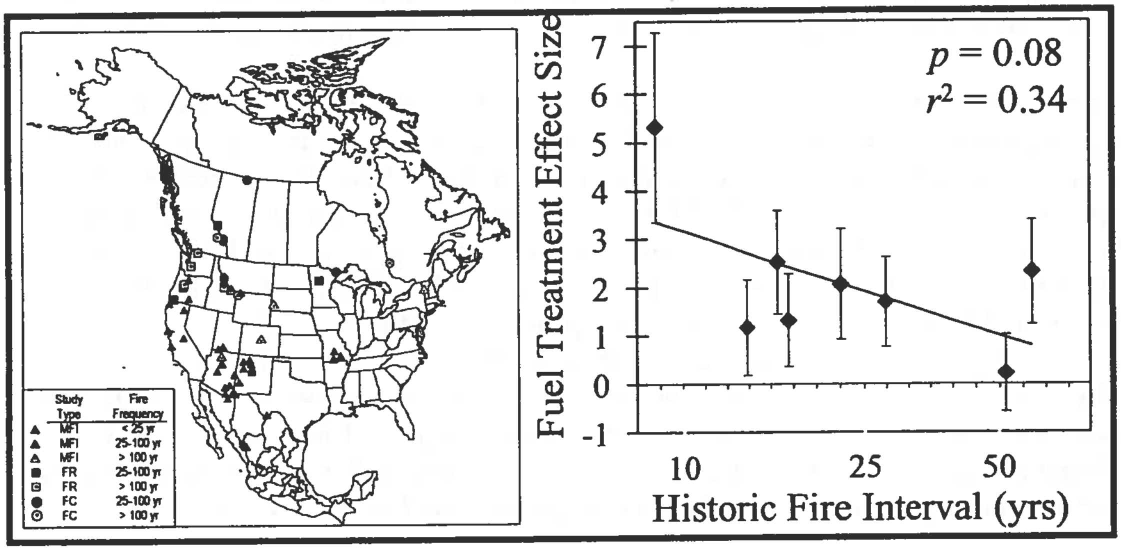
Final Report

Fuel Treatments and Fire Regimes



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Executive Summary

The size and severity of recent fire episodes are widely attributed to altered fuel profiles as a result of fire exclusion and fire regime disruption in many ecosystems. Current national fuels management initiatives propose widespread application of prescribed fire and other treatments both to reduce the potential of catastrophic wildfire and to restore the structure and function of altered ecosystems. However, the chain of hypotheses that link historic fire regimes to appropriate fuel treatment application has not received a systematic assessment. This project seeks to provide such an assessment with a series of quantitative literature syntheses that focus on the following questions: 1) Are the effects of 20th Century fire exclusion on fire frequency related to historic fire regimes? 2) Are 20th century changes in fuel conditions and fire hazard most apparent in ecosystems where fire was historically most frequent? 3) Is there a relationship between historic fire regimes and fuel treatment efficacy? 4) Can geographic variables be used as predictors of historic fire regimes to facilitate their incorporation into fuel management planning?

We standardized the information contained in 75 North American fire history studies to develop a general linear model that predicts historic fire frequency from geographic information (i.e., latitude, longitude, elevation, and aspect). Spatially and temporally standardized mean fire free periods (MFFP) were calculated each study. Development of the fire frequency model employed weighted least squares regression with each study weighted in proportion to statistical confidence about its MFFP estimate. The final model resulted from a 3-way cross-validation procedure and includes the following as predictors of log-transformed historic MFFP: latitude, longitudinal region (east of the Rockies, west of the Cascades/Sierra-Nevadas, and Intermountain West), elevation, and a two-way interaction between elevation and the eastern region. The model is highly significant and can provide reasonable estimates of historic MFFP at sites with unknown fire history in many regions of North America, particularly the western US.

Fire exclusion effect sizes were calculated for each of the fire history studies used to develop the historic fire frequency model. We used the statistical techniques of meta-analysis to determine if there has been an overall change in fire frequencies in the 20th Century and whether this change varies by historic fire regime as predicted from our historic fire frequency model. We found a statistically significant overall mean effect size of fire exclusion when calculated from the combined evidence of all studies. However, the test statistic for heterogeneity among studies was highly insignificant, indicating that variability between studies in mean fire exclusion effect sizes is overwhelmed by uncertainty about the means. Nonetheless, we found that the effect of fire exclusion across ecosystems decreases with marginal significance as historic fire frequency decreases.

Unlabeled photo pairs depicting historic versus recent vegetation conditions at seven diverse locations in the western U.S. were evaluated by 32 wildland fire professionals. Their ratings demonstrated a large and significant increase in perceived crown fire potential and a moderate and significant increase in fire severity potential, but no change in spread rate potential. Perceived changes in crown fire potential and potential fire severity were both significantly related to the historic fire regime of forested photo locations, with the greatest amount of change perceived where fire was historically most frequent.

Finally, we synthesized the results of fire severity assessments in eight recent wildfires that were sampled with standardized methods in adjacent treated and untreated stands. Sampled sites occurred in a variety of conifer forests throughout the Western U.S. and treatments included reduction of surface fuels and crown fuels, both in isolation and in combination. Meta-analysis of these studies indicated that treatment effectiveness is most significantly related to differences in tree size (mean diameter) between treated and untreated stands, but we also found historic fire frequency to be a marginally significant predictor. Our results suggest that fuel treatments will be most effective when they complement ecosystem restoration objectives, such as the removal of small trees from ecosystems that historically experienced frequent fire. We conclude that the historic fire frequency model produced by this project can facilitate incorporation of fire regime considerations into fuels management planning.

Acknowledgments

Mark Finney and William Reed offered helpful comments on some of the calculations necessary for the development of our historic fire frequency model. We thank the participants in the 2001 Technical Fire Management course held in Seattle, WA for their fire potential evaluations of repeat photographs. Corey Larson, Esther Schnur, and Emily White Hat assisted with information retrieval and data entry. Individual sections of this report were reviewed separately and improved by the thoughtful comments of Sarah Gallup, Stacy Lynn and five anonymous reviewers. The Conference on Fire, Fuel Treatments, and Forest Restoration was held in Fort Collins April 16-18, 2002 as a deliverable for this project and was made possible by the Rocky Mountain Research Station and numerous individuals who served as steering committee members, session chairs, field trip leaders, or student volunteers. This project was made possible by funds provided by the Joint Fire Science Program.

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1. Project Background

1.1 *Rationale*

Extreme fire episodes in recent years support assertions of increased wildfire severity, complexity, and cost (e.g., individual fires or complexes exceeded 100,000 acres in 2003 [Montana], 2002 [Alaska, Arizona, California, Colorado, Georgia, and Oregon], 2001 [Alaska, Oregon, and Nevada], 2000 [Alaska, Idaho, Montana, Washington, and Wyoming], 1999 [California, Nevada, and Idaho], and 1998 [Florida]). Natural resource managers and scientists have long attributed increased wildfire potential to altered fuel profiles as a result of 20th Century fire exclusion (Dodge 1972). Current fuels management initiatives propose reducing surface and canopy fuels via prescribed fire, tree removals, and other treatments both to mitigate catastrophic wildfire and to restore ecosystem structure and function (USDA Forest Service 2000).

Fire is a keystone process that influences the structure and function of most natural ecosystems (Agee 1993). However, the general attributes of historic fires varied widely across landscapes such that the historic fire regime concept has developed as an organizing feature of ecosystems (Kilgore and Heinselman 1990). Historic fire regime constructs are now advocated as guides for fire management activities (e.g., Arno et al. 1995; Fule et al. 1997; Agee 2002). A fire regime characterizes the general attributes of historic fire events that contributed to the development and persistence of plant communities. These fire attributes may include frequency, intensity, areal extent, and seasonality (Agee 1993). Covington and Moore (1994) suggest that fire exclusion has had the greatest impact on ecosystems that historically experienced a regime of frequent, small, low intensity fires.

Fire history studies provide widespread graphic evidence that fire exclusion in the 20th Century has dramatically reduced fire frequency in many ecosystems, though this evidence is most abundant from Southwestern ponderosa pine forests (Swetnam et al. 1999). The effects of fire exclusion and the appropriateness of remedial management activities are more debatable in other ecosystems, even in ponderosa pine forests outside the Southwest (Shinneman and Baker 1997). Measures of fire regime alteration (e.g., Keifer et al.'s [2000] Fire Return Interval Departure) and development of fire regime maps (e.g. Hann and Bunnel 2001; Mckenzie et al. 2000; Frost 1998) illustrate the current management need for greater spatial guidance in fuel treatment and forest restoration applications.

Where fire exclusion has altered fire regimes, increased fuel hazard is a reasonable expectation. Since fire is an agent of mortality (Ryan et al. 1988) and a process of accelerated decomposition (Ottmar et al. 1993), reduced fire frequency would be expected to result in greater fire hazard due to increased surface fuel loads, more abundant ladder fuels, and denser canopy fuels (Agee 1996). Euro-settlement era descriptions (e.g., Cooper 1960), photographs (e.g., Gruell et al. 1982; Veblen and Lorenz 1991), and stand reconstructions (e.g. Arno et al. 1995) do support suppositions of increased fuel accumulation in some areas since the advent of organized fire suppression. Nonetheless, the relationship between reduced fire frequency and increased fuel hazard remains a largely untested hypothesis.

Climate and topography, in addition to fuels, influence wildfire behavior. But of these three fire environment factors only fuels can be readily influenced by management action. If past management activities have increased fuels and the incidence of expensive catastrophic wildfires, pre-suppression treatments to reduce fuels and wildfire potential may be economically justified. Further, where human ignitions and increased fuel loads have altered the timing and intensity of fires, fuel treatments may be ecologically justified to restore fire to its 'natural' role. Reviews of the effects of various fuel treatments on fuels exist, as do reports of changes in wildfire intensity across treatment areas (Omi 1997). However, the immediate and long-term effectiveness of fuel treatments in modifying potential wildfire behavior across ecosystems and treatment intensities remains to be quantitatively synthesized.

1.2 *Objectives and Hypotheses*

The goal of this research was to assess current ecological justifications for national fuel management programs through quantitative syntheses of existing information. We addressed 5 objectives in support of our research goal:

1. Synthesize available information on changes in historic fire regimes since initiation of fire exclusion policies in the US.
2. Relate 20^{th} Century changes in fuel hazard to historic fire regimes.
3. Assess fuel treatment effectiveness for reducing fire behavior potential in ecosystems with different fire regimes.
4. Identify knowledge gaps in our understanding of fire regimes and fuel treatments.
5. Convene a conference for the dissemination of current information on fuel treatments and forest restoration.

We tested four null hypotheses in support of our research goal:

H_{o1}: Variations in historic fire frequencies cannot be explained by geographic variables.

H_{o2}: 20^{th} Century fire frequency reductions are not positively correlated to historic fire frequencies.

H_{o3}: 20^{th} Century fuel hazard increases are not positively correlated to historic fire frequencies.

H_{o4}: Fuel treatment effectiveness is not positively correlated to historic fire frequencies.

2. Geographic Variations in Historic Fire Regimes

A fire regime is characterized by a number of factors, including frequency, intensity/severity, size, and seasonality (Agee, 1993). However, empirical information on historic fire regimes is limited to those areas where fire history studies have been conducted and restricted primarily to frequency estimates. Measures of fire frequency vary by the types of vegetation in which fire history studies are conducted, but tree-ring analyses provide the greatest spatial and temporal resolution. Measures of fire frequency based on tree-ring analysis include the Mean Fire Interval (MFI), Fire Rotation (FR), and Fire Cycle (FC). The appropriate measure depends on the characteristic intensity of historic fires and vegetation sensitivity to fire induced mortality (Agee, 1993). An MFI is commonly calculated in ecosystems that generally experience relatively low severity fires, an FC is most appropriate where fires destroy existing vegetation and initiate even-aged stands, while an FR may be calculated where fires are variable in severity. Each measure involves distinct assumptions and limitations, but all attempt to estimate the same parameter – the average interval between fires at any point on a given landscape (Johnson and Gutsell 1994).

