



## Review

## Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior?

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## ABSTRACT

We carried out 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. Ponderosa pine (*Pinus ponderosa*) and Jeffrey pine (*Pinus jeffreyi*), with co-occurring species, are adapted to a disturbance regime of frequent surface fires, but extended fire exclusion and other factors have led to historically uncharacteristically dense stands and high fuel loadings, supporting high-severity fires. Treatments to begin to reverse these changes and reduce fuel hazards have been tested experimentally and observations of wildfire behavior in treated stands have also been reported. Using a systematic review methodology, we found 54 studies with quantitative data suitable for meta-analysis. 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. There are a number of qualifications to the findings. First, because it is not feasible to subject treated areas to severe fire experimentally, inferences about potential fire behavior rely on imperfect modeling techniques. Second, research has not been carried uniformly over the ranges of the pine forests, although we found no significant differences in treatment effects between regions or forest types. Overall, however, 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.

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## 1. Introduction

Ponderosa pine (*Pinus ponderosa*) and Jeffrey pine (*Pinus jeffreyi*), alone or in mixed forests with other conifers or broadleaved species, range over approximately 10 million ha of western North America, forming forests of great ecological and social value. These pines are adapted to a disturbance regime of frequent surface fires

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(Keeley and Zedler, 1998; Stephens et al., 2003), consistent with the dry, fire-prone habitats they have occupied over evolutionary time scales. Frequent fires maintained relatively open uneven-aged forests with abundant, diverse understories over most of the landscape (Cooper, 1960; Minnich et al., 1995; Brown and Cook, 2006), although some areas may also have experienced infrequent high-severity fires (Sherriff and Veblen, 2007; Pierce and Meyer, 2008; Brown et al., 2008; Jenkins et al., 2011). Forest structure, composition, and disturbance patterns across the vast range of these species were affected by impacts associated with industrialized society: grazing of large herds of introduced livestock (Belsky and Blumenthal, 1997), logging and conversion to even-aged forests (Naficy et al., 2010), and extended fire exclusion starting as early as the mid-19th century (California, Oregon, South Dakota) or beginning as late as the mid-20th century (northern Mexico) (Allen et al., 2002; Stephens and Fulé, 2005). As a consequence, forest structure changed to dense stands of young trees, forest floor fuels accumulated, and fire-sensitive conifers such as *Abies* and *Pseudotsuga* expanded in pine/mixed-conifer ecotones (e.g., Coker et al., 2005). High-severity wildfires that killed most or all overstory trees in patches >10 ha (hereafter called “severe” fires) were reported in ponderosa pine forests of the Sierra Nevada as early as the mid-19th century (Leiberg, 1902) and in the early 20th century in the Pacific Northwest (Weaver, 1943) and Southwest (Cooper, 1960). But in recent years, heavy contiguous canopy and surface fuels (Fiedler et al., 2002) facilitated the exponential growth in the size of severe fires, especially during droughts that have become increasingly frequent with warming temperatures (Westerling et al., 2006). Severe fires in these formerly fire-adapted forests have led to widespread topsoil loss (Moody and Martin, 2001), tree mortality, conversion to non-forest vegetation (Savage and Mast, 2005), and invasion by introduced weedy species (Keeley, 2006). Strikingly similar patterns of larger fires resulting from higher fuel loads and warmer climate have been observed across pine forests of the Mediterranean Basin in southern Europe and northern Africa (Pausas, 2004; Leone and Lovreglio, 2004).

Early in the 20th century, Aldo Leopold (1924, 1937) called attention to the problems stemming from changing patterns of ecosystem structure and disturbances. Early experiments in ecological restoration through reinstatement of surface fire by means of controlled burns (Weaver, 1951; Lindenmuth, 1960; Sweeney and Biswell, 1961) were poorly received by some forest managers (Brown, 1943), who preferred to rely on intensive silvicultural cuttings to control density. By the 1960s and 70s, fire policies were adjusted to account for the ecological role of fire and permit more burning (Stephens and Ruth, 2005). Relatively progressive fire-use policies are credited with successful restoration of fire-resilient forests in some places, especially remote and unharvested forests such as those of the Gila Wilderness in New Mexico (Rollins et al., 2001). However, many forests have become altered to the point where surface fires are insufficient to reduce many dense stands (Sackett et al., 1996; Miller and Urban, 2000). Impelled by the costly and damaging effects of severe fires, a number of experimental and observational studies have focused on combined treatments of tree thinning, prescribed burning, and other interventions that may restore fire-resilience as well as structural, compositional, and functional attributes that were characteristic of these ecosystems before recent anthropogenic disruption (Covington et al., 1997; Stephenson, 1999; Allen et al., 2002; Stephens et al., 2009). The literature on this topic has grown rapidly but has not been synthesized in a comprehensive manner.

