United States Department of Agriculture

Forest Service

Rocky Mountain Research Station

Research Paper RMRS-RP-103WWW

June 2013

Fuel Treatments and Fire Severity: A Meta-Analysis

Erik J. Martinson and Philip N. Omi

Martinson, Erik J.; Omi, Philip N. 2013. **Fuel treatments and fire severity: A meta-analysis**. Res. Pap. RMRS-RP-103WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 38 p.

Abstract

We employed meta-analysis and information theory to synthesize findings reported in the literature on the effects of fuel treatments on subsequent fire intensity and severity. Data were compiled from 19 publications that reported observed fire responses from 62 treated versus untreated contrasts. Effect sizes varied widely and the most informative grouping of studies distinguished three vegetation types and three types of fuel treatment. The resultant meta-analytic model is highly significant ($p<0.001$) and explains 78% of the variability in reported observations of fuel treatment effectiveness. Our synthesis highlights several considerations that both support and inform the current fuels management paradigm.

Keywords: thinning, prescribed burning, wildfire, effect size, synthesis

Authors

Erik J. Martinson is a Consultant and Partner at MarLynn Ecological Consulting in Fort Collins, Colorado.

Philip N. Omi is a Professor Emeritus at Colorado State University and Principal of Omi Associates in Sebastopol, California.

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Rocky Mountain Research Station
240 West Prospect Road
Fort Collins, CO 80526

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Introduction

Changes in land use and management over the last century or more have increased the vertical and horizontal continuity of wildland fuels in many areas of North America (Pyne 1982, but see Keeley and Fotheringham [2001] and Johnson and others [2001] for discussion of exceptions). This increase in fuel hazard is compounding with climate change (Brown and others 2004) and exurban development (Cova and others 2004) to place ever more values at risk to wildfire damages. While the problem has been recognized for decades (Cooper 1960), political and land management attention on mitigating hazardous fuels has recently increased (Stephens and Ruth 2005), piquing an interest for more research into the effects and effectiveness of these activities (Botti and others 1998). Consequently, the volume of fuel treatment studies has expanded greatly over the past decade (figure 1), spawning a number of literature reviews to synthesize findings (Hudak and others 2011; table 1).

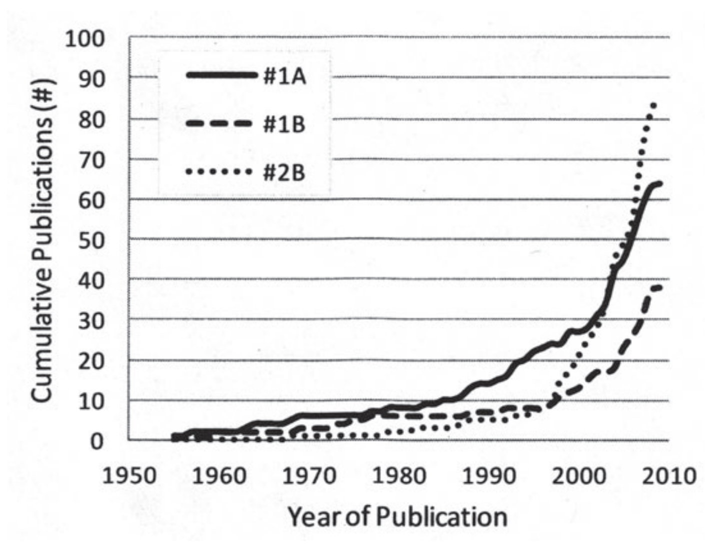

Figure 1—Cumulative number of fuel treatment effectiveness publications by year and type of study:
1A = observed wildfire response to actual fuel treatment, 1B = simulated wildfire response to actual fuel treatment, 2B = simulated wildfire response to hypothetical fuel treatment.

Table 1—Recent literature reviews related to fuel management that were used to identify studies to consider for inclusion in our synthesis. The Joint Fire Science Program database of final reports for completed projects (www.firescience.org) was also searched.

1. Greenlee, J.M.; Sapsis, D.B. 1996. Prefire effectiveness in fire management: A summary and a review of the state-of-knowledge. Fairfield, WA: International Association of Wildland Fire.
2. Carey, H.; Schumann, M. 2003. Modifying wildfire behavior—the effectiveness of fuel treatments. Santa Fe, NM: National Community Forestry Center Southwest Region Working Paper #2.
3. Martinson, E.J.; Omi, P.N. 2003. Performance of fuel treatments subjected to wildfires. USDA Forest Service Proceedings RMRS-P-29: 7-14.
4. Fernandes, P.M.; Botelho, H.S. 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire 12: 117-128.
5. Graham, R.T.; McCaffrey, S.; Jain, T.B. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service General Technical Report RMRS-GTR-120: 143.
6. Agee, J.K.; Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.
7. Peterson, D.L.; Johnson, M.C.; Agee, J.K.; Jain, T.B.; McKenzie, D.; Reinhardt, E.D. 2005. Forest structure and fire hazard in dry forests of the Western United States. USDA Forest Service General Technical Report PNW-GTR-628: 1-30.
8. Keeley, J.E.; Aplet, G.H.; Christensen, N.L.; Conard, S.C.; Johnson, E.A.; Omi, P.N.; Peterson, D.L.; Swetnam, T.W. 2009. Ecological foundations for fire management in North American forest and shrubland ecosystems. USDA Forest Service General Technical Report PNW-GTR-779: 1-92.

A paradigm for fuels management has emerged from these reviews that emphasizes the importance of first distinguishing ecosystems where fire was historically frequent and benign while limited primarily by fuel quantity (such as dry conifer forests) from those where fire was historically infrequent and stand-replacing while limited more by climate (such as sub-arctic and sub-alpine forests or California chaparral). The paradigm suggests that large-scale fuels management may be inappropriate and counter-productive in the latter types of ecosystems (Johnson and others 2001; Keeley and Fotheringham 2001), but should be successful in the former to the degree that more resilient conditions result from reducing surface fuels, removing ladders, opening canopies, and selecting for fire resistance (such as by leaving large trees), in that order (Agee and Skinner 2005). Keeley and others (2009) noted that empirical studies in lower-elevation western conifer forests consistently demonstrate reduced wildfire severity from combinations of thinning and burning, but caution that the slash produced by thinning will exacerbate fire hazard until it is also treated. Guidance is less clear for ecosystems where the interactions among fire, weather, and fuels are more complex and the historic fire regime was a mixture of frequencies and severities (such as mesic mixed forests at middle elevations and latitudes). Thus, the recommendation for fuels management in these systems has been for limited and cautious application (Schoennagle and others 2004).

However, traditional literature reviews are inherently qualitative in their syntheses of the information provided in research reports (Cooper and others 2009). They are also prone to bias in selection and interpretation of findings and tend to over-emphasize contradictory conclusions with inadequate attention to sources of variability. Since 1955, the medical sciences have relied instead on an alternative approach to research synthesis using the techniques of meta-analysis (Stroup and others 2000).

Meta-analysis is a systematic and quantitative approach to research synthesis that combines and compares results from independent trials to assess the direction, magnitude, and consistency of reported responses (Cooper and others 2009). Meta-analysis is now commonly applied to ecological questions (Gurevitch and others 2001) and has been recently applied to the wildland fuels treatment literature, as well (Martinson 1998, Wan and others 2001, Kopper 2002, Boerner and others 2009, Kalies and others 2010, Youngblood 2010). Kopper and others (2002, 2009) conducted a meta-analysis on the effects of prescribed fire on fuel reduction. The focus of the current meta-analysis is on the literature documenting fuel treatment performance in mitigating subsequent fire intensity and severity to assess the empirical support for the current fuel management paradigm.

Methods

Meta-analysis involves a comprehensive literature search for relevant studies, quantification of the magnitude of effects reported in the studies selected for inclusion, and an analysis of study heterogeneity to identify the strength and significance of any emergent trends. Robust methods for extracting and analyzing data embedded in disparate studies contribute to the strength of meta-analytic investigations.

Literature Search

Our literature search employed eight documents (table 1) as sources to identify the scientific publications relevant to our meta-analysis. These sources are traditional literature reviews that address fuel management issues and all references cited in them were subjected to an initial screening, as was any subsequent document published prior to September 1, 2009, that included at least one of the reviews in its literature cited (as identified by Google Scholar [http://scholar.google.com]). Final reports submitted to the Joint Fire Science Program (http://www.firescience.gov) prior to June 1, 2010, were also screened for relevant data and additional publications.

Study Selection

The initial screening broadly categorized all identified publications (n = 1213) based on the characteristics of the fuel treatments investigated (actual treatment [n = 280], hypothetical or planned treatment [n = 97], or no fuel treatment [n = 836]) and the response variable analyzed (actual fire characteristic [n = 105], simulated fire characteristic [n = 161], or no fire characteristic reported as a response variable [n = 947]). All publications that included information from actual fuel treatments exposed to actual fire (n = 60) were thoroughly reviewed and coded with respect to the following information: study design, location, dominant vegetation, fuel and fire variables measured, and treatment characteristics reported (Appendix A). Publications that did not include both a fuel treatment and a subsequent fire test were outside the focus of our meta-analysis, while simulation studies were excluded from further consideration for being more theoretical than empirical and overly encumbered by inherent inconsistencies in investigator assumptions and model errors (Cruz and Alexander 2010).

Studies of fuel treatment performance generally employ one of three basic designs: pre-planned block experiments (n = 9) burned intentionally or serendipitously, retrospective paired comparisons of treated and untreated areas affected by wildfire (n = 18), and landscape or regional surveys of wildfire severity or area burned (n = 33). Most of the latter lacked any semblance of control for variations in weather and topography (n = 28) and were excluded from further analysis, though recent advances in the application of spatial statistics show promise of improved information from such studies in the future by accounting for auto-correlated influences on fire behavior (for example, Wimberly and others 2009).

A variety of response variables are reported in the fuel treatment performance literature, and many report more than one measure. Among the 32 publications that remained under consideration for our meta-analysis, reported response variables comprised flame length (n = 7), fire spread rate (n = 5), percent canopy consumption (n = 6), percent canopy scorch (n = 11), scorch height (n = 7), bole char height (n = 8), percent mortality (n = 8), categorical canopy damage rating (n = 10), categorical ground char rating (n = 9), remotely sensed severity (n = 4), and area burned (n = 2). Rather than restricting our analysis to a single response or performing separate meta-analyses for each, we used correlation and simple regression analysis to determine if any could be reasonably treated as substitutes for one another and combined in a single meta-analysis. This allowed inclusion of a broader range of vegetation and treatment types in our meta-analysis, but also may have introduced additional error, so we compared the results of our meta-analysis with and without incorporating response variable substitution. Publications that reported responses with metrics that could not be equated to others were reserved for potential separate meta-analyses, resulting in the exclusion of 13 additional publications from the primary meta-analysis and a remainder of 19.

Data Extraction

Central to any meta-analysis is the calculation of effect sizes: dimensionless measures of the magnitude of difference between treatment and control means reported in the selected publications. Hedge's *d* (Hedges and Olkin 1985) is the conventional effect size metric for difference data (such as treatment-control comparisons), but the log response ratio (Hedges and others 1999) has been found to be a more flexible metric for meta-analysis of ecological and natural resource studies (Kopper and others 2009). The log response ratio is calculated as a treatment mean divided by a control mean with the ratio log transformed, and is the measure of effect size used in in the current application. Data on responses and explanatory variables were extracted and effect sizes were calculated for the 19 publications selected for inclusion in a step-wise analysis of heterogeneity using MetaWin software (Rosenberg and others 2000).