Both FC and FR derive point fire frequencies from a spatial distribution of fire dates via space-for-time substitutions, while an MFI may provide a point fire frequency from the actual temporal distribution of fire dates recorded by trees at individual points (Lertzman et al. 1998). However, MFI's are often calculated and reported as composites for entire study areas rather than for points. Since trees rarely record every fire they experience, it is generally considered more realistic to assume the entire study area was burned by any fire that scarred a portion of the sampled trees (Dieterich 1980). But the resultant composite MFI's are impossible to compare between studies since they are dependent on study area size (Arno and Petersen 1983; Baker and Ehle 2001) in a way that is both non-linear and probably site-specific. Composite MFI's are also much more sensitive to dating errors, particularly when cross-dating methods are not employed (Madany et al. 1982). Quantitative synthesis of fire history studies therefore requires spatial standardization through calculation of point fire frequencies for all studies.

Fire frequencies reported in the literature are also incomparable temporally and are not equal in accuracy. Reported fire frequencies are referenced to time periods that differ among studies by species' life spans and individual research objectives (Lertzman et al. 1998). Since fire frequency may change over time with climatic and human land use fluctuations, quantitative synthesis of fire history studies should analyze fire frequencies from a standardized temporal scale. Also, extrapolations from a synthesis of average fire frequencies will be biased unless the model is developed from means weighted in proportion to their variance (Cooper and Hedges 1994).

We developed a continental fire frequency model based on a quantitative research synthesis in which frequencies reported in extant tree-ring studies were standardized both spatially and temporally and weighted in proportion to their variance. Our model is intended to provide a first estimate of historic fire frequency in North American locations where no local fire history information currently exists, which may facilitate quantification of land management objectives related to historic fire regimes.

2.1 *Methods*

Development of our synthetic model comprised four procedures: literature search for studies to include in the synthesis, extraction of information on site characteristics and fire frequency from each study, development of a general fire frequency model with study site characteristics as predictors, and validation of the final model. Within the bounds of our literature search and selection criteria this synthesis is comprehensive of all fire history studies. However, we have no doubt that our search method overlooked some studies, that relevant unpublished studies exist, and that there are locations and ecosystems with unstudied fire history. Therefore, our synthesis may not accurately reflect actual fire history in all North American locations.

2.1.1 *Information Sources*

Our literature search relied on four sources to identify fire history studies: the 1970-1999 AGRICOLA database (Cambridge Scientific Abstracts, 1999), the University of Arizona's online *Bibliography of Dendrochronology* (Grissino-Mayer 1996), Heyerdahl et al.'s (1995) *Fire History Database of the Western United States*, and Mastrogiuseppe et al.'s (1983) *Forest and Rangeland Fire History Bibliography*. The synthesis includes all citations identified with these sources that met the following selection criteria: (*i*) Conducted in North America. (*ii*) Reported in English. (*iii*) Published in a peer-reviewed journal, conference proceedings, or as a federal agency scientific report. (*iv*) Provided sufficient information to calculate a point-fire frequency for the period 1710-1779. This 70 year period was chosen to represent historic fire frequency after noting the earliest date of European settlement reported in our selected studies (1779 *op cit* Baisan and Swetnam 1997) and to provide a temporal frame of reference comparable in extent to the post-1930 epoch of effective fire suppression (Pyne 1982). Also, few fire history studies based on tree-ring analyses extend back beyond 1700 (Lertzman et al. 1998).

Four geographic variables (latitude, longitude, elevation, and aspect) were extracted from each study and explored as predictors of the study area's historic fire frequency. All studies provided an elevation for their research site, though it was generally a range for which we calculated the midpoint. Many studies did not provide a latitude and longitude for their research sites, in these cases we obtained approximate values with the aid of geographic nameservers available on the Internet, primarily a USDI Geological Survey (2000) website (http://geonames.usgs.gov/pls/gnis/web_query. gnis_web_query_form). Latitude and longitude were converted to decimal degrees and longitude was also classified by one of three regions: east of the Rocky Mountains, west of the Cascade-Sierra-Nevada Mountains, and Intermountain. Aspect was classified as north, south, or unspecified for each study. We also noted the dominant vegetation species, mean annual precipitation (as reported in the study or from the nearest weather station provided online by the Western Regional Climate Center (2000) at http://www.wrcc.dri.edu/climsum.html), the general severity (lethal, non-lethal, mixed) of fires observed in each study, and whether or not the study was cross-dated.

We used one of three methods to calculate a point fire frequency statistic from the information presented in each study for the period 1710-1779 (see Table 1 for equations). We calculated Mean Fire Intervals for studies that provided fire scar dates with the statistical methods presented by Lawless (1982) for lifetime data that follows a negative exponential distribution with Type I censoring and sample replacement. Data were Type I censored since open intervals resulted from exclusion of information outside the dates of our pre-determined period and samples were considered replaced since trees generally survived fires to record multiple 'lifetimes'. We calculated fire cycles for studies that presented cumulative area distributions for stand age classes with the statistical methods presented by Reed et al. (1998) for estimating temporally distinct hazards from time-since-last-fire data. All cumulative area distributions were also assumed to follow a negative exponential model. We calculated fire rotations for studies that reconstructed past fire areas from a combination of fire scars, stand origin dates, and logical decision rules with the estimate proposed by Heinselman (1973).

Table 1. Equations for calculating means and confidence intervals for the three types of data presented in fire history studies that provide point fire frequency information. The equations allowed an unbiased synthesis of standardized means weighted in proportion to statistical confidence.

	Mean	95% Confidence Interval
Mean Fire Interval (MFI)[a]	$\hat{\theta} = \left(\sum_{j=b}^{E}\sum_{i=1}^{n} T_{i(j)}\right)/r$	$\{\theta; \Lambda \le \chi^2_{1;0.05}\}$ $\Lambda = -2r\ln\left(\frac{\hat{\theta}}{\theta}\right) + 2r\left(\frac{\hat{\theta}}{\theta} - 1\right)$
Fire Rotation (FR)[b]	$\hat{\theta} = (E - B)/P$	$\{\theta; \Lambda \le \chi^2_{1;0.05}\}$ $\Lambda = -2nP\ln\left(\frac{\hat{\theta}}{\theta}\right) + 2nP\left(\frac{\hat{\theta}}{\theta} - 1\right)$
Fire Cycle (FC)[c]	$\hat{\theta} = 1/\left[-\frac{1}{t}\ln\hat{S}_0\right]$ *where* $\hat{S}_0 = \frac{\sum_{j=E}^{B+t} C_j}{\sum_{j=E}^{B+t}(C_j + A_j)}$ *and* $C_j = \sum_{i=j-t}^{B} A_i$	$\{S_0; \Lambda \le F_{1,[(E-B)/t]-1,0.05}\}$ $\Lambda = \sum_{j=E}^{B+t}\left[C_j\ln\left(\frac{\hat{S}_0}{S_0}\right) + A_j\ln\left(\frac{1-\hat{S}_0}{1-S_0}\right)\right]$

Notes: $\hat{\theta}$ is a point fire frequency estimated for the period that begins with the first year recorded after the start of 1710 (*B*) and ends with the last year recorded prior to 1780 (*E*), θ is the set of values that include the true mean frequency with (approximately) 95% confidence.

[a] $T_{i(j)}$ is a fire-recording tree in year *j*, *r* is the total number of scars recorded by all trees between *B* and *E*.

[b] *P* is the proportion of a study area burned between *B* and *E*, *n* is the size of the study area.

[c] $\hat{S}_0$ is the average point survival probability between *B* and *E*, S_0 is the set of values that include the true mean survival probability with (approximately) 95% confidence, A_i is the amount of area in an age class of width *t* that ends at the start of year *i*, and C_j is the cumulative area burned prior to the year *j-t*.

Fire dates were taken directly from tables or manually digitized from graphs with an engineer's scale. Area information for FC and FR calculations was likewise obtained from tables and graphs except for two cases in which we used dot grids to extract information from maps. The three statistics (MFI, FR, and FC) each represents a more easily interpreted reciprocal of point fire frequency and are not distinguished in our model. For simplicity, we therefore refer to any or all of the three statistics with a single term - mean fire free period (MFFP).

2.1.2 *Statistical Analysis*

We used the information extracted from the selected fire history studies to develop a weighted multiple linear regression model with historic (1710-1779) MFFP as the response variable and geographic characteristics as predictors. Each study was weighted in proportion to statistical confidence about its estimated MFFP (as measured by the inverted width of its 95% confidence interval (CI)). We calculated the asymmetrical CI's numerically with likelihood ratio methods suggested by Lawless (1982) for MFI estimates, adapted from Lawless (1982) for FR estimates, and adapted from Reed et al. (1998) for FC estimates (see Table 1 for equations). We hasten to add that these CI's are not exact, but merely approximations used to assign relative weights in an attempt to build a model that produces best linear unbiased estimates (Neter et al. 1990).

The equations for CI's shown in Table 1 assume a negative exponential distribution produced by a Poisson process and derived from independent samples. While a negative exponential model may be reasonable in most cases, fire is a contagious process that leaves spatially non-independent evidence (Reed et al. 1998). Non-independent samples produce an overdispersed distribution with underestimated variance (though expected means are unaffected). Reed et al. (1998) propose a contagion scalar to correct CI's calculated for FC with the equation in Table 1. However, since similar corrections are not currently available for MFI and FR, we excluded Reed et al.'s (1998) scalar to avoid under-weighting FC studies relative to other studies.

A method to estimate variance for FR has not been formally developed, so we adapted the CI equation for MFI to allow inclusion of fire history studies conducted in areas where FR is the best or only measure of historic fire frequency obtainable. Our adaptation simply equates area burned in FR studies to total number of scars in MFI studies, which would hold if fire history studies could produce perfect information. Unfortunately, the quantity of area burned, and thus the CI for FR, depends on the choice of unit-area. This is also the case for FC when the equation for its CI is not multiplied by Reed et al.'s (1998) contagion scalar. We investigated the effect of expressing area in various units ranging between 1 ha and 1 km^2 on the distribution of weights assigned to MFI studies relative to FC and FR studies. Since we have no quantifiable justification for weighting by study type (i.e., MFI versus FC or FR), we chose 10 ha as the unit-area that most evenly distributed MFI studies among FR and FC studies when ranked by CI width.

We assigned each study to one of three groups to allow for model development with 3-way cross-validation (Burman 1989). Group assignment followed sorts on longitudinal region, study type, and MFFP to assure full variable coverage in all groups (Neter et al. 1990). Three model building datasets resulted from each pairwise combination of groups, with one group left out for validation of each model produced. Independent models were developed with the aid of standard statistical software (SAS 1999) for each dataset through a backward elimination procedure with standard transformations and diagnostic checks to meet normality assumptions. Predictor variables significant at the $p<0.05$ level for at least two of the datasets were retained for the final model. We checked the stability of parameter estimates fitted to each model-building dataset, as well as their ability to predict MFFP for studies in the corresponding validation datasets (Pedhazur 1997). Satisfactory validation allowed a final model to be fitted with the data combined from all three groups (Neter et al. 1990).

2.2 *Results*

We reviewed over 450 publications in our search for point-specific fire frequency information from the period 1710-1779. Fifty-six of these articles met the selection criteria for inclusion in our synthetic model and are listed in Appendix B. Several publications provided information for multiple study areas such that a total of 75 studies were included in the synthesis. We relaxed our temporal extent criteria for four studies that reported 18^{th} Century fire dates, but that otherwise could not have been included since none of these dates occurred between 1710 and 1779 (which results in undefinable MFFP, as well as undefinable study weight).

2.2.1 *Study characteristics*

The spatial extent of the 75 studies included in our synthesis is broad but clustered in the western US (Figure 1), with 63% conducted in the Intermountain region and almost half of these (23 of 51) in New Mexico and Arizona. Historic fire history information is conspicuously lacking for the Southeastern US. Elevations represented by included studies ranged from 175m to 3,100m with a median of 2,080m. Aspect could not be characterized for the majority of studies (69%), but of the remainder 65% were conducted on southerly aspects. Studies were conducted in a wide variety of forest types, though ponderosa pine was the species most commonly listed as dominant or co-dominant (44%).