Our focus in this systematic review is to ask if thinning and/or burning treatments on ponderosa pine and related forests in western USA produce restoration of natural fire behavior. Ecological restoration is “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” as compared

to reference conditions (Society for Ecological Restoration International, 2004). Ecologists have debated the merits of the term “natural” vs. “historical” in describing reference ecosystems (a detailed discussion including the role of Native Americans is available in Stephenson, 1999). Here we use “natural,” first because reference ecosystems are not only found in the historical past but also in modern times, such as remote or protected areas, and second because the implicit link to specific time periods in the term “historical” tends to understate the evolutionary lineage of ecological attributes.

Many practical fuel treatments have been developed outside the specific framework of “ecological restoration,” but still with strong consideration of reference conditions. A key example is the USA-wide research program called “National Fire and Fire Surrogate Study” (FFS) (Stephens et al., 2009). A “fire surrogate” is a treatment designed to restore stand structure without the function of burning, which may be useful because of the costs, risks, and smoke associated with fire use. Research from these experimental sites includes assessment of effects on fire behavior (e.g., Stephens and Modhaddas, 2005). Some treatments to reduce fuels or alter fire behavior were designed with no attention or resemblance to reference ecosystems. For example, clearing of long but narrow firebreaks was a common, albeit often ineffective and ecologically damaging, forestry practice to interrupt fuel continuity (Agee et al., 2000). These latter of treatments are now uncommon in the western USA and will not be considered in this review.

Literature reviews have not kept pace with the growing body of literature in the field and there are no systematic reviews on the topic. Existing reviews have examined specific aspects of the effectiveness of forest treatments. For example, Fernandes and Botelho (2003) reviewed the effectiveness of prescribed burning treatments. Graham et al. (2004) integrated silvicultural and fire behavior concepts to develop treatment recommendations. Agee and Skinner (2005) drew upon the literature to standardize concepts and terminology associated with fuel reduction. The most recent and thorough review, published by Hunter et al. (2007), included the topics of treatment effects on fire behavior and the relationship between ecological restoration and other fuel treatments, but these themes comprised a small fraction of the report (2 of 75 pages).

Systematic review methodology is increasingly utilized in environmental issues to provide a thorough assessment of published evidence using a predetermined protocol (Fazey et al., 2005; Pullin and Stewart, 2006). We undertook a systematic review of the literature to examine the primary question, do thinning and/or burning treatments on ponderosa pine and related forests in western USA produce restoration of natural fire behavior? We used studies with quantitative data that could be compared with meta-analysis techniques (Gurevitch et al., 1992). We addressed three sub-questions: (1) what is the functional relationship between forest structure and fuel variables and fire behavior? (2) How might relationships differ among pure ponderosa or Jeffrey pine forests versus related forests (pine-oak and dry mixed conifer)? (3) How might regional variability (Pacific Northwest, Sierra Nevada, Rocky Mountains, and Southwest) affect outcomes?

## 2. Methods

We initiated the review following the steps suggested by Pullin and Stewart (2006): (1) formulate questions, (2) design protocol and search strategy, (3) perform data extraction, and (4) conduct analysis. The review team (co-authors) drafted primary and secondary questions, which were then refined in informal discussions with outside experts. We completed a review protocol that described criteria for data searching, inclusion, and quality of evidence (Table 1). The protocol was formally reviewed by the

**Table 1**  
Criteria for inclusion of studies and corresponding quality of evidence assigned in the review.

Inclusion category	Specific criteria
Subjects	Western (Pacific Northwest, Sierra Nevada, Rocky Mountains, and Southwest) coniferous forests dominated by (1) ponderosa pine ( <i>Pinus ponderosa</i> ), Jeffrey pine ( <i>Pinus jeffreyi</i> ), (2) pines mixed with oak ( <i>Quercus</i> spp.), or (3) dry mixed conifer forests dominated by one of these pine species but also containing firs ( <i>Abies</i> spp.), Douglas-fir ( <i>Pseudotsuga menziesii</i> ), other pine species (e.g., <i>Pinus lambertiana</i> , <i>Pinus coulteri</i> ) and aspen ( <i>Populus tremuloides</i> )
Timeframe	Searched 1970–present, but references to relevant earlier research that appeared in the literature were incorporated
Treatments	Thin only; burn only (prescribed fire and/or wildland fire use); thin and burn; control (untreated)
Outcomes	Forest stand and fire behavior modeling variables: species composition, surface fuels, tree density, basal area, canopy cover, canopy bulk density and canopy base height, crowning index and torching index based on fire behavior simulation models, and observations of actual fire behavior and severity

Centre for Evidence-Based Conservation, a non-profit international organization at Bangor University, Wales, that supports systematic reviews. The final version of the protocol, after addressing peer reviewer comments, was posted online (<http://www.cebc.bangor.ac.uk/>, Systematic Review No. 42).

