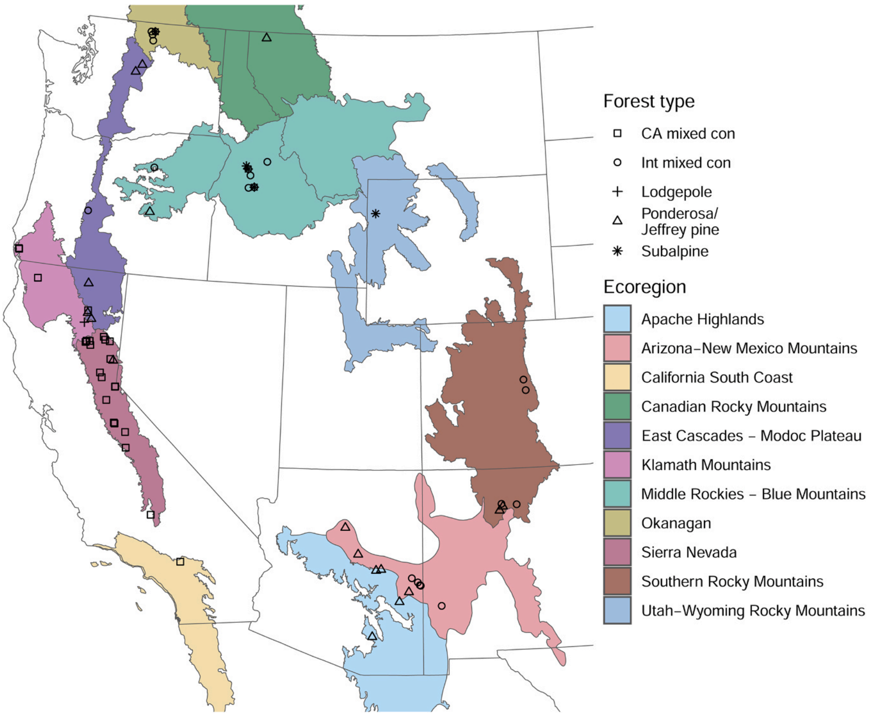

Fig. 2. Map of study site locations, symbols represent forest type and colors represent ecoregions. Study sites are unique combinations of treatments, locations, and wildfires. Multiple responses were measured at some sites and some studies contained more than one site.

that experienced infrequent, stand-replacing severity fire (subalpine and lodgepole pine). We removed 11 observations (2 in ponderosa/Jeffrey pine, 4 in interior mixed conifer, and 5 in CA mixed conifer) with a negative or zero response ratio because we could not calculate the log (response ratio). These are observations where wildfire severity was reduced to zero (Appendix A Table A3), and thus by removing these observations we may underestimate the true effect size. We chose not to add some constant value before taking the log because the effect size varied significantly depending on which value we chose to add.

2.3.1. *CA mixed conifer, interior mixed conifer, and ponderosa/Jeffrey pine forests analyses*

For the observations in CA mixed conifer, interior mixed conifer, and ponderosa/Jeffrey pine forests we created a four-level meta-analytic mixed-effects model with the metafor package (Viechtbauer, 2010) to account for the hierarchical structure of our data with random effects for observations nested within sites which are nested within studies. We also included “measure of wildfire severity” as a random effect to account for potential differences in effect size due to different metrics of wildfire severity (Table 1). First, to test the significance of treatment effects for different treatment types overall, we included treatment type (Table 1) as a moderator (predictor) in our model. We then assessed if effects vary across treatment age (categorical $\leq$10 yr or $>$10 yr) and forest types, after accounting for treatment type, by including these additional variables as moderators in a second model. We also tested for two-way interactions between moderators.

To examine in more detail the influence of treatment age when exposed to wildfire, we used a continuous treatment age metric from a subset of studies. We selected the studies which either gave the exact age of the treatment or combined treatments that occurred $<$5 years apart. The subset included only six observations with prior wildfire as the initial treatment, five of which were in the same forest type. With these observations removed, we proceeded with a total of 127 observations from 19 studies. For studies with multiple treatment years, we calculated mean treatment age to use as a predictor. Treatment age varied from $<$1–17 years in this subset of the data; however only seven observations had treatment ages $>$10 years. To test the effect of our continuous treatment age metric, we used the same four-level meta-analytic mixed-effects model described above, except the categorical treatment age variable was replaced with the continuous treatment age as a moderator in the model. Due to the smaller sample size, however, we omitted the interaction between treatment type and forest type (to help with model convergence).