Our primary hypothesis was that there would be broad differences in effects reported from different types of ecosystems, as defined by general categories of geographic location (Northwestern, Southwestern, and Eastern United States and outside of the continental United States) and vegetation (long-needle conifer forests, mixed conifer forests, other woodlands, and grasslands). We also hypothesized that fuel treatment effects would vary among different types of fuel treatment. Treatments were categorized for comparisons into six broad types based on expected change to canopy and surface fuels (table 2).

Many of the 19 studies selected for inclusion in the meta-analysis contained information from more than one treatment type, and these were considered independent observations such that a total of 62 were included; their distribution among vegetation, region, and treatment categories is summarized in table 2 and listed along with reported responses and calculated effect sizes in Appendix B. Any remaining variability in effect sizes within the ecosystem and treatment categories was explored for relationships to treatment age and treatment intensity, as indicated by changes to measured fuel conditions.

Table 2—Distribution of observations included in the meta-analysis among treatment type categories within vegetation and region groups.

	Treatment type[a]						
	1	**2**	**3**	**4**	**5**	**6**	**Total**
Vegetation							
Long-needle pine forest	6	12	1	1	0	3	23
Mixed conifer forest	9	6	1	0	1	13	30
Woodlands other than conifer forest	0	2	0	2	0	1	5
Grasslands	0	2	0	2	0	0	4
Total	15	22	2	5	1	17	62
Region							
Northwest U.S.	9	6	2	1	1	7	26
Southwest U.S.	6	8	0	0	0	9	23
Eastern U.S.	0	3	0	4	0	1	8
Non-U.S.	0	5	0	0	0	0	5

[a] Treatment descriptions in order of expected effectiveness (most to least):
1. Canopy thinned with slash and surface fuels reduced by burning or mechanical removal.
2. Canopy untreated, but surface fuels reduced by burning, mechanical removal, or grazing/browsing by livestock or other biological vectors.
3. Canopy thinned with no change to surface fuels via whole tree extraction.
4. Canopy untreated, but surface fuels rearranged by physical or chemical means (mastication, chipping, crushing, piling, herbicide application).
5. Canopy thinned with slash and surface fuels rearranged as above.
6. Canopy thinned with no treatment of the activity fuels added to the surface.

Data Analysis

Meta-analyses of classically designed laboratory experiments typically employ parametric fixed effects statistical models that weight each study by its sample size and variance. However, field studies in ecology (Adams and others 1997) and especially in wildland fire research (Van Mantgem and others 2001) are more often observational than experimental, rarely conform to parametric assumptions, and are generally pseudo-replicated (in the sense of Hurlbert 1984). Measures of variability are thus often misspecified or unreported and any conditional weighting scheme would seem capricious. Kopper and others (2009), for example, could find only eight studies that met the criteria for inclusion in a parametric fixed-effects meta-analysis of fuel reduction by prescribed fire in ponderosa pine, even though it is unlikely there is another fuel treatment topic more thoroughly studied.

Adams and others (1997) suggested that mixed-effects and/or non-parametric meta-analysis may be most appropriate for many ecological topics. A non-parametric meta-analysis that employs randomization procedures (that is, resampling and bootstrapping) to estimate within-group effect size distributions and tests of between-group heterogeneity is analogous to a mixed-effects model (Gurevitch and Hedges 1999). Given the limited number of studies that address our topic of interest and their general inability to strictly adhere to parametric assumptions, we erred on the side of inclusiveness in using an unweighted, non-parametric, mixed-effects model for this meta-analysis. Kalies and others (2010) similarly found the relaxed assumptions of this model formulation most useful for their meta-analysis of wildlife responses to fuel treatments in the Southwest. We also followed Adams and others' (1997) recommendation of 4999 resampling iterations for significance tests and the use of bias-correction for bootstrapped confidence intervals.

Nonetheless, an unweighted meta-analysis is more prone to bias from small studies. We performed diagnostic checks for the potential influence of small study bias on our meta-analysis with funnel plots and correlation analysis of study size versus effect size (Rothstein and others 2005). However, statistical reporting is inconsistent across the publications synthesized in our meta-analysis, including the definition of a sampling unit. We therefore determined the apparent number of distinct treatment units sampled for each study as the measure of its relative size for purposes of our bias diagnostics.

Parametric meta-analyses proceed with study segregation and tests for between-group heterogeneity until within-group heterogeneity is no longer found to be significant or there are no additional grouping variables available. But no statistical test for within-group heterogeneity is available for non-parametric meta-analysis (Gurevitch and Hedges 1999). We instead relied on an information-theoretic approach (Burnham and Anderson 2002) to determine whether additional segregation within groups was warranted given the information available. Specifically, additional segregation of studies within groups was added only if it reduced model error when adjusted for degrees of freedom as calculated by Akaiki's Information Criterion (*AICc*) corrected for small samples:

$$AICc = n * ln\left(\frac{Q}{n}\right) + 2k + \left(\frac{2k(k+1)}{n-k-1}\right), \quad [1]$$

where *n* is the number of observations, *k* is the number of parameters (that is, group means) estimated, and *Q* is the maximum likelihood value for the meta-analytic model (also known as the homogeneity statistic), calculated in an unweighted meta-analysis as the sum of the squared errors for observed study effects when estimated from group means (Rosenberg and others 2000).

Model selection proceeded in a step-wise fashion, initiating with the most informative fully categorized main effect. The best model was determined at each step by comparison of Akaiki weights (*w*) representing the probability that a given model is the most informative of those considered (Burnham and Anderson 2002):

$$w_i = \frac{\exp(-\Delta_i/2)}{\sum_{r=1}^{M}\exp(-\Delta_r/2)}, \quad [2]$$

where Δ_i and Δ_r are differences between the *AICc* value for a given model and the minimum *AICc* value found in the set of models considered at each selection step, and *M* is the number of models considered at each selection step. The model with the greatest Akaiki weight in each selection step was retained as the null model for the next step until all available explanatory variables had been considered.

Results

Correlation Among Response Variables

Percent crown volume scorch was the most prevalent response variable reported in studies of actual fuel treatment performance when subjected to fire. Within studies that reported more than one response measure, strong correlations were found among effect sizes calculated from percent crown scorch, scorch height, and canopy damage ratings (table 3). All studies that reported responses in terms of

Table 3—Cross-correlation matrix for effect sizes derived from studies that reported multiple response variables. Number of contrasts for each pair of variables is in parentheses, and significant ($p<0.05$) correlation coefficients are emboldened.

Response	% scorch	scorch ht	char ht	rating[a]	mortality	intensity
%scorch	1					
scorch ht	**0.78 (34)**	1				
char ht	**0.54 (32)**	**0.45 (30)**	1			
rating[a]	**0.78 (33)**	**0.78 (29)**	**0.69 (26)**	1		
mortality	0.56 (7)	0.80 (4)	0.40 (3)	na (0)	1	
intensity	0.98 (3)	na (0)	na (0)	na (0)	0.99 (3)	1

[a]Rating of canopy damage based on scorch and/or consumption.

one of these three variables were equated to a common measure of effect with the regression relationships shown in figure 2. However, effect sizes were calculated from percent crown volume scorch for most (77%) of the studies included in the meta-analysis. Effect sizes were calculated from canopy damage ratings for three studies from prescribed burns in northwestern long-needled pine forests and one study from a prescribed burn in an eastern long-needled pine forest. Effect sizes were calculated from scorch height for the one study of surface fuel rearrangement in a long-needled pine forest, as they were for all studies in woodlands and grasslands by conversion of flame length measurements on experimental fires to potential scorch heights using relationships developed by Byram (1959) and Van Wagner (1973). The influence of these effect size substitutions on the final meta-analytic model is subsequently discussed.

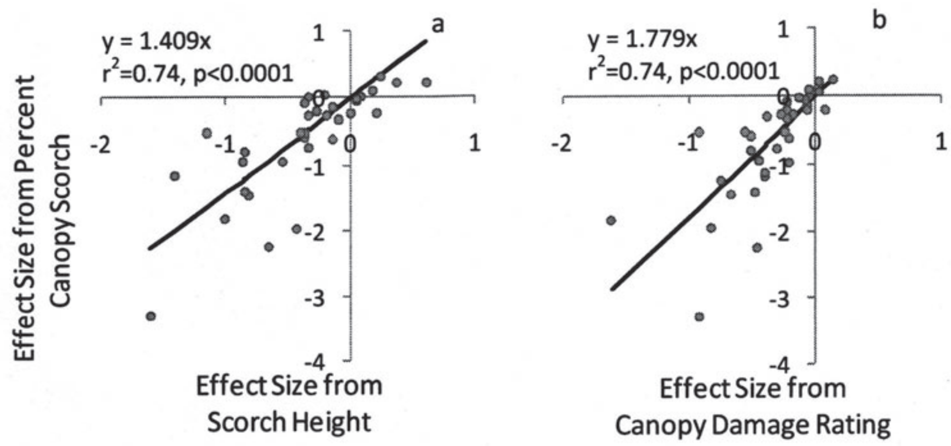

Figure 2—Regression relationships to equate effect sizes calculated from (a) scorch height and (b) canopy damage ratings to effect sizes calculated from percent canopy scorch.

Distribution of Fuel Treatment Effect Sizes

Fuel treatment effect sizes varied widely among the studies included in the meta-analysis (figure 3), but the overall mean is large (-0.90) and significant with a 95% confidence interval that does not include zero (-1.32 to -0.56). Effect sizes ranged from -6.72 to 2.89 with 14 observations (22.5% of the total) demonstrating a negligible treatment effect, defined by convention as an absolute effect size less than 0.20 (Cohen 1988). Observations of non-negligible effects were mostly in the intended direction (43 of 48 [90%]) and these tended to be large (22 of 43 effect sizes <-0.8). Just one observation demonstrated a large counter-productive treatment effect, that is, a positive effect size greater than 0.8, indicating more extreme fire behavior in the treated areas as compared to surrounding untreated areas. Paired photographs representing a range of effect sizes corresponding to those presented here are shown in figure 4, and additional examples from treatments sampled by Omi and Martinson (2002) and Omi and others (2006) are available online (http://omiassociates.net/fueltreatment/) along with a database selection tool.