Most fire frequency information was derived as MFI from fire scars (73% of studies), but FR and FC are the predominant statistics at latitudes above 40^{o} (Figure 1). Mean fire free periods calculated for included studies ranged from 8.7 to 825 years. However, most studies were conducted in areas of relatively high historic fire frequency (median MFFP ~ 33 years) and the distribution of MFFP varied by study type, tending to be shortest in MFI studies (Figure 2). Though a majority of the studies were crossdated (63%), the use of this more accurate dating method also varied by study type. Crossdating was common in MFI studies (80%), but encountered in only a third of FC studies and not at all in FR studies.

2.2.2 *Fire frequency model*

Weights assigned to studies for development of the fire frequency model were negatively related to calculated MFFP, since certainty about mean fire frequency statistics is greatest in areas where evidence of past fires is most abundant (Figure 2). However weights also depended on sample size and were distributed fairly evenly among the three study types, even though the shortest MFFP's are observed in MFI studies.

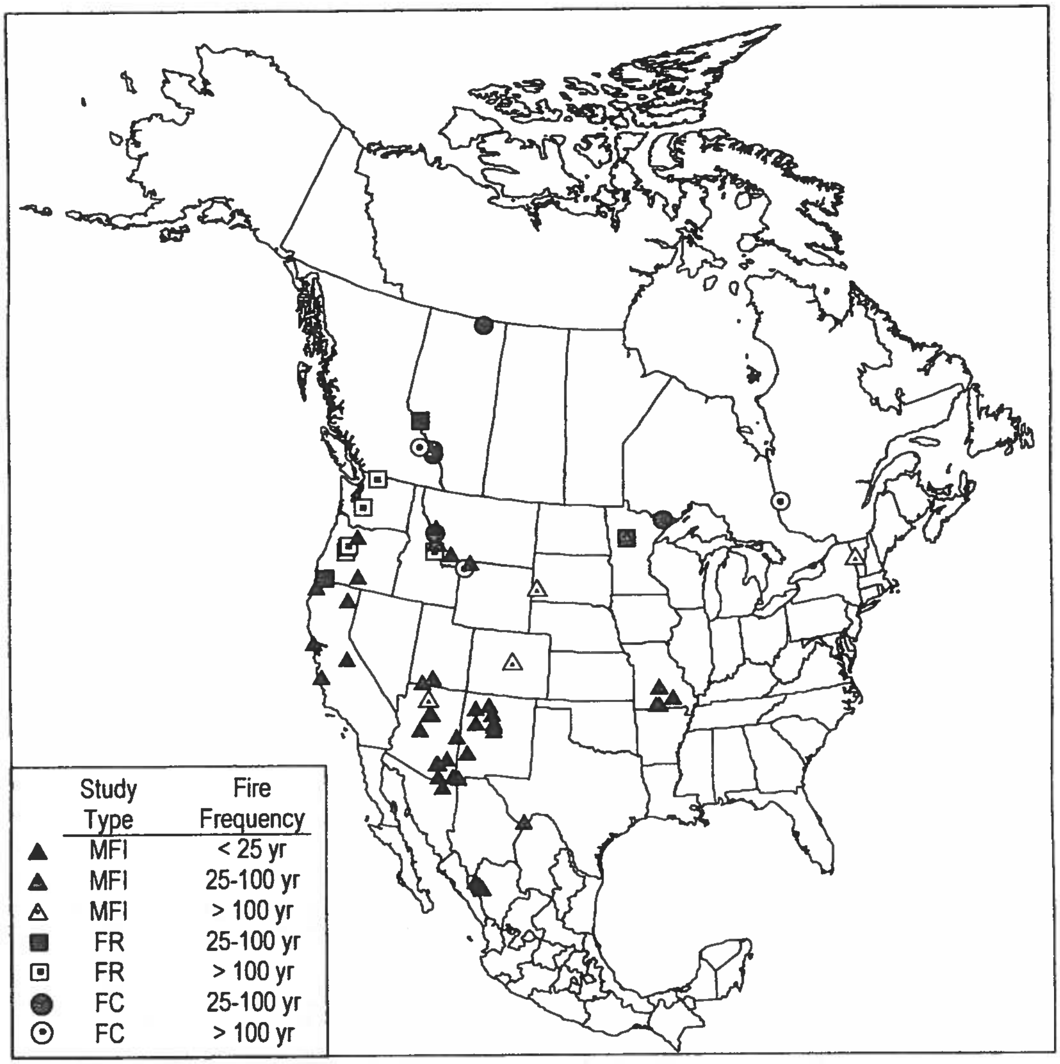

Figure 1. Spatial distribution of the 75 fire history studies synthesized for the development of a geographic fire frequency model. Studies are grouped by point fire frequency during the period 1710-1779, as well as by study type in terms of the fire frequency statistic calculable as a result of typical fire severity (i.e., Mean Fire Interval (MFI) in low severity regimes, Fire rotation (FR) in moderate severity regimes, or Fire Cycle (FC) in high severity regimes).

Model selection resulted in a similar choice of predictors for the three model-building datasets. Elevation, latitude, and longitudinal region were significant predictors for all three datasets. Two of the three datasets also included the interaction between elevation and the eastern region. The dataset that did not include this interaction instead included the interaction between elevation and latitude. One of the datasets also included aspect as a predictor of historic MFFP. However, we chose to retain for the final model only those predictors selected for at least two of the datasets (i.e., latitude, longitudinal region, elevation, and the interaction between elevation and the eastern region).

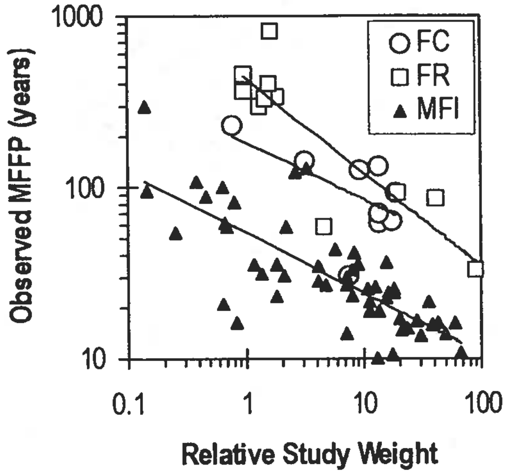

Figure 2. Relationship among study type (Cycle (FC), Rotation, (FR), and Interval (MFI)), observed Mean Fire Free Period (MFFP), and relative study weight. Study weight is proportional to statistical confidence about its observed MFFP and tends to decline as MFFP increases for all study types. Though observed MFFP varies by study type, weights do not favor one type of study over another.

Table 2. Parameter estimates for the full dataset and each of the three model-building datasets from which a third of the full dataset was excluded (e.g., A / B excludes C). Stable parameter estimates and reasonable cross-validation coefficients support the validity of the final model fitted with the full dataset.

	Dataset Parameters[a] (s.e.)			
Coefficient	A / B	A / C	B / C	Full
Intercept	-1.165 (0.347)	-0.665 (0.336)	-0.785 (0.296)	-0.888 (0.256)
Latitude[b]	0.051 (0.006)	0.041 (0.005)	0.045 (0.004)	0.045 (0.004)
Elevation[c]	0.272 (0.078)	0.226 (0.084)	0.203 (0.081)	0.242 (0.065)
Eastern Region[d]	1.677 (0.536)	1.424 (0.418)	1.260 (0.363)	1.412 (0.332)
Pacific Region[d]	0.707 (0.139)	0.576 (0.144)	0.493 (0.174)	0.615 (0.120)
Elevation X East	-3.093 (1.084)	-2.687 (0.848)	-2.165 (0.708)	-2.539 (0.658)
R^2 [e]	0.74	0.69	0.75	0.73
R^2_{cv} [f]	0.61	0.71	0.66	0.66

Notes:

[a] Parameters fitted to predict $\log_{10}$ transformed Mean Fire Free Period.

[b] Latitude expressed in decimal degrees.

[c] Elevation expressed in kilometers above sea level.

[d] Longitudinal regions (east of Rocky Mountains, west of Cascade-Sierra-Nevada Mountains, and Intermountain) expressed as dummy variables.

[e] R^2 is the correlation coefficient and indicates how well a model explains variability in the data from which it was developed.

[f] R^2_{cv} is the cross-validation coefficient and indicates how well a model explains variability in data not used in its development.

Values of predictor coefficients fitted to each dataset appear stable – signs do not change direction and the standard errors of each parameter estimate overlap across the three datasets (Table 2). Coefficients of cross-validation indicate that the predictors fitted with the studies in the model-building datasets can explain 61 to 71 percent of the variability in MFFP observed in independent validation datasets.

Parameters for the final model were fitted with the information from all 75 studies in the full dataset. The final model is highly significant ($p<0.0001$), as are all predictors ($p<0.001$), and has reasonable explanatory ($R^2=0.73$) and predictive ($R^2_{cv} = 0.66$ (average of the three model-building datasets)) power. Predicted MFFP for the 75 synthesized studies range from 9.3 to 160 years. The 95% Prediction Interval (PI) of the model includes the predicted log_{10}-transformed MFFP plus or minus 0.618. The PI for back-transformed historic MFFP is thus asymmetrical and widens as predicted MFFP increases (Figure 3).

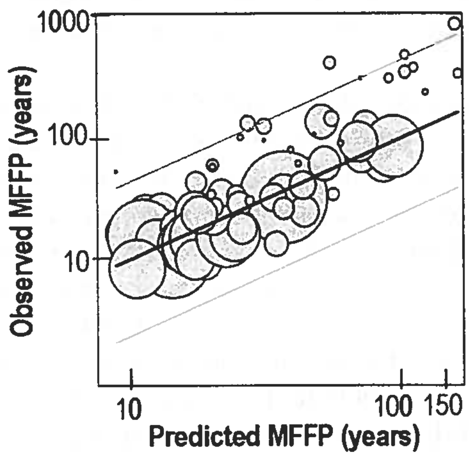

Figure 3. Predicted versus observed historic Mean Fire Free Period (MFFP) with 95% Confidence Interval. A weighted least squares method was used to fit the regression model and bubble sizes in the figure are proportional to study weights. Note the logarithmic scale of the axes.

2.3 Discussion

This synthesis of fire history studies produced a model that suggests a predictable relationship between historic fire frequency and geographic gradients of latitude, longitude, and elevation. Mean fire free periods are shortest in the Intermountain region but lengthen at higher latitudes and elevations. These general relationships are expected from regional climatic influences on fuel availability -- Martin's (1982) synthesis also suggested relationships among climatic patterns, fuel availability, and historic fire frequency.

Fuel is generally drier and more available for burning in the Intermountain region where climate is controlled by dry continental air masses in contrast to the moist maritime air masses that control climate in more coastal areas (Henderson-Sellers and Robinson 1986). Precipitation increases at higher elevations and temperature decreases at higher elevations and latitudes, reducing the likelihood of fire ignition and spread. However, in the eastern region we found a negative relationship between MFFP and elevation, as indicated by the significant interaction between these two predictors. This results from the large area covered by our eastern region, which extends to the Rocky Mountains with generally westward increases in both elevation and the influence of continental air masses on climate. Thus, in the eastern region, elevation represents a continental effect rather than one of topography.

Though we sought to generalize beyond specific vegetation types, minimal faith should be put in model outputs for areas of non-forest vegetation or in forests that are located beyond the geographic range of the studies that contributed to model development (see Figure 1). Our model may not account for the distinct fuel conditions and climate patterns that influenced historic fire frequencies in these areas that lack old trees. Historic fire history information in areas that lack old trees is sparse and based on methods such as inferences from species life history (e.g., Keeley et al. 1989) or sedimentary charcoal accumulation (e.g., Clark and Royall 1996). Fire frequencies based on such methods are not comparable to tree-ring analyses in spatial and temporal resolution and were thus excluded from our synthesis, but they may be more realistic estimates of historic fire frequency for their study areas than our model's predictions.

Even in areas represented by the studies included in our synthesis, model predictions should be considered merely first approximations. While we believe our model captures coarse spatial gradients in historic mean fire frequencies, it does not consider local variations in site conditions. We expected slope aspect, with its effect on solar radiation, temperature, and fuel moisture, to emerge as a predictor of historic fire frequency. Slope aspect was selected as a significant predictor for one of our model-building datasets, but this variable was not reported in fire history studies with enough consistency to be generally informative. Barrett (1980) found that historic fire frequency in Montana was influenced by proximity to areas of Native American habitation, but we did not have enough information to include this as a potential predictor in our model. Other potential sources of local variability not considered by our model include the presence and arrangement of natural fuel breaks (Bergeron 1991) and variations in fuel flammability represented by different vegetation types (Mutch 1970).

