Fuel Treatment Effectiveness in the United States

Mark A. Cochrane and Michael C. Wimberly
GISCE, South Dakota State University

Jeffery C. Eidenshink, Zhi-Liang Zhu and Don Ohlen
USGS-EROS

Mark Finney and Matt Reeves
USFS Fire Sciences Lab, Missoula

Abstract: The fire situation in the United States is well documented with a growing prevalence of larger and more intense fires that have increasingly severe consequences for affected ecosystems and human health and well being. Increasingly, fuels management has been put forth and implemented as part of an integral strategy for limiting extreme fire behavior, reducing the area affected by wildfire and minimizing the economic and ecological costs of fires. Communities and land management agencies are now treating millions of acres of wildland fuels annually and an ever-increasing number of wildfires are burning treated lands. Although the scientific premises of various fuels treatments are well established, their actual performance and combined effectiveness on landscapes have been difficult to assess at the national level. Wildland fire managers and policy makers require specific guidance about the effectiveness of various treatments types, ages (time since treatment), sizes, spatial configurations and their placement on the landscape to support strategic decisions about fuel management policy, planning, implementation and maintenance.

To address this, here we provide preliminary assessments of the site level effectiveness on fire severity of many thousands of fuels treatments that were involved in 651 wildfires and detailed landscape-level assessment of the combined effects of 3,489 fuels treatments on the probabilistic spread of 85 large wildfires using >3,000 FARSITE wildfire simulations based on LANDFIRE datasets and ancillary fuels treatment and weather information. The methods for both the assessment of local treatment-related severity (Wimberly et al. 2009) and the stochastic modeling of fire spread (Cochrane et al. 2012) have been established in the peer-reviewed literature, and the project's research also has resulted in four completed masters theses (Arnold 2009, Pabst 2010, Moran 2011, Timilsina 2011).

Important findings from the research include quantifiable differences in the performance of treatment types (thinning, prescribed burning with or without thinning, mastication) within different ecoprovinces across the country. Although most treatment types are being tried to varying degree in most regions, it is clear that certain treatments function well while others work poorly, if at all, but the optimal choices differ by region. We provide management recommendations for regional optimization of fuels treatment selection. This information should help in the development of region-specific land management plans and also provide preliminary life cycle estimation for the performance over time of different treatment types.

Using the stochastic modeling studies, we show that fuels treatments act to both increase and decrease burning risk across different portions of landscapes in all wildfires. In general, thinning leads to increased surface rates of spread due to exposure and greater cover of light fuels, while treatments also act to reduce long distance spread via spotting through their tendency to limit or prevent crowning of fires (Cochrane et al. 2012). The net effect of all treatments for the 56 wildfires with statistically significant changes in treatment-related fire extents averaged a 7% reduction in burned area. However, this simple average is an inappropriate measure, as it masks a near dichotomy between wildfires experiencing significant reductions and those with significant increases in area burned due to treatments. In wildfires that had significantly reduced burned area, the average decrease in size was 25%, while wildfires that were significantly increased expanded by an average of 28%. In wildfires significantly decreased in size, for every hectare burned because of the fuels treatments, just over 18 hectares were prevented from burning. Conversely, for significantly increased wildfires, every hectare of fire prevention resulted in nearly 7 hectares of additional burning because of the fuels treatments. We provide suggestions for future research to better understand and implement these findings.

Study description and location

Project Objectives

The project made use of national datasets from the Monitoring Trends in Burns Severity (MTBS) Project and the LANDFIRE Project to test the overarching hypothesis that fuel treatments are having a measurable impact on site (fire severity) and landscape (fire extent) characteristics of wildfires that have been occurring in the United States in recent decades (1984-2008). The specific objectives of the project have been to:

1. Compare the effectiveness of prescribed fire and various types of mechanical fuel reductions
2. Assess the influence of topography on fuel treatment effectiveness
3. Determine whether treatment effectiveness varies with forest type
4. Quantify the extent to which site and landscape level treatment effectiveness is contingent upon and sizes and spatial arrangement of treatments.

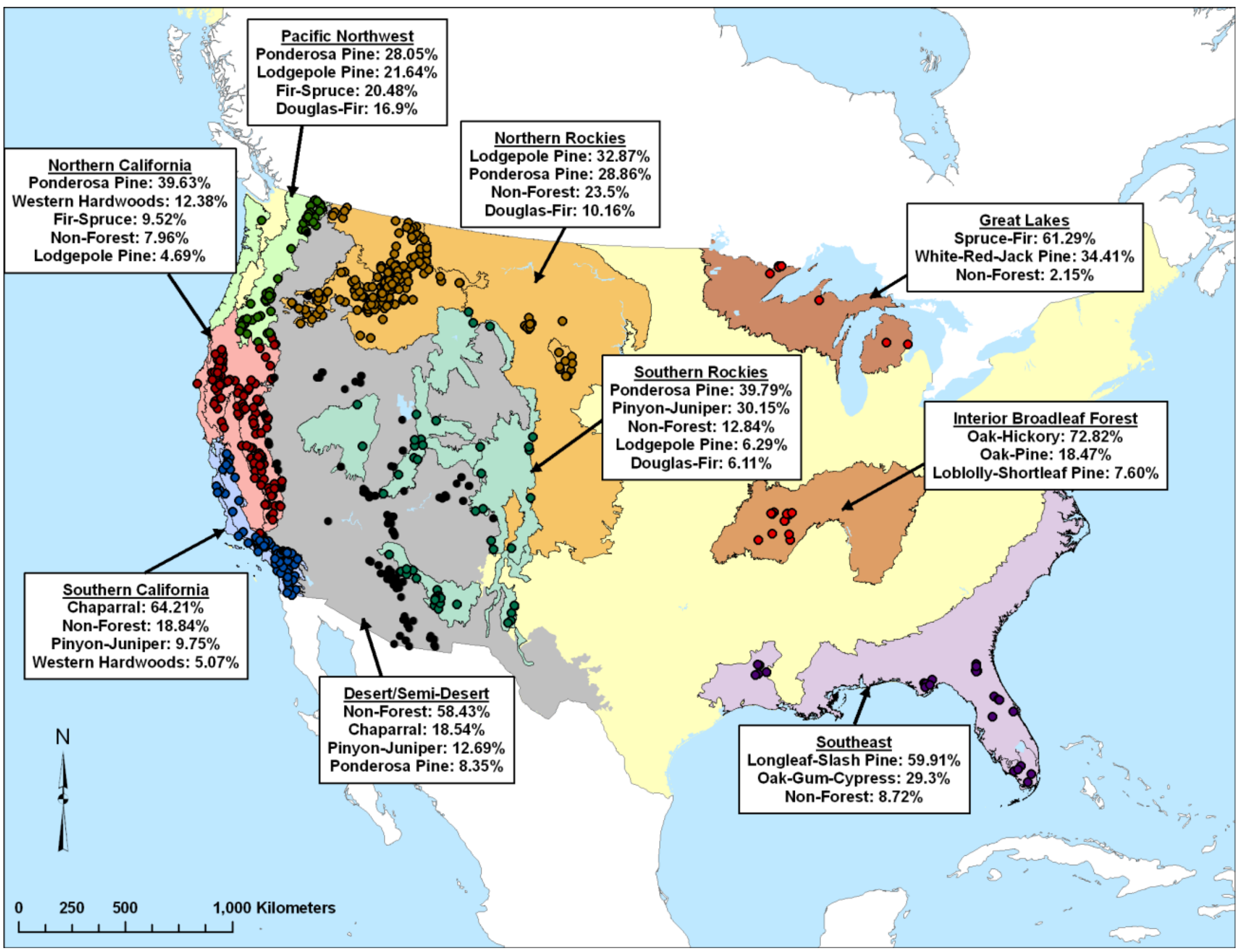


Figure 1: Continental map of the United States showing the location of all of the studied wildfires that involved burning of fuels treatments. The data are grouped by eco-provinces and the forest and land cover composition of the area encompassed by the regional wildfires are provided in the associated text boxes. No evidence of large wildfires, as recorded in the MTBS database, was found to have burned through established fuels treatments in the yellow areas.

Study Sites

Study sites were not predetermined due to the variable locations of wildfires from year to year. Between 1984 and 2008 there were 5,283 large wildfires in the MTBS database, 1,816 met the criteria for study, namely presence in the MTBS database, identifiable fuels treatments, with sufficient information on the treatments (contact with land managers) and the fires. Of the study fires, 56% (1,014) had fuels treatment involvement, 651 of which were analyzed for site-level impact of measured fire severity, and 85 with detailed landscape-level assessment of the effects of fuels treatments on fire spread. Fuels treatment assessments included both planned treatments (e.g. thinning, prescribed burning, mastication…) and unplanned treatments (previous wildfires).

Remote Sensing - In order to assess landscape level information about fire severity, especially over regional to national scales, the use of remotely sensed imagery is the only practical way of analyzing large fire complexes and national burning trends. We made use of the following major national remote sensing-derived products.

LANDFIRE - LANDFIRE is a joint multi-agency project between the US Department of Agriculture Forest Service, the US Geological Survey, the Bureau of Land Management, the National Park Service, the Bureau of Indian Affairs, the Fish and Wildlife Service, and The Nature Conservancy, with the principle investigators located at the USDA Forest Service Rocky Mountain Research Station Fire Sciences Laboratory (Missoula, Montana) and the DOI USGS National Center for Earth Resources Observation and Science (Sioux Falls, South Dakota). LANDFIRE provides the spatial data needed by land managers to accurately identify the amount and locations of lands or communities with hazardous fuel build-up or extreme departure from historical conditions. LANDFIRE provides all of the fuels, vegetation and topographic information necessary to run the FARSITE fire growth simulation model. These spatial data and predictive models are hierarchically designed so that they can be used at the national, regional, and local levels.

MTBS - The Monitoring Trends in Burn Severity (MTBS) Project, run jointly by the US Geological Survey, National Center for Earth Resources Observation and Science (EROS) and the USDA Forest Service, Remote Sensing Applications Center (RSAC), is an operational outgrowth of earlier JFSP funding. MTBS produces and delivers standard post-fire map products for monitoring trends in burn severity. Burn severity is mapped using the differenced Normalized Burn Ratio (dNBR) approach at 30m spatial resolution for all fires in the United States (1984-present) meeting a minimum size requirement. The minimum size is 500 acres or greater for all eastern fires (east of the -97^{o} longitude) and 1,000 acres or greater for the rest of the United States.

This Project – We integrated the LANDFIRE and MTBS products with information from land managers on historical land management and disturbance to assess the effectiveness of fuels treatments nationally, thereby testing the operational utility of these tools. By providing a common basis for analysis, and incorporating large numbers of fire events, this project provides the most comprehensive and detailed assessment to date of how fuels treatments of different types and ages function in different ecosystems and topographic locations. Through analysis of the MTBS data, and relating the burn severity measurements to individual fuel treatments, we quantified treatments effects on burn severity at the site-level. Subsequently, by incorporating LANDFIRE fuels and ancillary data layers with recorded information from actual fires, we calibrated FARSITE simulations of landscape-level treatment effects.

Methods

Site-level

To characterize fire behavior and validate remotely sensed fire severity (dNBR) in fuel treatment areas, we validated estimates of burn severity differences at 10 wildfires in the MTBS database. Sites were chosen to provide a good representation of multiple treatment types, sizes and ages in different ecosystems. The main purpose of the field visits was to verify fire behavior in and near treatments and test and verify the correspondence of the 215 field-derived Composite Burn Index (CBI) plots with the remotely-sensed differenced Normalized Burn Ratio (dNBR) values in fuel treatment areas. Based on this validation (Wimberly et al. 2009), we analyzed site-level treatment effectiveness for 651 wildfires.

Description of Spatial Statistical Methods Used to Estimate Treatment Effects for Each Fire

Simultaneous Autogression

There are several methodological challenges associated with using geospatial data sets to assess treatment effectiveness. A major issue is that fuel treatments are not randomly located within fires, and are therefore usually confounded with other environmental variables. A treated stand with fire severity lower than an untreated stand may result from the treatment itself, from differences in topography and vegetation characteristics between the treated and untreated areas, or from differences in weather and the resulting fire intensity between the times when the treated and untreated areas burned. For this reason, simple overlays of treatment polygons onto burn severity maps can result in misleading conclusions about the effectiveness of treatments.

Regression analysis is frequently used in observational studies to make inferences about treatment effects conditional on the effects of one or more confounding variables (Gelman and Hill 2007). We estimated treatment effects by fitting a simultaneous autoregressive model for each individual wildfire. The form of the simultaneous autoregressive model was

$$dNBR = b_0 + \sum_{i=1}^{p} b_i x_i + \sum_{j}^{q} \gamma_j t_j + \lambda W u$$

where b_0 is the intercept term, x_i are independent variables representing *i* covariates measured in each pixel (e.g., topography and fuels), b_i are the parameters for these covariates, t_j are independent variables representing *j* treatment classes (indicator variables, each representing a combination of treatment type and treatment age class), γ_i are the parameters for each treatment, λ is the autoregressive parameter, *W* is a spatial weights matrix, and *u* is a spatially structured error term.

In this type of multivariate regression model, the estimates of the treatment effects (γ_i) are conditional on the effects the confounding variables included in the model, which include topographic indices, vegetation indices, and the spatial autoregressive term. Another way of saying this is that the γ_i represent the change in *dNBR* that is attributable to each treatment class t_j after *controlling* for the effects of these confounding variables. Alternately, one can say that the treatment effects assume that all other variables included in the model are “held constant”.

The covariates that we controlled for in our regression models (the x_i variables) included elevation, slope, aspect, canopy cover, and fuel model. However, despite controlling for these variables, analyses of fire severity can still be confounded by omitted or ‘‘lurking’’ variables, particularly those related to fire weather. Although there have been attempts to incorporate fire progression maps and weather data into spatial analyses of fire severity (e.g., Collins et al. 2007), they have only been partially successful because of the coarse scale of fire progression polygons and the large differences between conditions at the flaming front and weather data collected at the nearest stations.

Spatial regression analysis provides an approach for incorporating information about fire weather and other omitted variables. The phenomenon of spatial autocorrelation can be framed as a missing variables problem, in which the pattern of model errors represents one or more spatially structured independent variables that are missing from the regression model (Ver Hoef et al. 2001). In the case of the SAR model, these unmeasured variables are modeled indirectly via the autoregressive term, which is represented by the spatial weights matrix W and the autoregressive parameter λ. For example, on the Warm fire in northern Arizona, the autoregressive term controlled for spatial differences between portions of the fire that burned under less severe fire weather and portions of the fire that burned under plume-dominated conditions (Wimberly et al., 2009). On the School fire, the autoregressive term controlled for spatial differences between areas with landscape-level effects resulting from high treatment density and areas with lower treatment density.

Treatment Effect Summaries

Treatment effects were summarized by computing the weighted mean treatment effect and associated confidence interval for each combination of treatment type and treatment age class.

Treatment age classes were distinguished as follows
Class 1: 0-1 Years
Class 2: 2-5 Years
Class 3: 6-10 Years
Class 4: > 10 Years

Treatment type classes were grouped as follows:
Class 1: Wildfire
Class 2: Mastication/Site Prep
Class 3: Intermediate Thin
Class 4: Heavy Thin/Clearcut
Class 5: Prescribed Burning
Class 6: Prescribed Burning + Thinning

All treatment effects parameters (the γ_i described in the previous section) were combined across all fires. Each treatment effect’s parameter was associated with one of the treatment age classes and one of the treatment type classes listed above. These data were used to fit a weighted analysis of variable model with treatment effect as the dependent variables and treatment type class, treatment age class, and an interaction term included as independent variables. The absolute value of the t-statistic associated with each parameter from its respective SAR model was used as the weight. This approach gave higher weight to the treatment effects in which we had greater statistical confidence.

A multiple comparisons approach was used to calculate the mean of the treatment effects for each treatment type class/treatment age class combination along with groupwise 50% and 95% confidence intervals. These summaries were computed for all fires in the western United States combined, along with regional summaries based on combinations of Bailey's provinces.

Landscape-level

Methods followed those developed by Cochrane et al. (2012). The modeling studies of fire spread and landscape level effectiveness of fuel treatments used the fuels information from LANDFIRE as a base and added treatment-related adjustments as warranted. Given the changing nature of fuels over time, resulting in growing departure from the LANDFIRE baseline, we limited our analyses to 2001-2010 fires. Wildland fire perimeters were acquired from the Monitoring Trends in Burn Severity (MTBS) database (Eidenshink et al. 2007). Fuel treatment involvement, type, age, and spatial attribute information were gained directly from personnel at each of the individual land management units. Wildfires were selected to cover a wide range of sizes (96 to 187,278 hectares, average 7,082) and amount of treated lands (1.2 to 95.2%, average 21.8%) (Table 1). Research teams conducted field visits at ten of the selected wildland fire sites and measured burn severity in a total of 215 Composite Burn Index (CBI) plots (Key and Benson 2005) to validate the MTBS fire perimeter, burn severity, and fuels treatment data (cf. Wimberly et al. 2009).

Table 1 (next page). **Information for 85 wildfires and associated fuels treatments that were involved in the respective wildfires.** The ten fires in italics were visited by field teams that conducted 215 Composite Burn Index (CBI) plots to validate fire severity and fuels treatments information.

