Project Title: Assessing the effectiveness of spatially heterogeneous fuel reduction restoration treatments

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I. Abstract

In response to increasing wildfire severity and extent across the dry forests of the western United States in the last several decades, federal policy initiatives have encouraged joint vegetation management and fuels treatments to restore ecosystem composition, structure and function and reduce the potential for extreme fire behavior (e.g. National Fire Plan, 10-year Implementation Strategy, Healthy Forest Restoration Act of 2003). To meet these broad objectives managers are increasingly emphasizing treatments that simultaneously reduce potential fire behavior and create or maintain complex forest structures. However, our understanding of the effect that complex forest structures have on fire behavior are limited due to non-spatial fire management tools and a lack of well-designed field studies. Consequently there is knowledge gap between the fuels treatment theory and actual management practices which limits manager's ability to adequately design effective fuel treatments and develop monitoring and assessment strategies that can provide reliable information regarding the long-term efficacy of restoration treatments and support policy and budgetary decisions. The overall objective of this research was to examine the influence of forest restoration treatments on vertical and horizontal fuel heterogeneity and the effect of altered forest heterogeneity on potential fire behavior. To address these overall objectives we used a combination of intensive field-sampling, and numerical modeling to: 1) examine changes in horizontal and vertical heterogeneity following restoration treatments in the southern Rocky Mountains; 2) characterize changes in surface fuel variability and the scale of spatial autocorrelation in surface fuels following restoration treatments; 3) simulate changes in potential fire behavior following restoration treatments using the Wildland Urban Interface Fire Dynamics Simulator and operational fire behavior models; and 4) develop and refine methods of quantifying forest complexity and surface fuel load in dry western forests.

This study highlights several key findings: 1) current restoration treatments in the southern Rocky Mountains are not meeting all non-spatial principles of fuels reduction treatments but are still effective in reducing potential fire behavior, 2) restoration treatments are resulting in an aggregated spatial pattern of trees consisting of a matrix of individual trees, clumps and similar to descriptions of historical dry, 3) Restoration treatment longevity in the southern Rocky Mountains is dependent upon the magnitude and timing of regeneration, 3) WFDS was capable of reproducing reasonable predictions for crown fires 4) Surface fuel are highly variable and have small scales of spatial autocorrelation. This variability was altered following thinned and thin-and-burned treatments however, this effect varied by fuel component.

II. Background and purpose

In response to increasing wildfire severity and extent across the dry forests of the western United States in the last several decades, federal policy initiatives have encouraged joint vegetation management and fuels treatments to restore ecosystem composition, structure and function and reduce the potential for extreme fire behavior (e.g. National Fire Plan, 10-year Implementation Strategy, Healthy Forest Restoration Act of 2003). Previous research has suggested that silvicultural interventions which reduce surface, ladder and canopy fuel are an effective strategy for the prevention of high-severity fires (Agee & Skinner 2005). However, the implementation of this research has often resulted in an emphasis on implementing evenly spaced thin-from-below treatments, hereafter called traditional fuels reduction treatments. Although such treatments have been shown to be effective in reducing potential fire behavior and severity they often result in forest stand with low vertical and horizontal structural complexity. As suggested by Larson and Churchill (2012) and documented by numerous studies, such forest structures were not typical of the historical stand structures found in many frequent fire western forests. These forest structures have likely resulted in altered ecosystem processes such as microclimate, fire behavior, seed dispersal and regeneration, and tree growth and mortality (Bigelow and North 2012). For these reasons forest managers have increasingly emphasized treatments which simultaneously seek to reduce potential fire behavior and create or maintain complex forest structures characterized a matrix of single isolated trees, clumps of trees and canopy gaps (Larson & Churchill 2012), hereafter referred to as restoration treatments.

Although there has been a considerable amount of research that has characterized the potential effects of traditional fuel hazard reduction treatments on fire behavior (e.g. Pollett and Omi 2002, Graham et al 2004, Stephens et al 2009; Fulé et al 2012, Hudak et al. 2011) most studies have either ignored or not explicitly accounted for spatially heterogeneous forest structures. Previous studies have suggested that differences in residual forest spatial heterogeneity can alter the within-stand wind velocity and turbulence and subsequent fire behavior within a stand and on a stand level (Pimont et al. 2011, Bigelow and North 2012, Hoffman et al. 2012, Linn et al. 2013, Hoffman et al. 2015). However, this work has not yet isolated the causal mechanisms driving these tradeoffs or developed rules of thumb that can better assist managers in the design of treatments because of: 1) a paucity of methodologies that can rapidly assess the spatial distribution of fuels, 2) a lack of fire behavior models that explicitly account for fuel spatial and the interactions among fuel, atmosphere and fire and 3) the difficulty and expenses required to conduct replicated manipulative field experiments that consider fuel spatial heterogeneity. Consequently there is knowledge gap between the fuels treatment theory and actual management practices which limits manager's ability to adequately design effective fuel treatments and develop monitoring and assessment strategies that can provide reliable information regarding the long-term efficacy of restoration treatments and support policy and budgetary decisions.