To assess the influence of fire weather on treatment efficacy, we selected the subset of studies that reported varying aspects of fire weather. This resulted in 95–127 observations from 8 to 16 studies (depending on fire weather variable). To test the effect of fire weather metrics, we used the same four-level meta-analytic mixed-effects model described above, with the addition of either minimum relative humidity (RH), maximum temperature, maximum wind speed, energy release component (ERC), or 10-hour fuel moisture as a moderator in the model. Due to the smaller sample size, however, we omitted the interaction between treatment type and forest type (to help with model convergence).

2.3.2. *Subalpine and lodgepole pine forests*

Subalpine forest observations occurred in treatment types “prior wildfire” (6) and “thin and pile burn” (7). The “thin and pile burn” treatments were conducted around communities to reduce fire risk. Lodgepole pine forest observations occurred only in treatment type “prior wildfire.” We were unable to statistically test for a significant treatment effect due to small sample sizes and because 79% of variances and 57% of sample sizes for subalpine observations were imputed, which could result in mean effect size estimates that deviate from the true mean (Kambach et al., 2020).

3. Results

3.1. *Summary of studies*

A total of 40 studies fit our criteria (Appendix A Table A1; Davis et al., 2024), resulting in 172 sites (Fig. 2) with 256 observations (given multiple observations at some sites). The studies included 32 peer-reviewed publications, two Joint Fire Science Program final project reports, two reports by the USFS Fire Behavior Assessment Team, one joint report by the USDA Forest Service Region 6 and the BLM, one report by the BIA, and one General Technical Report and one research paper published by the USFS Rocky Mountain Research Station. Treatments burned in over 43 fires from years 1994–2021 in 12 ecoregions (Appendix A Table A2), with most observations in the Sierra Nevada (90), AZ-NM Mountains (56), Middle Rockies-Blue Mountains (31), and Okanagan (23) ecoregions. Most observations occurred in CA mixed conifer forests (106), followed by interior mixed conifer forests (69) and ponderosa/Jeffrey pine (61) forests (Appendix A Fig. A1). Treatments occurred on all aspects and slopes. The most common type of treatment was "thin and prescribed burn" (79 observations) and "prior wildfire" (66 observations), with other treatment types represented by 25–45 observations each. The most common response measured was percent crown scorch and/or torch (73 observations), followed by satellite-derived wildfire severity (66 observations) and char and/or scorch height (43 observations). Treatments burned under a range of fire weather conditions ranging from the 62nd-99th percentile of the Energy Release Component (ERC).

3.2. *Treatment effect*

3.2.1. *Treatment effect in CA mixed conifer, interior mixed conifer, and ponderosa/Jeffrey pine forests*

All treatments except "thin only" and "prior wildfire" significantly reduced wildfire severity in CA mixed conifer, interior mixed conifer, and ponderosa/Jeffrey pine forest types (p<0.001; Fig. 3; Appendix A Table A4). The mean reduction was 72% for "thin and prescribed burn" treatments, 62% for "thin and pile burn", and 62% for "prescribed burn". The mean effects of "thin only" (27% reduction) and "prior wildfire" treatments (25% reduction) were not significantly different than zero (t=-1.43, df=217, p=0.16 and t=-1.48, df=202, p=0.14, respectively). Variability in the effect of "prior wildfire" may be related to the fire severity of the initial wildfire (Fig. 5), but we were unable to test the statistical significance of prior wildfire severity because it was only reported in a subset of studies, most of which didn't also report the variance associated with the mean.