We searched online databases using internet search engines (Ingenta, Web of Science, JSTOR, Google Scholar), online government databases, and electronic libraries of universities in the western U.S. with graduate programs in Forestry. Search terms included: western forests AND fuels treatments, fuels treatments AND ponderosa pine, fuels treatments AND Jeffrey pine, fuels treatments AND mixed conifer, thinning AND ponderosa pine, thinning AND Jeffrey pine, thinning AND mixed conifer, burning AND ponderosa pine, burning AND Jeffrey pine, burning AND mixed conifer, fire behavior AND ponderosa pine, fire behavior AND Jeffrey pine, fire behavior AND mixed conifer. Searches were conducted on both the common and scientific names of the species. Types of literature included refereed journal articles, peer-reviewed and non-peer-reviewed reports such as government documents and conference proceedings, theses and dissertations, and unpublished management reports. We applied inclusion criteria (Table 1) to each study we encountered in the search; those considered relevant were imported into a database for review.

All studies were reviewed by a member of the review team. Reviewers did not assess papers that they authored. Review data were summarized in a spreadsheet using categories describing the subjects (forest type, geographic region), treatments, and outcomes (Table 1).

Although the review question focused on fire behavior, testing treatment effectiveness in restoring natural fire behavior is not amenable to direct experimentation. Numerous studies have shown that treated sites can be burned safely and effectively with prescribed fire (e.g., Sackett et al., 1996; Stephens and Modhaddas, 2005), but it is not possible to deliberately ignite severe experimental fires in treated pine forests. Two alternative methods of research, both included in this review, are simulation modeling of fire behavior (e.g., Scott, 1998; Stephens, 1998; Fiedler et al., 2002) and retrospective observational studies evaluating the behavior of severe wildfires that burned through treated and paired untreated forests (e.g., Pollet and Omi, 2002; Cram et al., 2006; Martinson and Omi, 2003; Finney et al., 2005).

Quantitative data on fuel and forest structure were compared across treatments, forest types, and regions using meta-analysis techniques (Gurevitch et al., 1992). Meta-analyses commonly use “effect sizes” (i.e., Hedges’ *d*, Cohen’s *d*), which are calculated based on sample size and variance, assuming that studies with large sample sizes and smaller variances are more reliable (Hedges and Olkin, 1985; Rosenberg et al., 2000). However, standard deviation between replicate means is often not: (1) reported, (2) available because sample size is one, or (3) meaningful because the size of a replicate varies dramatically from study to study. Thus, we used a response ratio as our effect size calculation, defined as ln

(treatment mean/control mean) (Hedges et al., 1999). This metric has become more commonly used in meta-analysis (Mosquera et al., 2000; Côté et al., 2001) as it is designed to measure relative differences (often appropriate in ecological studies). In addition, rather than weighting by the inverse of the sample variance, we used a biologically meaningful weighting scheme where each effect size was weighted by the total number of sites sampled (Mosquera et al., 2000).