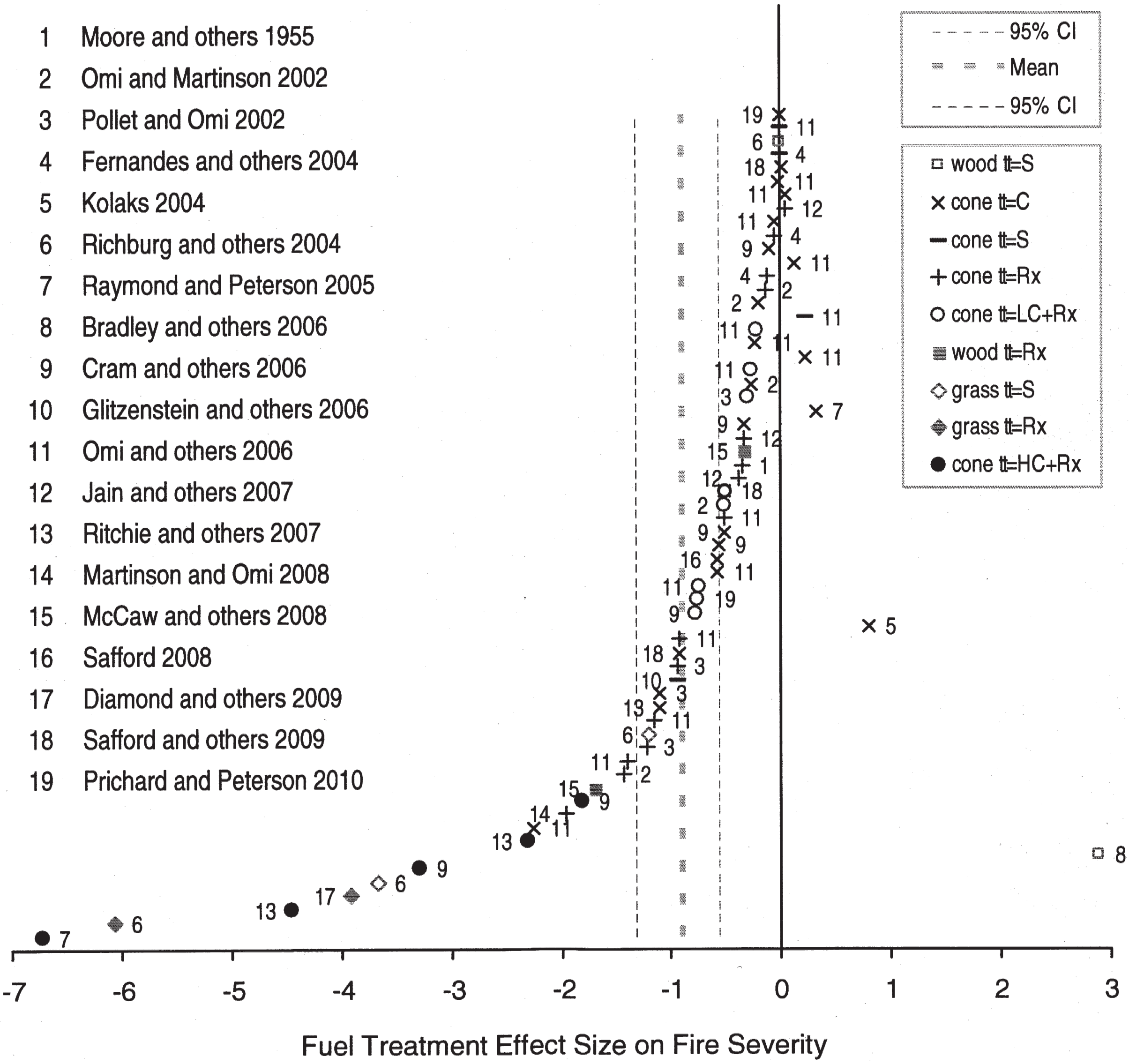

Figure 3—Distribution of fuel treatment effect sizes calculated from the 19 publications included in the meta-analysis, distinguished by the characteristics found to be most informative from the model selection process. Legend abbreviations are: cone = conifer forest, wood = woodland other than conifer forest, grass = grassland, C = canopy thin, HC = heavy thin, LC = light thin, Rx = recent surface fuel reduction, and S = surface fuel treatment other than recent reduction. Negative effect sizes indicate lower fire intensity/severity in areas that received fuel treatment. Effect sizes are arranged from top to bottom in order of increasing absolute difference from zero, or no effect. Additional details and literature citations for the referenced data sources are provided in the appendices.

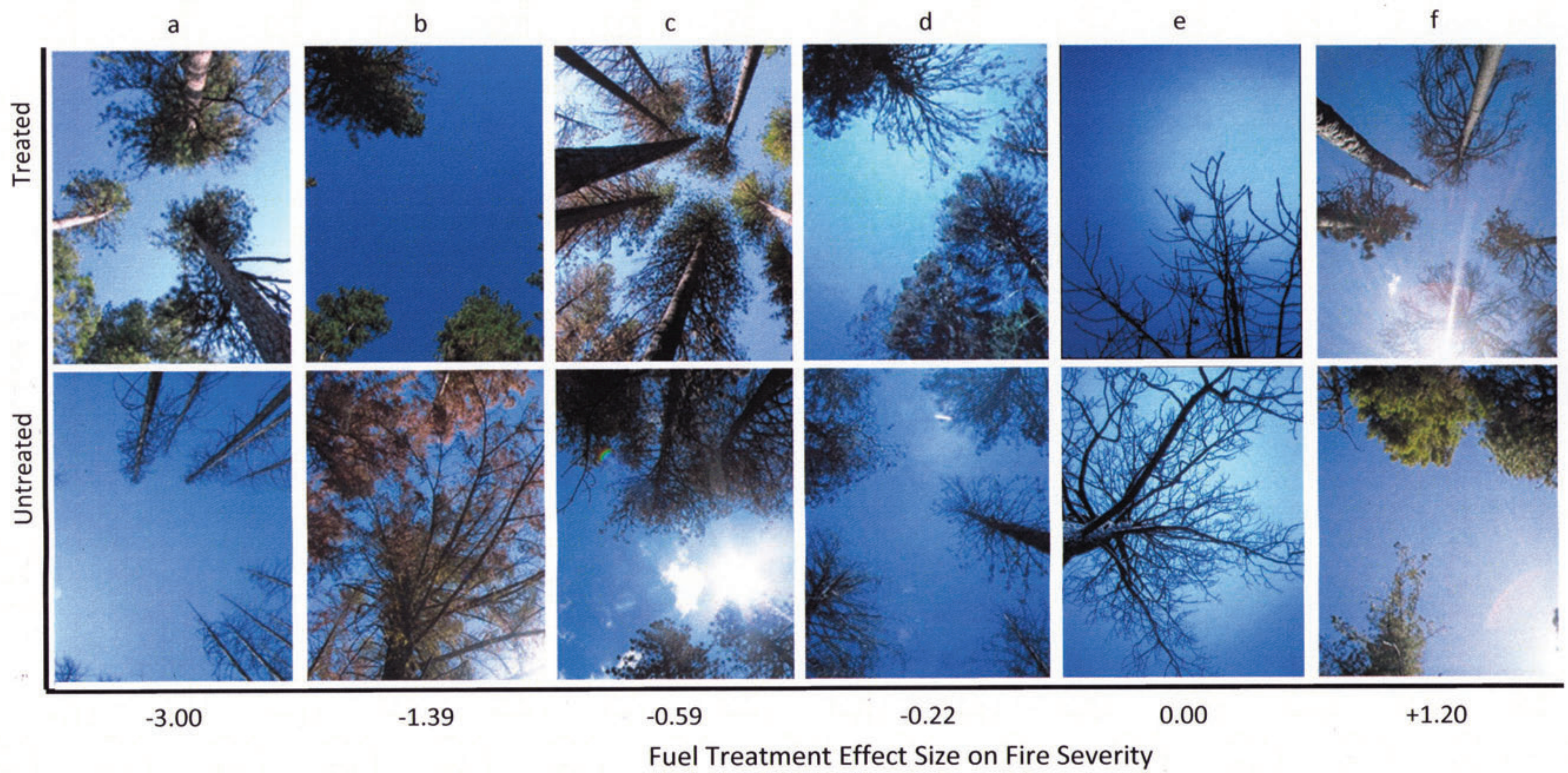

Figure 4—Pictorial representation of a range of effect sizes corresponding to those used to standardize study findings for the current meta-analysis. Photos in the top row are of treated areas adjacent and topographically similar to the untreated areas pictured in the bottom row with both affected by wildfire in the same burning period (Omi and Martinson 2002, Omi and others 2006):
(a) mechanical thin with slash yarded and burned in 2001 within the 2003 Davis Fire in Oregon
(b) mechanical thin with slash piled and burned in 2002 within the 2004 Fischer Fire in Washington
(c) 1994 underburn within the 2004 Power Fire in California
(d) blowdown fuels yarded and burned in 1997 within the 1999 Megram Fire in California
(e) mechanical thin with no slash treatment within the 2000 Cerro Grande Fire in New Mexico
(f) mechanical thin with no slash treatment within the 2003 Aspen Fire in Arizona

Model Selection

The goal of our meta-analysis was to identify the most informative organizing characteristics of fuel treatment studies to explain the variability in reported findings. Study characteristics considered were ecosystem and treatment conditions defined in terms of: vegetation, geographic region, treatment type, treatment age, and treatment intensity.

Vegetation Type

Most studies of fuel treatment effectiveness that met our study selection criteria were conducted in conifer forests (85%), with nearly half of those in long-needle pine systems (table 2). Just five studies were identified from grassland ecosystems and only four from woodlands other than conifer forests. Initial model selection suggested that the most informative study segregation was by these vegetation types (w>0.99, relative to a maximum possible value of 1.0) when compared to grouping studies only by geographic region or treatment type (table 4, step 1). Three study grouping schemes by vegetation type were then considered: separating grasslands from non-grasslands (table 4, step 2.a), further separating non-grasslands into conifer forests and other woodlands (table 4, step 2.b), and further separating long-needled pine from other conifer forests (table 4, step 2.c). The model with three vegetation groups (grassland, conifer forest, and other woodlands) had the most support in the data (w = 0.54), while the model that further distinguished long-needled-pine from other conifer forests had the least support (w = 0.17).

Geographic Region

The fuel treatment studies included in our synthesis were concentrated in the western United States (79%), with these divided roughly evenly between northwest and southwest (distinguished approximately by the 40th parallel). Eight studies were identified from east of the Rocky Mountains and five from outside of the continental United States (Portugal and Australia). We next assessed whether there was support in the data for adding these regional groupings within the selected vegetation groupings for grasslands, conifer forests, and other woodlands. We first separated studies conducted in the continental United States from those that were not (table 4, step 3.a), then separated the western United States from the eastern (step 3.b), and finally northwest from southwest (step 3.c). However, the data did not support a more refined separation of studies than simply continental United States versus non-United States (w = 0.40), and the second best model for a regional effect was the null (table 4, step 3.0). Treatments in conifer forests appear to perform better in the United States (lower 95% confidence interval<mean effect size<upper 95% confidence interval = -1.25<-0.85<-0.56) than elsewhere (-0.11<-0.06<0.00), while treatments in woodlands performed better outside the United States (-1.70<-1.02<-0.34) than within (0.27<1.23<2.89). However, any regional influence on treatment effectiveness proved uninformative upon inclusion of treatment type and age as explanatory variables (table 4, step 5.c).

Table 4—Selection of most informative meta-analytic model for fuel treatment effect sizes: variables included (Model), the homogeneity statistic (*Q*), number of estimated parameters (*k*), Akaiki's Information Criterion (*AICc*), and probability (*w*) of each model being the most informative of those considered at each step in the selection process. The model selected from each step is emboldened and italicized and was included as the null for the subsequent step.