Fire name	State	Fire year	Fire size (ha)	Treated (ha)	Number of treated areas	Percentage previous wildfire	Planned treatments (%)	Total land treated (%)
Beaverhead	AZ	2006	575	327	28	0.0	100.0	57.0
Indian	AZ	2002	642	228	12	1.8	98.2	35.6
Maverick AZ	AZ	2003	718	72	2	100.0	0.0	10.0
Rodeo	AZ	2002	186,874	53,423	567	41.6	58.4	28.6
Sand	AZ	2006	450	24	1	0.0	100.0	5.4
Three Forks	AZ	2004	2,770	682	51	0.0	100.0	24.6
Warm	AZ	2006	23,575	1,261	79	0.0	100.0	5.3
West WFU	AZ	2006	851	486	20	0.0	100.0	57.1
Antelope	CA	2007	9,351	1,910	59	64.5	35.5	20.4
Comb Complex	CA	2005	4,299	552	3	100.0	0.0	12.8
Copper	CA	2002	7,708	1,107	42	88.3	11.7	14.4
Deep	CA	2004	1,364	337	24	91.7	8.3	24.7
Eagle	CA	2004	3,773	519	7	100.0	0.0	13.8
Esperanza	CA	2006	16,416	8,548	234	99.2	0.8	52.1
Frog	CA	2006	2,700	486	37	57.4	42.6	18.0
Gap	CA	2001	965	45	15	0.0	100.0	4.7
Honeydew	CA	2003	5,486	910	1	100.0	0.0	16.6
Meadow	CA	2004	2,235	792	7	48.9	51.1	35.5
Moonlight	CA	2007	26,595	2,765	21	53.0	47.0	10.4
Padua	CA	2003	4,280	568	51	100.0	0.0	13.3
Peterson Complex	CA	2008	3,210	416	72	0.0	100.0	13.0
Power	CA	2004	6,987	120	27	0.0	100.0	1.7
Soboba	CA	2005	822	33	2	0.0	100.0	4.0
Stanza	CA	2002	1,251	23	1	100.0	0.0	1.8
Big Elk	CO	2002	1,759	128	2	0.0	100.0	7.3
Bucktail	CO	2002	923	332	7	0.0	100.0	36.0
Mason Gulch	CO	2005	4,461	52	1	0.0	100.0	1.2
Maverick CO	CO	2003	461	131	7	0.0	100.0	28.3
Missionary Ridge	CO	2002	27,891	1,396	106	0.0	100.0	5.0
Pack Trail WFU	CO	2005	412	112	3	100.0	0.0	27.0
Beetle	FL	2005	1,524	258	14	0.0	100.0	16.9
Juniper	FL	2006	4,855	1,613	46	99.8	0.2	33.2
Lindsey Bay	FL	2006	454	166	17	23.3	76.7	36.5
Tracy	FL	2008	480	172	12	0.0	100.0	35.8
Black Canyon	ID	2005	773	103	9	0.8	99.2	13.3
Elk Creek	ID	2005	645	42	1	100.0	0.0	6.5
Falconberry	ID	2003	10,775	265	3	100.0	0.0	2.5
Fish	ID	2003	1,480	601	13	84.4	15.6	40.6
Gregory	ID	2005	486	82	5	0.0	100.0	16.9
Hale Gulch	ID	2005	1,079	163	7	0.0	100.0	15.2
Hall	ID	2003	584	59	9	0.0	100.0	10.1
Marble	ID	2003	2,461	221	4	100.0	0.0	9.0
Mustang WFU	ID	2005	471	91	1	100.0	0.0	19.3
Sapp	ID	2003	3,949	3,758	2	100.0	0.0	95.2
Six Mile Creek	LA	2005	1,322	695	3	97.1	2.9	52.6
Galion	MI	2007	258	24	2	0.0	100.0	9.4
Hughes Lake Fire	MI	2006	2,336	328	26	0.0	100.0	14.0
Meridian	MI	2010	3,073	566	45	0.0	100.0	18.4
Cavity Lake	MN	2006	10,850	295	35	100.0	0.0	2.7
Ham Lake	MN	2007	18,963	6,309	107	0.5	99.5	33.3
Crooked Truck Trail	MO	2006	331	100	14	0.0	100.0	30.1
Running Boy	MO	2007	270	124	16	0.0	100.0	45.8
School House Hollow	MO	2006	263	53	11	0.0	100.0	20.2
Sellers	MO	2004	96	19	3	0.0	100.0	19.8
Big Creek	MT	2003	541	344	12	72.9	27.1	63.6
Camp 32	MT	2005	365	134	10	0.0	100.0	36.7
Jimtown	MT	2003	448	52	13	100.0	0.0	11.5
Lincoln	MT	2003	14,968	1,168	123	0.0	100.0	7.8
Little Salmon Creek	MT	2003	13,372	1,621	3	100.0	0.0	12.1
Prospect	MT	2005	1,327	267	15	2.4	97.6	20.1
Sawmill Gulch	MT	2005	775	500	22	26.6	73.4	64.6
Signal Rock	MT	2005	5,120	1,110	62	78.7	21.3	21.7
Trapper Creek	MT	2003	7,296	247	2	100.0	0.0	3.4
Bear Paw	NM	2006	1,374	50	5	34.5	65.5	3.6
Borrego	NM	2002	5,211	1,715	54	54.8	45.2	32.9
Lakes	NM	2002	1,743	372	16	0.0	100.0	21.4
Peppin	NM	2004	24,502	749	8	91.4	8.6	3.1
Apple	OR	2002	7,745	963	60	79.2	20.8	12.4
Boulder	OR	2002	19,629	1,104	200	1.9	98.1	5.6
Buckeye	OR	2002	1,047	538	76	0.0	100.0	51.4
Bull Springs	OR	2003	515	144	13	0.0	100.0	28.0
Davis	OR	2003	8,370	2,864	469	0.0	100.0	34.2
GW	OR	2007	5,552	2,881	144	85.2	14.8	51.9
Kelsay	OR	2003	528	101	22	0.0	100.0	19.1
Otter Creek	OR	2007	1,217	603	46	0.0	100.0	49.5
Ricco	SD	2005	1,438	398	28	0.0	100.0	27.6
Bull Complex	UT	2006	11,111	2,479	16	100.0	0.0	22.3
Six Mile	UT	2004	1,659	166	8	0.0	100.0	10.0
30 Mile	WA	2001	3,691	526	1	100.0	0.0	14.2
Dirty Face	WA	2005	557	8	2	0.0	100.0	1.5
Fischer	WA	2004	6,555	128	19	0.0	100.0	1.9
Fourth of July	WA	2001	2,836	281	5	81.9	18.1	9.9
School	WA	2005	20,923	1,221	62	0.0	100.0	5.8
Togo Mountain	WA	2003	2,224	448	61	0.0	100.0	20.1
Cement	WY	2005	1,227	69	18	0.0	100.0	5.6

Data sources

To investigate landscape-level influences of the treatments, we used the FARSITE modeling system (Finney 2004) to simulate the observed wildfire progression and spread rates. Model simulations were parameterized with LANDFIRE fuels and topographic data layers. LANDFIRE provides consistent and comprehensive digital maps of vegetation composition, structure, wildland fuels, and topographic data at a 30 m resolution for the United States (Rollins and Frame 2006; Rollins 2009). The expanded set of 40 standard fire behavior fuel models (Scott and Burgan 2005) were used in all simulations. Relevant weather conditions and wind velocities before and during each wildfire were acquired from individual Remote Automated Weather Stations (RAWS) in the vicinity of each fire. RAWS data were imported to FireFamily Plus (Bradshaw and McCormick 2000) to summarize temperature, precipitation, humidity, and wind speed and direction in a format compatible with FARSITE. Fuels treatment maps were acquired as shape files from responsible land management personnel (cf. Wimberly et al. 2009). Fuel treatments included silvicultural thinning of a wide range of intensities and practices, mastication, prescribed fire, and thinning followed by prescribed fire. Historic wildfire boundaries, fire ignition locations and, when possible, daily fire progression maps for each fire were also acquired from the responsible land management units. In addition, the spatiotemporal progression of actively burning fire fronts were derived from the Forest Service's Active Fire Mapping Program, based on MODIS fire detection points (available at http://activefiremaps.fs.fed.us/). Additional information, including daily fire behavior observations during each of the individual fire events, was acquired from Incident Status Summary (ICS 209) fire reports (available at http://fam.nwcg.gov/fam-web/).

Analysis methods

Recognition of linkages between parameters and their impacts on overall fire behavior within modeled simulations is critical to producing robust calibrations of the degree of influence that weather, topography, and fuels have on actual wildfire behavior. Scaling calibration, whereby interrelated parameters are adjusted through multipliers so as to retain proportional relationships to each other, overcomes some limitations in recent fuel treatment simulation research (Martinson and Omi 2008) and model weaknesses (Cruz and Alexander 2010; Stratton 2006, 2009) by matching observed fire behavior to observed weather and fuel conditions, thereby producing realistic, albeit relative, evaluations of the effects of fuels treatments.

Many fuels treatments have been implemented since the Healthy Forests Restoration Act (HFRA) was signed in December of 2003 (H.R. 1904 2003), therefore, the LANDFIRE 1.0.0 data layers that were used, which are from circa 2001, do not accurately represent fuels and vegetation structure in many treated forests at the time of the selected wildfires. To reflect the reported treatment activities and forest conditions at the time of each wildfire, we adjusted the relevant fuels and structure data to more accurately represent conditions existing within each treatment area, prior to calibrating each fire simulation. Treatment updates were based on regional silviculture books, the Forest Service Activity Tracking System (FACTS) database's activity code descriptions, and/or information given by local land managers.

To conduct the analyses, an initial FARSITE simulation was calibrated to approximate the observed daily fire behavior and progression of each wildfire. Fire spread rates and behavior are functions of wind velocity, terrain, and fuel type, quantity, moisture, and structure. Many fire modeling systems, including FARSITE, rely on integration of Rothermel's (1972, 1991) surface and crown fire spread rate models and Van Wagner's (1977, 1993) crown fire transition and propagation models. Recognizing the substantial under-prediction biases for crown fire behavior in these systems (Cruz and Alexander, 2010), all input variables were evaluated and, if needed, modified to match observed fire behavior.

Universal updates, primarily through percentage multipliers, were applied to landscape fuels (i.e. surface fuel model type, CBH, CBD, FMC, and CC) and weather (primarily wind) variables to correct for known biases, following procedures similar to Stratton (2006, 2009). For example, wind speed and surface fuel type substantially influence both surface and crown fire intensities, spread rates, and the thresholds for passive and active crown fires. RAWS station data are often many kilometers away from the active burning zone, and local winds are influenced by topography and vegetation in the vicinity of a fire. Therefore, all wind speeds, or only those during known periods of extreme fire spread, were scaled by percentage multipliers, in possible conjunction with surface fuel model changes, until both fire spread rates and behavior matched observations, to control for biased data. If surface spread rates were accurate, but the quantity of passive and/or active crown fire was suspect, then CBH, FMC, and CBD were scaled to produce observed behavior without affecting surface spread rates. Because of the semi-empirical nature of fire models, we maintained the values of the inputs within initial experimental ranges (e.g. >67% foliar moisture content and <83km hr^{-1} wind speeds (Cruz and Alexander 2010)). This maintained proportional relationships among inputs, under the assumption that the quantitative values of these inputs are not as important as the linear and non-linear relationships among them in determining their cumulative influence on calculated fire behavior.

Pre- and post-fire Landsat imagery and MTBS fire severity estimates were used to verify the appropriateness for simulating observed fire behavior of the fuels adjustments within treated areas. For example, if MTBS showed low fire severity within a fuel treatment, then crown fire could not have occurred in these areas. Changes to surface fuel models or canopy base heights were constrained to be in line with known treatment practices while also producing simulated fire behavior consistent with observed fire effects in treated areas.

All wildfires that were simulated experienced crown fire behavior, with the exception of the 2002 Copper Fire (CA). During crown fires, large numbers of firebrands are lofted into the air, frequently resulting in downwind spot fires. Spot fires can greatly accelerate wildfire spread rates and often bypass potential barriers to fire spread (e.g. roads, rivers, lakes, fuel treatments). FARSITE simulates this behavior by estimating firebrand numbers and sizes based on empirical data from different tree species. The distances traveled, spatial distribution, and number of still burning firebrands that reach the ground are calculated based on particle size distribution, wind velocities, and fire intensity (lofting height) (Albini 1979). The modeler sets the fraction of embers that result in new fire ignitions. We adjusted this fraction to calibrate our simulation with observed fire behavior, although the range of values used was small (~0.5-1.0% ignition frequency) (Stratton 2006, 2009). Because of this stochastic behavior, model simulations are unique each time they are run, even though all parameters remain unchanged.

Once realistic simulations, qualitatively similar to observed fire progressions, were achieved, the same simulation parameters were used for all subsequent analyses of the respective fires. Due to the stochastic results caused by the varying numbers and locations of spot fires, multiple simulations of each fire were conducted. We experimented with up to 100 repeated simulations but settled on 10-30 simulations for fires with the potential for crowning behavior as adequate for establishing likely fire extents, with the final number dependent upon variability in final simulated perimeters and the computational time required for each simulation. It is noteworthy that, regardless of the total number of days that individual wildfires burn, the vast majority of area burned generally occurs during a relatively few hours or days, when extreme weather conditions result in rapid fire spread. The period of each day's active fire growth (burn periods) were determined by weather events and observed fire behavior. Insufficient data existed to explicitly model fire suppression activities. Suppression activities can reduce or stop fire spread along fire fronts but can also increase area burned, sometimes substantially, when fuels are intentionally burned in front of a fire to break fuel continuity and prohibit spread. Model simulations were not constrained or forced to generate perimeters that matched MTBS fire perimeters.

Subsequently, a second set of simulations, equal in number to the original 'treated' simulations, were used to derive new probability maps of the likely fire extent that would have occurred over the time periods of the respective wildfires, in the absence of existing landscape fuel treatments, the 'untreated' landscape. Treatments conducted before LANDFIRE image acquisition (1999-2001), thus already included in the treated landscape, were replaced by estimates of fuel quantity and structure similar to surrounding untreated areas for the untreated simulations. Between the treated and untreated simulations, no other spatial or temporal parameters were changed, isolating the influence of fuels treatments on realized fire behavior and spread for each wildfire. Neither the treated nor untreated simulations included fire suppression activities.

The multiple simulations of each wildfire were used to derive maps of the probability of each area burning and tabular results of the range, average, and variance of simulated fire extents (Table 2). By overlaying the two probability maps and calculating the difference in the spatial probability of burning between the treated (actual) and untreated (hypothetical) landscapes for each 30 m pixel, we created maps of the probability that any given location had experienced altered fire risk because of the presence of the fuels treatments (Figure 2). To examine the relative effects of planned and unplanned (previous wildfires) fuels treatments, their separate effects were calculated by comparison of each type of treatment, in the absence of the other, with an untreated landscape (as above) for three fires (Antelope, Borrego, Moonlight) where previous wildfires comprised roughly half of the total treated area (64.5%, 57%, 54.8%) (Table 1).

Table 2 (next page). **Model simulation data for 85 wildfires.** Comparison of the multiple simulations run for treated and untreated conditions (equal numbers of each) to account for stochastic fire behavior under the extreme wildfire conditions during these large fires. For example, area burned if landscapes were simulated as being untreated versus those when the treated (real condition) condition was used, standard deviations of respective model scenarios. All values in hectares unless otherwise noted. Significant size difference from untreated, Welch two-sample *t*-test: * P<0.05; ** P<0.01; *** P<0.001; **** P<0.0001, *****P<0.00001. Data sorted from greatest reduction in fire size to greatest increase in fire size caused by fuels treatments. Treatment-related areas of changed fire risk, likely area burned/unburned and treatment efficiency (promoted/prevented).

Fire Name	Number of Simulations	**Average Untreated Fire Size**	**Standard Deviation**	**Average Treated Fire Size**	**Standard Deviation**	**p-value**	Average burn area change	Increased risk	Decreased risk	Treatment-related burned	Treatment-related saved	Promoted treated hectare	Prevented per treated hectare
Jimtown	10	1,987	103	681	28	*****	-66%	53	1,735	15	1,676	0.3	32.4
West	10	3,035	48	1,106	19	*****	-64%	35	2,456	8	1,975	0.0	4.1
Mustang WFU	10	799	77	340	28	*****	-57%	40	960	10	483	0.1	5.3
Pack Trail WFU	10	2,052	41	986	34	*****	-52%	12	1,471	3	1,069	0.0	9.6
Stanza	10	2,424	214	1,232	37	*****	-49%	6	2,202	1	2,054	0.0	89.5
Fish	30	3,401	458	1,743	158	*****	-49%	39	2,575	21	1,692	0.0	2.8
Sand	10	862	39	474	234	***	-45%	3	364	0	131	0.0	5.4
Copper	1	15,963	-	8,834	-		-45%	362	7,941	362	7,941	0.3	7.2
Meadow	10	5,831	623	3,265	307	*****	-44%	150	5,002	26	2,649	0.0	3.3
Bucktail	30	2,090	118	1,212	37	*****	-42%	84	1,039	11	911	0.0	2.7
Eagle	10	8,681	68	5,200	287	*****	-40%	756	4,254	207	3,687	0.4	7.1
Little Salmon Creek	10	24,681	1,154	16,031	1,793	*****	-35%	2,805	17,131	1,080	9,709	0.7	6.0
Trapper Creek	10	10,117	978	6,979	556	*****	-31%	464	6,364	64	3,230	0.3	13.1
Marble	20	3,752	382	2,672	120	*****	-29%	30	3,358	3	2,787	0.0	12.6
Togo Mountain	30	3,838	286	2,814	229	*****	-27%	55	2,188	7	1,029	0.0	2.3
Big Creek	10	656	58	484	48	*****	-26%	72	359	8	95	0.0	0.3
Prospect	10	7,990	349	6,251	256	*****	-22%	643	4,824	83	1,852	0.3	6.9
Antelope	10	9,821	483	7,717	389	*****	-21%	928	4,822	150	2,252	0.1	1.2
Hall	10	999	103	815	74	***	-18%	92	655	14	199	0.2	3.4
Fischer	30	12,884	1,170	10,623	755	*****	-18%	283	6,124	39	2,321	0.3	18.2
Bull Complex	10	13,873	131	11,568	226	*****	-17%	821	4,296	142	2,562	0.1	1.0
Falconberry	10	11,066	656	9,267	715	*****	-16%	4,768	4,878	1,946	3,756	7.3	14.2
School	10	26,418	618	22,178	596	*****	-16%	653	10,561	83	4,319	0.1	3.5
Deep	10	1,710	13	1,435	18	*****	-16%	16	542	4	443	0.0	1.3
Soboba	10	1,539	5	1,304	34	*****	-15%	40	375	10	246	0.3	7.5
Peterson Complex	20	3,301	119	2,852	67	*****	-14%	616	1,098	78	537	0.2	1.3
Elk Creek	10	2,453	80	2,140	104	*****	-13%	180	691	19	326	0.5	7.8
Frog	20	3,264	649	2,925	823		-10%	1,700	1,948	131	472	0.3	1.0
Cavity Lake	20	13,461	420	12,171	273	*****	-10%	1,807	3,292	271	1,559	0.9	5.3
Ham Lake	20	18,805	1,052	17,072	3,044	*	-9%	16,976	8,265	3,649	5,382	0.6	0.9
Maverick AZ	10	1,095	48	1,007	31	***	-8%	32	302	4	93	0.1	1.3
Moonlight	10	35,490	1,413	32,644	1,439	***	-8%	4,532	8,537	708	3,583	0.3	1.3
Otter Creek	30	1,380	102	1,274	102	***	-8%	370	321	131	152	0.2	0.3
Meridian	10	4,172	157	3,852	211	**	-8%	561	1,476	93	427	0.2	0.8
GW	20	5,541	110	5,213	129	*****	-6%	1,194	1,125	405	753	0.1	0.3
Lakes	30	3,511	306	3,309	283	*	-6%	330	1,229	39	272	0.1	0.7
Borrego	20	8,074	1,302	7,618	1,128		-6%	1,873	5,616	325	788	0.2	0.5
Black Canyon	30	1,025	543	968	240		-6%	316	1,665	102	178	1.0	1.7
Esperanza	10	18,836	300	17,937	466	***	-5%	1,172	2,769	214	1,150	0.0	0.1
Warm	10	29,089	3,709	27,702	3,130		-5%	7,614	14,670	1,447	2,673	1.1	2.1
Signal Rock	20	9,491	423	9,055	350	***	-5%	2,865	2,957	506	948	0.5	0.9
Missionary Ridge	30	60,059	3,699	57,597	6,256		-4%	26,508	17,703	3,084	3,733	2.2	2.7
Six Mile Creek	30	430	41	412	34		-4%	53	157	16	33	0.0	0.0
Fourth of July	30	3,370	1,320	3,236	1,277		-4%	102	330	225	413	0.8	1.5
Ricco	10	1,109	133	1,070	187		-3%	490	435	80	107	0.2	0.3
Mason Gulch	20	4,460	660	4,317	980		-3%	2,406	2,927	142	292	2.7	5.6
Sellers	10	167	8	161	3		-3%	10	33	3	9	0.2	0.5
Peppin	10	27,268	2,283	26,405	1,490		-3%	6,579	8,255	970	1,840	1.3	2.5
30 Mile	30	4,855	1,231	4,744	908		-2%	2,110	2,533	402	461	0.8	0.9
Rodeo	10	279,908	5,558	273,993	12,622		-2%	36,950	60,043	7,339	14,013	0.1	0.3
Gap	30	1,444	108	1,421	82		-2%	155	333	20	51	0.5	1.1
Bear Paw	20	1,747	70	1,731	72		-1%	432	484	46	63	0.9	1.3
Dirty Face	30	981	33	975	35		-1%	88	107	11	18	1.4	2.2
Padua	10	4,536	60	4,509	103		-1%	437	481	95	96	0.2	0.2
Honeydew	10	6,317	168	6,296	138		0%	768	803	111	136	0.1	0.1
Galion	30	363	18	362	15		0%	53	64	8	10	0.3	0.4
Big Elk	30	3,448	165	3,472	153		1%	546	803	181	156	1.4	1.2
Apple	10	7,525	1,114	7,613	815		1%	2,517	2,696	446	362	0.5	0.4
Buckeye	20	1,785	64	1,821	42	*	2%	416	409	101	66	0.2	0.1
Hughes Lake Fire	20	5,026	215	5,138	164		2%	1,399	1,724	355	260	1.1	0.8
Three Forks	10	4,947	628	5,089	212		3%	2,117	1,648	394	250	0.6	0.4
Six Mile	20	1,539	119	1,611	120		5%	696	422	122	48	0.7	0.3
Tracy	30	366	41	384	36		5%	97	56	33	13	0.2	0.1
Boulder	20	20,205	305	21,422	263	*****	6%	4,132	546	1,247	44	1.1	0.0
Hale Gulch	10	1,558	53	1,655	87	**	6%	758	302	151	66	0.9	0.4
Gregory	30	498	83	530	82		6%	197	28	39	4	0.5	0.1
Comb Complex	10	14,252	550	15,340	494	***	8%	3,080	800	1,204	116	2.2	0.2
Juniper	30	6,591	309	7,287	229	*****	11%	1,364	633	804	126	0.5	0.1
Cement	30	1,058	164	1,183	143	**	12%	633	155	149	21	2.2	0.3
Lincoln	30	14,243	829	15,986	1,002	*****	12%	5,577	1,163	2,015	254	1.7	0.2
Beetle	30	1,774	57	1,996	144	*****	13%	835	119	257	32	1.0	0.1
Davis	10	12,975	786	14,719	849	***	13%	5,027	3,615	3,072	1,822	1.1	0.6
Beaverhead	10	495	42	578	56	**	17%	360	51	94	8	0.3	0.0
Lindsey Bay	30	789	29	934	50	*****	18%	346	18	154	8	0.9	0.0
Camp 32	20	399	62	478	47	*****	20%	399	305	79	53	0.6	0.4
Power	10	7,021	1,167	8,428	924	**	20%	5,891	2,395	1,689	264	14.1	2.2
Sawmill Gulch	20	546	123	671	124	**	23%	691	125	156	31	0.3	0.1
School House Hollow	20	548	0	680	16		24%	99	1	58	0	1.1	0.0
Sapp	10	3,993	776	5,001	679	**	25%	2,819	1,138	933	116	0.2	0.0
Crooked Truck Trail	20	304	-	382	-		26%	117	32	117	32	1.2	0.3
Maverick CO	30	605	75	819	79	*****	35%	300	102	256	18	2.0	0.1
Bull Springs	30	608	38	835	54	*****	37%	477	97	284	42	2.0	0.3
Running Boy	20	308	-	433	2		41%	142	5	129	5	1.0	0.0
Kelsay	20	666	120	973	127	*****	46%	955	326	339	27	3.4	0.3
Indian	20	446	177	1,375	24	*****	208%	1,289	119	950	9	4.2	0.0