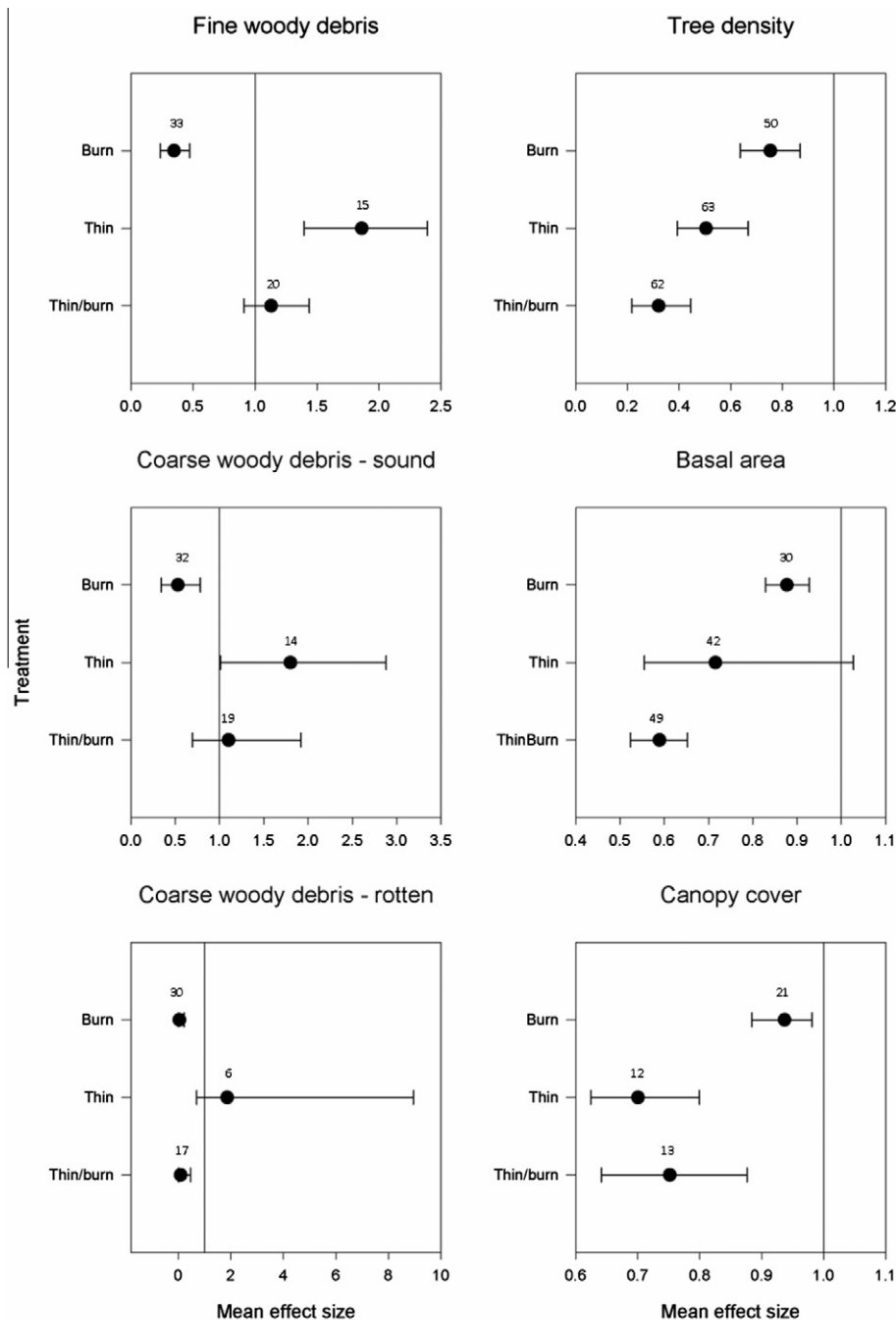
Using Metawin software (v.2, Rosenberg et al., 2000), we built generalized linear models to examine relationships between effect sizes and covariates (treatment, forest type, geographic region). For each categorical variable with  $\geq 2$  observations, we calculated a mean effect size (MES) with confidence intervals generated by bootstrapping (Adams et al., 1997), corrected for bias for unequal distribution around the mean. We presented the back-transformed response ratios which reflect the number of times greater the treatment mean was than the control mean. Effect sizes were considered to be significantly different from 1 when the confidence interval did not include 1. An effect size of 1, positive, or negative indicated no change between treatment and control, an increase in the response variable compared to the control, or a decrease in the response variable, respectively (Rosenberg et al., 2000).

Publication bias in meta-analysis occurs because studies with significant results are more likely to be published than those without significant results (Arnqvist and Wooster, 1995). We reduced the possibility of bias by thoroughly searching theses, government documents, and other non-published studies to acquire data. In addition, we visually examined normal quantile and funnel plots to confirm data normality. We controlled for the problem of lack of independence in data (i.e., multiple effect sizes can be calculated from the same study using the same control for multiple treatments) by including a covariate to identify the origin of the data (reference), which was an indicator variable to uniquely identify each study. This approach allowed us to analyze the relative importance of “reference” compared to the other covariates in our model selection approach. The analysis revealed that only one variable (crowning index) showed a “reference” effect, making this a relatively unimportant variable in explaining effect sizes.

### 3. Results and discussion

We found 139 publications that met the inclusion criteria (Table 1) for incorporation into the review, of which 54 studies had quantitative data suitable for meta-analysis (Appendix A). The studies covered most of the ranges of the subject forest types but the southern part of the region, especially Arizona and California, were the most represented (Fig. 1). Relevant studies were published relatively recently, with 108 (78%) of the 139 having been published after 2000.