Model	*Q*	*k*	*AICc*	*w*
Step 1: Most informative main effect				
null	140.07	1	52.60	0.00
Region (R)	133.93	4	56.45	0.00
Treatment (T)	123.79	6	56.40	0.00
Vegetation (V)	100.42	4	38.60	1.00
Step 2: Vegetation categories				
a) V(g = grassland) x V(w+c = non-grassland)	106.28	2	37.62	0.28
b) ***V(g) x V(w = woodland) x V(c = conifer forest)***	***100.44***	***3***	***36.32***	***0.54***
c) V(g) x V(w) x V(cm = mixed conifer) x V(cp = long-needle pine)	100.42	4	38.60	0.17
Step 3: Geographic categories				
0) V* = V(g) x V(w) x V(c) x R(null)	100.44	3	36.32	0.33
a) ***V* x R(US = United States) x R(xUS = non-US)***	***92.64***	***5***	***35.97***	***0.40***
b) V* x R(xUS) x R(USw = west of Rocky Mountains) x R(USe = eastern US)	91.02	6	37.33	0.20
c) V* x R(xUS) x R(USe) x R(USnw = north of 40th parallel) x R(USsw = Southwest)	90.68	7	39.65	0.06
Step 4: Treatment types				
0) V* x R* = R(US) x R(xUS) x T(null)	92.64	5	35.97	0.02
a) V* x R* x T(c = canopy thin) x T(no c)	92.24	6	38.16	0.01
b) V* x R* x T(s = surface treatment) x T(no s)	86.56	6	34.90	0.03
c) V* x R* x T(c&s) x T(c or s)	83.93	6	32.30	0.10
d) V* x R* x T(c) x T(s) x T(c&s)	82.58	7	34.59	0.03
e) ***V* x R* x T(c) x T(s- = reduce) x T(c&s-) x T(s_o = other surface treatment)***	***71.33***	***8***	***28.31***	***0.73***
f) V* x R* x T(c) x T(s+) x T(s-) x T(c&s_o) x T(c&s-)	71.77	9	32.35	0.10
Step 5: Treatment age				
0) V* x R* x T* = T(c) x T(s_o) x T(s-) x T(c&s-) x age(null)	71.33	8	28.31	0.07
a) V* x R* x T* x T($_{10}$s- = recent surface fuel reduction)	66.92	9	27.18	0.13
b) V* x R* x T* x T($_{10}$s-) x T($_{10}$c = recent thin)	66.93	9	27.19	0.13
c) V* x T* X T($_{10}$s-)	67.88	8	24.34	0.52
d) V* x T* X T($_{10}$s-) x T(c&s_o)	67.69	9	26.90	0.15
e) V* x T* x T($_{age}$s- = age of surface reduction)	74.46	9	32.81	0.01
Step 6: Treatment intensity				
0) V* x T* = T(c) x T(s_o) x T($_{10}$s-) x T(c&$_{10}$s-) x T_i = treatment intensity(null)	67.88	8	24.34	0.00
a) V* x T* x T_i(c&$_{10}$s-)	40.61	9	-3.28	0.00
b) V* x T* x T_i ($_{10}$s-) x T_i (c&$_{10}$ s-)	43.30	10	9.11	0.00
c) V* x T* x T($c_{h=\text{heavy thin}}$&$_{10}$s-)	40.64	8	-7.47	0.00
d) V* x T* x T_i (c_h&$_{10}$s-)	31.42	9	-20.69	0.11
e) V* x T* x T_i(c) x T_i (c_h&$_{10}$s-)	31.09	10	-4.70	0.00
f) ***V* x T($_{10}$s-) x T_i (c_h&$_{10}$s-) x T(-$_{10}$s- = treated w/o recent surface reduction)***	***30.73***	***8***	***-24.80***	***0.89***

Treatment Type

Different treatment types varied in prevalence among vegetation types and geographic regions (table 2). Reduction of natural fuels (treatment type 2), primarily by underburning, was the most common treatment overall (35%), but concentrated in long-needle pine forests (55%), while fairly evenly distributed across all regions. Canopy thinning without subsequent treatment of activity fuels (type 6) was the next most common treatment (27%), but concentrated in mixed conifer forests (74%) and roughly evenly divided between the northwest and southwest regions of the continental United States. Canopy thinning followed by reduction of activity and natural surface fuels (type 1) was somewhat less common overall (24%) but more prevalent in the northwest region (60%) and in mixed conifer forests (60%). The remaining 14% of the observations included in our analysis were scattered scantily among the other treatment types and across vegetation and region categories, though it is notable that rearrangement of natural fuels (type 4) was concentrated in non-conifer systems east of the Rocky Mountains.

Given the grouping of studies among the three vegetation types in U.S. ecosystems versus non-U.S. ecosystems, we next explored further distinguishing observations of treatment performance by treatment type (table 4, step 4). We first considered the simplest models of treatment type by separating studies into two groups based on the fuel strata treated (steps 4a-c): (a) canopy (table 2 treatment types 1, 3, 5, and 6 versus types 2 and 4), (b) surface (types 1, 2, 4, and 5 versus types 3 and 6), and (c) canopy plus surface (types 1 and 5 versus types 2, 3, 4, and 6). Next, we grouped studies into three treatment categories (table 4, step 4.d): canopy plus surface treatment (table 2, types 1 and 5), canopy treatment-only (types 3 and 6), and surface treatment-only (types 2 and 4). Finally, we distinguished between surface treatments that result in fuel reduction (types 1 and 2) versus rearrangement (types 4 and 5). The most informative model ($w = 0.73$) included four treatment groups (table 4, step 4.e): canopy thin with surface fuel reduction (type 1), surface fuel reduction-only (type 2), canopy thin without surface fuel reduction regardless of whether the slash was otherwise rearranged (types 3, 5, and 6), and surface rearrangement-only (type 4). There are currently not enough studies to support a separation of whole-tree extraction from slash rearrangement or simply letting it lay (table 4, step 4.f: $w = 0.10$). The one study of thinning-only in a deciduous forest was grouped with the two studies of surface fuel rearrangements in that vegetation type, as the effect sizes were similar (0.80 versus 0.00<1.45<2.89).

Treatment Age

The median age of the treatments included in our synthesis was 3 years old when tested by fire, with a maximum of 20 years old in conifer forests, 8 years old in other woodlands, and 2 years old in grasslands. Treatments involving rearrangement of surface fuels were the most recent (median age of less than 1 year), followed by surface fuel reduction treatments (median age of 2.5 years).

Canopy-only treatments were generally oldest when affected by fire with a median age of 5 years.

We considered several variations of treatment age to further explain remaining variability within conifer forests, including surface reduction treatments categorized as recent (less than 10 years) or old (table 4, step 5.a), both surface reduction treatments and canopy treatments categorized as recent or old (table 4, step 5.b), and age of surface reduction as a continuous predictor of treatment effect size (table 4, step 5.e). The separation of old and new at approximately 10 years was apparent from visual inspection of the scatter plot of effect size versus treatment age (figure 5) and was the break point that minimized model error and *AICc*.

The most informative treatment age model distinguished recent surface reduction treatments in conifer forests from those older than 10 years, with older surface reduction treatments then grouped with surface rearrangement treatments (table 4, step 5.a). The model was further improved by removing the regional distinction between U.S. and non-U.S. studies (table 4, step 5.c: $w = 0.52$). Distinguishing slash treatments by any method other than recent reduction remained unsupported given the available data (table 4, step 5.d), thus treatment types 3, 5, and 6 from table 2 were grouped together along with those treatments of type 1 that were more than 10 years old. Treatment age was not explored as a predictor of effect size in grasslands and woodlands due to the paucity of available studies within

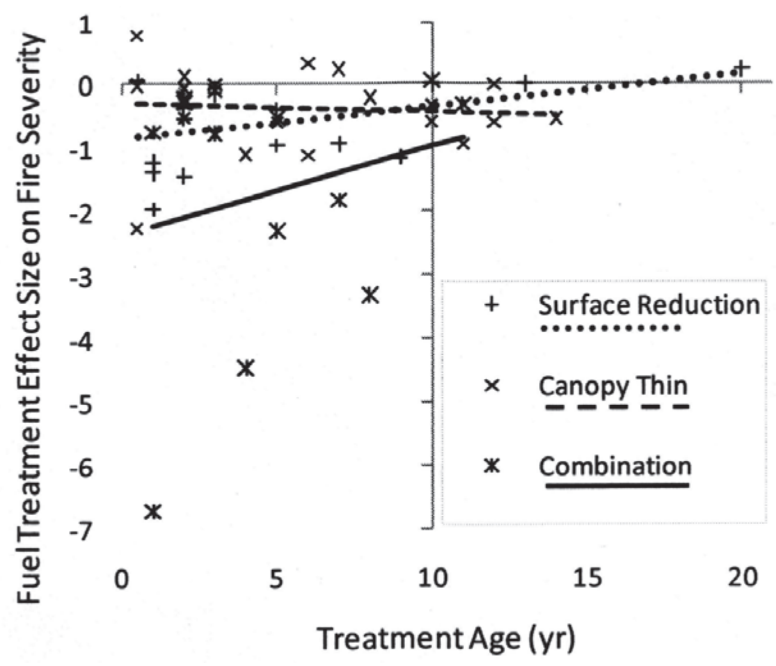

Figure 5—Fuel treatment effect size versus treatment age distinguished by treatment type among studies conducted in coniferous forests.

treatment categories and the limited range of treatment ages that have been investigated in these vegetation types. Mean effect sizes with 95% confidence intervals for the three vegetation groups and separated by the selected treatment type and age categories are displayed in figure 6 for coniferous forests and in figure 7 for grasslands and woodlands.

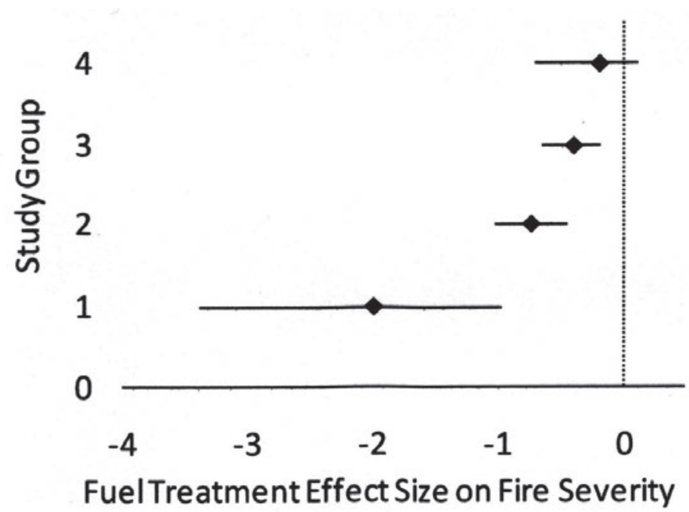

Figure 6—Fuel treatment effect sizes (mean and 95% confidence interval) among studies conducted in coniferous forests and grouped by (1) thinning followed by recent (<10 years prior to wildfire) surface fuel reduction, (2) recent surface fuel reduction with no canopy treatment,(3) surface fuel treatment excluding recent reduction, and (4) thinning without recent surface fuel reduction.