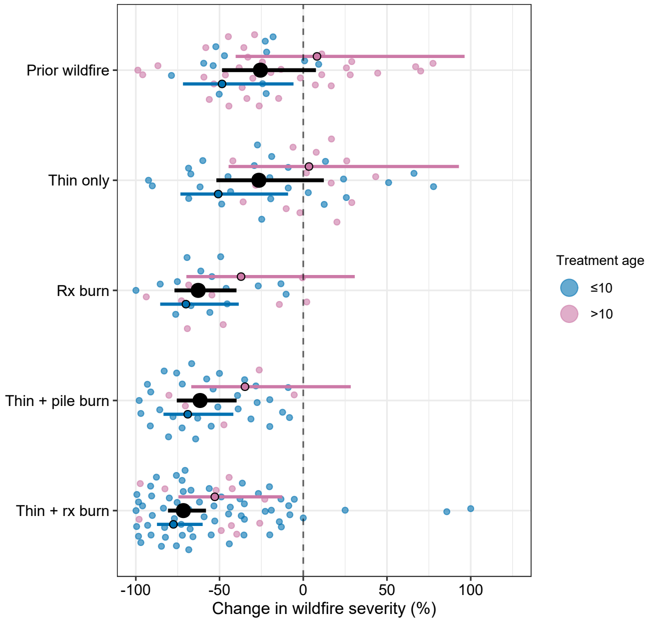

Fig. 3. Effect of treatments on wildfire severity in treated compared to untreated areas across treatment types. Black points represent the pooled point estimate from the meta-analytic mixed-effects model with only treatment type as a moderator and the black line represents the 95% confidence interval. The colored points with a black outline and the colored lines represent the pooled point estimate and 95% confidence interval, respectively, from the meta-analytic mixed-effects model with treatment type*forest type and treatment age as moderators. The colored points with no black outline represent individual observations. Blue (pink) points are those where the treatment was ≤10 (>10) years old when burned by a wildfire. "Rx burn" refers to prescribed burn. Note that two points with an increase in severity of >200% in the wildfire category are not shown for visual clarity (treatment age >10 years for those two points).

In the model that included treatment type, treatment age, and forest type as moderators, we found a significant interaction between treatment type and forest type ($F_{8,209}=2.81$, p=0.0056) after accounting for treatment age. Specifically, this interaction was significant because the effect of "prior wildfire" differed between interior mixed conifer forests and both ponderosa/Jeffrey pine (t=-2.62, df=201, p=0.0094) and CA mixed conifer forests (t=-3.47, df=203, p=0.0006); however the effects of other treatment types did not differ significantly among forest types (p>0.05; Fig. 4; Appendix A Table A5). We found a significant effect of treatment age ($F_{1,209}=16.53$, p<0.001) after accounting for treatment type and forest type, with a trend towards lower efficacy when treatments were >10 years old (Fig. 3). The mean percent reduction in severity decreased from 66% for areas burned within 10 years of treatment to 28% for areas that burned >10 years following treatment, averaged over treatment and forest types. While the overall effect of "thin only" and "prior wildfire" treatments were not statistically different than zero, when these treatments burned in a wildfire within 10 years of treatment, they did tend to reduce wildfire severity (Fig. 3). "Thin and prescribed burn" was the only treatment to significantly reduce wildfire severity when treated areas were older than 10 years when burned in a wildfire (Fig. 3). There was no significant interaction between treatment type and treatment age ($F_{4,213}=0.31$, p=0.87) or treatment age and forest type ($F_{2,215}=0.85$, p=0.43).

When considering only studies that provided more specific treatment

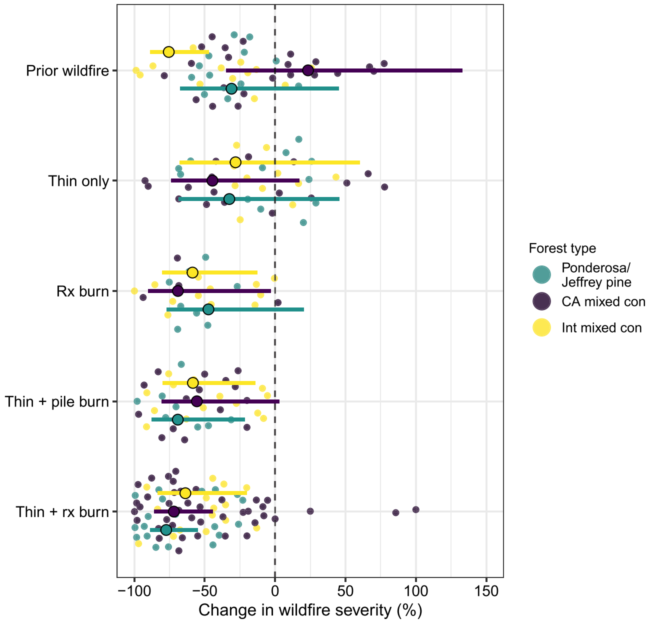

Fig. 4. Effect of treatments on wildfire severity in treated compared to untreated areas across treatment types. Black outlined points represent the point estimate, the line represents the 95% confidence interval, and the colored points represent individual observations (averaged across treatment age). "Rx burn" refers to prescribed fire. Note that two points with an increase in severity of >200% in the wildfire category are not shown for visual clarity (forest type "CA mixed con").