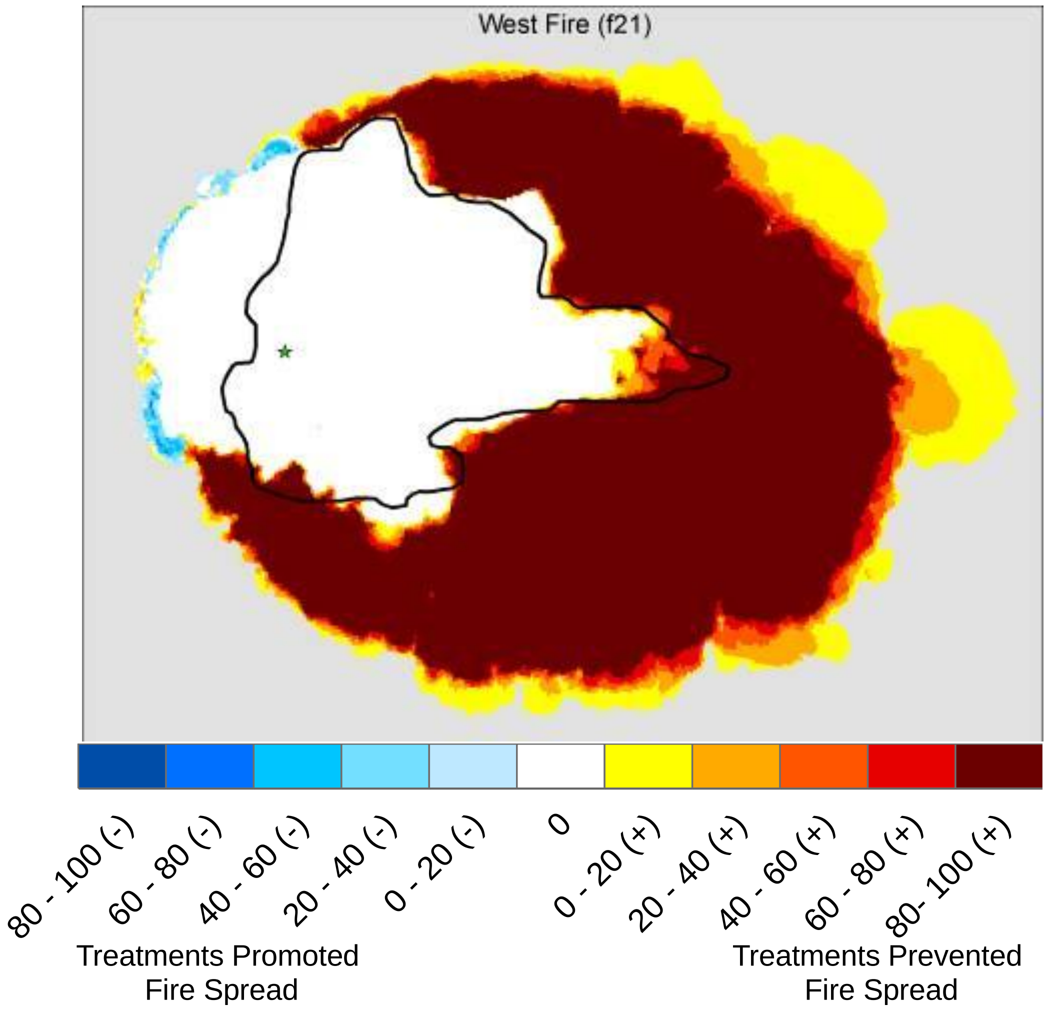


Figure 2. Simplified example of the landscape-level risk probability alterations caused by treatments for the Warm Fire (2006, Arizona). The dark black polygon is the MTBS fire perimeter (25,575 ha). The green star shows the fire's ignition location. All areas in bright white burned in all simulations of both the treated and untreated landscape. Fire suppression activities were not simulated. Areas in blues burned at a greater frequency in the treated landscape conditions than under untreated conditions. Areas in warm colors burned with corresponding greater frequencies in the untreated scenarios. See scale for color ramp frequency correspondence. This fire burned into 20 different planned treatments (Table 1) and had one of the greatest average treatment related decreases in burned area (-64%) due to fuels treatments (Table 2). The specific treatment polygons for this fire can be seen in the final panel of Figure 6.

Key findings

1. Effective fuels treatments act to reduce fire severity but these effects decay over time. Different treatment types have demonstrably varying levels of effectiveness and temporal responses, both within and between different ecoprovinces.

We tested treatment-related alterations in fire severity exhibited within treated lands (as measured with MTBS dNBR values) during 651 large wildfires from 2001-2010 across the continental United States (Lower 48 States). For these analyses, we considered previous wildfires as 'unplanned treatments' to provide a comparative category for evaluating the performance of the different planned fuels treatments. Planned treatments were grouped into five general classes including, Prescribed Burn (Rx), Thin and Prescribe Burn (Thin/Rx Burn), Thin (light to moderate thinning), Mastication/Site Prep, and Clear Cut/Heavy Thin. Figure 3 graphically presents the data for each treatment class in three forms, first the 'All' bar simply relates the summary statistics for all groups of a given treatment type across all fires, indicating the percentage of which showed a net reduction (blue) or increase (yellow) in observed burn severity as a function of the treatment activity, while controlling for other factors (e.g. slope, aspect etc.) (Wimberly et al. 2009). The next bar ($p<0.1$) presents only those data from treatments that resulted in burn severity measurements that were significantly different than expected in the absence of the treatment activities at the 0.1 level. The remaining bars represent the given treatment types and their effectiveness at changing observed fire severity as functions of age since implementation ($0\text{-}1^{+}$, $2\text{-}5^{+}$, 6-10, >10 years). Although we present the 0-1+ age class data, we do not consider the information to be relevant to assessments of performance in this aggregate form for the following reasons; 1) the MTBS methodology for dNBR assessments utilizes pre- and postfire images but in many cases the pre-fire imagery also pre-dated the implementation of many fuels treatments, so the treatment effect is misinterpreted as increased fire severity due to the vegetation removal during thinning or burning; 2) some of the fuel treatments burned prematurely under adverse fire weather conditions during the implementation process, skewing the implied severity change. For all age classes, data from all treated areas of an age class were lumped together for effectiveness estimation. Therefore, within the age class bars, the numerical values represent the number of large wildfires where a given treatment type of a certain age was observed to either diminish or increase fire severity. For example, of the 651 examined wildfires, 401 burned over areas of previous wildfire >10 years old. Within 236 (59%) of these fires, older burned areas reduced fire severity but in the other 165 (41%) older burned areas increased apparent fire severity. Likewise, we examined 79 large wildfires that involved thinned and prescribe burned treatments that were >10 years old, with 65 (82%) reducing fire severity and 14 (18%) increasing observed fire severity.

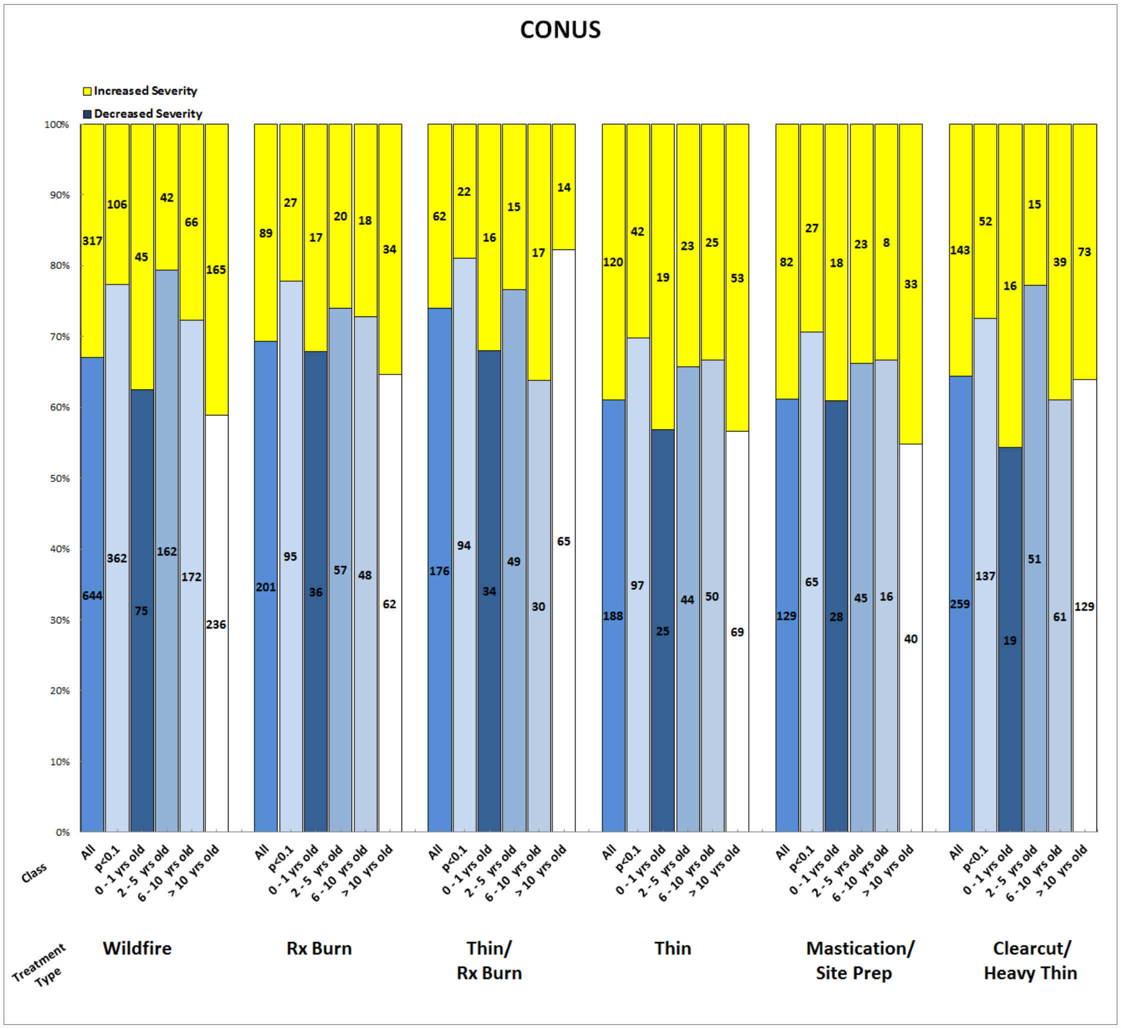


Figure 3. **Wildfires with Severity Changes by Treatment Type and Age across the United States** – The graphic shows both the percentage and number of examined wildfires that experienced either fire severity reductions (cool colors) or increases (yellow) as functions of treatment type and age of treatment. The 'All' class combines all treatments of the type regardless of age, the 'p<0.1' class indicates just those fires with a high degree of statistical certainty of the changed severity, the other classes show severity changes for the subset of each treatment class by age category. The increased/decreased fire severity distinction is based upon the average response experienced among all burned treatment polygons of a given type and age class within a given wildfire. As mentioned in the text, the 0-1 age class results are an artifact that appears erroneously ineffective due to issues related to MTBS image selection dates and cases where treatments burned prior to completion, not because of actual treatment effects.

To provide better quantification of the level of effect that treatments had on fire severity, we examined the range of dNBR values within fuels treatments exhibiting a high degree of likelihood of the effects being solely related to treatment, corresponding to the p<0.1 class in figure 3. In the following graphics (Figures 4 & 5), we indicate the mean change in dNBR as functions of treatment type and age, together with the 50th and 90th confidence intervals to better bracket the range of expected performance. Figure 4 shows the lumped performance of the various treatment types and ages for the entire western United States.

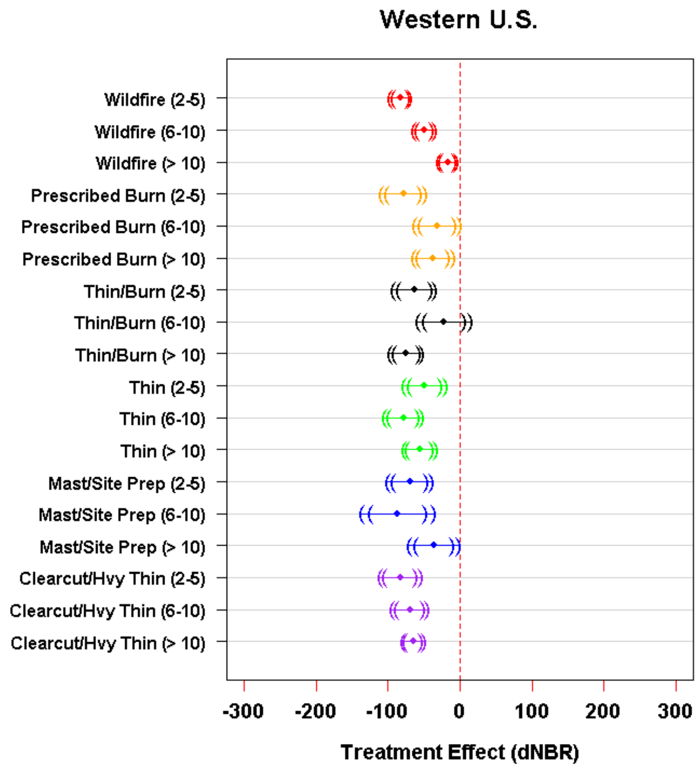


Figure 4. Statistical analyses of fire severity changes for different fuels treatment types and ages. The figure shows the mean change (central dot) in fire severity, as measured from MTBS dNBR values, and the 50th and 90th confidence intervals for the expected range of the treatment effect. Note, the 0-1^{+} age class was excluded from the statistical analyses due to the aforementioned interactions with the MTBS pre-fire date selections. Data with dNBR values less than zero indicate a reduction in fire severity due to the fuel treatment type, while values greater than zero indicate exacerbation of fire severity due to the fuel treatments. Taken as a group, all fuel treatment types and age classes appear to reduce fire severity on average across the West, however, we contend that this level of analysis inappropriately lumps different ecosystem types and can lead to general conclusions that may be inaccurate for regional applications.

Although Figure 4 seems to show that all treatments appear to be fairly effective for the western United States, we caution against inferring much from this figure. We have concluded that aggregating the treatment performance data at this coarse of a scale leads to erroneous and potentially misleading information about appropriate and effective regional land management. We illustrate this in Figure 5, which provides the same information as Figures 3 and 4, but for the 9 specific ecoprovinces presented in Figure 1. It quickly becomes apparent that, unlike in Figure 4, regional fuels treatment performance during multiple wildfires varies considerably. There is no one size fits all treatment type or intimation of a generic, any treatment will do, when the data are examined regionally.