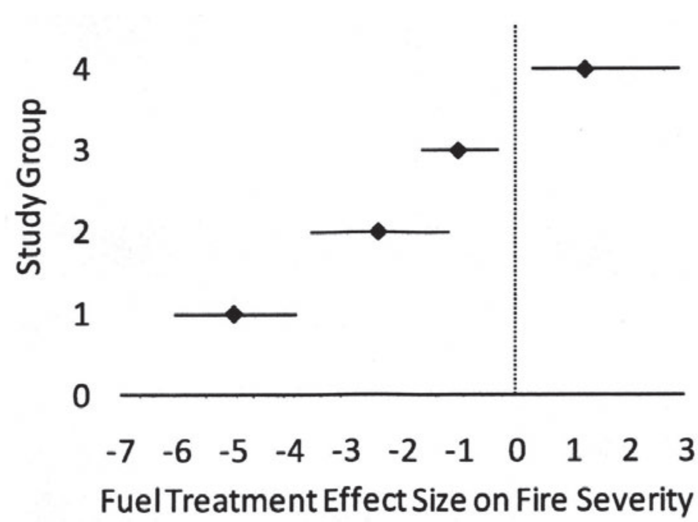

Figure 7—Fuel treatment effect sizes (mean and 95% confidence interval) among studies conducted in ecosystems other than coniferous forests and grouped by (1) surface fuel reduction in grasslands, (2) surface fuel rearrangement in grasslands, (3) surface fuel reduction in woodlands, and (4) surface fuel rearrangement in woodlands (including thin-only).

Treatment Intensity

Finally, we investigated whether our meta-analytic model would be improved by including a measure of treatment intensity. We considered four measures of treatment intensity for studies conducted in conifer forests: treatment effect size (log response ratio) on residual tree diameter, effect size on height to canopy, effect size on canopy bulk density, and a composite measure of treatment intensity calculated as the average of treatment effect sizes on all of the above (with the effect on canopy bulk density inverted). As a point of reference, untreated stands had an average tree diameter of 25.3 cm, an average height to canopy of 4.7 m, and an average canopy bulk density of 0.11 kg/m^3. Though treatment effects on surface fuels likely would be an informative measure of treatment intensity as well, pre-wildfire loadings generally cannot be reconstructed in retrospective studies (Martinson and Omi 2008) and were not reported with enough consistency to include in our synthesis ($n<5$ for all treatment categories).

Recent surface reduction treatments preceded by canopy thinning produced the greatest change in all measures of treatment intensity (MES = 0.51, 0.73, and -0.93 for residual tree diameter, height to canopy, and canopy bulk density, respectively, with all 95% confidence intervals excluding zero). The best predictor of this treatment type's effect on crown scorch metrics of wildfire severity was the composite that combined all three measures ($r^2 = 0.62$, versus 0.43 for residual diameter, 0.36 for canopy bulk density, and 0.26 for height to canopy). Thinning followed by surface fuel reduction on average increased mean tree diameter by 16.8 cm (range in percent change = -11% to 228%), raised height to canopy by 5.0 m (range in percent change = 0% to 267%), and reduced canopy bulk density by 0.07 kg/m^3 (range in percent change = -78% to 6%).

Recent surface reduction without canopy treatment was found to increase both residual tree diameters (mean effect size [MES] = 0.22) and height to live canopy (MES = 0.42) by significant amounts (95% confidence interval does not include zero), though the differences in tree diameters had the strongest relationship to differences in wildfire severity for this treatment type ($r^2 = 0.28$ versus $r^2<0.04$ for all other measures of treatment intensity). Recent surface reduction treatments on average effectively increased mean tree diameter by 6.2 cm (range in percent change = -15% to 95%) and height to canopy by 2.5 m (range in percent change = -11% to 828%).

Canopy treatments not followed by recent surface reduction significantly increased residual tree diameters (MES = 0.22) and decreased canopy bulk density (MES = -0.74), but no measure of treatment intensity demonstrated a relationship to wildfire severity for this treatment type (all $r^2<0.06$ with canopy bulk density marginally strongest). These treatments on average increased mean tree diameter by 6.2 cm (range in percent change = -11% to 112%) and reduced canopy bulk density by 0.06 kg/m^3 (range in percent change = -93% to 70%).

Surface treatments other than recent fuel reduction and not preceded by canopy thinning had no significant effect on any measure of treatment intensity, and these were not assessed for a relationship to wildfire severity due to the small number of available studies in this treatment category (n = 3 that included treatment intensity data).

The best measure of treatment intensity for each treatment type was then considered for inclusion in the overall meta-analytic model (table 4, steps 6.a-b, e). Visual inspection of the scatter plots of treatment intensity effect sizes versus fire severity effect sizes also suggested a threshold effect for the thinning followed by surface reduction treatment type, such that studies with a composite intensity value less than 0.80 (a change to a less hazardous condition of approximately 125%, as measured by the combination of tree diameter, height to canopy, and canopy bulk density) appear to perform more like surface reduction-only treatments (figure 8).

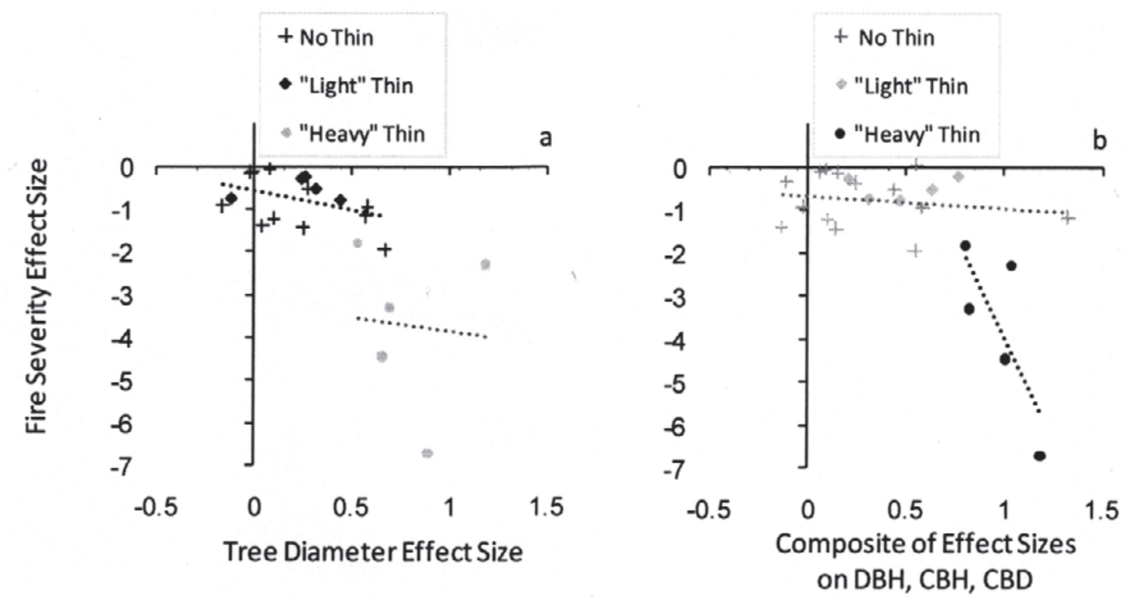

Figure 8—Scatter plots for studies conducted in coniferous forests that included recent surface reduction treatments showing fuel treatment effect sizes on fire severity versus two measures of treatment intensity; (a) effect size on residual tree diameter and (b) a composite of effect sizes on residual tree diameter (DBH), height to canopy (CBH), and inverted canopy bulk density (-CBD). Surface reduction treatments are distinguished by whether they were preceded by "heavy" thinning (composite measure of intensity≥0.8), "light" thinning (composite intensity<0.8), or no thinning.

The most informative treatment intensity models distinguished "heavy" thinning from "light" thinning (table 4, step 6.c), grouped light thinning with no thinning when followed by recent surface fuel reduction, and included the composite indicator of treatment intensity as a continuous predictor of the effectiveness of heavy thinning treatments that were followed by recent surface fuel reduction (table 4, step 6.d). The final model selected (table 4, step 6.f: w = 0.89) also grouped thinning treatments not followed by recent surface fuel reduction with surface treatments in conifer forests other than those involving recent reduction (that is, rearrangement or reduction treatments more than 10 years old). While there appears to be some relationship between the effect of recent surface reduction on residual tree diameter and subsequent fire severity (figure 8.a), it is not strong enough to support inclusion in the overall model (table 4, step 6.b: w = 0.00).

Final Model Parameterization

The last model displayed at the bottom of table 4 was the final model selected for our meta-analysis of the literature on fuel treatment effectiveness; it is highly significant ($p < 0.001$) and explains 78% of the variability in reported findings (figure 9). The parameterized final model may be expressed as:

$$\hat{y} = -0.36 - 0.32T({}_{10}s\text{-}) + 6.11T(c_h+{}_{10}s\text{-}) - 9.43T(c_h+{}_{10}s\text{-}) * T_i + 1.59V(w) - 1.93V(w) * T({}_{10}s\text{-}) - 2.07V(g) - 2.24V(g) * T({}_{10}s\text{-}), \quad [3]$$

where $\hat{y}$ is the estimated fire severity effect size expressed as the natural log of the ratio of percent crown volume scorch in a treated area to crown scorch in an adjacent and topographically similar untreated area; $T({}_{10}s\text{-})$ is an indicator variable equal to 1 for surface fuel reduction treatments completed less than 10 years prior to a wildfire; $T(c_h+{}_{10}s\text{-})$ is an indicator variable equal to 1 for surface fuel reduction treatments completed less than 10 years prior to a wildfire and preceded by heavy thinning such that T_i is at least 0.8; T_i is a measure of thinning intensity calculated as the average of the treatment effect sizes on mean residual tree diameter, height to canopy, and canopy bulk density with the latter multiplied by -1; $V(w)$ is an indicator variable equal to 1 for woodlands other than conifer forests; and $V(g)$ is an indicator variable equal to 1 for grasslands. The intercept value of -0.36 thus represents the expected effect size when all indicator variables are equal to zero, that is, any treatment in a conifer forest that does not include recent surface fuel reduction.