Our model appears to severely underestimate observed historic MFFP's longer than 100 years (Figure 3). However, the positive relationship between predicted MFFP and the prediction error of our model realistically reflects greater uncertainty about historic fire frequency in areas where evidence of past fire events is sparse. Since observed MFFP's longer than 100 years tend to be the least accurate (Figure 2), they received the least weight in the parameterization of our model.

Our weights were relative to the most statistically accurate study, but no reconstruction of historic fire history can be truly accurate since fire evidence becomes increasingly censored with time (Finney 1995, Lertzman et al. 1998). Also, study weights may not have been optimal since they did not include the effect of non-independence in recorded fire events, which probably varied among studies that differed in sampling extent and/or the size of typical fires. Finally, statistical accuracy does not consider methodological errors, which are probably greater in uncrossdated studies. Weighting by methodology is not recommended in research synthesis because the effect on accuracy generally is not quantifiable (Cooper and Hedges 1994). But crossdated studies may have serendipitously received greater weight in our synthesis since crossdating methods are most likely to be employed in high frequency fire regimes. Regardless, regional variations in the use of crossdating made exclusion of uncrossdated studies from our synthesis an undesirable option.

3. Meta-analysis of 20th Century Changes to Historic Fire Regimes

Many fire history studies conclude that fire exclusion has dramatically reduced fire frequency in the 20th Century, but very few statistically test this hypothesis. Concerns have recently arisen that fire exclusion effects are too widely presumed outside of the Southwestern ponderosa pine forests that epitomize the model of reduced fire frequency and increased fire hazard (Shinneman and Baker 1987; Keeley et al. 1999; Gutsell et al. 2001; Johnson et al. 2001). We used meta-analysis (MA) techniques to standardize and quantitatively synthesize the data reported in North American fire history studies to determine if there has been an overall change in fire frequencies in the 20th Century and whether this change varies by national boundaries, forest types, and historic fire regimes. An MA comprises several general procedures that include a literature search and selection of relevant studies to be synthesized, calculation of a standardized effect size for each study, and statistical analysis of heterogeneity among studies.

3.1 *Methods*

3.1.1 *Information Sources*

The studies used in this analysis were identified and selected using the same criteria as those described in section 2.1.1, with one additional requirement: sufficient information was provided to calculate a point-fire frequency for the period of effective fire exclusion. Though the start of this period is geographically variable, throughout much of the US it is generally considered to be coincidental with the adoption of national fire suppression policies and mobilization of the Civilian Conservation Corps in the 1930's (Pyne 1982). For the sake of temporal comparability, we considered 1930 the beginning of the fire exclusion period at all fire history study sites.

3.1.2 *Statistical Analysis*

Meta-analysis depends on an estimate of effect size (ES): the magnitude of the 'treatment' mean (fire frequency during the post-1930 period of fire exclusion) relative to the 'control' mean (fire frequency during the 1710-1779 pre-settlement period). Fire frequencies are commonly reported as the average interval between fires at a point (mean fire interval or MFI), or equivalently, the amount of time it would take to burn an area the size of a given study area (fire cycle (FC) or fire rotation (FR)). The prevalence of undefined fire intervals in the fire exclusion period makes a less common conceptualization of fire frequency more useful for our purposes: fire frequency as the probability of a dichotomous event derived from a series of trials (i.e., in a given year each sampled point (trial) either does or does not experience fire (event)). The most appropriate measure of ES for such dichotomous data is the log odds ratio ($\ln\Omega$) derived from a fourfold table such as that represented by Table 3 (Cooper and Hedges 1994).

Table 3. Generalized fourfold table representing the data from a given fire history study.

Fire Year	Period: Fire Exclusion	Period: Pre-settlement	Total
Yes	n_{11}	n_{12}	n_{1+}
No	n_{21}	n_{22}	n_{2+}
Total	n_{+1}	n_{+2}	n_{++}

Notes: The cell count n_{1j} is equal to the annual probability of fire occurrence (fire frequency, p_{1j}) in period *j* multiplied by the sample size for period *j* (n_{+j}).

An ES is estimated from a single study *k* with the notation in Table 3 as:

[1]
$$\ln o_k = \ln\left(\frac{n_{11}n_{22}}{n_{12}n_{21}}\right).$$

A negative ES indicates greater fire frequency in the historic period, a positive ES indicates greater frequency in the fire exclusion period, while an ES of zero indicates no difference between the two periods. Effect sizes are weighted by the inverse of their sampling variance to allow optimal pooling with MA procedures. The approximate sampling variance of ln o_k is:

[2]
$$v_k = \frac{1}{n_{11}} + \frac{1}{n_{12}} + \frac{1}{n_{21}} + \frac{1}{n_{22}}.$$

Equation 2 requires each of the n_{ij} to exceed zero. The fire exclusion period was therefore extended back to the date of the last recorded fire for the numerous studies that did not observe fire after 1930. The historic period was also extended slightly for a few studies (four) that recorded 18th Century fires, but none between 1710 and 1779. Equation 2 also assumes independent samples, an assumption violated by the contagious nature of fire (Reed et al. 1998). We expect the principal consequence of this violation to be underestimated sampling variances that produce sub-optimal study weights. However, we are unaware of an applicable remedy.

The annual probability of fire at a given point (p_{1j}) is the inverse of MFI, FR, or FC (see section 2.1.2). The sample size (n_{+j}) for studies that estimate FC or FR depends on an arbitrary choice of unit-area (Reed et al. 1998), which consequently influences v_k and study weight (but not ES). We investigated the effect of expressing area in various units ranging from 1 ha to 1 km^2 on the distribution of weights assigned to MFI studies relative to FC and FR studies. Since we had no quantifiable justification for weighting by study type (i.e., MFI versus FC or FR), we chose 1 km^2 as the unit-area that most evenly distributed MFI studies among FR and FC studies when ranked by v_k.

Statistical analyses were conducted with software designed specifically for MA (MetaWin [Rosenberg et al. 2000]). Our principal hypothesis was that North American fire history studies demonstrate an overall significant change in fire frequency in the 20th Century relative to the historic period, but that the amount of change is heterogeneous among studies. We attempt to explain this hypothesized heterogeneity with a nested model. We first grouped studies by country with the hypothesis that the 'effect' of fire exclusion has been greater and more heterogeneous in the US than in Canada and Mexico due to more aggressive fire suppression polices and more intensive land-use. We then tested the hypothesis that ponderosa pine forests have been more affected by fire exclusion than other US forest types. Finally, we determined if a significant positive relationship between ES and historic fire frequency (log_{10}-transformed MFI, FR, or FC, which we collectively term Mean Fire Free Period, or MFFP) is demonstrated by US fire history studies. MetaWin allowed investigation of both parametric and non-parametric (via resampling procedures with 5,000 iterations) mixed-effects models.

3.2 *Results*

Most of the fire histories selected for development of the historic fire frequency model (section 2.2) also provided sufficient information for the recent (post-1930) period: all but five were included in this MA of fire exclusion effects (Appendix B). Several publications provided information for multiple study areas such that a total of 66 studies were included in the synthesis.

3.2.1. *Study Characteristics*

Study effect sizes (ES) ranged from –7.14 to 0.44, where a negative value indicates higher frequency in the historic period and a positive value represents higher frequency in the fire exclusion period. Though only two studies appear to demonstrate a significantly altered fire frequency by themselves (Figure 4), the overall mean effect size of all studies when combined is significant (-0.56, 95% upper confidence limit equals -0.08). A few US studies observed no fire exclusion effect despite a relatively high historic fire frequency (Figure 5). We excluded one of these studies (the kipukas in Grissino-Mayer and Swetnam 1997) from further analysis since the authors suggest that the exceptional physiographic isolation of their site precluded fire suppression and grazing effects on fire frequency.

The test statistic for heterogeneity among studies is highly insignificant (p=1.0: Table 4), indicating that any variability between studies in mean fire exclusion effect sizes is overwhelmed by uncertainty about the means. There is thus little statistical motivation for further analysis. However, curiosity compelled us to investigate our substantive hypotheses.

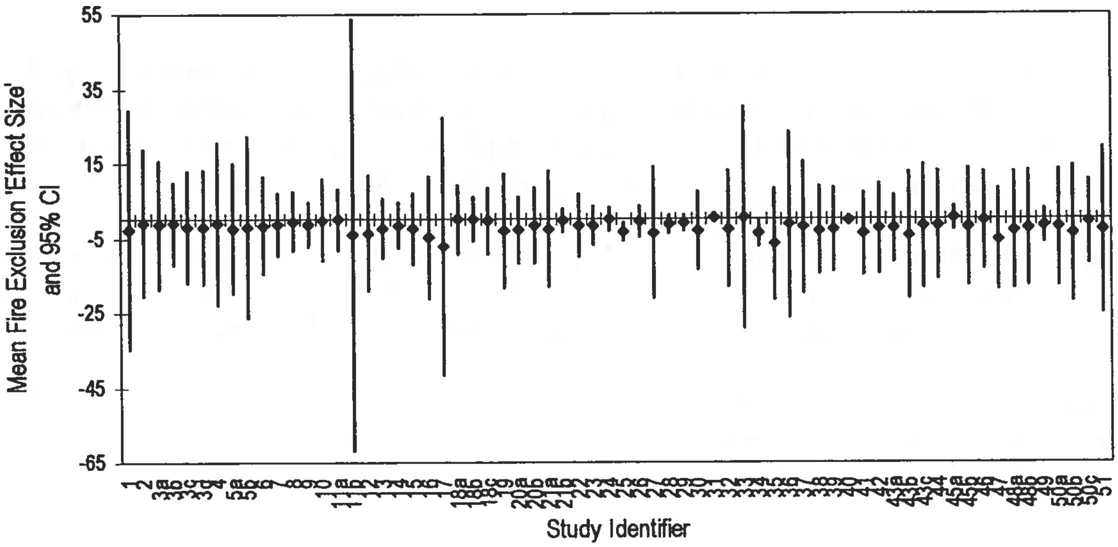

Figure 4. Mean fire exclusion 'effect' size and 95% Confidence Interval for each study included in the synthesis. Most studies have too little power to demonstrate statistically significant 20th Century alterations to fire frequency by themselves: only two studies (25 and 34) appear to show a significant change. Study identifiers reference Appendix B.

Table 4. Sources of heterogeneity in fire exclusion 'effect' sizes calculated from fire history studies (n=66 [a]).

Source [b]	Q [c]	df	P (χ^2)	P (NP)
All	18.56	65	1.00	
Country:	2.61	2	0.27	0.33
Canada	7.09	5	0.21	
USA	8.81	54	1.00	
Mexico	0.04	3	1.00	
Vegetation (USA)	1.12	1	0.29	0.46
Southwestern Ponderosa Pine	0.46	18	1.00	
Other	7.23	35	1.00	
Observed Historic MFFP (USA)	2.38	1	0.12	0.05
Predicted Historic MFFP (USA)	2.32	1	0.13	0.11

Notes:

[a] One study was removed as an outlier in analyses of country, vegetation type, and historic (1710-1779) fire frequency as sources of heterogeneity among studies.

[b] Vegetation type, observed historic fire frequency, and predicted (from the geographic model described in Section 2) historic fire frequency were explored as predictors of heterogeneity only among US studies.

[c] Q is a meta-analysis heterogeneity statistic that is analogous to an ANOVA sum of squares. The statistical significance of Q is provided for both parametric (compared to a chi-square distribution) and non-parametric (NP: compared to a distribution derived from data permutation) analyses.

3.2.2 *Hypothesis Tests*

Though the test statistic for between-group heterogeneity is insignificant for studies grouped by the country in which they were conducted, comparison of non-parametric Confidence Intervals about group mean ES does provide interesting contrasts (Figure 5). Mean ES among studies conducted in Canada and Mexico are small and insignificant, while the mean ES of fire exclusion in the US is moderate and significant. Also, the C.I. for the US group mean does not overlap that of the Mexico group mean, suggesting a significant difference between these groups. However, the CI for the Canada group mean overlaps those of the other two groups and indicates that the greatest heterogeneity exists among Canadian studies, rather than among US studies.