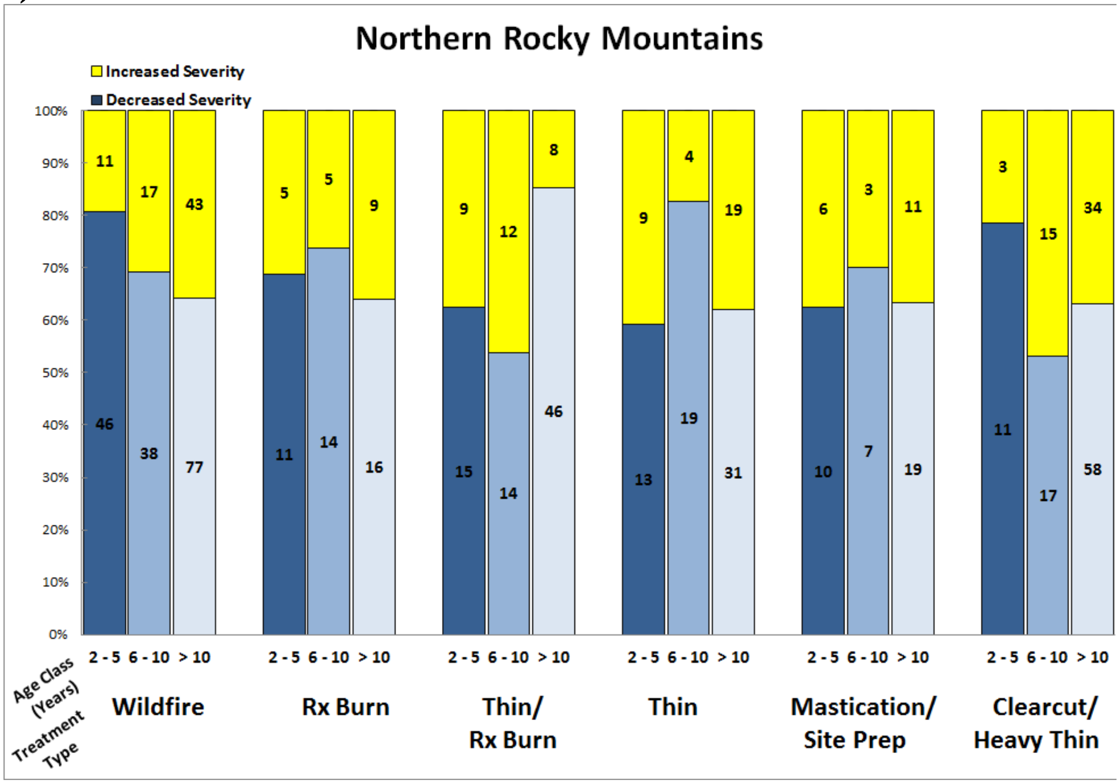
While there are multiple objectives in land management activities, it is possible, with these data, to evaluate which fuels treatments are most effective for each region and estimate how they will continue to perform over time since implementation. Similarly, it is possible to determine if prescribed burning, as practiced in each region, is approximating wildfires in treatment affects for future wildfire impacts. In the case of the Pacific Northwest, prescribed burning as a standalone activity may have a function in landscape management, but it does not perform similarly to wildfires and appears to be largely ineffective or even detrimental as a treatment for reducing future vegetation mortality in subsequent wildfires. However, if combined with thinning, prescribed burning of these ecosystems works well to reduce future fire severity (Figure 5c). Similarly, in Northern California, mastication has become the most common fuel treatment in recent years, but the observations to date (ages 2-5 years) indicate that this treatment may be increasing fire severity and certainly is not reducing it (Figure 5d). The data do not yet indicate whether this treatment type will perform better with age.

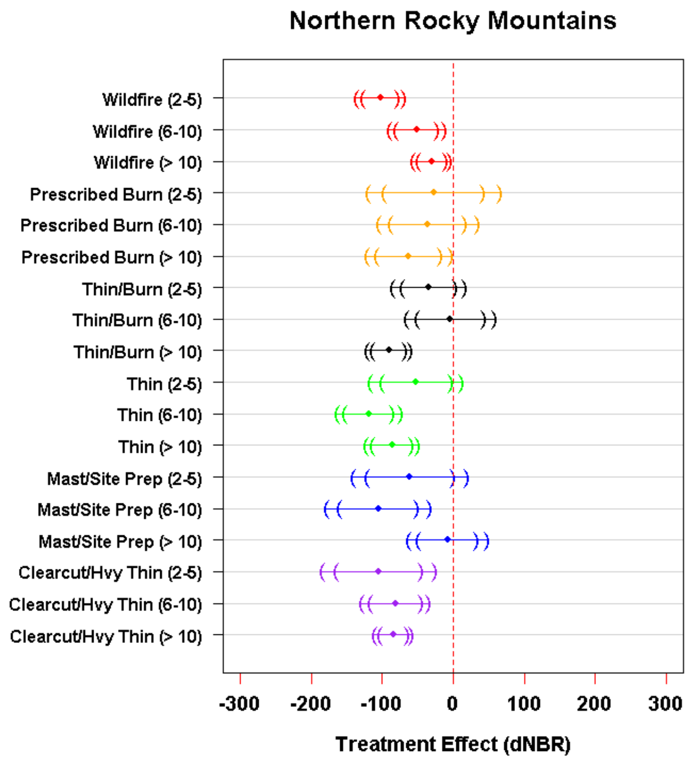
Land managers will have to balance multiple objectives but it is clear that fuel treatment activity decisions need to be regionally appropriate. This analysis cannot determine if there are differences in the ways that certain activities (e.g. prescribed burning) are being implemented that could affect the observations but they do show that current practices are having different results in different locations. In the Northern Rockies (Figure 5a), thinning works well as a treatment but its effectiveness is degraded if it is also burned. Conversely, in the Southern Rockies (Figure 5b), thinning is only effective as a fuels treatment if it is also prescribed burned. Interestingly, in the Interior Broadleaf ecoprovince (Figure 5g), prescribed fires are not simulating wildfires in their effect but, as practiced, they are the only effective fuel treatment for these forests. All other treatments, including wildfires, either have no effect or exacerbate future fire severity.

Figure 5 (a-i: next 9 pages) Fuels Treatment Effectiveness by Ecoprovince for Different Treatment Types and Ages. The next several pages of figures provide both the numbers of wildfires within each ecoprovince (Figure 1) experiencing net increased/decreased fire severity (top figures) and the statistical mean and 50th and 90th confidence intervals of the severity changes as measured using MTBS dNBR values (bottom figures). Note that the confidence bands show the likely range of the mean dNBR response for each treatment type and age class, with negative values indicating reduced severity and positive values potentially increased severity. Values outside of this range can occur but make up a small percentage of areal conditions. Each ecoregion exhibits differing responses by treatment type and time since treatment. These regional data lead to more specific and locally appropriate management guidance than the overall composite data (Figures 3 & 4).

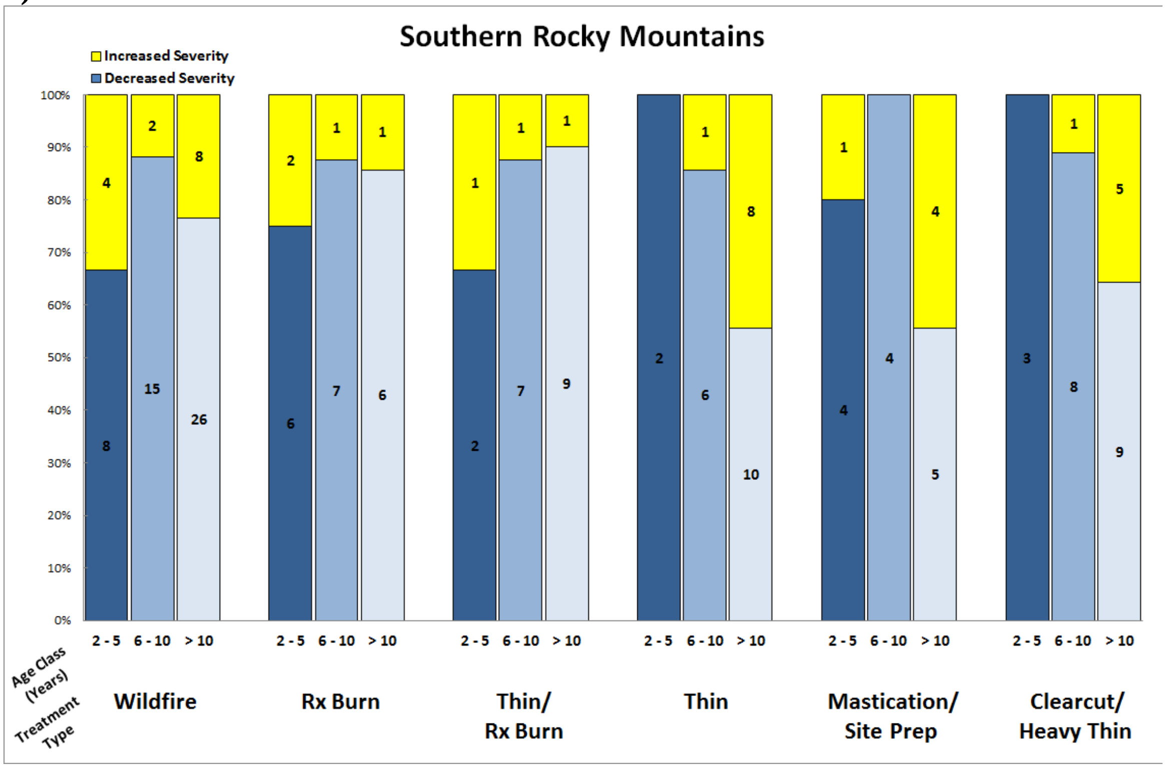
Ecoprovince-level Fuels Treatment Effects on Fire Severity by Treatment Type and Age

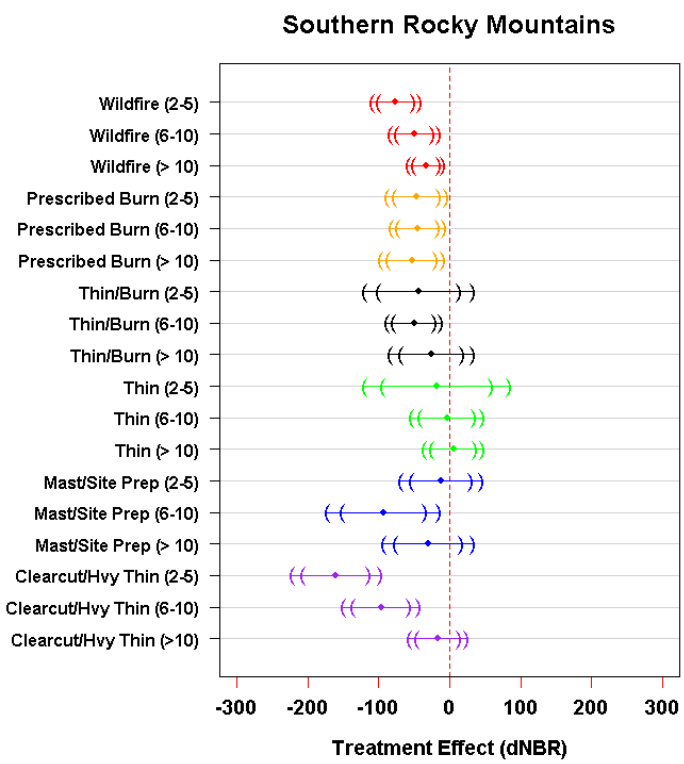
a)



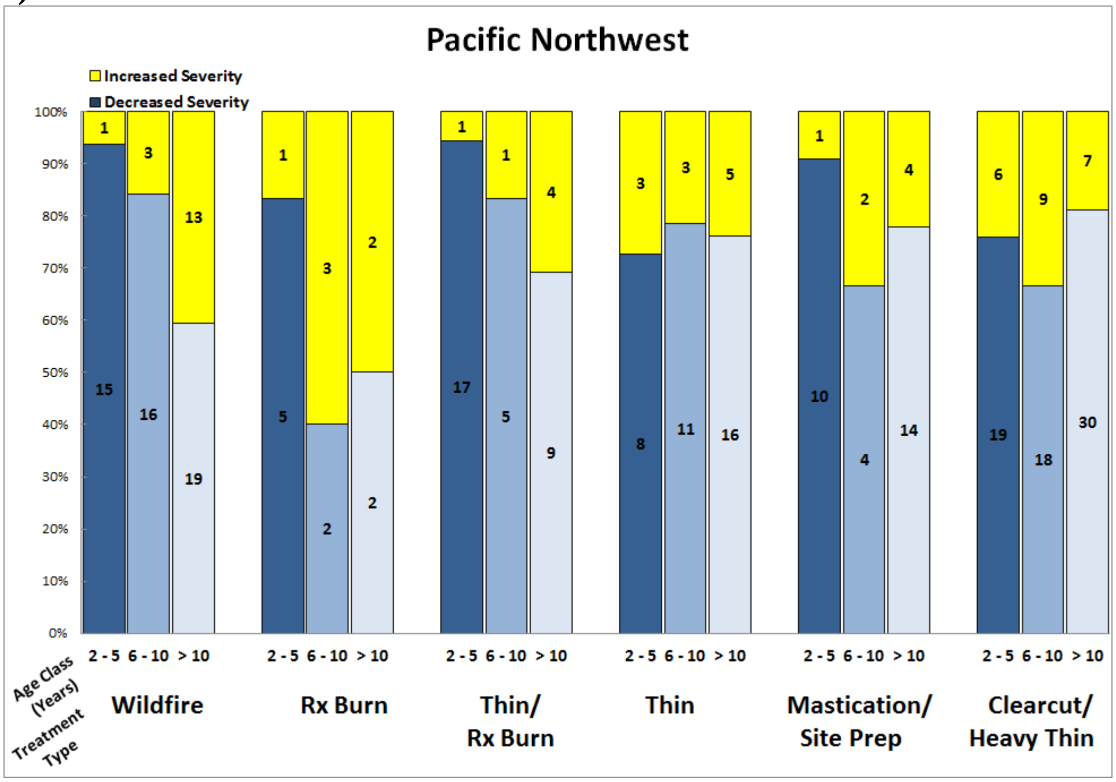


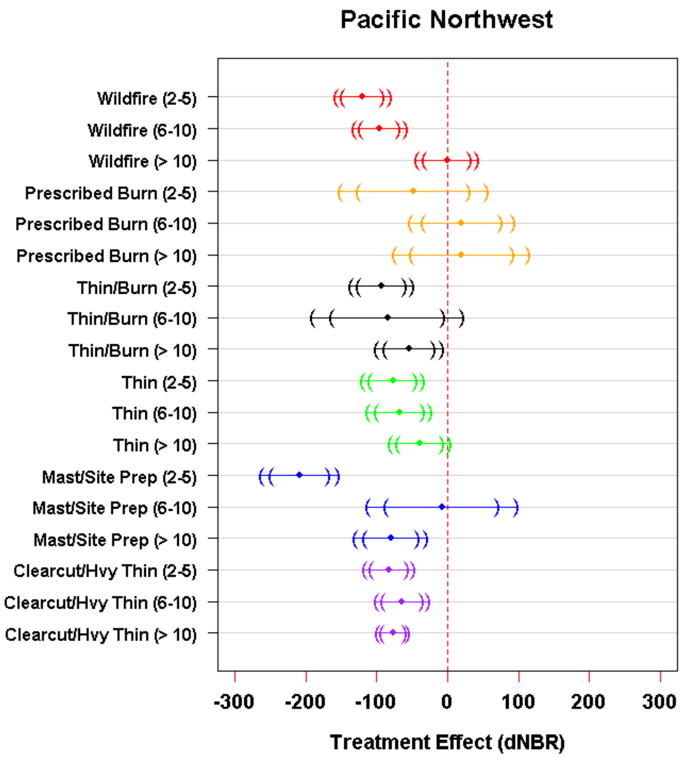
b)


Southern Rocky Mountains
Increased Severity
Decreased Severity
Age Class (Years)
Treatment Type
2 - 5
6 - 10
> 10
Wildfire
Rx Burn
Thin/ Rx Burn
Thin
Mastication/ Site Prep
Clearcut/ Heavy Thin

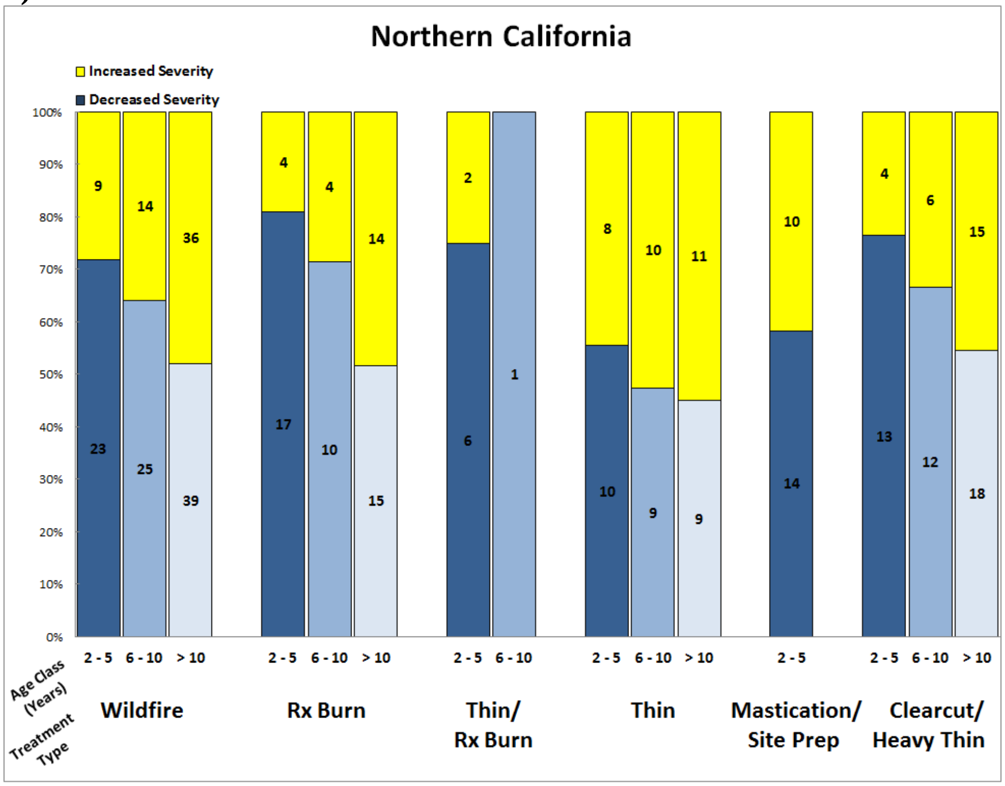

Southern Rocky Mountains
Wildfire (2-5)
Wildfire (6-10)
Wildfire (> 10)
Prescribed Burn (2-5)
Prescribed Burn (6-10)
Prescribed Burn (> 10)
Thin/Burn (2-5)
Thin/Burn (6-10)
Thin/Burn (> 10)
Thin (2-5)
Thin (6-10)
Thin (> 10)
Mast/Site Prep (2-5)
Mast/Site Prep (6-10)
Mast/Site Prep (> 10)
Clearcut/Hvy Thin (2-5)
Clearcut/Hvy Thin (6-10)
Clearcut/Hvy Thin (>10)
Treatment Effect (dNBR)