Effect size estimates for fire behavior observations in woodlands and grasslands are scaled for comparison purposes to the effect size estimates calculated from fire severity measurements in coniferous forests. Observed effect sizes from flame length measurements would be approximately half as large as estimates predicted by the meta-analytic model within the detectable range of crown volume scorch measurements. Had we restricted the meta-analysis to only those studies

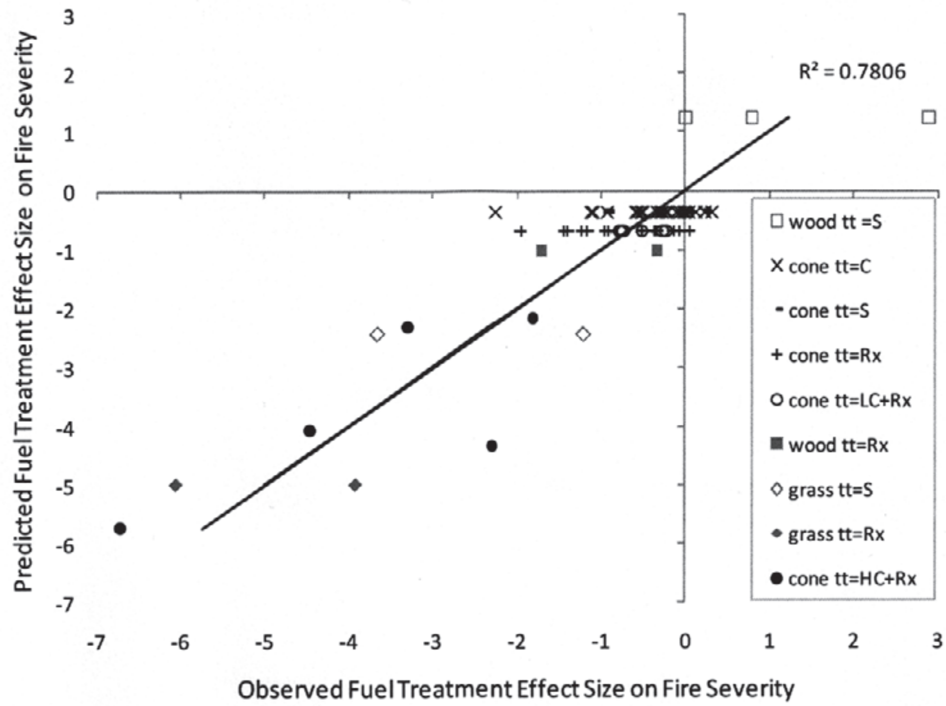

Figure 9—Predicted versus observed fuel treatment effect sizes on fire severity (negative values indicate lower severity in a treated area). Legend abbreviations are: cone = conifer forest, wood = woodland other than conifer forest, grass = grassland, C = canopy thin, HC = heavy thin, LC = light thin, Rx = recent surface fuel reduction, and S = surface fuel treatment other than recent reduction.

that reported responses in terms of crown volume scorch, then woodlands and grasslands would be excluded from the model, the mean effect size estimate for recent surface fuel reduction treatments in conifer forests would be 15% larger with its 95% confidence interval 23% wider, and the estimate for any treatment in a coniferous forest that does not include recent surface fuel reduction would be 7% smaller with its 95% confidence interval 5% wider.

Diagnostics for Bias

An unweighted meta-analysis such as that presented here may be unduly influenced by large and inaccurate effect sizes produced by small studies. Any research synthesis is also vulnerable to publication bias—a tendency for statistically non-significant results or unexpected findings from small studies to be omitted from the published literature. The funnel plot for all studies included in our meta-analysis (figure 10a) suggests possible bias from small studies; small study effect sizes are larger and more variable about the overall mean than are effect sizes from larger studies. The plot is also asymmetrical with an apparent omission of small studies that demonstrate counter-productive treatment effects.

However, funnel plots may be misleading when there is real heterogeneity among study categories (Lau and others 2006). Evidence of small study bias largely disappears when studies are segregated by the categories selected in our final meta-analytic model (figures 10.b-d). Significant small study bias would be indicated by a strong correlation either between study size and effect size or between study size and deviation from the group mean, but such correlation coefficients were found to be weak ($r<0.33$) and not significantly different from zero ($p>0.15$) for all study groups. We therefore conclude that our meta-analysis was not compromised by potential small study biases.

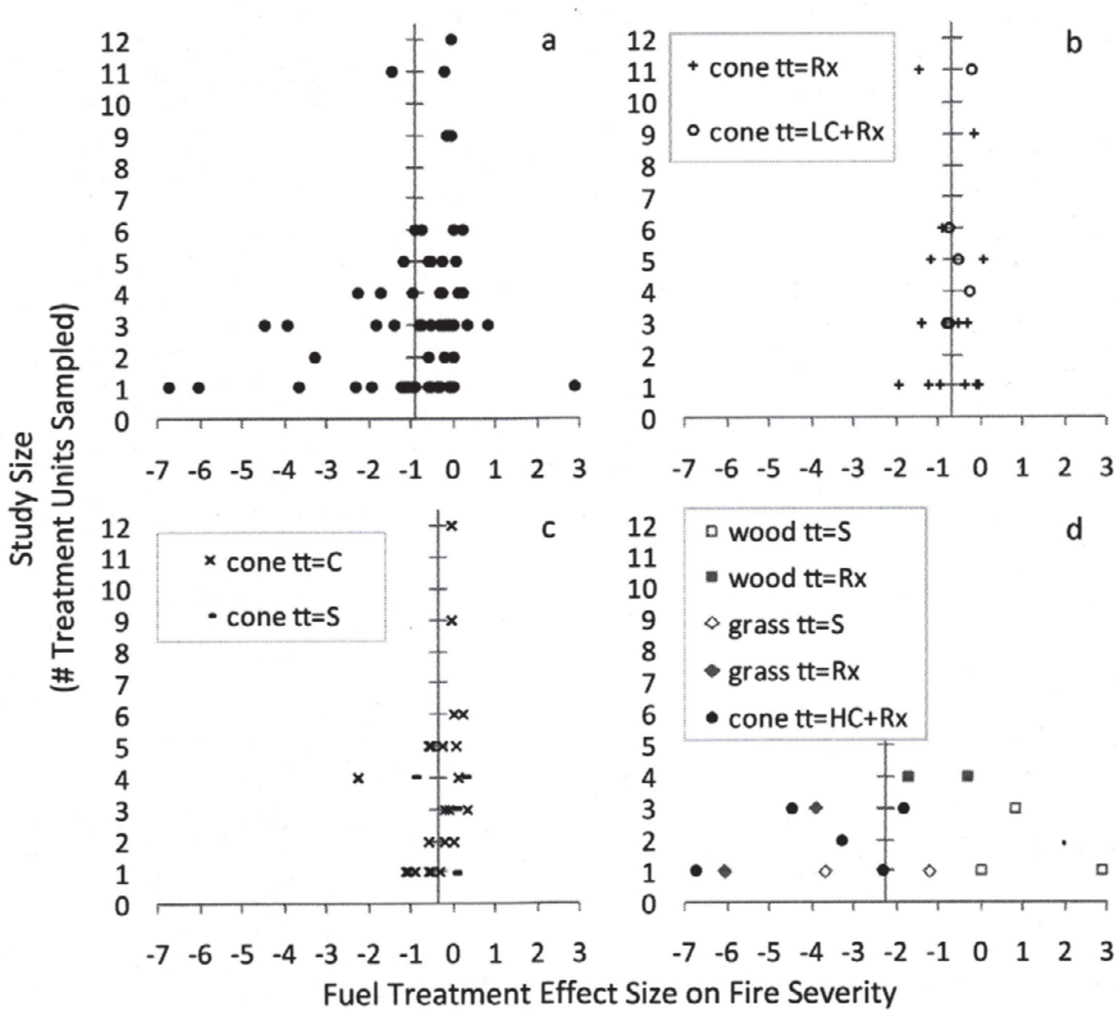

Figure 10—Funnel plots of study size versus effect size: (a) across all studies, (b) among studies in coniferous forests that included recent surface fuel reduction not preceded by heavy thinning, (c) among studies in coniferous forests treated by any means that did not include recent surface fuel reduction, and (d) among the less well-studied groups not included in (b) or (c). The asymmetrical form of (a) is suggestive of publication bias in the fuel treatment literature, but also appears to be explained by the study grouping selected for the final meta-analytical model. Legend abbreviations are: cone = conifer forest, wood = woodland other than conifer forest, grass = grassland, C = canopy thin, HC = heavy thin, LC = light thin, Rx = recent surface fuel reduction, and S = surface fuel treatment other than recent reduction.

Discussion

Previous reviews of the literature on fuel treatment effectiveness have noted above all a paucity of empirical data and heavy reliance on anecdote, theory, and modeling (Carey and Schumann 2003, Martinson and Omi 2003, Graham and others 2004, Peterson and others 2005). Martinson and Omi (2003) abandoned an initial attempt to conduct a meta-analysis on this topic due to the lack of comparable quantitative information. But the literature on fuel treatment effectiveness has expanded considerably in the last few years and the number of publications (19) we were able to include in this meta-analysis is comparable to others that have recently been conducted on fuel treatment topics (22 in Kalies and others' [2010] meta-analysis of wildlife responses, 12 in Boerner and others' [2009] meta-analysis of effects on soil properties, 8 in Kopper and others' [2009] meta-analysis of effects on fuel loads, and 7 in Youngblood's [2010] meta-analysis of effects on diameter distributions). Our synthesis of fuel treatment effectiveness studies highlights several considerations that both support and inform the current fuels management paradigm.

We found that the overall mean effect of fuel treatments on fire responses is large and significant, equating to a reduction in canopy volume scorch from 100% in an untreated stand to 40% in a treated stand, a reduction in scorch height from 30.5 m to 16.1 m, or an inferred reduction in flame length from 3.4 m to 2.1 m. But our synthesis demonstrates that fuel treatments vary widely in effectiveness, which is largely explained by vegetation and treatment type.

Treatments have proved most effective in grasslands and in conifer forests that were heavily thinned and subsequently burned, while the least effective treatments have been mechanical rearrangements in woodlands. The extreme case of treatment effectiveness observed a reduction in crown volume scorch from 83% in untreated mixed conifer forest to less than 1% in an adjacent stand that was thinned and burned one year previously (an effect size 7.5 times larger than the overall mean). The extreme case of treatment ineffectiveness reported an increase in flame length from 25 cm in untreated oak woodland to 74 cm in adjacent fuels treated by mechanical mastication (an effect size 3.2 times greater than the mean and in the opposite direction).

The relative effectiveness of treatments in grasslands, conifer forests, and woodlands is as would be expected from the hypothesis that treatments will be most effective where available fuel accumulates most rapidly and where fire was historically most frequent, based on coarse fire regime constructs (such as Schmidt and others 2002). However, we were surprised to find no differences in fuel treatment effectiveness between long-needle pine and mixed conifer forests or between the northern and southern latitudes of the western United States. This suggests that fuel treatment effectiveness may be less sensitive to climatic gradients in western forests than has been proposed in previous reviews (Schoennagel and others 2004), though it should be noted that none of the studies included in our synthesis extended into the upper elevations or latitudes dominated by short-needle conifers where fire was historically least frequent. One anecdote from such systems indicates that thinning may exacerbate fire behavior (Alexander and Lanoville 2004), but data have not been presented that could be included in our synthesis.

That no relationship (r^2<0.06) was found between canopy fuel variables and the effectiveness of either surface reduction treatments without thinning or thinning treatments without subsequent slash treatment supports the assertion that surface fuel reduction is of primary importance in influencing treatment effectiveness. Much of the variability within these treatment types would likely be explained by the amount of change in surface fuels that was actually produced, but surface fuels information was not reported with enough consistency to include in our synthesis.

However, it is notable that more often than not, thin-only treatments have been found to moderate fire responses in spite of the addition of slash fuels to the surface, though to a lesser degree than surface reduction treatments with or without prior thinning. Just 5 of the 18 studies of untreated slash (including the one where slash was left in piles) reported a counter-productive treatment effect, as compared to 1 of 3 studies of masticated fuels, 1 of 3 studies of underburns more than 10 years old, and 1 of 17 studies of more recent surface fuel reduction treatments (figure 3). The effectiveness of thin-only treatments likely depends on whether fire enters the treated stand as an active crown fire or as a surface fire, as the additional surface fuels increase the likelihood of torching, but the more open canopy reduces the likelihood of sustained crown fire (Scott and Reinhardt 2001).