Fire frequency in Southwestern ponderosa pine forests of the US has been reduced by a very large and significant amount. The mean fire exclusion ES of all other US ecosystems is more moderate, but also significant with a 95% C.I. that overlaps that of Southwestern ponderosa pine forests (Figure 5).

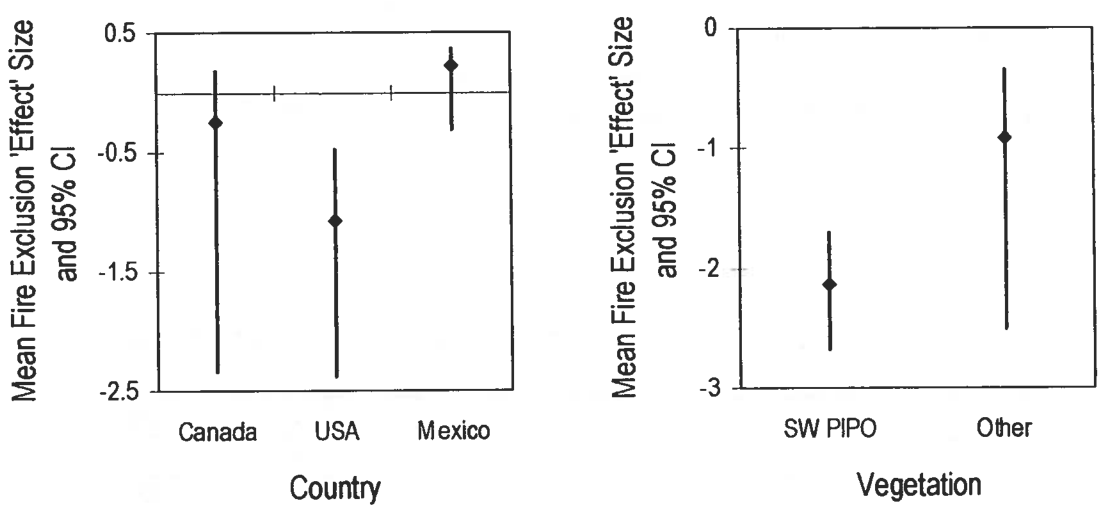

Figure 5. Mean fire exclusion 'effect' sizes and 95% Confidence Intervals for studies included in the synthesis when grouped by the country and vegetation type in which they were conducted. Only US studies are included in the vegetation groups: 'SW PIPO' refers to southwestern ponderosa pine.

Non-parametric estimation of regression coefficients suggests that fire exclusion ES tends to increase with observed historic fire frequency among US studies (Table 4, Figure 6). Though less significant, this relationship appears to hold even when the historic fire frequency variable is predicted from the geographic model described in section 2 (Table 4).

3.3 ***Discussion***

Few individual fire history studies have the statistical power to detect significant 20th Century changes to fire regimes. Nonetheless, the weight of evidence from North American fire history studies when combined suggests an overall reduction in fire frequency that is statistically significant, at least in those ecosystems where tree ring analysis is possible. The hypothesis of heterogeneity among studies in fire exclusion effects is not supported unequivocally, but there do appear to be differences between national borders and vegetation types. But the most useful variable in distinguishing fire exclusion effects is historic fire frequency; the effect of fire exclusion across ecosystems does appear to decrease as historic fire frequency decreases. However, statistical criticisms of fire history study designs (see Johnson and Gutsell 1995; Baker and Ehle 2001) and the absence of control in assessing the 'treatment' (i.e., fire exclusion) effect necessitate caution in the interpretation of this MA applied to the fire history literature. In particular, the effects of fire exclusion cannot be separated from those of climate change in the Effect Sizes that were calculated and analyzed in this synthesis.

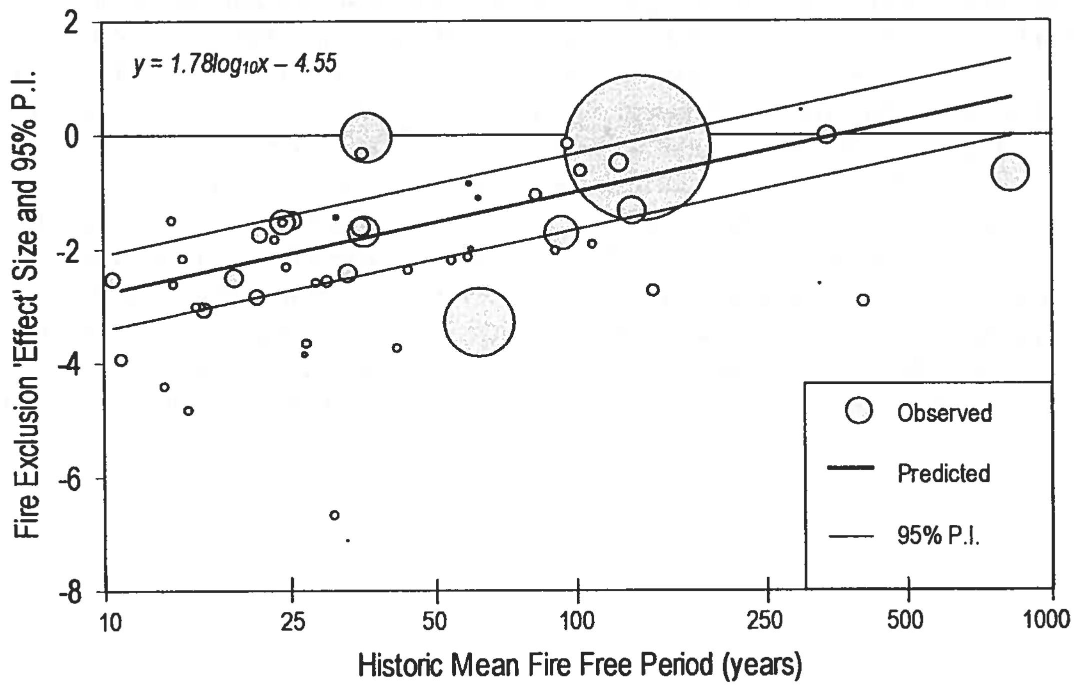

Figure 6. Mean fire exclusion 'effect' sizes among US studies in relation to observed historic fire frequency. Studies were weighted in inverse proportion to effect size variance, as indicated by bubble sizes. Bands around the prediction line represent the 95% Prediction Interval and indicate that fire frequency has likely been significantly reduced in the 20th Century wherever the historic mean fire free period was less than about 150 years.

Johnson et al (2001) suggest that climatic shifts are primarily responsible for any recent changes in the fire regimes of many ecosystems, particularly boreal and sublapine forests. Several Canadian fire histories note 20th Century reductions in fire frequencies in uninhabited areas where there has been no fire suppression effort. However, it is notable that the largest fire frequency changes among the Canadian studies included in our synthesis were from those nearest centers of human population (i.e., Masters 1990 and Tande 1979). Thus it seems likely that fire exclusion has had some effect beyond that caused by climate in at least some parts of Canada.

The degree of heterogeneity in the Effect Sizes exhibited by the few Canadian studies we were able to include in our synthesis warrants further investigation. Our literature selection method prioritized inclusion of US studies in that the time frame we chose for the historic reference period was based on Euro-American settlement in the US and is beyond detection in most areas of Canada. However Euro-American settlement in Canada occurred somewhat later, where it occurred at all. A more comprehensive meta-analysis of Canadian fire history studies would be possible by advancing the historic reference period, as long as the purpose was not a comparison to fire exclusion effects in the US.

It is evident that changes to fire frequencies have been much greater in Southwestern ponderosa pine forests than in other ecosystems of the US. Nonetheless, as a group the other ecosystems represented by the studies included in this synthesis demonstrate a significant fire exclusion effect. Certainly it must be recognized that there are areas of the US that have been little affected by fire exclusion, perhaps most notably mesic subalpine forests (Johnson et al. 2001) and southern California chaparral (Keeley et al 1999). It is important to identify ecosystems such as these and recognize that they might not benefit from fuel hazard mitigation. However, in the wake of broad-scale fuels planning efforts by federal land management agencies, it seems to have become popular to distinguish Southwestern ponderosa pine forests as a special and limited case where fuels mitigation might be warranted. Based on the results of our synthesis we suggest that it may be more useful and appropriate for fuels management efforts to distinguish ecosystems by their historic fire frequency rather than their vegetation. Figure 6 suggests that areas where estimated mean fire-free periods were less than 150 years have likely been altered to a significant degree in the 20th Century. In the US such areas are both common and widespread (Figure 1).

4. Relating Historic Fire Regimes to 20th Century Fire Potential

Where fire frequency has been reduced in the 20th Century, fuels and fire hazard have likely increased. Writings (e.g., Cooper 1960) and photographs (e.g., Veblen and Lorenz 1991) from the period of Euro-American settlement qualitatively support suppositions of increased fuel accumulation in some ecosystems since the advent of organized fire suppression. Gruell et al. (1982) used hazard ratings by a fuels specialist in their repeat photography study to quantify a hazard increase since 1909. We took a similar but broader approach to quantify and differentiate changes in fire potential represented in repeat photographs that have been published for a variety of ecosystems in the Western U.S. We tested the hypothesis that the degree of perceivable difference in fire potential represented in repeat photographs is related to the estimated historic fire frequency at each photo location.

4.1 *Methods*

4.1.1 *Information Sources*

Our assessment of changes in fire potential was based on published repeat photography. We identified applicable publications during our literature search for fire history studies (see Section 2.1.1). From each publication identified, we randomly selected 1 pair of photos that met 2 criteria: A pre-1900 photo was paired with a post-1970 photo of the exact same location and neither photo contained evidence of the period in which it was taken (e.g., people, buildings, roads, trains). The sources and geographic locations of the 7 selected photo pairs are displayed in Figure 7.

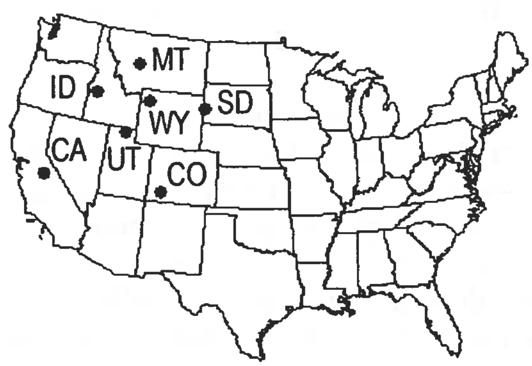

Figure 7. Locations of repeat photography studies used in our analysis. The photos of the CA site are from pages 28-29 in Kilgore (1970). The photos of the CO site are from page 73 in Baker and Veblen (1990). The photos of the ID site are from pages 124-125 in USDA Forest Service (1993). The photos of the MT site are from page 41 in Gruell (1983). The photos of the SD site are from pages 56-57 in Progulske (1974). The photos of the UT site are from pages 60-61 in Rogers (1982). The photos of the WY site are from pages 16-17 in Gruell (1980).

The selected photo pairs were scanned into a Power Point (Microsoft 2000) presentation comprising 21 slides. Each slide displayed 2 photo pairs, such that every pair-wise comparison between photo pairs was depicted once. The location of each of the 4 photos on each slide was randomly determined, as was the order of slides in the presentation. The power point presentation was shown to 32 fire management practitioners participating in a March 2001 Technical Fire Management fuels course in Seattle, WA. Participants ranked the 4 photos on each slide in order of increasing fire potential in terms of spread rate, crowning, and severity (ground char depth). These fire potential variables were chosen to correspond to the new national fuel characteristics classification system (Sandberg et al. 2001). Participants were given no information regarding the date and location of the photos or the purpose of the rankings.

The 6 ranks by each participant for each photo were summed for each of the fire potential variables. Thus, each of the 14 photos received relative scores from each of the participants that ranged between 6 and 24. We chose this method of evaluation to avoid ties between photos, as well as potential inconsistencies among participants in interpretation of ratings (e.g., high, medium, low). We also sought to avoid overwhelming participants with a large number of photos to compare simultaneously.