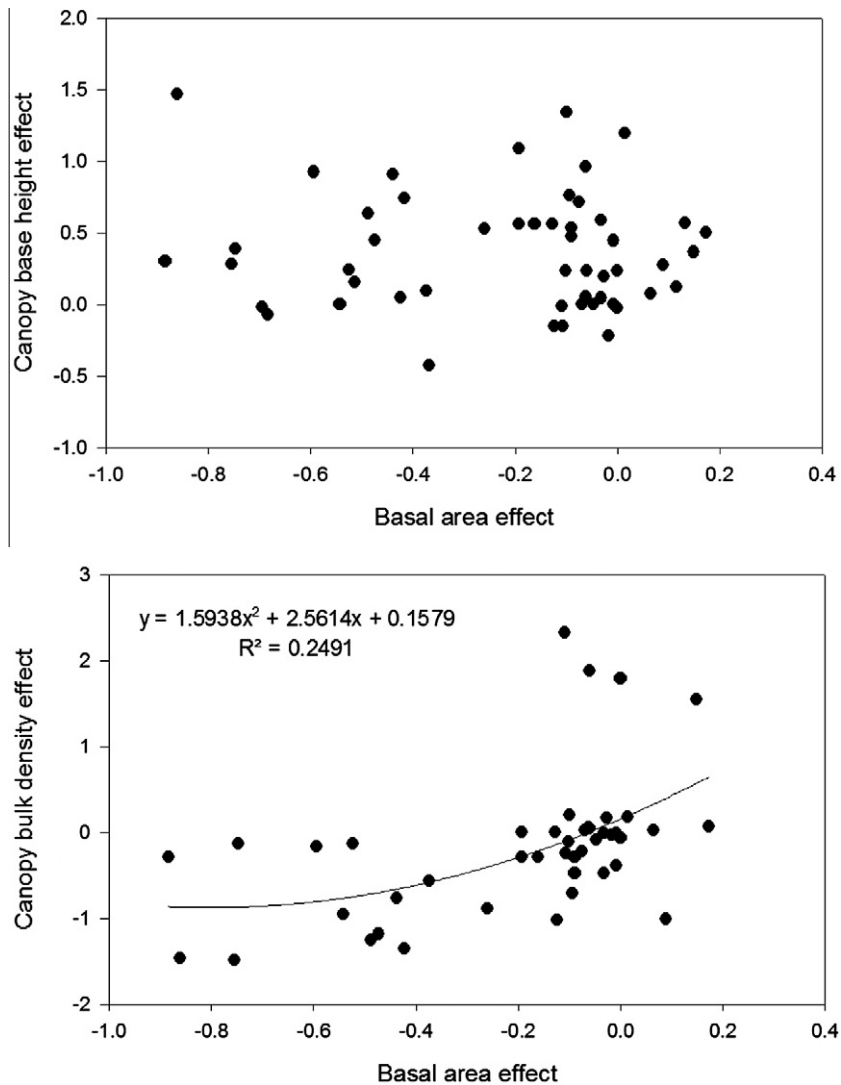


**Fig. 2.** Mean effect size and bootstrapped confidence intervals for six fuel and forest structure variables compared by treatment. Mean effect sizes are scaled as proportions of control values (1.0 or 100%); values above 1 indicate proportional increases over controls, values below 1 indicate decreases. Numbers above effect sizes indicate number of observations for each treatment.

ponderosa pine, which yield numerically disparate values (Roccaforte et al., 2008), and with a variety of methods (e.g., canopy biomass divided by canopy volume, density profile; Cruz et al., 2003). The canopy volume method in particular lends itself to conflicting results because canopy volume shrinks as canopy base height rises, so the reduction in canopy biomass may be overridden by a greater decrease in volume, leading to the paradoxical result of *increased* CBD following treatment. Two implications may be drawn from the canopy fuel results: first, treatments did alter canopy fuels to make forests less vulnerable to both passive and active crown fire. Second, the high variability in the canopy fuel data is likely due in part to the lack of standard calculation methods and the small

number of sites where these variables have actually been measured (Scott and Reinhardt, 2005). Until the analytical environment is improved with new data, it may be helpful to weigh treatment effects on canopy fuels in relative terms rather than relying on absolute values.

Simulation modeling results came from studies using several different software packages, such as Nexus (Scott and Reinhardt, 2001), FlamMap (Finney, 2006), or Fuel Management Analyst (Carlton, 2005). Although these programs differ in some respects, they share central algorithms for fire type and spread (Rothermel, 1972, 1991; Van Wagner, 1977). Effect sizes of the two indices that have been widely reported to assess potential crown fire



**Fig. 3.** Comparison of basal area effects of all treatments with canopy base height effects (upper panel) and canopy bulk density effects (lower panel). All effect sizes were calculated as response ratios, defined as  $\ln(\text{treatment mean}/\text{control mean})$ .