The overall objective of this research was to examine the influence of forest restoration treatments on vertical and horizontal fuel heterogeneity and the effect of altered forest heterogeneity on potential fire behavior. To address these overall objectives we used a combination of intensive field-sampling, and numerical modeling to: 1) examine changes in horizontal and vertical heterogeneity following restoration treatments in the southern Rocky Mountains; 2) characterize changes in surface fuel variability and the scale of spatial autocorrelation in surface fuels following restoration treatments; 3) simulate changes in potential fire behavior following restoration treatments using the Wildland Urban Interface Fire Dynamics Simulator and operational fire behavior models; and 4) develop and refine methods of quantifying forest complexity and surface fuel load in dry western forests.

III. Study Description and Location

A. General description of the study area

We worked within ponderosa pine and dry mixed conifer forest of the Southern Rocky Mountains and Colorado Plateau regions of Colorado, New Mexico and Arizona. The distribution of forest types across this landscape is driven by elevation, aspect, and proximity to riparian areas with lower elevations tending to be dominated by ponderosa pine (*Pinus ponderosa*), with increasing amounts of Douglas-fir (*Pseudotsuga menziesii*), blue spruce (*Picea pungens*), and Engelmann spruce (*Picea engelmannii*) at higher elevations. A variety of disturbance agents including fire, drought, bark beetles, western spruce budworm (*Choristoneura occidentalis*), and pathogens such as mistletoe (A*rceuthobium* spp.) are present across this landscape and play an important role in determining stand structure in these forest types (Swetnam and Lynch 1993).

This area is similar to other portions of the western United States where fire suppression and past management have resulted in a departure from historical stand structure and disturbance regimes leading to undesirable forest conditions and increased recognition of a growing wildfire threat (Fitzgerald 2005, Hood and Miller 2007, Collins et al. 2011). Following several federal policy initiatives (e.g. the Collaborative Forest Landscape Restoration Program, Public Law 111-11) several partnerships among federal, state, and local agencies, utility providers, conservation groups, private business representatives, and other stakeholders were formed within this area and identified the use of restoration principles as a means to achieve shared goals and objectives. Although the specific goals of restoration treatments across this region differ based on the availability of site specific historical data generally all treatments sought to increase or maintain forest structural heterogeneity at multiple scales and create stand conditions that would result in a low to mixed severity fire. The silvicultural practices that are currently being implemented to meet these objectives often utilize variable tree spacing with a focus on retaining small to medium sized clumps of trees. Thinning is conducted throughout crown classes rather than from below to maintain vertical spatial heterogeneity. These goals are similar to individuals, clumps and openings (ICO) method (Larson and Churchill 2012, Churchill 2013a, 2013b) however, specific targets such as the proportion of trees within a clump size are often not explicitly stated within the region.

<u>B. Assessing changes in spatial and non-spatial forest structure following restoration treatments</u>

We evaluated the effects of forest restoration treatments on the vertical and horizontal forest structure with a combination of field collected fuels data and numerical modeling. Field data was collected on seven sites that had been mechanically treated within the past 10 years across the Colorado Plateau and southern Rocky Mountains. These sites were selected in consultation with local forest managers based on the criteria that sites must have relatively little (< 20%) slope and were typical of dry forest stands targeted for restoration. Six of the seven sites were dominated by ponderosa pine and one site (PC) was more mixed, dominated by Douglas-fir, and contained ponderosa pine, Engelmann spruce , blue spruce, and quaking aspen (*Populus tremuloides*). At each site a single 200 m x 200 m plot was established and all trees at least 1.37 m tall were mapped to a Cartesian coordinate system and had their species, tree height, diameter at stump height (DSH), diameter at breast height (DBH), crown radius, and crown base height recorded. Surface fuels were measured across the site using standard fuels inventory methods (Brown 1974).

We tested effects on non-spatial stand structure variables with a mixed-effects (PROC GLIMMIX; SAS Institute Inc, Cary, NC, USA) model with status (before and after thinning) as a fixed effect and site as a random effect. Pairwise differences between thinning for basal area, trees per hectare, quadratic mean diameter, crown fuel loads, canopy base height, and total fine surface fuel load were determined using least squares means with a Tukey-Kramer adjustment. For all significance tests we used an α of 0.05.

We examined changes in both vertical and horizontal structural complexity at both the stand and patch scales (Table 1). Stand pattern refers to the average or prevailing pattern type (e.g., aggregated, random, uniform) *across* an entire study area while patch scale pattern refers to spatial heterogeneity (e.g., tree clumps, openings, and widely spaced single trees) *within* a study area or forest stand (Fortin and Dale 2005; Larson and Churchill 2012). Stand scale pattern and effects of restoration on this pattern were assessed using the empirical pair correlation function while a spatial clump algorithm was used to identify the elements of individual trees, tree patches and openings (Clyatt et al. 2016; Plotkin et al. 2002; Sanchez-Meador et al. 2011). Vertical complexity in pre- and post-restoration stands was assessed using the height differentiation index (TH) (Kint et al. 2000) and by estimating the coefficient of variation of tree heights at the patch scale.