4.1.2 *Statistical Analysis*

We estimated the amount of change in the 3 fire potential variables at each location as Hedge's standardized mean difference, *d* (Rosenberg et al. 2000):

[3]
$$d \approx \frac{\mu_{>1970} - \mu_{<1900}}{\sigma_{pooled}} ,$$

where $\mu_{>1970}$ is the mean relative score from all participants for the recent photo, $\mu_{<1900}$ is the mean relative score for the historic photo and σ_{pooled} is the pooled standard deviation of the relative scores for the photo pair.

Hedges' *d* is a measure of effect size and as a dependent variable is analyzed most appropriately within the context of meta-analysis (Cooper and Hedges 1994). We used the standard meta-analytical software Metawin (Rosenberg et al. 2000) to relate fire potential effect sizes to an estimate of the historic fire frequency at each photo location. Historic fire frequencies were estimated from fire history studies conducted in relative proximity to each photo location (i.e, within 200 m of elevation, 2° of latitude, and in the same longitudinal region (west of the Cascade/Sierra Nevada Mountains, east of the Rocky Mountains, Intermountain)). We identified and selected applicable fire histories from those included in our quantitative synthesis of fire history information (see section 2).

Historic fire frequencies were standardized from each fire history by calculating the inverse of the average annual point-specific probability of fire in the period 1710-1779. This period was chosen to avoid influences associated with Euro-American settlement and to remain within the temporal extent of most fire histories. Baisan and Swetnam (1997) note grazing influences by Spanish cattle in New Mexico as early as 1779 and few fire history studies based on tree-ring analyses extend back beyond 1700 (Lertzman et al. 1998).

A weight was calculated for each fire history study that was inversely proportional to the variance about its fire frequency estimate. We estimated the historic fire frequency for each photo location as the weighted average of fire frequencies calculated from the proximal fire histories (Table 5).

Table 5. Sources of fire history information used to calculate historic[a] point-specific Mean Fire Intervals (MFI)[b] at the location of each repeat photography study[c] used in the analysis.

Location	Historic MFI	Fire History Citations
CO	17	Savage and Swetnam (1990: Fig. 1), Wolf and Mast (1998: Fig. 1c).
MT	21	Arno (1976: Fig.3), McCune (1983: Fig. 2), Weaver (1959: Table 1).
CA	24	Swetnam et al. (1991: Fig. 1).
UT	35	Young and Evans (1981: Fig. 5).
SD	61	Arno (1976: App. B, sites B,C,D,E,F,I), Arno and Gruell (1983: Fig. 6), Brown and Sieg (1996: Fig.2), Houston (1973: Table 3), Miller and Rose (1999: Fig. 4).
ID	87	Arno (1976: App. B, sites B,C,I), Arno and Gruell (1983: Fig. 6), Brown and Sieg (1996: Fig. 2), Miller and Rose (1999: Fig. 4).
WY	157	Arno (1976: App. B, sites G,H), Murray et al. (1998: Fig. 2), Romme (1982, Fig. 2c), Romme and Despain (1989: Fig. 2).

Notes:
[a] The historic period was standardized to mean 1710-1779 for all fire history studies.
[b] The MFI at each photo-point location was estimated from a weighted average of the listed studies, where weights were defined by the inverse of the 95% CI about each MFI (see Section 2).
[c] See Figure 7 for photo sources and locations.

The significance of historic fire frequency as an explanatory variable was tested non-parametrically by randomization with 5,000 iterations. Non-parametric 95% CI's were generated via bias-corrected bootstrapping (Rosenberg et al. 2000). Such non-parametric resampling techniques produce mixed-effects models. Mixed effects models incorporate random variation from unknown sources, such as the actual site-specific disturbance histories of the photo locations. We also conducted our analysis with parametric assumptions to allow estimation of the amount of random variance in each model (i.e., variation not explained by the uncertainty in the relative fire potential scores for each photograph, as indicated by their sampling errors). Comparison of the size of the random variance component (σ_θ^2) when the explanatory variable is included in the analysis to its size when the predictor is left out provides a measure of the explanatory power (r^2_{MA}) of a parametric mixed effects meta-analytical model (Cooper and Hedges 1994):

[4]
$$r_{MA}^2 = \frac{\sigma_\theta^2(no\ predictor) - \sigma_\theta^2(predictor\ included)}{\sigma_\theta^2(no\ predictor)}$$

4.2 *Results*

Unbiased evaluations by 32 fire management practitioners of the fire potential represented in repeat photography of 7 diverse Western landscapes suggest that crown fire potential and potential fire severity have generally increased significantly (since 95% CI's do not include zero) in the 20th Century ($d = 0.83$ and 0.66, respectively with 95% CI's of $0.34 \leq d \leq 1.23$ and $0.25 \leq d \leq 1.04$), while fire spread rate potential appears to have decreased, though insignificantly ($d = -0.29$, 95% CI = $-0.79 \leq d \leq 0.13$).

Perceived crown fire potential has increased at all but one of the photo locations (that in Utah) and at four of the locations this increase has been significant (Figure 8). Historic fire frequency was marginally significant as a predictor of the amount of 20th Century change in crown fire potential ($P = 0.074$, $r^2_{MA} = 0.26$). However, the Utah location might be considered an outlier in this analysis (see Discussion) and its exclusion strengthens the relationship between historic fire frequencies and altered crown fire potential ($P = 0.012$, $r^2_{MA} = 0.94$). Though this r^2_{MA} value is impressive, note that it is not directly comparable to the traditional coefficient of determination (r^2) produced by an ordinary regression. Unfortunately, interpretation of r^2 for a meta-analytical model is also ambiguous, since it would describe variation in mean effect sizes, but ignore the sampling error about the means. However, for completeness and to avoid appearing overly optimistic, we report the traditional coefficient of determination: $r^2 = 0.79$.

Twentieth Century changes in perceived fire severity potential were similar to changes in crown fire potential (Figure 9). Historic fire frequency was again a marginally significant predictor of the amount of 20th Century change in potential fire severity when the Utah location is included ($P = 0.069$, $r^2_{MA} = 0.33$). The relationship between historic fire frequency and changes in potential fire severity was also substantially improved by the removal of the Utah location ($P = 0.015$, $r^2_{MA} = 0.99$, $r^2 = 0.78$).

In contrast to changes in crown fire and fire severity potentials, spread rate potential was perceived to have decreased in the 20th Century at five of the seven locations, and at two of these locations (Montana and South Dakota) the perceived change was significant (Figure 10). The amount of change was insignificant at the two locations where spread rate appears to have increased (Colorado and Utah). The amount and direction of change in spread rate potential was not explained by estimated historic fire frequency ($P = 0.360$, $r^2_{MA} = 0$).

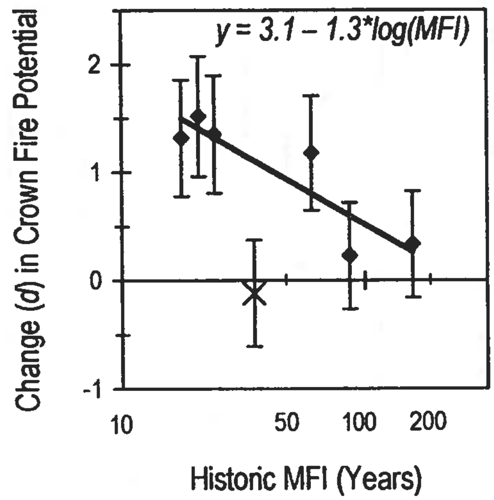

Figure 8. Standardized Mean Differences (*d*) between relative crown fire potential scores for photographs of recent vegetation conditions and those for historic conditions. Error bars represent 95% CI's and indicate a significant change where they do not include zero. The relationship between the amount of perceptible change in crown fire potential and the estimated historic Mean Fire Interval (MFI) of each photo location is significant ($P = 0.012$) when the non-forested Utah site (indicated by "X") is excluded from the analysis. Note the logarithmic scale of the abscissa.

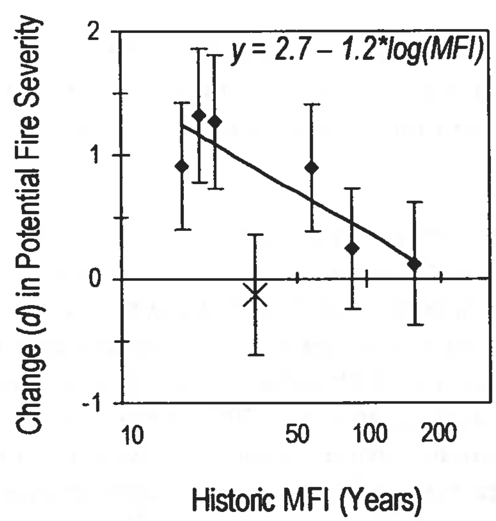

Figure 9. Standardized Mean Differences (*d*) between relative potential fire severity scores for photographs of recent vegetation conditions and those for historic conditions. Error bars represent 95% CI's and indicate a significant change where they do not include zero. The relationship between the amount of perceptible change in potential fire severity and the estimated historic Mean Fire Interval (MFI) of each photo location is significant ($P = 0.015$) when the non-forested Utah site (indicated by "X") is excluded from the analysis. Note the logarithmic scale of the abscissa.

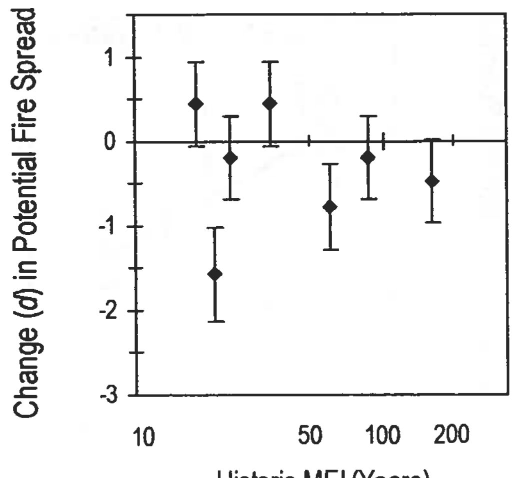

Figure 10. Standardized Mean Differences (*d*) between relative potential fire spread scores for photographs of recent vegetation conditions and those for historic conditions. Error bars represent 95% CI's and indicate a significant change where they do not include zero. The relationship between the amount of perceptible change in potential spread rate and the estimated historic Mean Fire Interval (MFI) of each photo location is not significant ($P = 0.36$). Note the logarithmic scale of the abscissa.

4.3 *Discussion*

Given the complex relationships among landscape disturbances, vegetation change, and future fire behavior, our approach to this assessment was rather simple. Nonetheless, our results do provide empirical substantiation of the linkages among historic fire regimes, altered fuel profiles, and current fire potential.

Increases in crown fire potential and potential fire severity were clearly perceptible at most of the locations included in our analysis, though changes in spread potential were less clear. The fuel conditions most likely to be associated with potential crown fire and severity, such as canopy closure, ladder fuels, and large logs, were easier to discern in most of the photos than the fine surface fuels that would be associated with potential fire spread. Even so, the lack of a relationship between historic fire frequency and 20th Century fire spread potential is not too surprising, since the effect of fire exclusion on fuels that would contribute most to fire spread is ambiguous. For example, a decrease in fire frequency might be expected to decrease production of fine herbaceous fuels, but increase the accumulation of litter from a greater number of shade-tolerant trees.

However, the positive relationship between historic fire frequency and the amount of change in both crown fire potential and potential fire severity is evident, and becomes striking when the non-forested Great Basin location is excluded from the analysis. There are several motivations for excluding this site, besides improvement of our statistical relationships.

Ecological justifications for fuel treatment activities presume that fire frequencies have generally decreased in the U.S. as a result of 20th Century fire exclusion. While this is undoubtedly true in many forested ecosystems, historic fire frequencies in non-forested ecosystems are not nearly as well-quantified. The historic fire frequency for the Great Basin sagebrush (*Artemisia tridentata*) site is probably not adequately reflected in the forest fire histories we used for its estimation. Therefore, a possible explanation for the Utah site's lack of fit in our analysis is that its historic fire frequency was overestimated. Historic fire intervals in Great Basin sagebrush are generally presumed to have been in the range of 30 to 70 years (Whisenant 1990), based on Houston's (1973) data for sagebrush in northern Yellowstone National Park. Though our estimate of the Utah site's historic fire frequency is within this range (Table 4), it is on the higher end of the frequency spectrum.