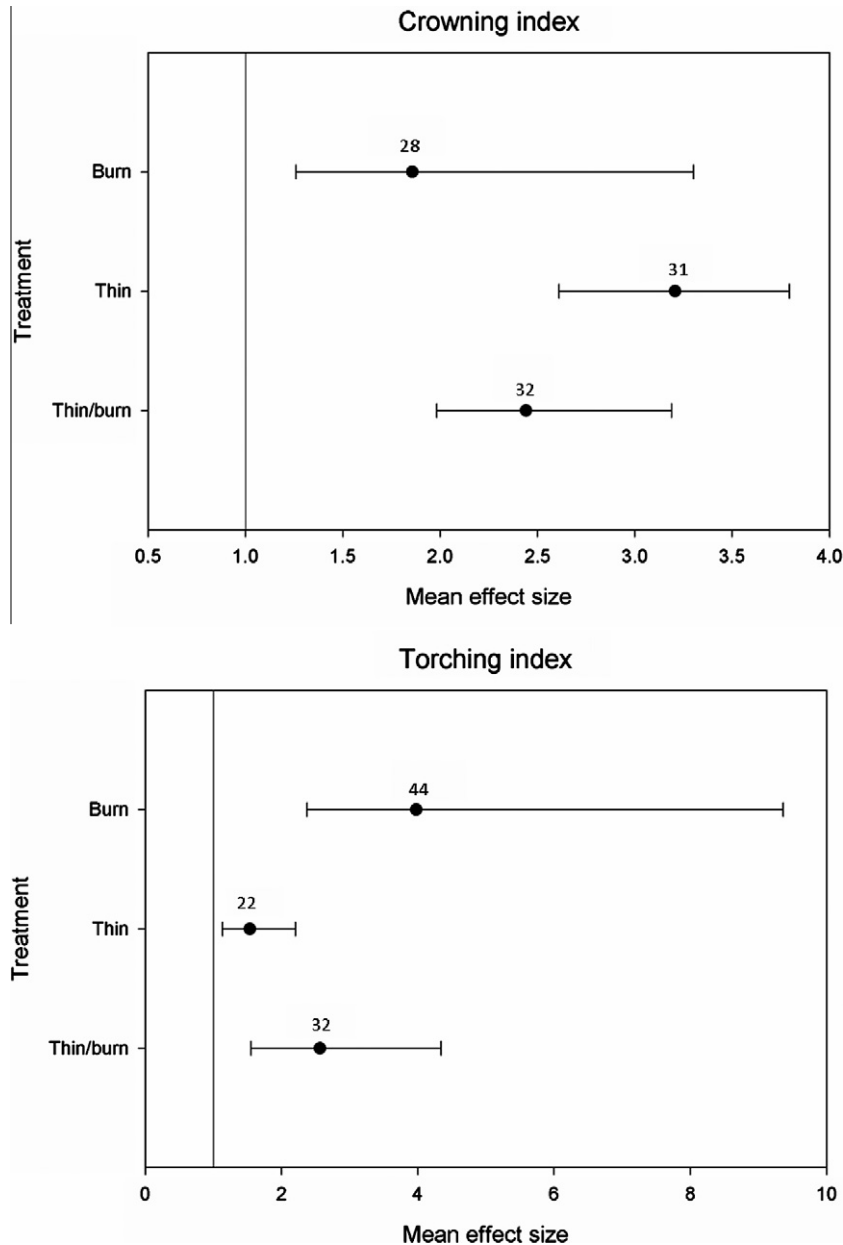
behavior—Crowning Index (CI), windspeed required to maintain active crown fire spread, and Torching Index (TI), windspeed required for transition from surface to passive crown fire (Scott and Reinhardt, 2001)—were compared (Fig. 4). Higher index values mean reduced forest susceptibility to crown fire. All treatments resulted in significant increases in CI and TI compared to controls. Mean increases in wind speed required to support crown fire behavior ranged from approximately 1.5 to 4 times (x-axis in Fig. 4), a substantial difference in predicted fire behavior as compared to controls, but there were no significant differences between treatments. Actual values of variables related to crown fire behavior are of uncertain precision and may be biased toward underprediction (Cruz and Alexander, 2010), but the relative differences compared to controls and the consistency across the studies in this review indicate that all treatments are likely to provide meaningful reductions in the likelihood of passive and active crown fire.

Studies that reported treatment performance in actual severe wildfires provided corroborating evidence that supported the relationship between treatment effects and reduction in fire severity. Several studies compared treated and untreated sites that burned under severe fire conditions and reported detailed quantitative

information on basal area, tree density, and other variables. These data were incorporated into the observations used for meta-analysis, as described above (e.g., Pollet and Omi, 2002; Cram et al., 2006; Strom and Fulé, 2007). These studies are particularly useful because they provide empirical evidence of the relationship between treatment effects and fire behavior. Other studies were conducted at landscape scale (e.g., Finney et al., 2005) or reported less-used variables that were not comparable across studies (e.g., Ritchie et al., 2007), but provided additional evidence of treatment effects on reducing fire severity. Finally, documents based on literature reviews and expert opinion (e.g., Brown et al., 2004; Hessburg et al., 2005) tended to concur on the physical and biological effects of treatments but expressed the greatest variation in terms of the implications of using treatments for restoration of natural processes and/or creating desired future conditions (e.g., Covington et al., 1997; Allen et al., 2002; Johnson et al., 2003).

### 3.2. (2) How might relationships differ among pure ponderosa pine forests versus related forests (pine-oak and dry mixed conifer)?