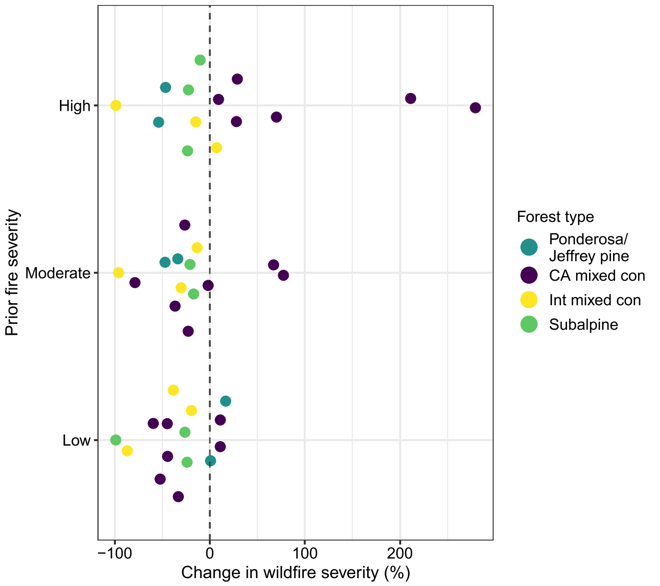

Fig. 5. Change in wildfire severity in areas treated with “prior wildfire” where the initial wildfire burned at low, moderate, or high severity. Colors represent forest types. Data are only shown for a subset of 43 observations (round points) which specified the fire severity of the prior wildfire and quantified effects separately for each prior wildfire severity category.

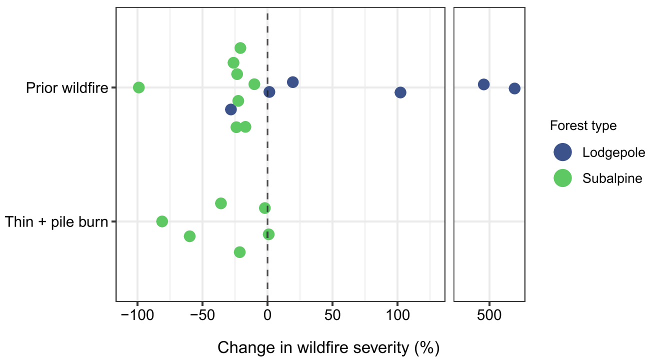

Fig. 6. Effect of treatments on wildfire severity in treated compared to untreated areas across treatment types in subalpine and lodgepole pine forests. Colors represent forest types.

ages, we found that with this reduced treatment age range (0–17 years, but age for 95% of observations was $\leq$10 years), treatment efficacy did not decline over time ($F_{1,119}=0.0030$, $p=0.96$; Appendix A Fig. A2) after accounting for forest type and treatment type.

For studies that provided information about fire weather, we found that after accounting for forest type, treatment type and treatment age, minimum relative humidity ($F_{1,118}=0.10$, $p=0.75$), maximum temperature ($F_{1,114}=0.24$, $p=0.62$), maximum wind speed ($F_{1,112}=0.0072$, $p=0.93$), and ERC ($F_{1,79}=0.14$, $p=0.72$) were not significantly related to effect size (Appendix A Figs. A3 – A6). After accounting for forest type, treatment type and treatment age, we found moderate support for a relationship between 10-hr fuel moisture and effect size ($F_{1,91}=4.07$, $p=0.047$) that indicated more reduction in fire severity with lower fuel moisture values (Appendix A Fig. A7). However, this effect was largely driven by five observations from one fire that occurred in California in April with high 10-hr fuel moisture (8%) and in which both the treated and untreated plots burned at low severity (Safford et al., 2012). When we removed observations from this fire from the analysis the effect of 10-hr fuel moisture was no longer significant ($F_{1,86}=1.28$, $p=0.26$; Appendix A Fig. A8).