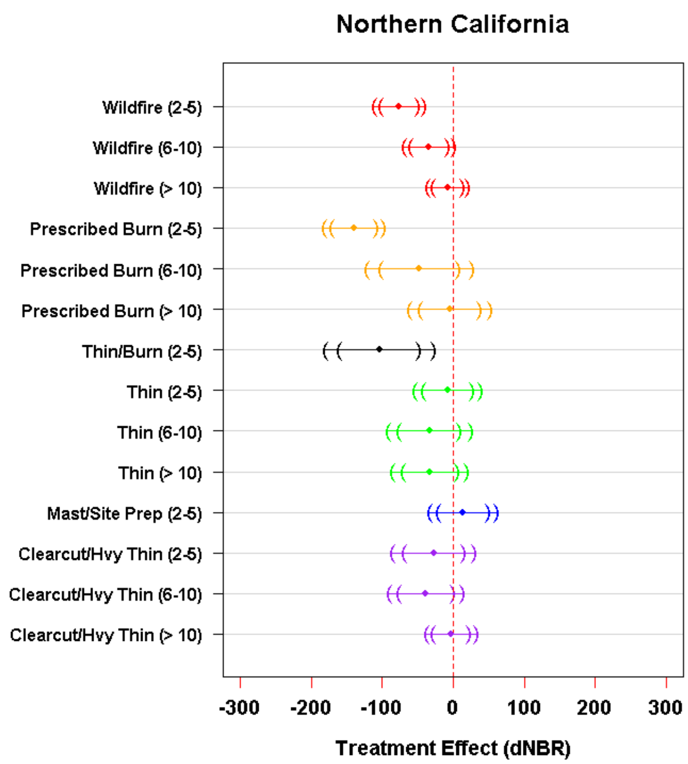
c)


Pacific Northwest
Increased Severity
Decreased Severity
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Age Class (Years)
Treatment Type
2 - 5 6 - 10 > 10
Wildfire
Rx Burn
Thin/ Rx Burn
Thin
Mastication/ Site Prep
Clearcut/ Heavy Thin
1 3 13
15 16 19
1 3 2
5 2 2
1 1 4
17 5 9
3 3 5
8 11 16
1 2 4
10 4 14
6 9 7
19 18 30

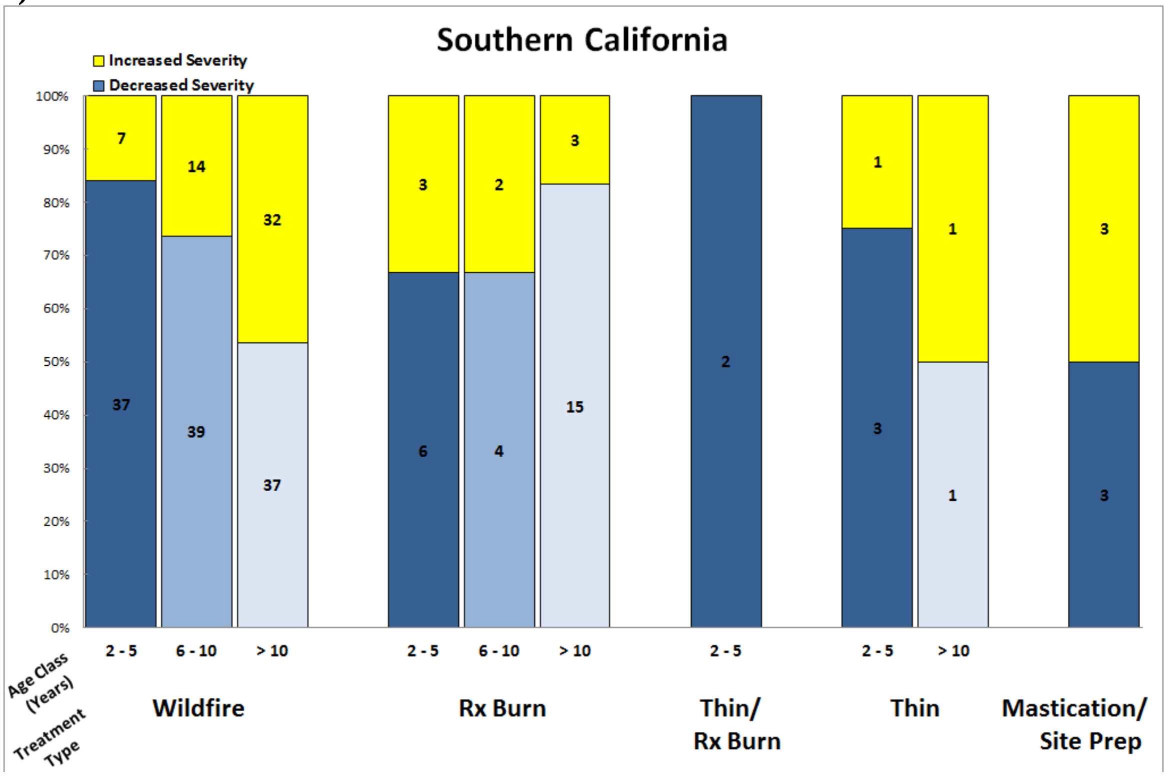

Pacific Northwest
Wildfire (2-5)
Wildfire (6-10)
Wildfire (> 10)
Prescribed Burn (2-5)
Prescribed Burn (6-10)
Prescribed Burn (> 10)
Thin/Burn (2-5)
Thin/Burn (6-10)
Thin/Burn (> 10)
Thin (2-5)
Thin (6-10)
Thin (> 10)
Mast/Site Prep (2-5)
Mast/Site Prep (6-10)
Mast/Site Prep (> 10)
Clearcut/Hvy Thin (2-5)
Clearcut/Hvy Thin (6-10)
Clearcut/Hvy Thin (> 10)
-300 -200 -100 0 100 200 300
Treatment Effect (dNBR)

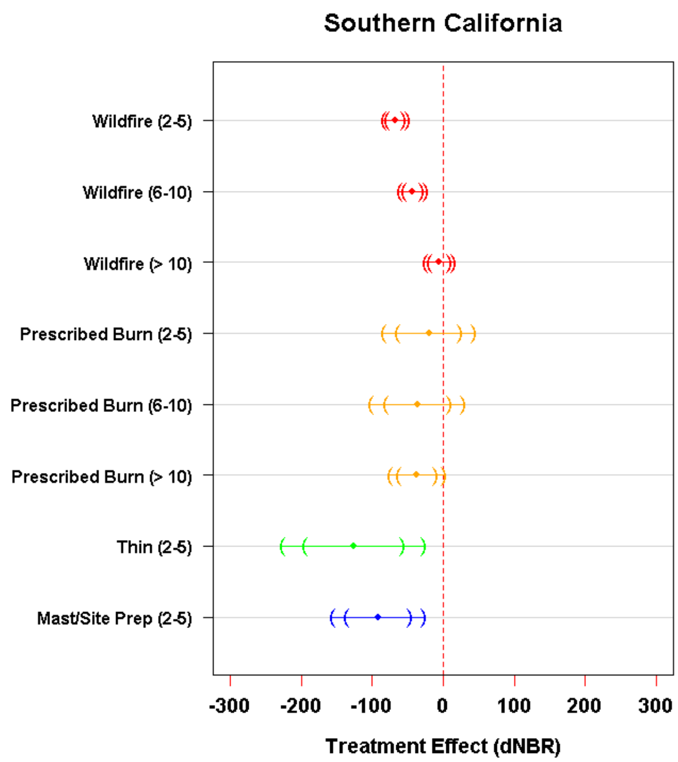
d)


Northern California
Increased Severity
Decreased Severity
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
9
14
36
23
25
39
4
4
14
17
10
15
2
6
1
8
10
11
10
9
9
10
14
4
6
15
13
12
18
Age Class (Years)
Treatment Type
2 - 5
6 - 10
> 10
Wildfire
Rx Burn
Thin/ Rx Burn
Thin
Mastication/ Site Prep
Clearcut/ Heavy Thin

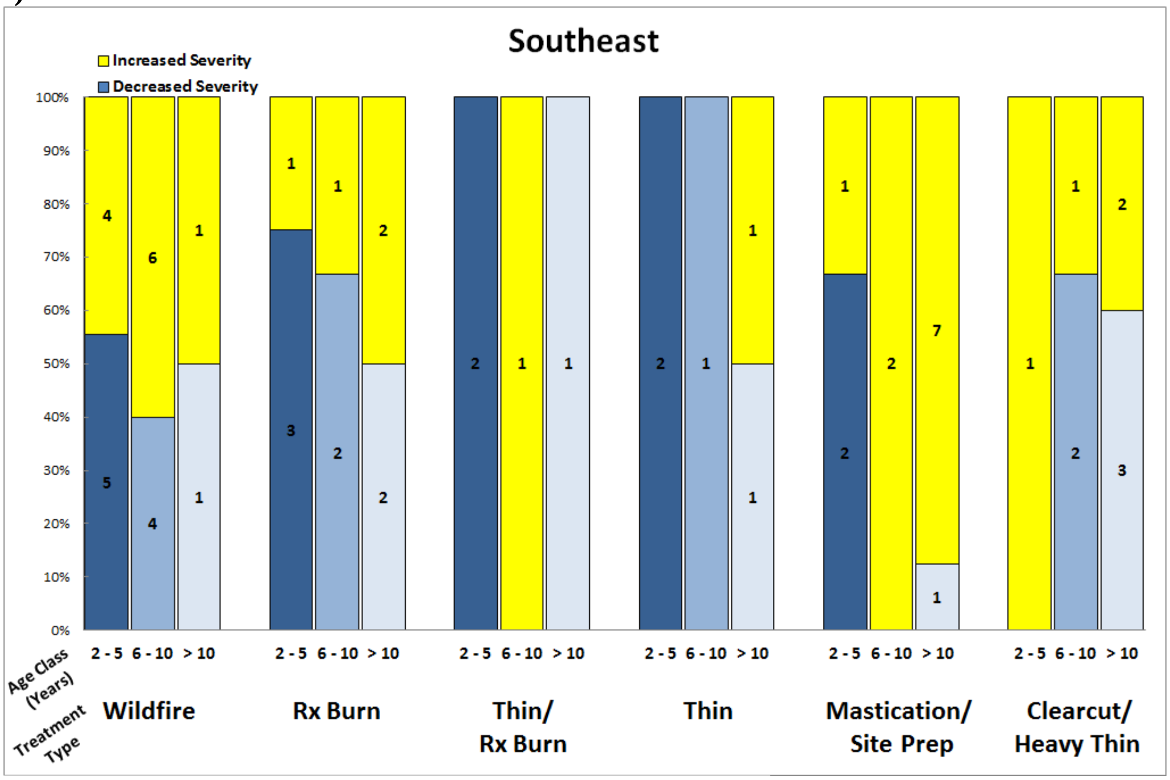

Northern California
Wildfire (2-5)
Wildfire (6-10)
Wildfire (> 10)
Prescribed Burn (2-5)
Prescribed Burn (6-10)
Prescribed Burn (> 10)
Thin/Burn (2-5)
Thin (2-5)
Thin (6-10)
Thin (> 10)
Mast/Site Prep (2-5)
Clearcut/Hvy Thin (2-5)
Clearcut/Hvy Thin (6-10)
Clearcut/Hvy Thin (> 10)
-300
-200
-100
0
100
200
300
Treatment Effect (dNBR)

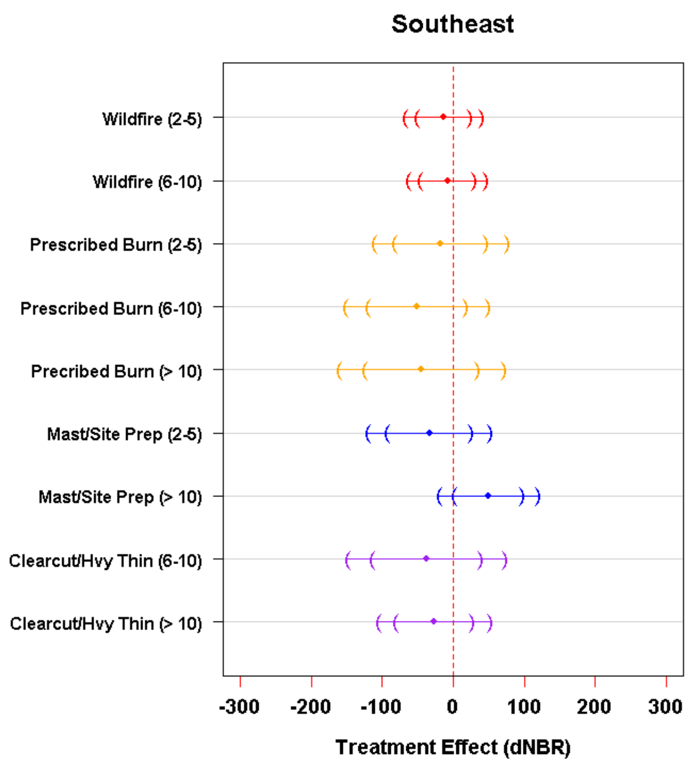
e)


Southern California
Increased Severity
Decreased Severity
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
7
14
32
37
39
37
3
2
3
6
4
15
2
1
1
3
3
1
3
2 - 5
6 - 10
> 10
2 - 5
6 - 10
> 10
2 - 5
2 - 5
> 10
Age Class (Years)
Treatment Type
Wildfire
Rx Burn
Thin/ Rx Burn
Thin
Mastication/ Site Prep

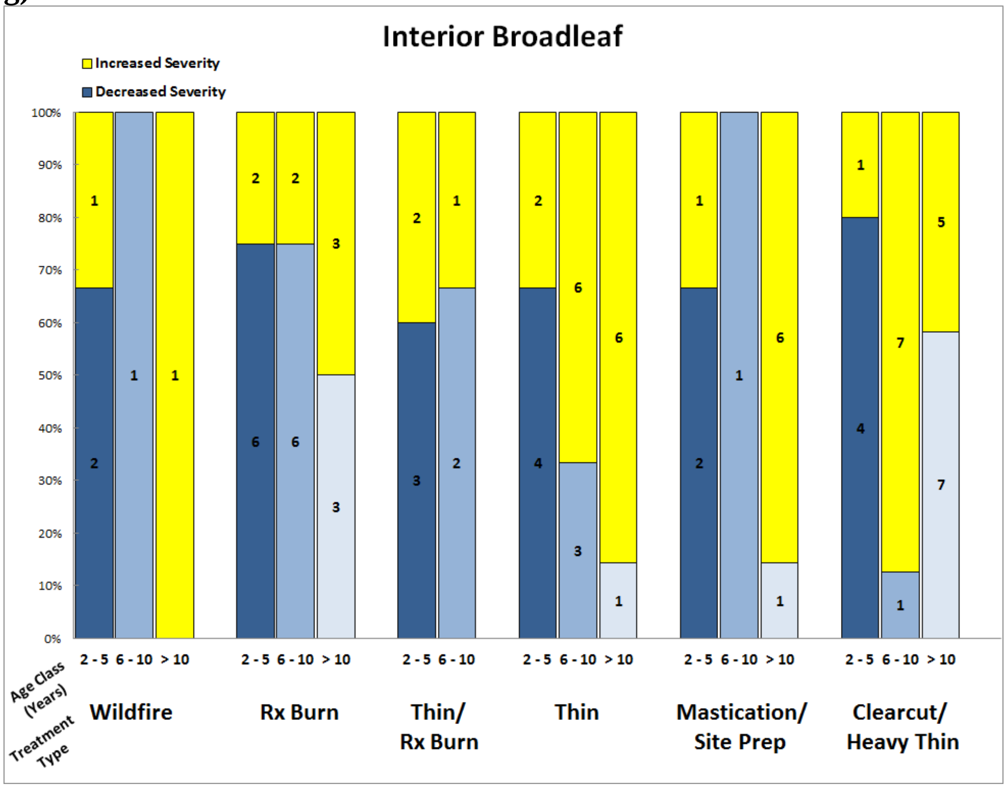

Southern California
Wildfire (2-5)
Wildfire (6-10)
Wildfire (> 10)
Prescribed Burn (2-5)
Prescribed Burn (6-10)
Prescribed Burn (> 10)
Thin (2-5)
Mast/Site Prep (2-5)
-300
-200
-100
0
100
200
300
Treatment Effect (dNBR)

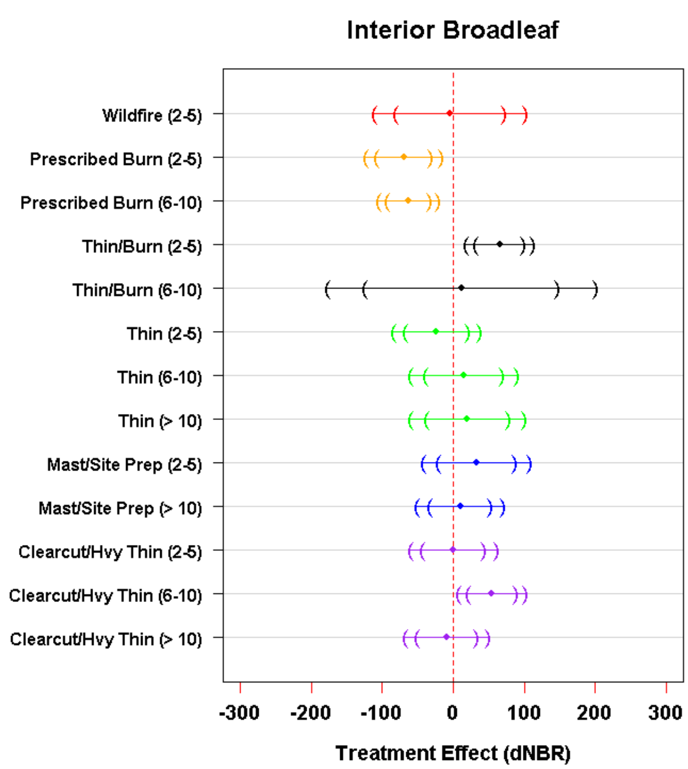
f)


Southeast
Increased Severity
Decreased Severity
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Age Class (Years)
Treatment Type
2 - 5 6 - 10 > 10
Wildfire
Rx Burn
Thin/ Rx Burn
Thin
Mastication/ Site Prep
Clearcut/ Heavy Thin