Ponderosa pine forests were the most common category encountered in the search (Fig. 5), but mixed conifer would have



**Fig. 4.** Mean effect size and bootstrapped 95% confidence intervals for two indices related to crown fire behavior, compared by treatment. Crowning Index is an estimate of windspeed required to maintain active crown fire. Torching Index Mean is an estimate of windspeed required for a surface fire to transition to crown fire. Effect sizes are scaled as proportions of control values (1.0 or 100%); values above 1 indicate proportional increases over controls, values below 1 indicate decreases. Numbers above effect sizes indicate number of observations for each treatment.

predominated if all the categories of mixed conifer forests that included ponderosa or Jeffrey pine were grouped together. No significant differences in effect sizes between forest types were observed for basal area, canopy cover, torching index, or crowning index. Ponderosa pine is the most shade-intolerant species of those considered in this review, so it would have been logical to expect forest structure to display a trend toward increasing density from pine and pine-oak toward mixed conifer forests.

The lack of difference associated with forest type is consistent with research findings of relatively high similarity in past fire regime and forest structure between pine and dry mixed conifer forest types. For example, in the Southwest the mean frequency of historical surface fire in pine forests was within 1–5 years of the mean fire frequency in mixed conifer forests (Swetnam and Baisan, 1996), with gradient studies showing these forest types to be linked by synchronous fire events (Fulé et al., 2003; Mar-

golis and Balmat, 2009). Differences in composition and structure are generally strikingly more pronounced in contemporary than in historical forests (e.g., Youngblood, 2001; Minnich et al., 1995; Brown et al., 2008). In some cases, modern “mixed conifer” forests may be largely an artefact of fire exclusion that permitted establishment of *Abies* or other mesic tree species (Weaver, 1951). Data from remote unlogged relict areas with continuing fire regimes provide modern-day examples similar to historical mixed conifer conditions of dominance by surface fire-adapted pines and Douglas-fir, relatively few ladder fuels, and low surface fuel loading, characteristics similar to those of undisturbed pure pine forests (Stephens and Fulé, 2005). Given the greater relative similarity among pine and mixed conifer forests in the past, we infer that treatments using historical reference points are likely to have converged, at least within a broad range of natural variability.

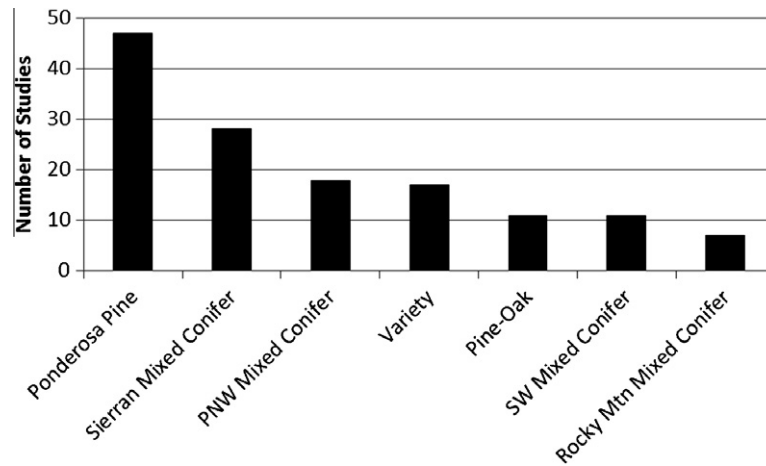


Fig. 5. Number of studies reviewed by forest type. “PNW” is Pacific Northwest, “SW” is Southwest.

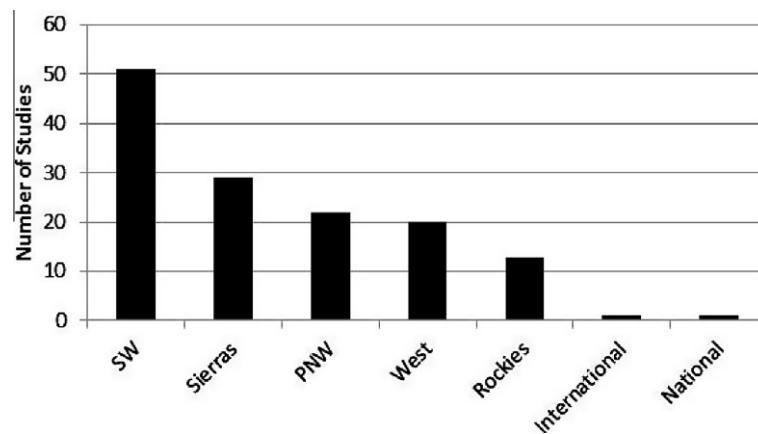


Fig. 6. Number of studies reviewed by region. “PNW” is Pacific Northwest, “SW” is Southwest. The international study was a U.S./Mexico comparison.