3.2.2. Treatment effect in subalpine forests

In subalpine forests, “prior wildfire” reduced wildfire severity between 10% and 99% while the effect for “thin and pile burn” treatments ranged from a 1% increase in wildfire severity to an 81% reduction in (Fig. 6). “Prior wildfire” resulted in variable effects in lodgepole pine forests (28% reduction to 519% increase in wildfire severity). Due to sample size limitations, we were unable to test for statistical significance of these effect sizes.

4. Discussion

We found overwhelming evidence that treatments that include a reduction in surface fuels, through prescribed burning or pile burning, are effective at reducing wildfire severity within treated areas by over 60%, on average, relative to untreated areas. The efficacy of treatments did not vary across the range of fire weather and forest types assessed in this study. Thus, where feasible, treatments that reduce surface fuels will help to reduce the risk of high severity fire and resultant impacts on forests and people. Our results demonstrating the overall efficacy of treatments are consistent with previous studies (Kalies and Yocom Kent, 2016; Martinson and Omi, 2013; Stephens et al., 2012), and our meta-analysis further quantifies the effect size of treatments across a broader range of recent fires that have burned under increasingly severe fire weather (Fig. 7; Johnson and Kennedy, 2019; Taylor et al., 2022; Yocom et al., 2022).

There was significant variability in efficacy among treatment types. We found that the “thin only” treatments reduced fire severity by less than half as much as the three most effective treatments, consistent with previous studies that conclude “thin only” treatments are less effective than those that treat surface fuels with, for example, prescribed fire (Cansler et al., 2022; Kalies and Yocom Kent, 2016; Martinson and Omi, 2013; Prichard et al., 2020; Prichard and Kennedy, 2012; Raymond and Peterson, 2005). Here we found that in some cases “thin only” treatments led to a reduction in wildfire severity, especially in younger treatments, however, not treating surface fuels following thinning led to increased wildfire severity compared to controls (positive effect size) in 40% of “thin-only” observations. Increased wildfire severity in “thin only” treatments may be due to increased surface fuel loads relative to controls (Fulé et al., 2012). Higher surface fuel loads can lead to higher likelihood of passive crown fire and more intense surface fire with longer flame lengths thus increasing cambial heating and crown scorch causing higher tree mortality (Fig. 1; Prichard et al., 2010; Stephens et al., 2012). The overall effect size for “prior wildfire” was also less than that of the three most effective treatments, which may be due to differences among forest types and variability in the severity of the initial wildfire as discussed below.

We found the largest and most persistent reduction in wildfire severity in “thin and prescribed burn” treatments (72% reduction), likely because these treatments target surface and ladder fuels and intermediate size trees which reduces the risk of active crown fire (Fig. 1; Stephens et al., 2012). Additionally, the overall effects of “thin and pile burn” (62% reduction) and “prescribed burn” (62% reduction) treatments were not statistically different from the “thin and prescribed burn” treatments. Thus, while treatments that include thinning and prescribed burning will likely result in larger and more persistent reductions in wildfire severity, where either prescribed burning or thinning are not possible, either prescribed burning alone or thinning with pile burning will likely still reduce wildfire severity. However, there are some key considerations that will influence the outcomes of these treatments. First, where “thin and pile burn” treatments are conducted, other ecological benefits that result from prescribed fire may be missed (e.g., Bernal et al., 2023; Valor et al., 2021) and if wildfire occurs before piles are burned, it may result in increased wildfire severity, compared to untreated areas (Hudak et al., 2011; Safford et al., 2009). Second, it is possible that sites with “prescribed burn” treatments were not thinned

Fig. 7. “Thin only” treatments are less effective at reducing wildfire severity than treatments that also utilize prescribed burning, with 68% of thin only treatments experiencing high severity in Oregon’s 2021 Bootleg Fire. This photo shows a mixed conifer forest where the Klamath Tribes, The Nature Conservancy, and Lomakatsi Restoration Project worked with the US Forest Service to thin trees and apply prescribed burning as part of the climate adaptive ‘Black Hills Project’ where, in some areas, prescribed burning had not been applied yet. Thinning only was not as effective at reducing wildfire severity as combining thinning with prescribed burning. Photo used with permission from Steve Rondeau, Klamath Tribes Natural Resources Director.

prior to burning because they had lower fuel loads and tree densities to begin with than sites that received “thin and prescribed burn” treatments. Third, there are many areas where accumulated fuel loads due to fire suppression (Hagmann et al., 2021) preclude prescribed burning without first thinning or reducing ladder fuels (Addington et al., 2020). Additionally, reducing tree density can help to shift species composition back towards fire-resistant pines and increase ecosystem resilience to bark beetle outbreaks and future fire (Hood et al., 2016). Thus, site-specific conditions will necessarily dictate which treatment option is most appropriate in any given location.