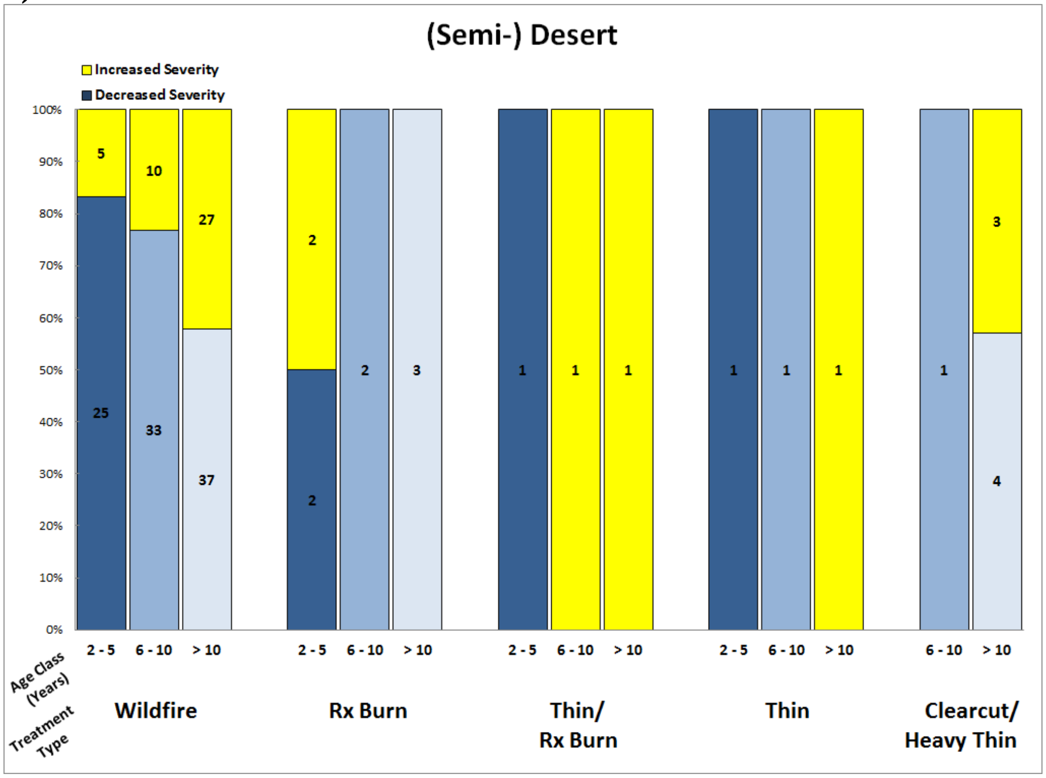

Southeast
Wildfire (2-5)
Wildfire (6-10)
Prescribed Burn (2-5)
Prescribed Burn (6-10)
Precribed Burn (> 10)
Mast/Site Prep (2-5)
Mast/Site Prep (> 10)
Clearcut/Hvy Thin (6-10)
Clearcut/Hvy Thin (> 10)
-300
-200
-100
0
100
200
300
Treatment Effect (dNBR)

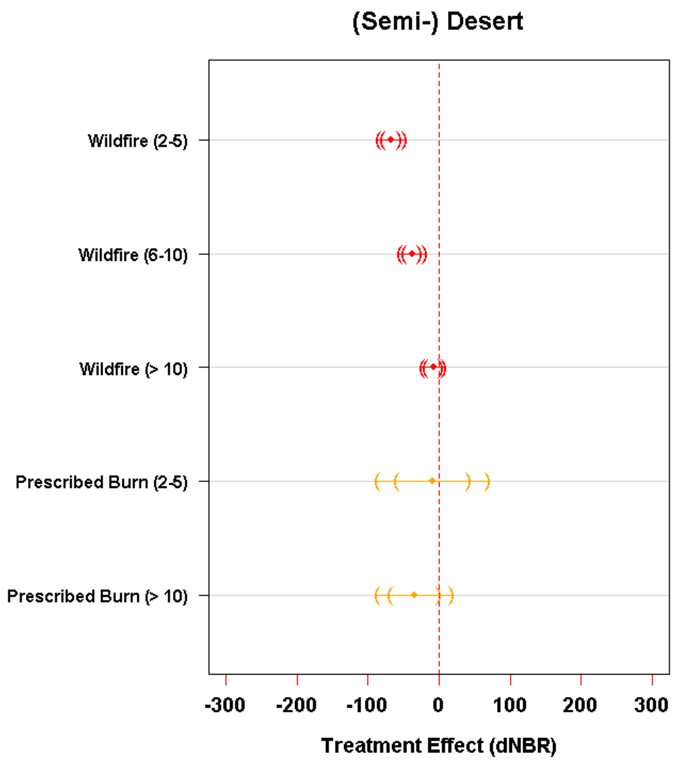
g)


Interior Broadleaf
Increased Severity
Decreased Severity
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Age Class (Years)
Treatment Type
2 - 5
6 - 10
> 10
Wildfire
Rx Burn
Thin/ Rx Burn
Thin
Mastication/ Site Prep
Clearcut/ Heavy Thin

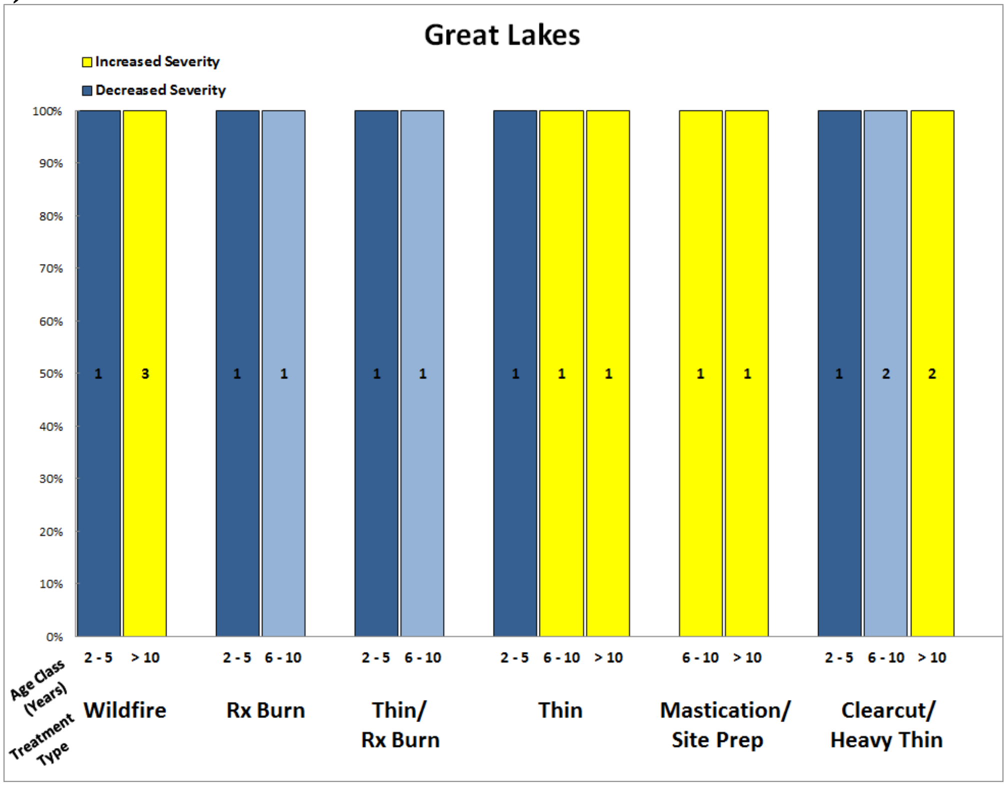

Interior Broadleaf
Wildfire (2-5)
Prescribed Burn (2-5)
Prescribed Burn (6-10)
Thin/Burn (2-5)
Thin/Burn (6-10)
Thin (2-5)
Thin (6-10)
Thin (> 10)
Mast/Site Prep (2-5)
Mast/Site Prep (> 10)
Clearcut/Hvy Thin (2-5)
Clearcut/Hvy Thin (6-10)
Clearcut/Hvy Thin (> 10)
-300
-200
-100
0
100
200
300
Treatment Effect (dNBR)

h)


(Semi-) Desert
Increased Severity
Decreased Severity
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
5
10
27
25
33
37
2
2
2
3
1
1
1
1
1
1
1
3
4
2 - 5
6 - 10
> 10
Age Class (Years)
Treatment Type
Wildfire
Rx Burn
Thin/ Rx Burn
Thin
Clearcut/ Heavy Thin


(Semi-) Desert
Wildfire (2-5)
Wildfire (6-10)
Wildfire (> 10)
Prescribed Burn (2-5)
Prescribed Burn (> 10)
-300
-200
-100
0
100
200
300
Treatment Effect (dNBR)

i)



Note: Given the paucity of data for this region, no meaningful statistics could be generated for treatment performance by type and age for this ecoprovince

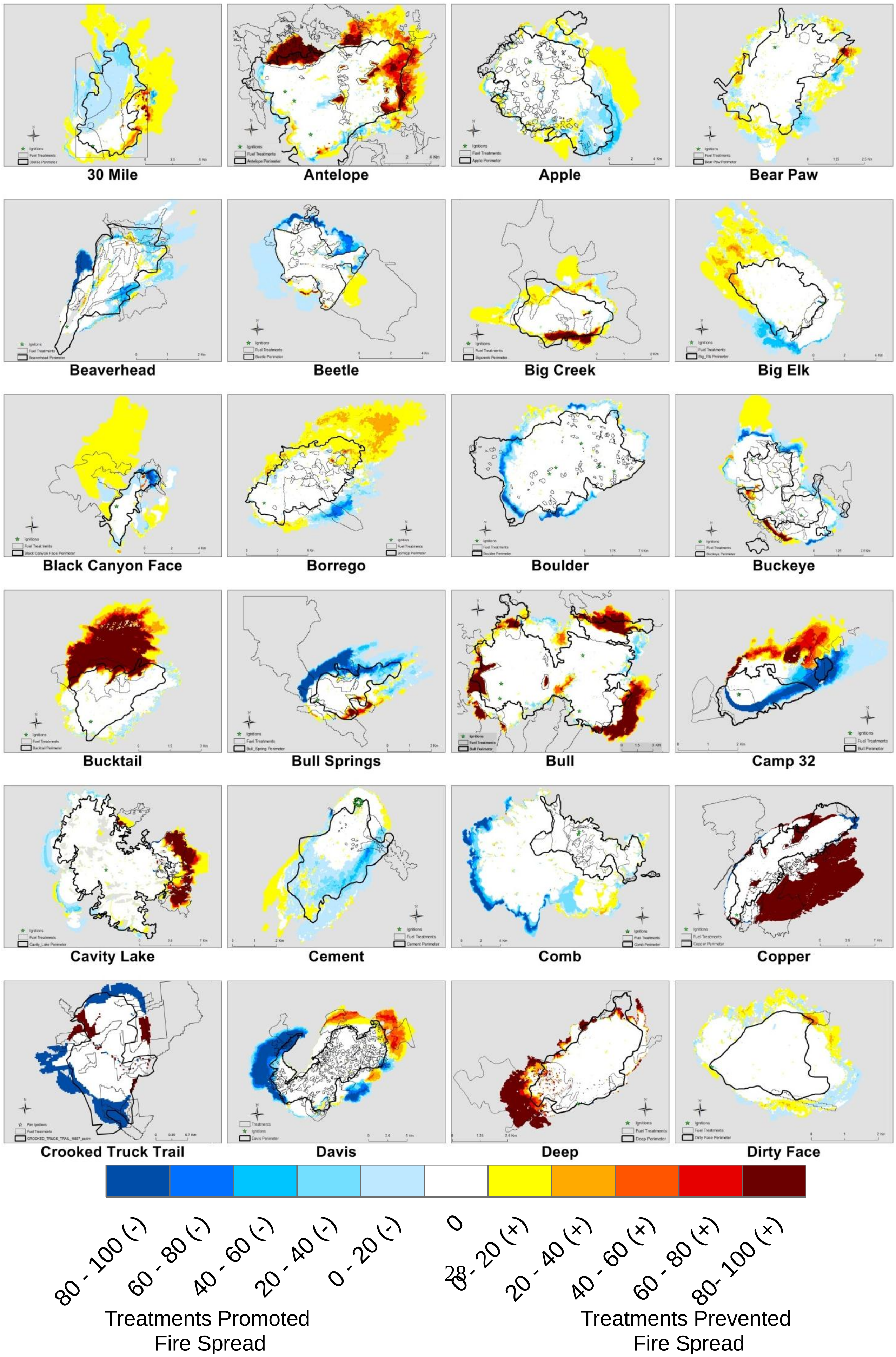
2. Fuels treatments can either increase or decrease the extent of burning in wildfires. In general, thinning leads to increased surface rates of spread due to the increasing cover of light fuels while they also act to decrease spread from spot fires due to their general tendency to limit or prevent crowning of fires (Cochrane et al. 2012).

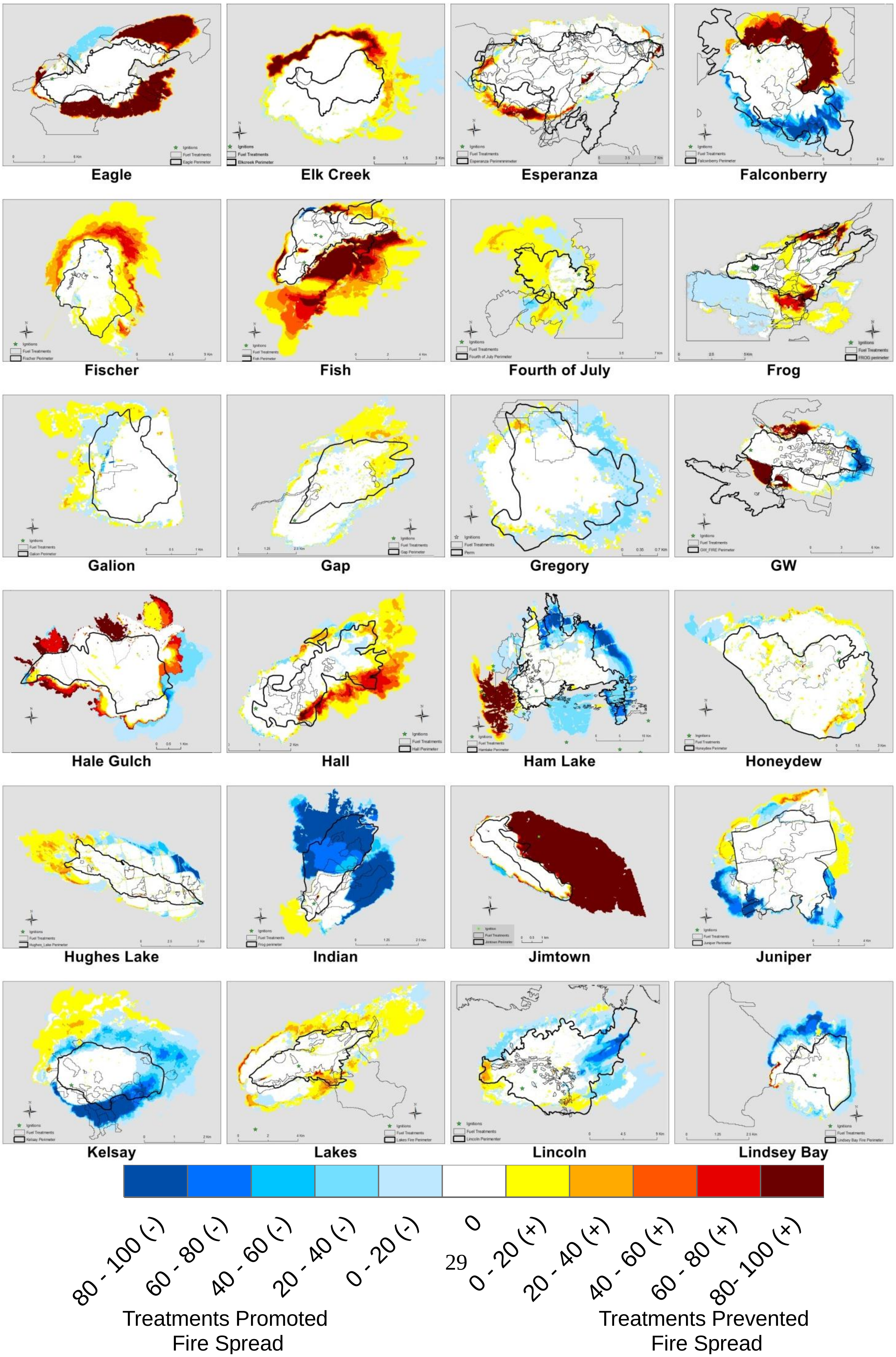
We examined the landscape effects of 3,489 wildland fuel treatments (117,140 ha) involved in 85 large wildfires that burned 591,452 ha of forests across the US states between 2001 and 2010. In terms of total area across all wildfires, planned treatments (thinning, prescribed burning, mastication) slightly exceeded unplanned treatments (previous wildfires) with 51% and 49% of the treated area, respectively. Fuels treatments altered the probability of fire occurrence both positively and negatively across landscapes in all fires, effectively redistributing fire risk by changing surface fire spread rates and reducing the likelihood of crowning behavior. Tradeoffs were created between formation of large areas with low probabilities of increased burning and smaller, well-defined regions with reduced fire risk.