The best available predictor of the effectiveness of surface reduction treatments was residual tree diameter. This variable was also included along with canopy variables as a predictor of the effectiveness of treatments that combined thinning and burning. Thus, Agee and Skinner's (2005) recommendation to favor retaining large trees over small ones in order to improve the fire resistance of treated stands is supported. Thinning followed by surface fuel reduction was found to be the most effective type of treatment, as expected, but the added benefit of thinning appears to depend upon achieving a substantial change to canopy fuel conditions. A threshold was identified for the effectiveness of these combination treatments; those that achieved at least a 100% change to a less hazardous stand condition increased in effectiveness as fuel hazard decreased (as measured by the average change to mean tree diameter, height to canopy, and canopy bulk density). Lighter thinning treatments that reduced canopy fuel hazard by less than 125% appear to perform no differently than surface fuel reduction treatments that did not include any mechanical thinning (figure 8). Based on average conditions in the represented untreated stands, the necessary thinning intensity to achieve any benefit beyond what would be produced by the surface treatment alone corresponds to an increase in mean tree diameter from 19 cm to 42 cm, an increase in height to canopy from 4 m to 9 m, and a decrease in canopy bulk density from 0.09 kg/m^3 to 0.04 kg/m^3. We hasten to caution against any inference of thinning effectiveness beyond the data included in our meta-analysis and note that further reductions in canopy fuel hazard beyond 150% would be of marginal practical value even when followed by treatment of the slash, corresponding to a reduction in expected crown volume scorch in the treated area from 5% to something less. Also, no relationship was found between thinning intensity and subsequent fire response among the thin-only treatments, suggesting that any benefit from the reduction in canopy fuels is largely offset by the increase in surface fuels until they are reduced as well.

Management Implications

The results of this meta-analysis add empirical support for the basic principles of fuels management proposed by Agee and Skinner (2005) that emphasize the reduction of surface fuels and the preservation of the largest trees in a stand, while recognizing the importance of opening the canopy in order to achieve the maximum benefits of hazard reduction. This meta-analysis also confirms that all treatments may not be beneficial in all locations and provides a quantifiable estimate of the expected relative effectiveness of different types of treatment in broad vegetation categories. However, caution is warranted in extrapolating the results to ecosystems other than long-needle pine and mixed conifer forests due to the lack of empirical information on treatment effectiveness and the potential for negative ecological consequences, such as invasion by more flammable non-native species (Martinson and others 2008).

But treatments that include surface fuel reduction, particularly by prescribed burning, are well supported for moderating potential wildfire behavior in both long-needle pine and mixed conifer forests. These treatments appear to remain effective for up to 10 years, though longevity should be expected to vary by ecosystem productivity. Where crown fire hazard has become so high as to preclude initial entry with prescribed fire, mechanical thinning may be a necessary precursor. Thinning treatments have demonstrated the greatest reductions in wildfire severity, but only by those treatments that produce substantial changes to canopy fuels, shift the diameter distribution towards larger trees, and are followed by broadcast burning or other means of removal. Until the residual activity fuels are disposed, they will largely offset much of the hazard reduction benefit achieved from opening the canopy. While follow-up slash treatment may be generally intended, untreated slash seems to be encountered by large wildfires with surprising frequency (table 2, treatment type 6).

Modifications in fire behavior achieved within a single treated stand, however significant, are unlikely to change the total area burned by a large wildfire, aid fire control efforts, or impact the distribution of severities across a landscape (Finney and others 2003). Fuel treatment effectiveness ultimately depends on the cumulative impact of a treatment regime applied across landscapes and maintained through time. Optimization and assessment of treatment regimes rely on models that presume treatments will perform as expected (Finney and others 2007). Empirical fuel treatment performance studies, such as those included in this meta-analysis, help define the conditions under which theoretical expectations are met. Records of treatment boundaries, prescriptions, and fuel conditions are therefore critical components of fuel treatment implementation to enable effective adaptive management.

Recommendations for Future Research

Wildfires provide the best test of treatment performance under extreme conditions, but information from retrospective studies is limited to that provided by chance encounters. Such encounters are most likely where treatments and wildfires are most common, thus information is unevenly distributed among ecosystems, geographic locations, treatment types, and treatment ages (table 2; figure 10). Our search for studies to include in this synthesis highlights the need for greater attention to identifying treatments encountered by wildfires in all areas other than long-needle pine and mixed conifer forests west of the Rocky Mountains. Also, alternatives to prescribed fire for treating surface fuels have so far received little evaluation in any ecosystem from a fuel hazard perspective. Few of the studies included in our synthesis documented more than a single treatment entry other than follow-up slash treatments, and the relative effectiveness of initial entry treatments versus treatments that have been maintained at varying frequencies is in need of investigation as opportunities arise. The influence of treatment scale on modifying fire behavior both within treatments and beyond them is another consideration that has received little empirical evaluation.

Retrospective wildfire investigations are also limited by their maximum detectable response, which decreases with the height of the dominant vegetation, as well as their capacity to connect treatment effectiveness to the altered condition of any fuels the wildfire consumes. Despite the large overall mean and wide variability in fuel treatment effect sizes demonstrated by our meta-analysis, these were likely small relative to what might have been produced had the recording vegetation been taller or had fire behavior been measured directly. The addition of percent crown volume consumed to percent scorch estimates may provide a closer approximation to the effect of fuel treatments on modifying fire behavior, but has so far not been reported in the literature with enough frequency to include in our meta-analysis (Appendix A).

We suspect that fuel treatment effectiveness also depends on fire weather conditions, such that potential effect size is maximized somewhere between the extremes of low and high fire danger. Under very moderate conditions, fire behavior may be so benign regardless of fuelbed characteristics that there will be little detectable difference between treated and untreated areas. For example, negligible responses to treatments that included recent fuel reduction in our own investigations (Omi and Martinson 2002, Omi and others 2006) occurred on days when the Burning Index of the National Fire Danger Rating System was below the 80th percentile. At the other extreme, fire weather may overwhelm the influence of fuel manipulations, especially those applied at small scales (for example, Finney and others 2003). However, observations of fuel treatment performance have not been connected to fire weather conditions with enough consistency in the extant literature to be considered quantitatively in our meta-analysis. Future studies should fully report all available metrics of fire weather and fuel conditions, as well as treatment responses.

The focus of the literature included in this meta-analysis has been on indicators of fire behavior at the flaming front. But fuel treatment effectiveness also ultimately depends on long-term effects determined by the total heat release that is augmented by post-frontal combustion, including smoldering of large or deeply buried fuels (Neary and others 1999). Indicators of total heat release have been long proposed (Wells and others 1979) with some standardization attempted (Ryan and Noste 1985, Key and Benson 2006), but the ground component of fire severity measurement remains subjective, qualitative, and poorly connected to fire behavior, and thus needs further research attention.

An ideal evaluation of fuel treatment effectiveness would include measurement of all fuelbed components that contribute to flammability, would compare potential fire behavior in treated and untreated fuelbeds with predictive models, and would compare model predictions to observations from experimental fires or serendipitous wildfire events, with connection to post-fire evaluation of fire severity and repeated measurements of vegetation response over time. Direct measurement of fire behavior is the only comparable means to evaluate fuel treatment performance in non-forest ecosystems and is a worthy research endeavor in all, despite a high potential for failure to fully meet experimental objectives (Fites and Henson 2004).

Acknowledgments

This project was funded by the Joint Fire Science Program project 08-2-1-09. We thank L. Scott Baggett, Brandon Collins, Molly Hunter, and Jolie Pollet for thoughtful reviews that improved this manuscript and Paula Fornwalt for coordinating publication through the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Appendix A—The 60 publications through May 2010 that contain empirical evidence of fuel treatment effectiveness, indicating study location(s), dominant vegetation type(s), treatment type(s), whether fuel conditions were measured, whether treatment age was reported, the response variable(s) measured, and whether control for weather and topography was demonstrated. The 19 publications that met all criteria for inclusion in the meta-analysis are emboldened.

			Treatment type[a]								Response variable[c]												
Publication	Location	Vegetation	1	2	3	4	5	6	Fuel[b]	Age	1	2	3	4	5	6	7	8	9	10	11	12	Control
Moore and others 1955	**NJ**	**Forest/mixed/ pine-oak**		**X**						**X**					**X**								**X**
Weaver 1957	WA	Forest/conifer/ mixed	X							X												X	
Davis and others 1963	GA	Forest/conifer/ pine		X						X							X					X	
Cumming 1964	NJ	Forest/mixed/ pine-oak		X						X							X						X
Van Wagner 1968	CA	Forest/conifer/ pine	X					X	X	X								X					
Kallander 1969	AZ	Forest/conifer/ pine		X						X												X	
Omi 1977	CA	Forest & chaparral	X																			X	
Wagle and others 1979	AZ	Forest/conifer/ pine		X						X								X	X				X
Minnich 1983	CA/ Mexico	Chaparral & scrub		X																		X	
Martin 1988	SE US	Unspecified		X						X												X	
Wilson 1988	Australia	Grassland	X																			X	X
Dunn 1989	CA	Chaparral		X						X												X	
Omi and others 1991	ID	Forest/conifer/ spruce-fir	X												X								
Buckley 1992	Australia	Forest/deciduous/ eucalypt		X						X				X									
Koehler 1992/93	FL	Unspecified		X						X												X	
Cheney and others 1993	Australia	Grassland				X			X	X		X											X
Vihanek and others 1993	OR	Forest/conifer		X															X				X

(continued)

Appendix A—(Continued)

Publication	Location	Vegetation	Treatment type[a] 1	2	3	4	5	6	Fuel[b]	Age	Response variable[c] 1	2	3	4	5	6	7	8	9	10	11	12	Control
Weatherspoon and others 1995	CA	Forest/conifer/ mixed	X	X		X		X												X			X
Agee 1996	WA	Forest/conifer/ fir	X						X												X		X
Minnich and others 1997	CA/ Mexico	Chaparral		X																		X	
Hall and others 1999	MT	Forest/conifer/ spruce-fir	X	X					X												X		
Keeley and others 1999	CA	Chaparral		X						X												X	
McCarthy and others 2001	Australia	Forest		X							X											X	
Omi and others 2002	**NM/CA/ CO**	**Forest/conifer/ mixed**	**X**	**X**				**X**	**X**	**X**			**X**	**X**	**X**	**X**	**X**		**X**				**X**
Pollet and others 2002	**MT/WA/ CA/AZ**	**Forest/conifer/ pine**	**X**	**X**	**X**				**X**	**X**				**X**	**X**								**X**
Prestemon and others 2002	FL	Forest		X				X		X												X	
Wilmes and others 2002	AZ	Forest/conifer/ pine	X	X				X												X			
Harma and others 2003	OR	Undescribed		X				X												X			
Martinson and others 2003	CO	Forest/conifer/ pine	X	X		X		X												X			
Moritz 2003	CA	Chaparral		X																		X	
Fernandes and others 2004	**Portugal**	**Forest/conifer/ pine**		**X**					**X**	**X**	**X**	**X**		**X**				**X**	**X**				**X**
Kolaks 2004	**MO**	**Forest/mixed/ pine-oak**						**X**	**X**	**X**	**X**												**X**
Oucalt and others 2004	FL/GA	Forest/conifer/ pine		X		X				X								X					
Richburg and others 2004	**MA/NY**	**Forest/deciduous & shrub**				**X**			**X**	**X**	**X**	**X**											**X**
Stone and others 2004	MT	Forest/conifer						X												X			
Finney and others 2005	AZ	Forest/conifer/ pine		X						X										X			
Keeley and others 2005	CA	Chaparral & scrub		X						X					X								