Treatment age when burned by wildfire had a significant effect on the subsequent reduction in wildfire severity, consistent with previous work (Dodge et al., 2019; Martinson and Omi, 2013). Treatments less than 10 years old reduced severity by 66% on average. Treatments older than 10 years (up to 34 years) were less effective, reducing wildfire severity by only 28%. This effect size may overestimate reductions in severity in older treatments because 25% of observations combined results from treatments older and younger than 10 years, which were counted in the “> 10 yr” category. Because many studies used in our meta-analysis combined treatments into coarse categories, we were unable to more precisely evaluate how treatment effectiveness varied with age. For the subset of studies where precise treatment ages were available, there was no statistically detectable decline in treatment effectiveness for the first decade following treatment (similar to Safford et al., 2012). In the case of prior wildfire as a treatment, other studies have found that significant reductions in subsequent wildfire severity last between nine to 20 years, depending on forest type (e.g., Cansler et al., 2022; Collins et al., 2009; Harris and Taylor, 2017; Harvey et al., 2023; Parks et al., 2014; Rodman et al., 2023). These results underscore the importance of recurring prescribed burning or other follow up treatments to maintain treatment efficacy over time. The length of time that treatments remain effective will likely vary with ecosystem productivity (Martinson and Omi, 2013; Prichard and Kennedy, 2014) and the level of fuel reduction achieved by the treatment. To quantify how treatment efficacy declines with time more precisely across forest types and productivity gradients, we need more studies that specifically quantify and account for treatment age in analyses.

The efficacy of different treatment types did not vary among forest types, with the exception of wildfire. While the classification of forest types was broad, due to sample size limitations, the similarity of effect size for mechanical and prescribed burning treatments across forest types (Fig. 4) is notable. The forest types included in our statistical analysis are generally characterized by low to mixed severity historical fire regimes (LANDFIRE, 2016). Fewer studies have examined the effects of treatments on wildfire severity in forests characterized by high severity fire regimes or in forests dominated by hardwood trees such as oak (*Quercus* spp.). Several studies included subalpine forests, but only one (Hudak et al., 2011) looked at mechanical and prescribed burning treatments instead of “prior wildfire”. Although Hudak et al. found that treatments can be effective when implemented in small areas around communities (Fig. 6), more information is needed to understand the efficacy of fuel-reduction treatments in subalpine forests more broadly. For example, it is unclear if treatments that lower tree density in subalpine forests would be consistently effective at reducing fire severity within treatment footprints, given the limited fire resistance (i.e., thin bark) of the dominant tree species and differences in fuel structure and accumulation rates compared to drier, lower elevation forests. Likewise, in wet forests of the Cascade and Coast Ranges in the Pacific Northwest, some studies suggest that forests are unlikely to benefit from fuel reduction treatments given that fuels accumulate rapidly in these systems and large fires are driven by strong wind events during which wildfire severity is more driven by weather than fuels (Reilly et al., 2022, 2021). In forests characterized by moderate to high severity fire regimes, historical forest resilience was largely maintained by landscape-scale heterogeneity in non-forest patches and successional stages (Hessburg et al., 2019; Prichard et al., 2021), and thus examining treatment effects within the treated footprint may not be as appropriate as examining treatment effects at larger spatial scales.

In contrast to other treatment types, the effect of “prior wildfire” varied among forest types (Figs. 4–5). “Prior wildfire” was more likely to reduce subsequent wildfire severity in interior mixed conifer forests than other forest types. Reductions in severity in these forest types for up to 22 years following an initial wildfire have been consistently found (Parks et al., 2014; Prichard et al., 2020; Stevens-Rumann et al., 2016). Despite the lack of statistical significance in the current study, all observations from ponderosa/Jeffrey pine forests also showed a reduction in wildfire severity after an initial “treatment” by wildfire, with the exception of two observations which burned at low severity in both the initial and subsequent wildfire (Fig. 4). One of the most comprehensive recent studies examining short-interval fires in ponderosa pine forests, which considered 2275 fires across AZ and NM, found that fire severity tended to decrease with each subsequent fire (Yocom et al., 2022).