Management implications of the lack of differences between forest types are, first, that treatments are likely to have a more significant impact than forest type on forest structure, fuels, and future fire behavior. Second, this finding is likely linked to underlying ecological similarities in historical composition, structure, and function between these forest types.

### 3.3. (3) How might regional variability (Pacific Northwest, Sierra Nevada, Rocky Mountains, and Southwest) affect outcomes?

The Southwest was the region best represented in the literature (Fig. 6), consistent with the dominance of ponderosa pine in this area of the U.S. The West Coast (Pacific Northwest plus Sierra Nevada) was the second most common region. As was the case with comparisons of forest type, no significant differences in effect sizes between regions were observed for any response variable except torching index. However, given the limited number of studies from Washington, Oregon, Idaho, Montana, Colorado and Utah, it would be helpful to expand fire and restoration research in these areas.

The lack of differences between regions may appear surprising because the review covered a broad, subcontinental range over approximately 10° of latitude. Conditions of temperature, precipitation, precipitation timing (monsoonal, continental, Mediterranean), effects of El Niño/Southern Oscillation and other climatic patterns, geological substrate, and topography varied widely and sometimes directionally over this extensive area. However, as noted above, the relative similarity in historical attributes of

process and structure, together with evidence of the long-term evolutionary role of fire (Keeley and Zedler, 1998), may be unifying characteristics even over a vast geographic region. The implications in terms of management are therefore similar to those for forest type: treatments have a stronger influence than regional differences, likely due to underlying ecological similarities among the disparate forest ecosystems.

## 4. Conclusions

The literature on effects of forest treatments has grown dramatically in the past decade. While this review covered a broad geographical region and a variety of treatments, meta-analysis of surface fuel and forest structure variables showed consistent and significant trends. Burning significantly reduced fine and coarse surface fuels compared to controls, while thinning significantly increased both fuel categories; thin/burn treatments were intermediate in effect. Almost all treatments significantly reduced tree density, basal area, and canopy cover. Individual treatments were not statistically distinguishable but thin/burn treatments tended to have the greatest mean effect. Canopy fuel variables, canopy base height and canopy bulk density, generally were changed by treatments toward reducing the potential for passive and active crown fire. However, the relationship between forest structural changes and canopy fuel changes was not linear, likely due in part to inconsistencies in the calculation methods that can lead to



paradoxical results. While these variables should be used with caution, the trend was consistent with treatments leading to reduced fire severity.

Fire behavior simulation studies showed that treatments had consistent and significant effects in reducing forest vulnerability to crown fire by increasing windspeeds necessary to support active crown fire (Crowning Index) and transition from surface to crown fire (Torching Index). There are uncertainties and potential biases associated with fire behavior simulation modeling, but the relative differences in the index values as compared to controls should be reliable. Studies that reported actual tests of fire behavior under severe weather and moisture conditions corroborated the trends observed in surface fuels, forest structure, canopy fuels, and simulated fire behavior: treated sites had substantially reduced fire severity.

Treatments had significant and much greater effects on all the studied variables than did pre-existing differences in forest type or region, implying that decisions about treatments are likely to have similar impacts on fire behavior across the broad range of forest types and geographical extent covered in this review. The similarities in response are likely due to underlying ecological and evolutionary similarities among these wide-ranging forest ecosystems. These ecological underpinnings provide support for considering treatments in the context of ecological restoration, rather than simply as an expedient approach to fuel reduction.

The literature shows that the primary question of the review (do thinning and/or burning treatments on ponderosa pine and related forests in western USA help restore natural fire behavior?) can be answered with a qualified “yes.” The literature includes a high proportion of replicated randomized experiments, a technique supporting strong inferences, and treatment effects were frequently statistically significantly different from controls. There are logical links between commonly reported and precisely measured variables (surface fuels and forest structure) and less-reported, less precise fire-related variables (canopy fuels, fire behavior) as well as some empirical support for linkages. However, the majority of the studies with quantitative data are relatively recent (<10 years) and contrasted small study areas. The modeling results most often reviewed do not account for heterogeneity in stand structure, fuels, and winds. Some treatments such as light thinning and/or low-intensity burning are so mild as to have limited effects on fuels, forest structure, or fire hazard. There are also uncertainties in the estimation of canopy fuels and simulated fire behavior. Over time, the true test of treatment effects will involve measurements at larger scales and under repeated burning regimes. The potential additional impact of climate change, probably not yet reflected in the recent literature, will also play an increasingly important role in the future trajectories of ponderosa pine and related dry forests. Despite a number of qualifications, however, scientific findings to date strongly indicate that thinning and/or burning treatments do have effects consistent with the restoration of natural fire behavior.

## Acknowledgements

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## Appendix A

Complete list of systematic review references. Reference numbers (bolded text) correspond to study locations in Fig. 1.

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