However, it has been argued that many non-forested ecosystems have not experienced reduced fire frequency in the 20th Century (Keeley et al. 1999). Current paradigm suggests that Great Basin sagebrush systems are actually under a more frequent fire regime now than in the past due to positive feedbacks promoted by exotic annual grasses (Young and Evans 1978). Indeed, the Utah location included in our analysis has been converted from sagebrush to cheatgrass (*Bromus tectorum*). It is not surprising, then, that crown fire potential and fire severity potential are lower in the current annual grassland than in the historic shrubland, regardless of what the historic fire frequency may have been.

Thus, the non-forested Utah site does not fit the model now used for ecological justification and prioritization of fuel treatment activities on public lands in the U.S. Morrison et al. (2001) suggest that the new National Fire Plan is misguided in its focus on forested lands for fuel treatment activities. They note that most of the areas burned by wildfires in the last decade have actually been non-forested. Correspondingly, our analysis indicates that while crown fire potential and potential fire severity have decreased at the non-forested Utah location, spread rate potential has increased more there than at any other site. We concur that a fuel treatment prioritization model that gives greater consideration to the unique fire regime situation on non-forested lands is needed.

Nonetheless, vegetation changes at all the other sites included in our analysis strongly support the intuitive assertion that 20th Century increases in wildfire potential are greatest where fire was most frequent prior to Euro-American settlement. Our results support the use of historic fire regimes as guides for fuel treatment prioritization, at least in forested areas. Fuel treatments should be applied where fire regimes have been most altered. Where there is no ecological justification for fuel treatments, they will likely be ineffective and may instead exacerbate problem fires. Alexander et al. (2001), for example, observed greater fire intensity in treated boreal forest of the Canadian Northwest Territories, where fire severity was and remains characteristically high and 20th Century fire exclusion has affected relatively little change in fire frequency (Larsen 1997). However, we have found that fuel treatments do reduce wildfire damages in systems where fire was historically frequent and of low severity, such as Southwestern ponderosa pine forests (Omi et al. *in press*). We therefore encourage land managers and policy-makers to continue their reliance on ecological justifications for guidance on fuel treatment applications.

5. Assessment of Historic Fire Regime as a Factor in Fuel Treatment Effectiveness

Justifications for expansion of fuel treatment practices are tenuous without empirical assessments of their performance in wildfires and the question of fuel treatment effectiveness has received surprisingly little scientific attention. An exhaustive literature search for evidence of fuel treatment effectiveness in the United States uncovered just 31 such publications since 1955 (Appendix C). Some perspective on the void this represents is gained by considering the number of citations in the Fire Effects Information System (more than 25,000 *op. cit.* Fischer et al. 1996). Further perspective is gained when these publications are organized by the methods used to assess treatment effectiveness. Fuel treatments in more than half of these publications were not tested by actual wildfires and the treatments themselves are also hypothetical in nearly a third of them. Among the 14 studies of treatments subjected to actual wildfires, just 5 quantify how fuels were changed by the treatment: a necessity if effective guidance is to be provided for future fuels management. Nonetheless, these publications do indicate with near unanimity that fuel treatments mitigate wildfire behavior and effects (Table 6).

Table 6. Characteristics and findings of published studies that document the performance of fuel treatments in actual wildfires.

Study	Treatment	Control	Response	Direction[a]
Moore et al. 1955	Prescribed burn	No activity	Crown damage	↓
Cumming 1964	Prescribed burn	No activity	Tree mortality	↓
Wagle and Eakle 1979	Prescribed burn	No activity	Live tree density	↑
Van Wagner 1968	Thin and prune	No activity	Tree survival	↑
Agee 1996	Thin and burn	No activity	Crown fire	↓
Oucalt and Wade 1999	Thin and burn	Thin	Tree mortality	↓
Vihanek and Ottmar 1993	Harvest and burn	Harvest	Soil damage	↓
Hall et al. 1999	Harvest and burn	Harvest	Crown fire	↓
Weatherspoon and Skinner 1995	Harvest and burn	No activity	Crown damage	↑
Omi and Kalabokidis 1991	Harvest and burn	No activity	Crown damage	↓

Notes:

[a]Direction indicates the amount of the measured response in the treated areas relative to that measured in the untreated control areas.

However, even among the 10 studies that assess the severity (as opposed to size) of actual wildfires, comparisons are complicated by lack of consistency both in the criteria for evaluating fire severity and in definitions of fuel treatments and controls. Several studies evaluate damage to tree crowns, but some authors define severe damage as more than 50 percent scorch, while others use 100 percent scorch or complete consumption as their highest rating. Treatments involve commercial harvest in several of the studies with activity fuels subsequently burned. Some of these assess treatment effectiveness with comparisons to areas where no management activity occurred; others use harvested areas where slash was left untreated. One study (Weatherspoon and Skinner 1995) makes comparisons to both types of areas, allowing interpretation of treatment effects as either positive or negative. This was the only study found that provides any indication that fuel treatments may be ineffective. But the weight of evidence represented in these few studies is far from overwhelming, especially since sampling designs are inadequately described in the earlier publications.

We initiated a project in 1995 to begin filling the research void on fuel treatment effectiveness. Eight wildfires have been investigated to date with details previously described (see Pollet and Omi 2002; Omi and Martinson 2002). Here we use meta-analytical methods to synthesize the results from these 8 study sites. We investigated the ability of several variables (type, age, and intensity of treatments and the historic frequency of fire in the treated ecosystems) to explain differences among study sites in observed treatment effects.

5.1 *Methods*

Study sites were restricted to wildfires that included adjacent treated and untreated areas within the perimeter and where treatment histories were documented and spatially explicit. We chose a narrow definition of fuel treatment that included only non-commercial or pre-commercial activities involving mechanical thinning (i.e., "low thinning"), debris removal, and/or broadcast burning with moderation of wildfire potential as a stated objective. Areas were defined as "untreated" if they had received no management action within the last 20 years, while treatments were applied within the last 10 years. We avoided areas where significant barriers (e.g., cliffs, major roads or drainages) or suppression activities likely impeded fire spread, as well as areas where post-fire salvage activities had taken place or were imminent. We further restricted our sampling visits to forested ecosystems, since these are where treatments are most often applied (Morrison et al. 2001) and where our methods are most applicable. A total of 38 wildfire areas were considered for sampling, but only ten of these met our selection criteria and two were excluded due to their proximity to areas we had sampled previously. Characteristics of the eight sampled sites are provided in Table 7.

Table 7. Characteristics of the eight study sites included in the synthesis.

Site	Treatment Type	Treatment Age (yr)	Vegetation	Historic MFI[a]
'94 Webb fire, MT	Prescribed burn	4	Ponderosa	14
'94 Tyee fire, WA	Thin and burn	10	Ponderosa	22
'94 Cottonwood fire, CA	Thin, slash removed	4	Ponderosa	28
'96 Hochderffer fire, AZ	Thin and burn	1	Ponderosa	16
'99 Fountainebleau fire, MS	Prescribed burns	1	Slash pine	9
'99 Megram fire, CA	Pile and burn	2	Mixed conifer	59
'00 Cerro Grande fire, NM	Thin	1	Ponderosa	17
	Thin and burn	4	Ponderosa	17
'00 Hi Meadow fire, CO	Prescribed burn	1, 3, 5	Mixed conifer	52
	Thin	9	Mixed conifer	52

Notes:
[a] Historic mean fire interval (MFI) was estimated for each site from the nearest available fire history information.

Data were collected at all sites from variable radius plots (Avery and Burkhart 1994) in adjacent treated and untreated stands. Measurements included stand density and basal area, tree diameter and height to pre-fire live crown, height of needle scorch and bole char, percent crown volume scorch, and standardized ratings for stand damage and depth of ground char (Omi and Martinson, 2002).

We used the standard meta-analytical software Metawin (Rosenberg et al. 2000) to relate fuel treatment effect sizes (i.e., Hedge's standardized mean difference, see Rosenberg et al. 2000) on percent crown volume scorch to each of several site characteristics. These included the type of treatment (in terms of the fuel stratum treated: canopy, surface, or both), treatment age when tested by wildfire (grouped into categories of 1 year, 2 to 4 years, and 5 to 10 years), standardized mean differences in tree densities and diameters between treated and untreated areas, and the estimated historic fire frequency of each site.

Historic fire frequency was estimated for each study site from proximal fire history studies. We identified and selected applicable fire histories from those included in our quantitative synthesis of fire history information (see Section 2). Historic fire frequency was standardized from each fire history by calculating the inverse of the average annual point-specific probability of fire in the period 1710-1779. We estimated the historic fire frequency for each site as a weighted (inversely proportional to variance) average of fire frequencies calculated from the nearest (in terms of latitude, longitude, and elevation) available fire histories.

We employed parametric mixed-effects models in all analyses. Since pseudo-replication (Hurlbert 1984) was unavoidable at several of the study sites, we did not employ the meta-analytical convention of weighting individual studies by their variance; all sites were given equal weight.

5.2 *Results and Discussion*

Similar to findings from previous research, results from our investigations unanimously indicate that fuel treatments reduced wildfire severity in treated areas. Crown volume scorch averaged 38% in treated areas across the eight study sites, versus 84.5% in untreated areas. Nonetheless, treatment effects among the study sites were variable in their significance. Meta-analysis suggests that much of the variability in the size of treatment effects can be explained by site characteristics, particularly the differences in mean tree diameter between treated and untreated areas (Table 8). Mean tree diameter in treated areas was 33.0 cm compared to 23.8 cm in untreated areas. Treatments that increase the average diameter of residual trees through removal of the smallest stems appear most effective. This result illustrates the importance of distinguishing fuel treatments from those silvicultural activities that "thin from above" through removal of the largest trees from a stand (Graham et al. 1999).

Vegetation in untreated areas was denser, on average, than in treated areas: 931 versus 319 trees/ha. But tree density differences between treated and untreated areas were insignificant as a predictor of fire severity differences among our study sites. This could be an artifact of the sampling method that we employed, since variable radius plots may provide inaccurate density estimates for small trees (Stage and Rennie 1994). However, they are more efficient than fixed area plots for sampling the larger trees that are more informative recorders of fire intensity. Nonetheless, the relative insignificance of tree density in our analysis suggests that treatment prescriptions based only on density (or basal area) without diameter specifications may be insufficient from a fuels management perspective. Further efforts to increase small diameter wood utilization are needed.

Table 8. Variation in fuel treatment effect sizes explained by various study site characteristics.

Explanatory Variable	P-value	R^2 [a]	R^2_{MA} [b]
Treatment Type	0.45	0.18	0
Treatment Age	0.50	0.13	0
Density Difference	0.17	0.24	0.20
Diameter Difference	<0.001	0.71	1.0
Historic Fire Frequency	0.08	0.34	0.41

Notes:

[a] R^2 indicates the amount of variation in mean effect sizes explained by the explanatory variable, but ignores sampling error.

[b] R^2_{MA} indicates the amount of reduction in the random variance component (i.e., variation not explained by sampling error) after inclusion of the explanatory variable (see Equation 4).

Though our study sites were limited to ecosystems where historic fires were probably fairly frequent (Table 6), our synthesis suggests that historic fire regimes may be an important consideration in fuel treatment applications. Among our study sites, fuel treatments were most effective in those ecosystems where fires were historically most frequent. This result might be expected, since these are the ecosystems where fuel hazard has likely increased the most in the 20th Century (see Section 4). Fuel treatment efficacy in ecosystems where fires were historically less frequent than at our study sites is questionable and remains to be investigated.

The insignificance of treatment type and age as predictors of effectiveness is surprising, but primarily indicates a need for additional studies. Particularly scarce is information for treatments more than 5 years old. Currently, variability is too great to distinguish the relative effectiveness of treating surface fuels (e.g. broadcast burning) or canopy fuels (e.g., mechanical thinning) versus combining treatments, but results from individual sites suggest that the safest bet is to treat fuel profiles in their entirety.