Combined with other studies (Parks et al., 2014; Rodman et al., 2023; Walker et al., 2018), evidence is accumulating indicating that prior wildfire will likely lead to reduced fire severity in subsequent wildfires in ponderosa pine forests of the Southwest.

The effect of prior wildfire in CA mixed conifer forests, including those in the Klamath Region of northern CA and southern OR, is complex and has been shown to relate to prior wildfire severity, fire weather, and time between fires (Collins et al., 2009; Grabinski et al., 2017; Harris and Taylor, 2017; Harvey et al., 2023; Taylor et al., 2021; Thompson et al., 2007; van Wagtendonk et al., 2012). Areas that initially burn at high severity are more likely to subsequently burn at high severity, often due to high shrub and coarse woody fuel loads; likewise, areas that initially burn at low or moderate severity are more likely to burn again at low or moderate severity in subsequent wildfires (Coppoletta et al., 2016; Harris and Taylor, 2017; Lydersen et al., 2017; Taylor et al., 2022, 2021). This pattern has also been found in some forests in the Southwest and Northern Rockies (Holden et al., 2010; Parks et al., 2014) but was not found in other studies in the interior Northwest (Cansler et al., 2022; Stevens-Rumann et al., 2016). While our results are consistent with these patterns (Fig. 5), we were unable to statistically test the significance of prior wildfire severity in this context due to limited sample size.

Our results and those of other recent studies (e.g., Parks et al., 2014; Rodman et al., 2023; Taylor et al., 2022; Yocom et al., 2022), highlight that low or moderate severity wildfire can serve as an effective fuel reduction treatment, lowering subsequent wildfire severity for 10–20 years. Given the potential for managed wildfires to affect much larger areas than prescribed burning alone, our results underscore the potential benefit of managing wildfires to burn under moderate weather conditions when they are more likely to result in low to moderate severity wildfire (Huffman et al., 2020; Parks et al., 2018; Prichard et al., 2021; Stevens et al., 2017). Land management agencies are increasingly recognizing and assessing the role that wildfires may play in treating landscapes (e.g., Churchill et al., 2022).

Fire weather is another important factor that may alter the efficacy of treatments (Lydersen et al., 2017; Prichard et al., 2020). We did not find a significant relationship between minimum relative humidity, maximum temperature, maximum wind speed, or ERC and effect size. However, it is important to note that few of the studies used in this meta-analysis were designed to test how treatment efficacy varies across gradients in fire weather. Further, studies reported varying aspects of fire weather in different ways and over different time scales; for example, some studies specified fire weather on the day the treatments burned while others provided a range of conditions characterizing the entire duration of the fire. Additionally, many studies combined all treated areas into a single analysis, necessarily obscuring if and how fire weather differed when different units were exposed to wildfire. Despite these caveats, our results suggest that treatments have the potential to reduce fire severity across a range of fire weather conditions. Some studies have found that treatments were less effective on days with extreme fire weather (Lydersen et al., 2017; Prichard et al., 2020), while others have found continued efficacy under extreme fire weather in recent large wildfire events (Prichard et al., 2020; Taylor et al., 2022; Walker et al., 2018; Yocom Kent et al., 2015). More precise reporting of fire weather, during the time of treatments burning, would allow for a more comprehensive analysis of the effect of fire weather on treatment effectiveness (e.g., Lydersen et al., 2017; Prichard et al., 2020). As climate change continues, it is increasingly important to understand if fire weather conditions may overcome the ability of fuels treatments to reduce subsequent wildfire severity.

Variation in treatment efficacy observed across studies that was not explained by treatment type or age, forest type, or fire weather, could be explained by variability in vegetation structure, topography, and cumulative history of management activities including fire suppression efforts, among other factors. Variation in specific treatment prescriptions, and thus vegetation structure, can result in varying efficacy, even within the same treatment type. For example, three units within the 2011 Wallow Fire in AZ were categorized as “thin and pile burn.” However, the specific thinning prescription varied among units, with one specifying higher retention of small trees for wildlife habitat. The unit with higher small-tree retention burned at higher severity than the two nearby units that had fewer small trees (Johnson and Kennedy, 2019). While some studies provided detailed information on stand structure and fuels before and after treatments, many studies presented little information on the silvicultural prescriptions, which would be helpful to better understand the effects of different types and intensities of thinning.