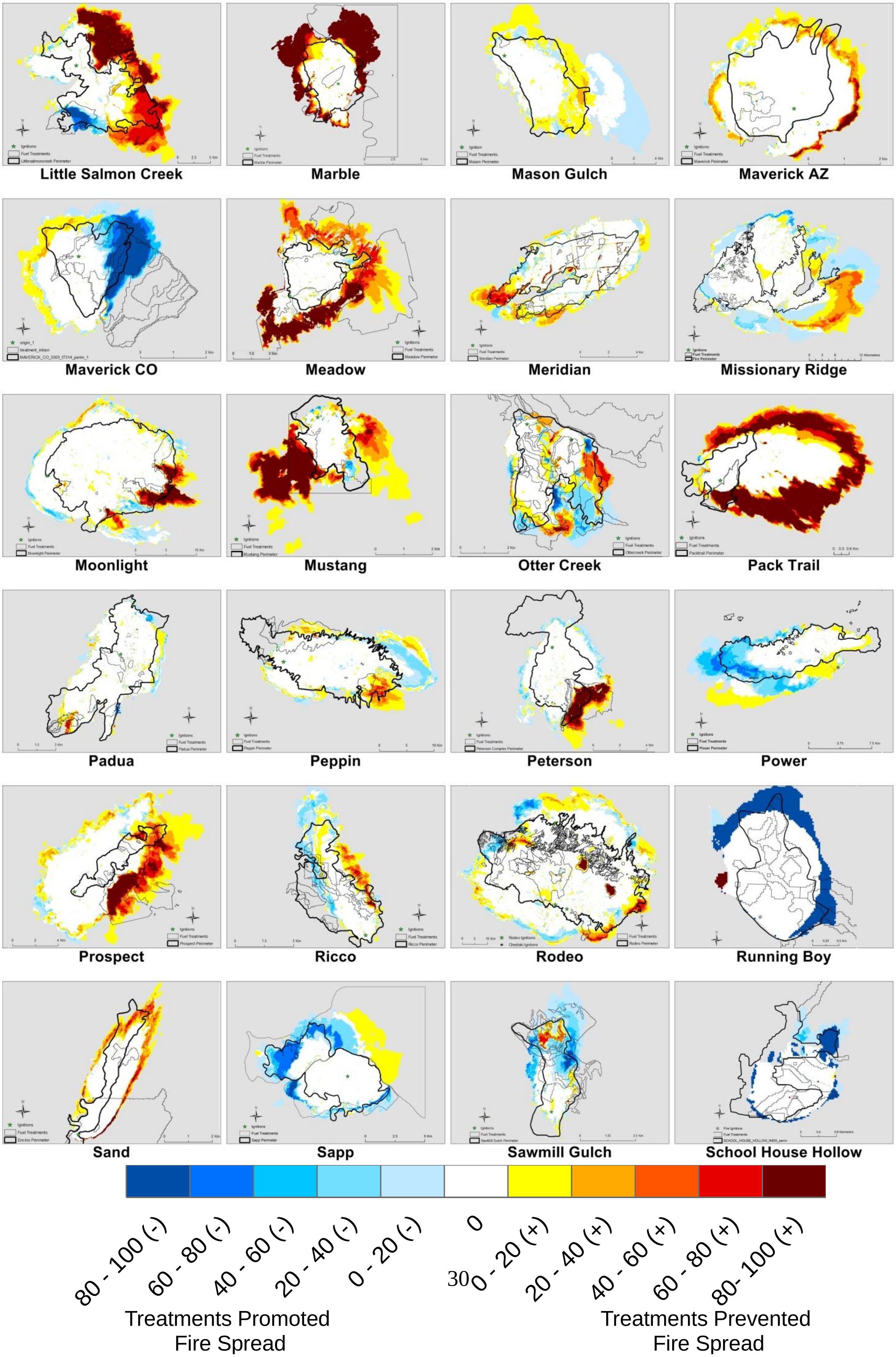
Although the net effect of all treatments was a 4% average reduction in burned area among all 85 examined wildfires, this increases to 7% when considering only the 56 fires with statistically significant changes in burned area among the treated/non treated scenarios. However, this simple average masks a wide range in variability among fires and a near dichotomy between those fires experiencing significant reductions or increases in area burned. Of the 85 wildfires, 54 (64%) (37 statistically significantly reduced at $p<0.05$) showed reduced burned area due to treatments, 29 (34%) (19 statistically significantly increased at $p<0.05$) wildfires showed increased burned area due to treatments, and 2 (2%) showed no effect from treatments. In wildfires that had reduced burned area, the average decrease was 19% (25% for significant fires) while those that experienced increased burned area expanded by 22% (28% for significant fires). The average size of wildfires experiencing augmented burned area was 4,737 ha, which was substantially smaller than average wildfire sizes exhibiting significant burned area reductions (7,542 ha). It was also less than the average burned area of all fires with non-statistically significant size changes (7,190 ha (excluding Rodeo)), and the combined average of all fires (6,751 ha (excluding Rodeo)). The Rodeo fire was excluded for these calculations because of its immense size (~190k ha) that skews comparisons. Within the 37 fires showing significant decreases in fire size, the ratio between area with promoted versus prevented burning was 1.0:18.1. In other words, for every hectare burned because of the existence of the fuels treatments, just over 18 hectares were prevented from burning. Conversely, for the 19 fires showing significant increases in area burned due to fuels treatments, the ratio was 6.9:1.0. Otherwise stated, for every hectare where fire was prevented, nearly 7 hectares burned because of presence of the fuels treatments.

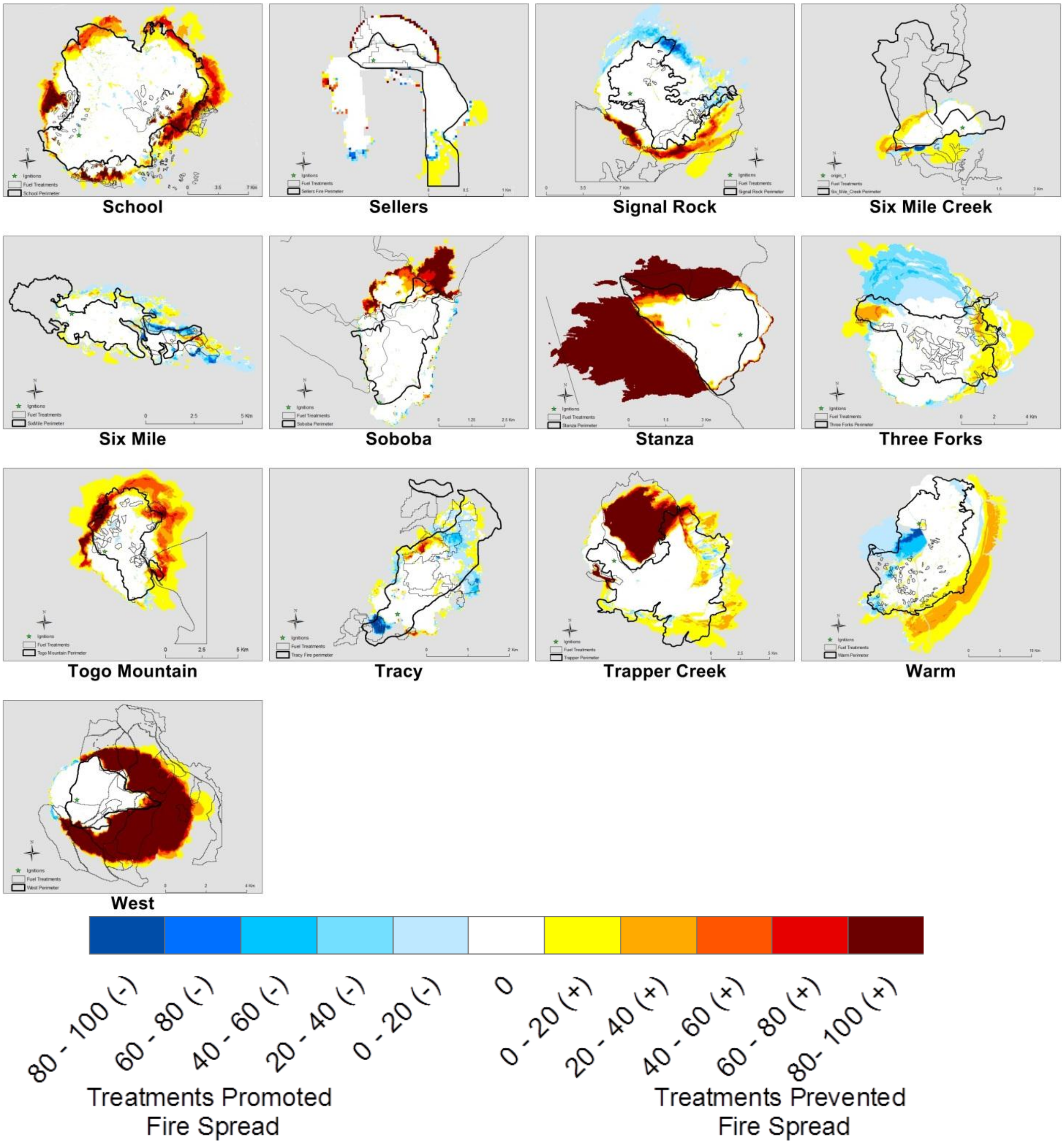
The specific probability change maps due to the treatment for the 85 simulated wildfires are presented in Figure 6. Fire simulations were not constrained to the MTBS fire perimeters and fire suppression activities were not simulated. The only difference between simulations was the presence or absence of the fuels treatments. All treatments are real and were present on the landscape at the times of respective wildfires.

Figure 6 (next 4 pages). **Spatial distribution of increased and decreased burn probability as a function of fuels treatments for individual models**. The following pages present the 85 individual multi-simulation wildfire model comparisons. The thumbnails represent the combined results of multiple model simulations (e.g 60 for the Bucktail fire with 30 untreated and 30 treated simulations) to represent the spatial probability of increased (blues) or decreased (warm colors) burn probabilities caused by the existing fuels treatments, areas that burned in all simulations are white. Note, the bold black outline is the MTBS fire perimeter and the thin black polygons are the individual fuels treatment polygons and previous wildfire boundaries, respectively. Model simulations were not constrained with the MTBS perimeter data and do not account for fire suppression activities. Fires such as the Marble, Stanza and West fires indicate almost complete success of fuels treatments in reducing probable area burned, while others such as Running Boy and Indian indicate potentially deleterious changes in fire spread due to treatments. Most fires are more nuanced or balanced in their fuels treatments effects. For example, fuels treatments almost certainly prevented fire spread to the north in the Falconberry fire but they also likely resulted in this fire's spread to the southeast. Each model run that exhibits spotting behavior produces a unique result because the probability of ignitions from spot fires is stochastic in the FARSITE model. This results in the fire front being present and potentially interacting with fuels at a given location during different times between simulations, when weather conditions may enhance or reduce fire spread. Treatments can have differing effects but, on the whole, tend to enhance the spread rate of surface fires while reducing the likelihood of spotting behavior from within treated lands.


30 Mile
Antelope
Apple
Bear Paw
Beaverhead
Beetle
Big Creek
Big Elk
Black Canyon Face
Borrego
Boulder
Buckeye
Bucktail
Bull Springs
Bull
Camp 32
Cavity Lake
Cement
Comb
Copper
Crooked Truck Trail
Davis
Deep
Dirty Face
80 - 100 (-)
60 - 80 (-)
40 - 60 (-)
20 - 40 (-)
0 - 20 (-)
0
0 - 20 (+)
20 - 40 (+)
40 - 60 (+)
60 - 80 (+)
80- 100 (+)
Treatments Promoted Fire Spread
Treatments Prevented Fire Spread


Eagle
Elk Creek
Esperanza
Falconberry
Fischer
Fish
Fourth of July
Frog
Galion
Gap
Gregory
GW
Hale Gulch
Hall
Ham Lake
Honeydew
Hughes Lake
Indian
Jimtown
Juniper
Kelsay
Lakes
Lincoln
Lindsey Bay
80 - 100 (-)
60 - 80 (-)
40 - 60 (-)
20 - 40 (-)
0 - 20 (-)
0
0 - 20 (+)
20 - 40 (+)
40 - 60 (+)
60 - 80 (+)
80- 100 (+)
Treatments Promoted Fire Spread
Treatments Prevented Fire Spread


Little Salmon Creek
Marble
Mason Gulch
Maverick AZ
Maverick CO
Meadow
Meridian
Missionary Ridge
Moonlight
Mustang
Otter Creek
Pack Trail
Padua
Peppin
Peterson
Power
Prospect
Ricco
Rodeo
Running Boy
Sand
Sapp
Sawmill Gulch
School House Hollow
80 - 100 (-)
60 - 80 (-)
40 - 60 (-)
20 - 40 (-)
0 - 20 (-)
0
0 - 20 (+)
20 - 40 (+)
40 - 60 (+)
60 - 80 (+)
80- 100 (+)
Treatments Promoted Fire Spread
Treatments Prevented Fire Spread


School
Sellers
Signal Rock
Six Mile Creek
Six Mile
Soboba
Stanza
Three Forks
Togo Mountain
Tracy
Trapper Creek
Warm
West
80 - 100 (-)
60 - 80 (-)
40 - 60 (-)
20 - 40 (-)
0 - 20 (-)
0
0 - 20 (+)
20 - 40 (+)
40 - 60 (+)
60 - 80 (+)
80- 100 (+)
Treatments Promoted Fire Spread
Treatments Prevented Fire Spread

Management implications

1. Fuels treatments can be effective for reducing both local severity (as measured by dNBR) and fire extent. However, the effectiveness on severity varies by ecoprovince, treatment type and treatment age. Spatial alterations of fire risk generally provide a large probability of reduced burning potential in the vicinity of treatments at the expense of creating large areas with slight to moderately increased risks of burning. Unsurprisingly, fuel treatments will be most effective for protecting highly valued resources when placed in close proximity to them.
2. Northern Rockies – Within this ecoprovince (see figure 1), prescribed fires as practiced do not mimic wildfires in their effectiveness. Prescribed burning as a stand-alone treatment is ineffective for dependable fire severity reduction and may completely offset the effects of thinning treatments for the 6-10 year interval if these treatments are combined. Stand-alone thinning treatments were the most reliably effective, with greater and longer lasting effectiveness (>10 years from treatment) than previous wildfire after 5 years (Figure 5a).
3. Southern Rockies – In this ecoprovince, prescribed burning with or without thinning reduces fire severity for >10 years after treatment. Prescribed burns were more reliable and longer lasting in their effectiveness when applied as standalone treatments without previous thinning. Thinning alone is ineffective for reducing fire severity and should be discouraged as a fuels treatment (Figure 5b).
4. Pacific Northwest – In this ecoprovince previous wildfires only reduce subsequent fire severity for ≤10 years after the initial fire. Prescribed burning was ineffective unless combined with thinning treatments. Thinning as a standalone treatment was the most consistent treatment for reducing fire severity with treatment effectiveness lasting longer than 10 years after implementation (Figure 5c).
5. Northern California – For this ecoprovince, prescribed burning provides similar or greater reductions in fire severity as previous wildfire but neither shows significant value beyond 10 years of age. Thinning reduces subsequent fire severity for more than 10 years but only after >5 years since implementation. The combination of thin+burn shows promise and may capture the short and long term effects of the two individual treatments but this requires further study since few older treatments of this type were involved in the studied fires. Mastication/site prep is the most prevalent treatment type in recent years but, at least in the short term (2-5 years), is ineffective and possibly detrimental for reducing fire severity (Figure 5d).
6. Southern California – In this ecoprovince, previous wildfires only reduce subsequent fire severity for ≤10 years while prescribed burning is most reliably effective at >10 years after implementation and highly variable in effectiveness for the first 10 years. Both thinning and mastication are apparently effective for at least 5 years, with thinning having somewhat greater effects, but there were relatively few treatments of these types and longer term performance is uncertain (Figure 5e).
7. Southeast – In this ecoprovince, previous wildfires have surprisingly little impact on fire severity of subsequent wildfires. In contrast, prescribed burning, although somewhat variable in its impacts, is the most effective treatment for reducing subsequent fire severity, with greater and more reliable effectiveness five or more years after implementation. Mastication/site prep is ineffective for fire severity reduction after the first five years, with enhanced fire severity apparent 10 years after treatment (Figure 5f).

8. Interior Broadleaf – Within this ecoprovince, prescribed burning is uniquely reliable and effective at reducing fire severity for at least 10 years after implementation. All other fuels treatments appear to be ineffective or detrimental to reducing wildfire severity. The combination of thin+burn has particularly lethal results. More study of fuel treatment effectiveness is needed in these ecosystems, especially for longer term performance (Figure 5g).
9. Semi-Desert – This ecoprovince has had few fuels treatments. Prescribed burning appears ineffective until >10 years, but may have greater effectiveness than wildfire after that point (Figure 5h).
10. Great Lakes – This ecoprovince has had few treatments impacted by subsequent wildfire. The limited data indicate that prescribed burning may be effective in these forests but more study is needed to confirm this (Figure 5i).

Relationship to other recent findings and ongoing work on this topic

Both theoretical and empirical research overwhelmingly indicate that fuel treatments reduce fire severity (Fulé et a.l 2012; Hudak et al. 2011; Martinson and Omi 2008), but a more pressing research question is their effectiveness over time and space. Predictive fire modeling has produced robust hypotheses but contains biases, usually employing hypothetical treatments, weather conditions, and/or wildfires (Hudak et al 2011). Natural experiments, where treated areas were burned in actual wildfires, provide an empirical gauge of treatment performance, but Martinson and Omi (2008) warn that empirical evaluation is scant and amounts to case studies. Nevertheless, Fulé et al. (2012) analyzed 54 studies in a systematic review approach and concluded that most treatments reduced fire severity with no significant difference between geographic regions or forest types, albeit with a number of significant qualifiers. Nearly all these studies use the simple and effective approach of comparing treated and untreated areas within the same fire or geographic location, while quantifying the redistribution of fire spread and behavior on the landscape has only been attempted on theoretical landscapes (Finney 2001) or using hypothetical fires (Ager et al. 2010). This study has quantified comprehensive treatment effects by empirically analyzing the within-site changes in severity of thousands of fuels treatments burned in 651 wildfires and modeled the likely change in fire spread beyond treatment boundaries for an unprecedented 85 wildfires, while incorporating the full range of weather, topographic, vegetative, and fire behavior conditions that can impact treatment effectiveness.

The effectiveness of a treatment can be seen as being related to the ambient weather and the landscape positioning at the time of burning, as the fire intensity and momentum leading up to the treated area inherently influence the treatment effect. The trade-offs involved in fuels treatments have been noted to include increased wind speeds, altered surface fuel loads, and decreased fuel moisture (Agee and Skinner 2005; Weatherspoon and Skinner 1995; Faiella and Baily 2007), but fire severity reduction has been the lone metric overwhelmingly used as the surrogate for fuel treatment effectiveness, overlooking potential changes in surface fire spread rates and their resulting effects. Here, we have provided a uniform approach for measuring changes in fire severity (Wimberly et al. 2009), along with probabilistic estimates of changes in fire spread (Cochrane et al. 2012), for a great number and array of treatment types and ages affected by wildfires. This research is unique in the literature and better quantifies landscape-wide effects of treatments by incorporating spatial arrangements and sizes of treatments (Finney et al. 2007), while better controlling for weather and topographic influences. The shortcomings of fire simulations (Cruz and Alexander 2010) are also minimized by calibrating each fire to observed behavior (Cochrane et al. 2012).

Uniform analysis of multiple treatment types and ages in multiple vegetation types across the USA has not been attempted until now. The need for treatments that raise canopy bases and reduce canopy continuity, while also reducing surface fuels, such as treating slash following thinning, have been emphasized (Omi et al. 2006), with the combination of mechanical thinning and prescribed burning championed as being the most effective (Hudak et al. 2011). Treatments of the landscape are conceived to be temporary and variable in their impact, becoming less effective with age as vegetation regrows (Finney et al. 2005, Cram et al. 2006). However, few studies exist of the speed of fuel treatment effectiveness degradation, and the process is likely to be ecosystem dependent (Hudak et al. 2011).

Our study both supports and contradicts findings from the existing literature. While treatment effects are certainly temporary, the response time for degraded effectiveness of each treatment type varies by region/forest type and does not necessarily proceed in a linear trajectory from maximum effectiveness at implementation to zero effectiveness at a future date. With much regional variation, some treatments, often prescribed burning, can increase in effectiveness over time for >10 years after implementation. In some regions, thinning may only become effective 5 years after implementation, while in others the addition of prescribed fire to thinning treatments can temporarily negate its effectiveness 6-10 years after treatment, presumably due to fire-induced successional processes, before they return to similar fire reduction function as thinning treatments alone. In short, there is no one size fits all treatment type or management schedule for all forests. Fuels treatment selection needs to be regionally/forest type appropriate but, in many regions, properly chosen fuels treatments can result in effective fire severity reduction for > 10 years after implementation, with upper time bounds still undefined. Meta-analyses that do not examine regional variations in treatment effectiveness and type, due to sample size or other limitations, will lead to conclusions that can be right on average but potentially erroneous for guiding regional forest management decisions at a regional level. Figure 4 which shows the combined effectiveness for fuels treatments across the western United States illustrates this point. In combination, the treatment effectiveness results from many hundreds of fires seem universally good, but when performance is assessed regionally there are clear differences in the effectiveness of different fuels treatment types. For example, in the Northern Rockies (Fig 5a) thinning is the most effective treatment for reliably reducing fire severity, with prescribed burning being of uncertain effect, while in the Southern Rockies (Fig 5b) prescribed burning is dependably effective, while simple thinning is completely ineffective as a fuels treatment for reducing fire severity. Similarly, fuels treatments can result in reductions or increases in fire extents depending on how they impact the probability of spot fire generation or ignition and alter the amount, type and fuel moisture of surface fuels, making fuels treatment selection a balancing of relative risks (Cochrane et al. 2012). In summary, fuels treatments can be effective for both reducing fire severity and wildfire extents but success will be as much a function of the application of regionally appropriate fuels treatment types for a given forest as the amount of forest that is actually treated.