For example, little difference in crown fuel conditions was found between treated and untreated areas of the Hi Meadow fire, despite a significant treatment effect on fire severity (Omi and Martinson 2002). Though we were unable to assess pre-fire surface fuel conditions, presumably the treatments sufficiently modified surface fuels to reduce wildfire intensity and effects.
In contrast, thinning treatments in the Cerro Grande fire were equally effective in reducing wildfire severity regardless of whether or not the slash was disposed. We speculate that under the extremely windy conditions during this fire, surface fuels may have had less influence on fire behavior than canopy fuels. Explicit inclusion of weather variables as predictors of fuel treatment effectiveness will be explored in future analyses.

6. Conclusions

Fuel treatments are increasingly applied on federal lands despite limited evidence of their effectiveness for mitigating wildfire spread and intensity. Nonetheless, there is little disagreement in the positive outcomes demonstrated by the few investigations of fuel treatment efficacy that have been conducted to date. Still, the eight studies we were able to include in a quantitative synthesis on this subject do suggest some variability in the degree of effect produced by fuel treatment. We found that the best single predictor of fuel treatment effect size was mean residual tree diameter, followed by historic fire frequency. The most effective treatments are those that favor removal of small trees while leaving the largest and most fire resistant individuals. Also, treatments tend to be most effective where fire was historically most frequent. These trends suggest that the most appropriate fuel treatment applications will be those that are consistent with the objectives of restoring ecosystems to their historic structure and function.

Areas where fire was historically frequent are generally presumed to have been the most altered by 20th century fire exclusionary forces. Our meta-analysis of fire history studies substantiates the hypothesis that the effect of fire exclusion on fire frequency has been greatest where fire was historically most frequent. Further, our analysis of repeat photography demonstrates that 20th century changes to forest structure and wildfire potential are most evident where fires were historically most frequent. A frequent fire regime results from a climate that provides abundant ignition sources and fuels that are generally dry and available for combustion. Fire exclusion has resulted in an accumulation of available fuels that produce more extreme fire behavior in these areas. Reversing the effect of fire exclusion in such locations through broad application of fuel treatments should allow fires to burn benignly under most conditions. However, in areas where fire was historically infrequent, climatic conditions are such that fuels are available for combustion only under the most extreme conditions. Fire exclusion has had little effect on fuel accumulation in these areas. Here fuel treatments may reduce the total amount of fuel, but nonetheless increase fire hazard by promoting fine fuel desiccation via increased winds and solar radiation.

Thus, historic fire regimes should be a key consideration in fuel treatment applications. This may be facilitated by the fire frequency model produced by our synthesis of fire history studies. Our fire frequency model quantifies geographic gradients in historic fire frequencies and can provide increased information for fire management objectives related to historic fire regimes, especially in areas where no fire history information currently exists. However, users of the model should recognize that it was developed from imperfect fire history reconstructions and that model predictions are merely approximate *average* fire frequencies. Model output should not be interpreted too literally, particularly when predicted historic MFFP exceeds 100 years.

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Appendix A: Dissemination of Project Results

Omi, PN and EJ Martinson. 1999. Fuel treatments and fire regimes. Study plan. Document submitted to the Joint Fire Science Program Governing Board, March 1999.

Omi, PN and EJ Martinson. 1999. Fire Regimes and fuel treatments. First Progress Report. Oral presentation delivered in September 1999 at the Joint Fire Science Program Principal Investigator Meeting in Boise, ID.

Omi, PN and EJ Martinson. 2000. Fire Regimes and fuel treatments. Second Progress Report. Oral presentation delivered in October 2000 at the Joint Fire Science Program Principal Investigator Meeting in Reno, NV.

Martinson, E.J. and P.N. Omi. 2000. Pre-settlement fire regimes of North America: a geographic model based on quantitative research synthesis. Oral presentation delivered in December 2000 at Fire conference 2000 in San Diego, CA

Martinson, EJ and PN Omi. 2001. Performance of fuel treatments subjected to wildfires. Oral presentation delivered in June 2001 at the Musgove Seminar on St. Simon's Island, GA.

Martinson, EJ and PN Omi. 2001. Relating historic fire regimes to 20th Century fire potential may augment ecological justifications for expanded fuel treatment programs. Oral presentation delivered in October 2001 at the Tall Timbers 22nd Fire Ecology Conference in Kananaskis, Alberta.

Omi, PN and EJ Martinson. 2002. Fire Regimes and fuel treatments. Third Progress Report. Oral presentation delivered in March 2002 at the Joint Fire Science Program Principal Investigator Meeting in San Antonio, TX.

Martinson, EJ and PN Omi. 2002. Performance of fuel treatments subjected to wildfires. Oral presentation delivered in April 2002 at the Conference on Fire, Fuel Treatments and Ecological Restoration in Fort Collins, CO.

Martinson, EJ and PN Omi. 2002. Effect of fuels treatment on wildfire severity. Oral presentation delivered in April 2002 at the US Forest Service National Fuels Specialists Meeting, Santa Fe, NM.

Omi, PN and EJ Martinson. 2002. Explaining broad-scale fire patterns in the western and southern US. Oral progress report to Southern Research Station, February 2002.

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Appendix B: Publications included in the fire history syntheses described in Sections 2 and 3.

Study ID[a]	Author(s)	Source
1	Agee et al. 1990	Canadian Journal of Forest Research 20:350–356
2	Agee 1991	Northwest Science 65:188–199
3	Arno 1976	USDA Forest Service RP-INT-187:1–29
4	Arno and Gruell 1983	Journal of Range Management 36:332–336
5	Baisan and Swetnam 1997	USDA Forest Service RP-RM-330:1–20
6	Bergeron and Archambault 1993	Holocene 3:255–259
8	Brown and Sieg 1996	International Journal of Wildland Fire 6:97–105
7	Brown and Swetnam 1994	Canadian Journal of Forest Research 24:21–31
9	Brown et al. 1999	Landscape Ecology 14:513–532
10	Brown et al. 1999	Northwest Science 73:205–216
11	Cissel et al. 1998	USDA Forest Service GTR-PNW-422:1–82
12	Clark 1990	Ecological Monographs 60:135–159
13	Cutter and Guyette 1994	American Midland Naturalist 132:393–398
14	Danzer et al. 1996	USDA Forest Service GTR-RM-289:265–270
15	Dieterich 1980	USDA Forest Service RP-RM-220:1–8
16	Dieterich 1983	Forest Ecology and Management 6:13–31
*	Dieterich and Hibbert 1990	USDA Forest Service GTR-RM-191:168–173
17	Frissell 1973	Quaternary Research 3:397–407
18	Fule and Covington 1997	Acta Botanica Mexicana 41:43–79
19	Fule et al. 1997	Ecological Applications 7:895–908
20	Grissino-Mayer et al. 1995	USDA Forest Service GTR-RM-264:399–407
21	Grissino-Mayer and Swetnam 1997	Bulletin of the New Mexico Bureau of Mines & Mineral Resources 156:163–171
23	Guyette and Cutter 1991	Natural Areas Journal 11:93–99
24	Guyette and Cutter 1997	USDA Forest Service GTR-NC-188:355–373
22	Guyette and McGinnes 1982	Transactions of the Missouri Academy of Science 16:85–93
25	Heinselman 1973	Quaternary Research 3:329–382
26	Hemstrom and Franklin 1982	Quaternary Research 18:32–51
27	Houston 1973	Ecology 54:1111–1117
28	Johnson et al. 1990	Journal of Ecology 78:403–12
29	Johnson and Larsen 1991	Ecology 72:194–201
30	Kaib et al. 1996	USDA Forest Service GTR-RM-289:253–264
31	Larsen 1997	Journal of Biogeography 24:663–673
32	Madany et al. 1982	Forest Science 28:856–861
33	Mann et al. 1994	Quaternary Research 42:206–215
34	Masters 1990	Canadian Journal of Botany 68:1763–1767
35	McCune 1983	Canadian Journal of Forest Research 13:212–218
36	Miller and Rose 1999	Journal of Range Management 52:550–559
37	Moir 1982	Southwestern Naturalist 27:87–98
*	Morrison and Swanson 1990	USDA Forest Service GTR-PNW-254:1–77
38	Murray et al. 1998	Journal of Biogeography 25:1071–1080
39	Romme 1982	Ecological Monographs 52:199–221
40	Romme and Despain 1989	BioScience 39:695–699
*	Savage and Swetnam 1990	Ecology 71:2374–2378
41	Seklecki et al. 1996	USDA Forest Service GTR-RM-289:238–246
42	Stein 1988	Great Basin Naturalist 48:58–63
45	Swetnam and Baisan 1996	USDA Forest Service GTR-RM-289:15–36
43	Swetnam and Dieterich 1985	USDA Forest Service GTR-INT-182:390–397
44	Swetnam et al. 1991	Yosemite Centennial Symposium Proceedings, pp. 249–255
46	Talley and Griffin 1980	Madroño 27:49–60
47	Tande 1979	Canadian Journal of Botany 57:1912–1931
48	Touchan et al. 1995	USDA Forest Service GTR-INT-320:268–272
49	Wallin et al. 1996	Forest Ecology and Management 85:291–309

*	Weaver 1959	Journal of Forestry 57:15–20
50	Wolf and Mast 1998	Physical Geography 19:1–14
51	Young and Evans 1981	Journal of Range Management 34:501–506

Notes:

[a] Study ID's reference Figure 4 in Section 3. Those without a numeric identifier were not included in the fire exclusion meta-analysis.

Appendix C. Published studies that quantify a fuel treatment effect on wildfire potential.

Study Type[a]	Author(s)	Source
a	Agee 1996	Proceedings[b] pp:52-68
b	Alexander and Yancik 1977	Fire Management Notes 38(3):7-9,20
c	Anderson and Brown 1988	USDA Forest Service General Technical Report INT 251:124-130
a	Cumming 1964	Journal of Forestry 62:535-537
a	Davis and Cooper 1963	Journal of Forestry 61:915-917
b	Dell and Ward 1969	USDA Forest Service research paper PSW 57:1-9
c	Finney 1999	Proceedings[c] pp:127-136
b	Fule et al. 2001	Journal of Forestry 99(11):24-29
c	Graves and Neuenschwander 1999	Proceedings[c] pp:162-166
a	Hall et al. 1999	Proceedings[c] pp:151-161
c	Johnson et al. 1998	Journal of Forestry 96:42-49
c	Jones and Chew 1999	Proceedings[c] pp:89-96
b	Kalabokidis and Omi 1998	International Journal of Wildland Fire 8:29-35
b	Kilgore and Sando 1975	Forest Science 21:83-87
a	Koehler 1992-93	Fire Management Notes 53-54(4): 9-13
a	Martin 1988	Fire Management Notes 49(4):21-24
a	Moore et al. 1955	Journal of Forestry 53:339-341
c	Omi, PN 1979	Environmental Management 3:73-80
a	Omi and Kalabokidis 1991	Northwest Science 65:149-157
a	Oucalt and Wade 1999	Proceedings[c] pp:271-274
a	Pollet and Omi 2002	International Journal of Wildland Fire 11:1-10
b	Scott 1998	USDA Forest Service research paper RMRS 5:1-19
c	Stephens 1998	Forest Ecology and Management 105(1/3):21-35
a	Van Wagner 1968	Journal of Forestry 66:622-625
c	van Wagtendonk 1996	SNEP[d] 37:1155-1165
a	Vihanek and Ottmar 1993	Proceedings[e] pp:709-714
a	Wagle and Eakle 1979	Forest Science 25:123-129
b	Wakimoto et al. 1988	USDA Forest Service General Technical Report INT 243:401-402
a	Weatherspoon and Skinner 1995	Forest Science 41(3):430-451
a	Weaver 1957	Journal of Forestry 55:133-138
c	Wood 1982	Journal of Forestry 80:96-107

Notes:

[a] Studies grouped as follows:

Group A assessed the performance of fuel treatments that were burned over by actual wildfires
Group B assessed fire potential in actual fuel treatments
Group C modeled fire potential in hypothetical fuel treatments.

[b] Proceedings of the 17th annual forest and vegetation management conference. The Conference, Redding, CA.

[c] Proceedings of the Joint Fire Science conference and workshop on crossing the millennium: integrating spatial technologies and ecological principals for a new age in fire management, Volume II. University of Idaho, Moscow.

[d] Sierra Nevada Ecosystem Project: Final Report to Congress, Volume II. Wildland Resources Center, UC Davis.

[e] Proceedings of the 12th conference on fire and forest meteorology. Society of American Foresters, Bethesda, MD.