This study focused on treatment efficacy for reducing wildfire severity within the treatment footprint. However, treating the entire landscape is not feasible or desirable in all cases, given the importance of landscape-level heterogeneity for conferring resilience to wildfire (Hessburg et al., 2019), which highlights the need to understand how much of the landscape to treat and where those treatments should be placed (McKinney et al., 2022; North et al., 2021). There is evidence from a few empirical studies that treatments can reduce the proportion of high severity fire outside of treatment units (McKinney et al., 2022). For example, two studies from California found that treating 10–40% of larger landscapes (>2023 ha) was sufficient to diminish the proportion of high severity fire (Lydersen et al., 2017; Tubbesing et al., 2019). However, more work is needed to better understand landscape-scale effects of treatments on environmental and ecological indicators and social values and how outcomes vary with the size and spatial arrangement of treatments (Hood et al., 2022; McKinney et al., 2022; Ott et al., 2023).

We limited the geographic scope of our study to seasonally dry conifer-dominated forests in the western US given the rich literature available for this region. Even this relatively narrow focus crosses an array of potential historic fire regimes, fire-adaptive species traits, vegetation flammability, fuel structures, and ecosystem productivity gradients, among other variables, all of which can affect treatment efficacy. Increased area burning in wildfires is a global phenomenon, and in many systems proactive treatments can effectively mitigate potential fire behavior and impacts (Moreira et al., 2020; United Nations Environment Programme, 2022). Our results do not necessarily apply directly outside the context of this geographic scope, but this study does contribute to a better understanding of the ways in which treatments interact with wildfires. Globally, studies in Mediterranean and Australian ecosystems have found that prescribed burning can result in lower fire severity of subsequent wildfires, however this effect seems to be slightly shorter lived (~2–6 years) than we found in our region (Boer et al., 2009; Collins et al., 2023; Espinosa et al., 2019; Fernández-Guisuraga and Fernandes, 2024; Hislop et al., 2020; Tolhurst and McCarthy, 2016). In forests that historically burned in high-severity fire regimes, such as boreal forests, different types of fuel treatments may be employed (e.g. “shearblading” which removes all aboveground tree biomass) and documented impacts of fuel treatments on fire behavior have been mixed (Beverly et al., 2020; Boyd et al., 2023; Thompson et al., 2020). Overall, more studies in diverse ecosystems are needed to better understand how different types of treatments will impact subsequent fire severity more broadly.

5. Conclusions

There is overwhelming evidence across dry to moist mixed conifer forests of the western U.S. that reducing surface and ladder fuels and tree density through varying treatments lowers subsequent wildfire severity by, on average, 62–72%. This result is found across several forest types, suggesting that treatments are an effective way to mitigate the impacts of increased fire severity under increasingly fire-conducive environmental conditions. Treatment efficacy is expected to decline over time as fuels rebuild, with treatments older than 10 years reducing wildfire severity by 28%, on average, which underscores the importance of repeated or “maintenance” treatments to sustain reduced risk of severe wildfire in areas where this is an important management goal.

Despite recent increases in funding and resources to complete thinning and prescribed burning treatments in the western US (USDA Forest Service, 2022), there are still significant logistical, policy, and economic limitations to the pace and scale at which these treatments can be implemented. The effectiveness of prior wildfire at reducing subsequent wildfire severity, with the notable exception of areas burned at high severity in CA mixed conifer forests, suggests that managing wildfires to burn under moderate fire weather when feasible may help to increase the scale at which forests can be treated across the West (North et al., 2021). Additional research on how to mitigate risks to firefighter and community safety is necessary to support increased use of managed wildfire. Finally, while our review clearly underscores the efficacy of treatments in reducing fire severity, more detailed studies are needed to understand how this varies over time, across different forest types, and across the range of fire weather conditions.

CRediT authorship contribution statement

Kimberley T. Davis: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Jamie Peeler:** Writing – original draft, Investigation, Conceptualization. **Joseph Fargione:** Writing – review & editing, Conceptualization. **Ryan D. Haugo:** Writing – review & editing, Conceptualization. **Kerry L. Metlen:** Writing – review & editing, Conceptualization. **Marcos D. Robles:** Writing – review & editing, Conceptualization. **Travis Woolley:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data will be publicly available in the Dryad Data Repository: https://doi.org/10.5061/dryad.zcrjdfnkp

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.121885.

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