Future work needed

The implications of this research are that fuels treatments can and have been effective tools for reducing subsequent wildfire severity and extents but that there needs to be greater regional attention to matching appropriate treatment types to the ultimate fire and land management goals. Now that there have been many hundreds of wildfires that have burned through thousands of fuels treatments, we have sufficient regional knowledge in many areas to help guide the selection of fuel treatment types and placement so as to optimize effectiveness and inform fire and land management decisions. The work presented here is a step in this direction but it has also delineated regions and subjects that require further study.

1. From our modeling studies, it is apparent that while LANDFIRE products are of great utility, the uniform local values of attributes such as canopy base height and canopy cover, in particular, lead to unrealistic transitions from surface to crownfire conditions, with the likely result that phenomena such as torching are not simulated effectively and the simulation of overall fire behavior, without the benefit of calibrations to known fire progression maps and behavior observations, will be fraught with difficulty. While full 3-D fire simulation modeling with convective heat transfer and atmospheric coupling will ultimately be needed to accurately model crowning activity, existing model results could be greatly improved through either direct measurement (e.g. LiDAR) or statistical parameterization of LANDFIRE forest attributes.

2. In particular, the Great Lakes region needs more investigation to establish the best fuels treatments for fire management. While most every type of fuels treatment seems to have been tried in these forests, the small numbers of wildfires that have burned through fuels treatments are inconclusive for guiding fire management. The two fires with mastication treatments both showed increased severity due to treatment as did 2 of the 3 fires with stand-alone thinning treatments. While each fire burned through multiple polygons of fuels treatments, the performance of each treatment type age category is represented by a single wildfire, making firm conclusions about the roles of these treatment types in forest management of this region impossible. Similarly, it is intriguing that the 4 wildfires that had prescribed fire (2 standalone, 2 with thinning) all reduced fire severity in both the 2-5 and 6-10 year age categories; each again representing a single age category for a single fire. Prescribed fires appear to be promising for fire severity reduction in this region, but the fact that the 3 observed >10 year-old previous wildfires all increased fire severity may indicate that longer term performance of prescribed burn treatments may be in doubt.

3. The project findings show that the performance of fuels treatments varies over time but they do not necessarily degrade in a linear fashion. Some treatment types (e.g. thin+burn in Northern Rockies) can initially work well for reducing fire severity (0-5 years), have little effect for a time (6-10 years), and then return to being highly effect (>10 years) (Figure 5a). The reasons for this are uncertain but could reflect a post burn flush of regeneration which rapidly greens up the treated areas within Landsat-based dNBR measurements. In the 6-10 year age class these trees are likely still highly vulnerable to subsequent wildfires but apparently become more resistant at >10 years. A similar pattern of effectiveness is seen for mastication treatments in the Pacific Northwest (Figure 5c),

while in the Southern Rockies, mastication treatments show the opposite pattern with little initial effectiveness (0-5 years), a window of good effectiveness (6-10 years) and then a return to less effectiveness (>10 years) (Figure 5b). More investigation and research would be helpful to provide ecosystem specific guidance on the regrowth and decay rates and patterns, especially as to how they relate to fuel loading and structure changes.

4. In principle, similar modeling techniques as were applied in this research could be utilized to evaluate and quantify the efficacy of fire suppression activities. We have done some preliminary research and have found that the main limitation is the lack of detailed and maintained records of fire suppression activities that were conducted during a given wildfire. In most cases, it seems that once the fire is declared out, the activity records, such as they are, become increasingly hard to locate. Even without such quantitative research, our stochastic modeling approach would be recommended for onsite fire modeling to estimate the likelihoods of loss of containment under expected near term conditions. Only such Monte-Carlo simulations can quantify the risk inherent in spotting behavior.

5. Additional research on the landscape-level interaction of treatments and their dual aspects of altering surface fire spread rates and crowning potential are warranted. It is clear that entire landscapes cannot be practically treated with planned activities. It is, however, possible to dramatically alter the odds of a fire spreading into or through regions with treatments. We have shown preliminary evidence that treatments (both planned and unplanned) can interact synergistically to create effects larger than their individual components would suggest in some, but not all conditions (Cochrane et al. 2012; table 3 and associated text). It would be beneficial if such interactions, or the conditions under which they operate, could be quantified as it would allow for better landscape design of effect treatment plans with limited resources or designs that take advantage of previous wildfires which have provided vast if unplanned treatment of large areas.

6. While we show decay in the performance of many treatment types within 10 years (e.g. mastication in the Southeast Figure 5f), there are other treatments locations and types (e.g. thinning in the Northern Rockies; Figure 5a and prescribed burning in the Southern Rockies; Figure 5b that show continued high levels of effectiveness for >10 years post-treatments. Such treatments need better evaluation of their long term effectiveness to determine their ultimate useful life spans in treatment plans.

7. Lastly, what the simulation studies show and what any wildland firefighter knows is that the weather matters a great deal in landscape-level fire behavior and spread. Land and wildland fire managers would benefit from greater regional information on how ongoing climate changes are likely to affect the fire danger, behavior and fuels treatment performance. Better regional climate models, with statistical or dynamical downscaling, need to be developed and their outputs used to determine the likely changes in fire weather-related climate parameters. Such information is needed to calibrate modeled fire behavior and fuel treatment performance sensitivity analyses for future climates.

Deliverables crosswalk table

Table 3. Deliverable, Description and Delivery Dates

Deliverable	Description	Delivery Dates
Fuel treatment database	Spatially attributed database with type and age of treatment	Incorporated in LANDFIRE refresh
Annual reports	Progress summaries of the project and analysis results	2007-2012 completed
Tabular results	Site reports on treatments and fuel treatment performance summaries by type, size, severity and ecosystem	Reports for all field sites completed and available on website
Treatment maps	All fuel treatments subjected to fires in MTBS – shape files and spatial attribute database	Completed for all 651 analyzed fires
FARSITE models	All model runs, with and without fuel treatments	Completed 3,062 simulations (1,531 treated, 1531 untreated)
Fuel tools	Drag and drop or upload fuel treatments onto LANDFIRE fuel data layers that are compatible with FARSITE and reflect treatment attributes	No generic tool developed. Treatment information from managers required custom modification for each treatment (*see below)
Training workshop	10 person 2 day hands on workshop utilizing tools and integrated LANDFIRE/MTBS system	4 Joint training with MTBS workshops 10/2008; 5/2009; 2/27/12; 12/3/2012 added JFSP Webinar 3/27/2012
Publication of results	Peer-reviewed publication of methods, statistical and spatial analyses, findings and recommendations	2009a, 2009b, 2010, 2011, 2012 – more pubs forthcoming

***** The MTBS project conducted two training workshops at national conferences in 2012 with about 15-20 participants at each conference. We provided MTBS application exercises that had attendees visualize treatment polygons in context with MTBS burn severity, view and evaluate statistically predicted reductions in dNBR severity due to treatment, and calibrate and run their own FARSITE model with and without fuel treatments on the landscape. Chris Moran attended the workshops and provided technical assistance to attendees attempting the exercises. Attendees included graduate students, NGO researchers, and land managers.

Additional Deliverables

To date, the project has provided 7 peer reviewed publications, including 4 master's theses from students involved with the FTEUS project.

Arnold, S. 2009. Changing Fire Return Intervals in Southern California. Geography *Master's Thesis*. South Dakota State University, Brookings, SD.

Cochrane, M.A., C.J. Moran, M.C. Wimberly, A.D. Baer, M.A. Finney, K.L. Beckendorf, J. Eidenshink, and Z. Zhu. 2012. Estimation of wildfire size and risk changes due to fuels treatments. *International Journal of Wildland Fire* 21(4): 357-367. http://dx.doi.org/10.1071/WF11079.

Moran, C.J. and M.A. Cochrane. 2012. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests?: Comment. *Ecology* 93 (4): 939-941.

Moran, C.J. 2011. Mountain pine beetles, mitigation treatments, and fire behavior in ponderosa pine of the Black Hills, SD. Biology *Master's Thesis*. South Dakota State University, Brookings, SD.

Pabst, K. 2010. Quantifying burn severity in a heterogeneous landscape: a comparison of the differenced Normalized Burn Ratio and the Relative differenced Normalized Burn Ratio in the Grand Canyon National Park, Arizona. Geography *Master's Thesis*. South Dakota State University, Brookings, SD.

Timilsina, K. 2011. Computer Science *Master's Thesis*. South Dakota State University, Brookings, SD.

Wimberly, M. C., M. A. Cochrane, A. D. Baer, and K. Pabst. 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. *Ecological Applications* 19(6): 1377-1384.

JFSP-supported FTEUS research has been presented at 18 national and international conventions/symposia/congresses/workshops.

January 21-25, 2013. University of Otago, Dunedin, New Zealand. Invited presentation, Cochrane, M.A., C.J. Moran, M.C. Wimberly, M.A. Finney, J. Eidenshink, and Z. Zhu. "Fuel treatment effectiveness in the United States: assessing site- and landscape-level effects of fuels treatments on wildland fires", for the VII Southern Connection Congress.

December 3-7, 2012. Portland, OR. Invited presentation, Cochrane, M.A., C.J. Moran, M.C. Wimberly, J. Eidenshink, Z. Zhu and M.A. Finney. "Combining remote sensing and spatial modeling to assess site and landscape level effects of fuels treatments on wildland fire." 5th International Fire Ecology and Management Congress, special session "Assessing Fire Effects with Remote Sensing and Geospatial Technologies".

December 3-7, 2012. Portland, OR. Invited presentation, Cochrane, M.A., M. Wimberly, J. Eidenshink, M. Finney, C.J. Moran, and Z. Zhu. "Forest management implications of recent fuel treatment effectiveness assessments for mitigating landscape-level risks from wildfires." 5th International Fire Ecology and Management Congress, special session "Mitigation of human risk from wildfires: the conundrum of the sword and the shield".

December 3-7, 2012. Portland, OR. Workshop Activity. Moran, C.J. and M.A. Cochrane. "Visualizing and modeling fuel treatment effectiveness." Activity presented as part of the Monitoring Trends in Burn Severity workshop. 5th International Fire Ecology and Management Congress.

June 26 – July 2, 2011. University of Queensland, Brisbane, Australia. Invited presentation. Cochrane, M.A., M. Wimberly, J. Eidenshink, M. Finney, M. Reeves, and Z. Zhu. *Fuel Treatment Effectiveness in the United States*. Given as part of the Australian Centre for Ecological Analysis & Synthesis (ACEAS) workshop on Pyrogeography: Integrating and Evaluating Existing Models of Australian Fire Regimes to Predict Climate Change Impacts.

March 27, 2012. Invited Webinar Presentation. Cochrane, M.A., C.J. Moran, M. Wimberly, J. Eidenshink, M. Finney, M. Reeves, Z. Zhu, D. Ohlen, K. Beckendorf, and A. Baer. "Effects of fuels treatments on the spatial probabilities of burning and final size of recent wildfires across the United States." Joint Fire Science Program and International Association of Wildland Fire http://www.iawfonline.org/webinars.php

February 27, 2012. Santa Fe, NM. Workshop Activity. Moran, C.J. and M.A. Cochrane. "Visualizing and modeling fuel treatment effectiveness." Activity presented as part of the Monitoring Trends in Burn Severity: Assessing Fires in the Southwestern US workshop. 2012 Association for Fire Ecology Southwest Regional Conference.

April 3-7, 2011. Portland, OR. (oral presentation) Wimberly, M.C., M.A. Cochrane and J. Werner. "*Influences of Fuel Treatment Type and Age on Fire Severity in the Western United States*" at the 2011 US-IALE Sustainability in Dynamic Landscapes Symposium.

March 17, 2011. Missoula, MT. Invited Oral Presentation. Cochrane, M.A., M. Wimberly, J. Eidenshink, M. Finney, M. Reeves, Z. Zhu, D. Ohlen, C. J. Moran, K. Pabst and A. Baer. "Estimating changes in wildfire size due to fuel treatments." Presented as part of the USFS Fire Sciences Seminar Series.

April 19-24, 2010. Santa Barbara, CA. Invited Presentation. Cochrane, M.A. "*The Diminishing Value of What We Think We Know about Managing Landscape Fire*". National Center for Ecological Analysis and Synthesis (NCEAS): Pyrogeography – Fire's Place in Earth System Science.

April 14-18, 2010. Washington D.C. Invited Presentation. Cochrane, M.A., M.C. Wimberly and A.D. Baer. "*Disturbance Interaction between Fuel Treatments and Fire in the United States*". Presented at the Annual Meeting of the Association of American Geographers.

November 30-December 4, and December 5, 2009. Savannah, GA. Session chair "*Fire Behavior*" for the 4^{th} International Fire Ecology & Management Congress. Also, Board Member of the Association for Fire Ecology participating in the post-Congress board meeting and board elections.

(oral presentation) Wimberly, M.C., M.A. Cochrane and A.D. Baer. "*Influences of Fuel Treatment Type and Age on Fire Severity in the Western United States*"

October 6, 2009 Sioux Falls, SD. Poster presentation Stricherz, B. and M.A. Cochrane "*Assessing Catastrophic Wildfire Risk in California*". American Society of Photogrammetry and Remote Sensing - Upper Midwest Chapter Annual Meeting 2009.

September 19, 2009 Logan, Utah. Poster presentation Stricherz, B. and M.A. Cochrane "*Assessing Catastrophic Wildfire Risk in California*". Presented at the Association of American Geographers Great Plains - Rocky Mountain Division Annual Meeting 2009

2009. Baer, Adam, K. Pabst, and M. A. Cochrane. Workshop Activity. "Working with MTBS data and fuels treatments." *4th International Congress on Fire Ecology and Management*. Savannah, GA.

April 6-10, 2008: Madison, WI. Oral Presentation: Cochrane, M.A., Wimberly, M.C., Finney, M. Eidenshink, J. and Z. Zhu, "*Evaluating the effectiveness of fuels treatments for mitigating the extent and severity of wildfires in the United States*". Presented at the annual meeting of the US Regional Association of the International Association for Landscape Ecology (US-IALE)

December 10-14, 2007: San Francisco, CA. Poster presentation at the Fall Meeting of the American Geophysical Union

M.C. Wimberly, M.A. Cochrane, A.D. Baer, and Z. Zhu. *Applying Spatial Statistics to Isolate the Effects of Fuels, Topography, and Weather on Burn Severity.*

February 26-30, 2007: Destin, FL. Participated in the 2nd Fire Behavior and Fuels Conference and presented the poster:

Cochrane, M.A., M. Wimberly, Z. Zhu, M. Finney and M. Reeves. 2007. "*Fuel Treatment Effectiveness in the United States*".

Personnel:

Dr. Mark A. Cochrane is a professor at South Dakota State University (SDSU) and the Principal Investigator with overall responsibility for coordination and implementation of the project. He supervised the analyses of LANDFIRE utility, FARSITE simulations and landscape effectiveness of fuels treatments. He advised Arnold, Moran and Pabst and served on the thesis committee for Timilsina.

Dr. Michael C. Wimberly is a professor at SDSU and had responsibility for spatial statistical data analysis for the project. He supervised the comparative analyses of the dNBR and CBI data and the local analyses of treatment effectiveness.

Dr. Jeffery C. Eidenshink is the Deputy Director of the EROS Data Center and a senior scientist took over responsibility as PI for the MTBS project and CO-I for the LANDFIRE project. He was the project's lead federal cooperator at USGS.

Don Ohlen is a senior scientist and a contractor at USGS/EROS. He implemented the CBI/dNBR analysis for the MTBS project and has assisted this project's analysis of dNBR and CBI in fuels treatment areas and participated in field work.

Dr. Zhi-Liang Zhu relocated to Washington DC and then to Reston, VA, having taken a position with the US Forest Service and then returned to USGS in another capacity. He was the project's lead federal cooperator and also PI for the MTBS project and CO-I for the LANDFIRE project. He maintains involvement with the project.

Dr. Mark Finney is a USFS research forester with the Missoula Fire Sciences Lab. He facilitated the inclusion of project personnel in the FARSITE Fire Area Simulator (S493) course (Destin, FL) and also provided several days of personal FARSITE training in Missoula, MT to project personnel on materials pertinent to this research.

Dr. Matt Reeves (USFS) is a member of the LANDFIRE Product Quality Working Team and assisted the project with making adjustments to the LANDFIRE data where necessary and providing access to beta-versions of the new LANDFIRE data products.

Kari Pabst was a Geography Master's degree student at SDSU and a contractor at USGS/EROS who works on the MTBS project. She conducted the initial NFPORS analysis, created all dNBR maps for the project and participated in all field collections of CBI data until completing her degree in 2010.

Adam Baer was a geospatial analyst at SDSU and responsible for supervising the project's temporary workers. He attended the FARSITE Fire Area Simulator (S493) course (Destin, FL) and implemented all FARSITE simulations under the supervision of Cochrane until 2009 when he took another position with the government. He also provided spatial data management and analysis under the supervision of Wimberly.

Sarah Arnold was a Geography Master's degree student at SDSU. She prepared the geospatial data for inclusion in the FARSITE analyses. She completed her thesis "Changing Fire Return Intervals in Southern California" and graduated in 2009.

Chris J. Moran was a Biology master's student with the project from 2010-2011. He completed an internship with the MTBS project at USGS/EROS with Kari Pabst before starting with the project in spring 2010. He has participated in field collection of CBI data since that time, taken over all modeling activities from Adam Baer and is currently pursuing a doctoral degree at SDSU.

Aaron Stingley and Brad Strichertz were SDSU-GIScCE undergraduate scholars who contribute to data acquisition and data processing operations. They were also involved in field collection of CBI data.

Arend Kuyper and Adam Schmidt were statistics graduate students who implement the statistical modeling of treatment effectiveness and report generation for each fire under the supervision of Dr. Wimberly.

Christopher Barber (Cochrane) and Narayana Ganapathy (Wimberly) were doctoral students and Izaya Numata (Cochrane) is a post doctoral scientist at SDSU who participated in field collection of CBI data.

Jay Knoblock and Robert Schilling were temporary student workers who contributed to data acquisition (calling and internet downloading) and data processing.

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