(continued)

Appendix A—(Continued)

Publication	Location	Vegetation	Treatment type[a] 1	2	3	4	5	6	Fuel[b]	Age	Response variable[c] 1	2	3	4	5	6	7	8	9	10	11	12	Control
Raymond and others 2005	**OR**	**Forest/conifer/ fir**	**X**					**X**	**X**	**X**				**X**		**X**		**X**					**X**
Bradley and others 2006	**CA**	**Woodland/mixed/ pine-oak**						**X**		**X**	**X**							**X**					**X**
Cram and others 2006	**AZ/NM**	**Forest/conifer/ mixed**	**X**					**X**	**X**	**X**			**X**	**X**	**X**	**X**	**X**		**X**				**X**
Glitzenstein and others 2006	**SC**	**Forest/conifer/ pine**				**X**			**X**	**X**	**X**	**X**				**X**						**X**	**X**
Omi and others 2006	**CO/AZ/OR/ CA/WA**	**Forest/conifer/ pine & mixed**	**X**	**X**				**X**	**X**	**X**			**X**	**X**	**X**	**X**	**X**		**X**				**X**
Schroeder 2006	NWT	Forest/conifer/ mixed	X						X	X											X		X
Collins and others 2007	CA	Forest/Conifer/ mixed		X																X			
Jain and others 2007	**MT**	**Forest/conifer/ pine**		**X**					**X**	**X**					**X**				**X**				**X**
Moghaddas and others 2007	CA	Forest/conifer/ mixed						X	X	X				X									
Ritchie and others 2007	**CA**	**Forest/conifer/ pine**	**X**					**X**	**X**	**X**				**X**			**X**	**X**					**X**
Strom and others 2007	AZ	Forest/conifer/ pine	X						X								X	X					X
Thompson and others 2007	OR	Forest/conifer/ mixed						X		X										X			X
Keeley and others 2008	CA	Chaparral		X						X					X								
Lezberg and others 2008	CO	Forest/conifer/ pine				X				X									X				X
Martinson and others 2008	**MS**	**Forest/conifer/ pine**		**X**					**X**	**X**			**X**	**X**	**X**	**X**			**X**				**X**
McCaw and others 2008	**Australia**	**Forest/deciduous/ eucalypt**		**X**					**X**	**X**	**X**												**X**
Safford 2008	**CA**	**Forest/conifer/ mixed**			**X**					**X**			**X**	**X**			**X**	**X**					**X**
van Leeuwen 2008	AZ	Forest/conifer/ pine		X						X										X			X
Collins and others 2009	CA	Forest/conifer/ mixed		X																X		X	
Diamond and others 2009	**NV**	**Grassland**	**X**			**X**			**X**	**X**	**X**	**X**											**X**

(continued)

Appendix A—(Continued)

Publication	Location	Vegetation	Treatment type[a]						Fuel[b]	Age	Response variable[c]												Control
			1	2	3	4	5	6			1	2	3	4	5	6	7	8	9	10	11	12	
Safford and others 2009	**CA**	**Forest/conifer/ mixed**					**X**	**X**	**X**	**X**			**X**	**X**	**X**	**X**	**X**	**X**					**X**
Wimberly and others 2009	AZ/MT/ WA	Forest/conifer/ pine	X	X				X												X			X
Prichard and others 2010	**WA**	**Forest/conifer/ mixed**	**X**					**X**		**X**				**X**				**X**					**X**

[a] See table 2 for definitions of treatment types.
[b] Indicator of whether any fuel conditions in both treated and untreated areas were measured pre-fire or reconstructed post-fire, such as surface fuel load and depth, tree density, basal area, tree diameters, height to canopy, and/or canopy bulk density.
[c] Fuel treatment response variables are:
1. Flame length
2. Spread rate
3. Percent crown volume consumed
4. Percent crown volume scorched
5. Canopy damage rating based on scorch and/or consumption
6. Height of needle scorch
7. Height of bole char
8. Percent tree mortality
9. Depth of ground char rating
10. Remotely sensed fire severity rating
11. Binary crown fire indicator
12. Area burned

Appendix B—Summary of the datasets from the 19 publications included in the meta-analysis.

Source	Location	Vegetation	Treatment type[a]	Treatment age	Response variable[b]	U[c]	T[d]	Effect size[e]
Moore and others 1955	NJ	Forest/conifer/ pine	2	2	5	2.6	2.2	-0.3
Omi and others 2002	CA	Forest/conifer/ mixed	2	2	4	71.4	16.9	-1.4
	CO	Forest/conifer/ mixed	2	3	4	57.7	50.1	-0.1
	CO	Forest/conifer/ mixed	6	8	4	88.4	72.3	-0.2
	NM	Forest/conifer/ pine	1	5	4	89.8	53.8	-0.5
	NM	Forest/conifer/ pine	6	2	4	99.6	75.7	-0.3
Pollet and others 2002	WA	Forest/conifer/ pine	1	11	4	100.0	74.0	-0.3
	AZ	Forest/conifer/ pine	2	1	4	99.0	29.0	-1.2
	MT	Forest/conifer/ pine	2	5	4	67.0	26.0	-0.9
	CA	Forest/conifer/ pine	3	4	4	78.0	26.0	-1.1
Fernandes and others 2004	Portugal	Forest/conifer/ pine	2	2	4	100.0	88.0	-0.1
	Portugal	Forest/conifer/ pine	2	3	4	100.0	94.0	-0.1
	Portugal	Forest/conifer/ pine	2	13	4	100.0	100.0	0.0
Kolaks 2004	MO	Forest/mixed/ oak-pine	6	0	6 (1)	12.9	22.7	0.8
Richburg and others 2004	MA	Grassland	2	2	6 (1)	64.0	0.0	-6.1
	MA	Grassland	4	0	6 (1)	64.0	4.8	-3.7
	MA	Grassland	4	0	6 (1)	64.0	27.3	-1.2
	MA	Forest/deciduous	4	0	6 (1)	1.0	1.0	0.0
Raymond and others 2005	OR	Forest/conifer/ mixed	1	1	4	83.0	0.1	-6.7
	OR	Forest/conifer/ mixed	6	6	4	71.0	97.3	0.3
Bradley and others 2006	CA	Woodland/mixed/ oak-pine	4	0	6 (1)	0.3	2.7	2.9

(continued)

Source	Location	Vegetation	Treatment type[a]	Treatment age	Response variable[b]	U[c]	T[d]	Effect size[e]
Cram and others 2006	AZ	Forest/conifer/ pine	1	3	4	100.0	45.9	-0.8
	AZ	Forest/conifer/ pine	6	3	4	100.0	90.8	-0.1
	NM	Forest/conifer/ mixed	1	7	4	97.2	15.9	-1.8
	NM	Forest/conifer/ mixed	1	8	4	100.0	3.7	-3.3
	NM	Forest/conifer/ mixed	6	10	4	99.2	71.5	-0.3
	NM	Forest/conifer/ mixed	6	10	4	94.8	53.6	-0.6
	NM	Forest/conifer/ mixed	6	14	4	100.0	59.4	-0.5
Glitzenstein and others 2006	SC	Forest/conifer/ pine	4	0	6	2.5	1.3	-0.9
Omi and others 2006	AZ	Forest/conifer/ pine	2	2	4	70.7	42.2	-0.5
	AZ	Forest/conifer/ pine	2	7	4	52.8	21.0	-0.9
	AZ	Forest/conifer/ mixed	6	2	4	75.0	59.7	-0.2
	AZ	Forest/conifer/ mixed	6	7	4	61.3	77.2	0.2
	CA	Forest/conifer/ mixed	2	9	4	82.5	25.9	-1.2
	CA	Forest/conifer/ mixed	2	20	4	77.7	96.7	0.2
	CA	Forest/conifer/ mixed	6	1	4	56.2	5.9	-2.3
	CA	Forest/conifer/ mixed	6	5	4	88.1	49.0	-0.6
	CO	Forest/conifer/ mixed	1	1	4	100.0	47.9	-0.7
	CO	Forest/conifer/ mixed	1	10	4	75.6	79.4	0.0
	CO	Forest/conifer/ mixed	2	1	4	81.0	20.1	-1.4
	CO	Forest/conifer/ mixed	2	10	4	100.0	100.0	0.0
	CO	Forest/conifer/ mixed	6	2	4	85.2	96.5	0.1
	OR	Forest/conifer/ mixed	1	2	4	100.0	76.2	-0.3
	OR	Forest/conifer/ mixed	6	0	4	99.7	97.7	0.0
	OR	Forest/conifer/ mixed	6	2	4	88.9	84.1	-0.1
	WA	Forest/conifer/ pine	1	2	4	55.5	44.4	-0.2

(continued)

Appendix B—(Continued).

Source	Location	Vegetation	Treatment type[a]	Treatment age	Response variable[b]	U[c]	T[d]	Effect size[e]
Jain and others 2007	MT	Forest/conifer/ pine	2	0	5	3.1	3.2	0.0
	MT	Forest/conifer/ pine	2	2	5	2.5	2.1	-0.3
	MT	Forest/conifer/ pine	2	5	5	2.9	2.3	-0.4
Ritchie and others 2007	CA	Forest/conifer/ pine	1	4	4	86.0	1.0	-4.5
	CA	Forest/conifer/ pine	1	5	4	99.3	10.0	-2.3
	CA	Forest/conifer/ pine	6	6	4	66.7	22.0	-1.1
Martinson and others 2008	MS	Forest/conifer/ pine	2	1	4	99.0	14.0	-2.0
McCaw and others 2008	Australia	Forest/deciduous/ eucalypt	2	4	6 (1)	31.3	9.3	-1.7
	Australia	Forest/deciduous/ eucalypt	2	8	6 (1)	31.3	24.6	-0.3
Safford 2008	CA	Forest/conifer/ mixed	3	12	4	93.8	52.5	-0.6
Diamond and others 2009	NV	Grassland	2	0	6 (1)	11.8	0.7	-3.9
Safford and others 2009	CA	Forest/conifer/ mixed	1	2	4	94.6	57.0	-0.5
	CA	Forest/conifer/ mixed	5	3	4	99.3	100.0	0.0
	CA	Forest/conifer/ mixed	1	11	4	41.5	16.4	-0.9
Prichard and others 2010	WA	Forest/conifer/ mixed	1	3	4	70.5	32.9	-0.8
	WA	Forest/conifer/ mixed	6	12	4	70.5	70.5	0.0

[a] See table 2 for description of treatment types.
[b] See Appendix A for description of response variables. For five publications, scorch height (6) was estimated from reported flame length or fireline intensity measurements (1) using relationships developed by Van Wagner (1972) and Byram (1959).
[c] Mean response recorded in untreated areas.
[d] Mean response recorded in treated areas.
[e] Effect size calculated as ln (T/U), multiplied by 1.409 for scorch heights (6) or 1.779 for canopy damage ratings (5) to equate to percent crown volume scorch (4)—see figure 2.

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