Table 1. Methodological framework for assessing alterations in structural complexity across dimensions and scales following restoration treatments.

Scale	Method	What was examined
Horizontal dimension		
Stand	Univariate and bivariate point correlation functions	Thinning impacts on the spatial pattern of trees and whether the pattern is more or less aggregated following thinning
Patch	Spatial patch detection	Changes in aerial cover of individual trees relative to patches and changes in patch size distributions, following thinning
Vertical dimension		
Stand	Height differentiation index	Thinning impacts on spatial mingling of differently sized trees
Patch	Patch scale coefficient of variation of tree heights	Changes in the variability of tree heights among patches following thinning

<u>C: Quantifying surface fuel load variability and the spatial scale of autocorrelation within untreated and restored ponderosa pine sites of the southern Rocky Mountains.</u>

We selected six sampling locations across the southern Rocky Mountains that represent a wide range of ponderosa pine-dominated forests and current fuel treatment prescriptions within the region (Figure 1). Potential sampling locations were restricted to areas that had experienced fire exclusion over the last 80 years and contained both untreated and recently treated (either mechanically thinned or mechanically thinned and burned within the past 8 years) stands that were: (1) within 10 km of each other; (2) each large enough to accommodate a 9-ha plot; (3) of similar overstory composition; (4) relatively flat with slope less than 5% to minimize influences on woody fuel alignment (Keane et al. 2012); (4) accessible within 2.5 km of a road; and (5) had similar pre-treatment tree size, density, basal area, and soil parent material. Within each of the six sampling locations we established two 300 x 300 m plots; one in the untreated fire-excluded stand and the other in either a fire-excluded stand that had recently been mechanically thinned or mechanically thinned and burned.

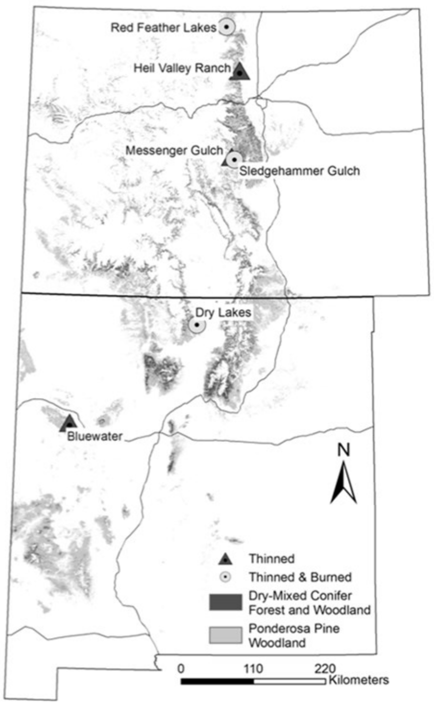

Figure 1. Location of the six study sites within the southern Rocky Mountains. Each study location had a treated stand and a paired adjacent unmanaged stand.

To determine variability and spatial autocorrelation of surface fuel load by fuel type and component within each 9-ha (300 x 300 m) plot we utilized a nested cluster sampling design similar to Keane et al. (2012) (Figure 2). Within each 300 x 300 m plot we established four 150 x 150 m quadrants. At the center of each quadrant we established three nested grids of sampling locations: 50 x 50 m, 25 x 25 m, and 7 x 7 m (Figure 2). Sampling locations (macroplot, subplot, and microplot) were placed at the corners of each quadrant and at the corners of the 50 and 25 m sampling grids, and throughout the 7 x 7 m intensive grid (Figure 2). This sampling design resulted in a range of separation distances between sampling locations for each fuel type and component, covering the range of reported spatial autocorrelation scales for western ecosystems (Keane et al. 2012).

To determine the scale of spatial autocorrelation and variability of fuel load in each treatment type, semivariogram analysis was performed following the approach outlined in Webster and Oliver (2007). Semivariograms present a graphical representation of the spatial continuity of a dataset by calculating the variance between all pairs of measured sample points as a function of their separation or lag distance. Semivariogram models are interpreted based on three modeled parameters: the range, sill, and nugget. The range is estimated as the point along the x-axis where the modeled curve flattens. Points located next to each other at scales below the range are spatially autocorrelated, while points spaced at distances larger than the range are spatially independent. The range value provides an estimate of the scale at which spatial autocorrelation occurs and represents the scale at which the fuel component is best described and measured. The corresponding y-axis value along the modeled curve at the range is called the sill, and represents the maximum variation of a process or system. The sill is similar to traditional statistical variance estimates. The nugget is the value of the fitted semivariogram at zero distance; a nugget other than zero represents measurement error or spatial variation at distances smaller than the sampling interval. A 'pure nugget' model, or one in which the sill and range are equal to zero and the nugget is non-zero, is the result of a process that occurs at smaller scales than those measured, or one which displays no spatial autocorrelation. To evaluate if differences existed among the modeled treatment sill and range values we compared the modeled range and sill values among treatments using a series of two-sample Z-tests.

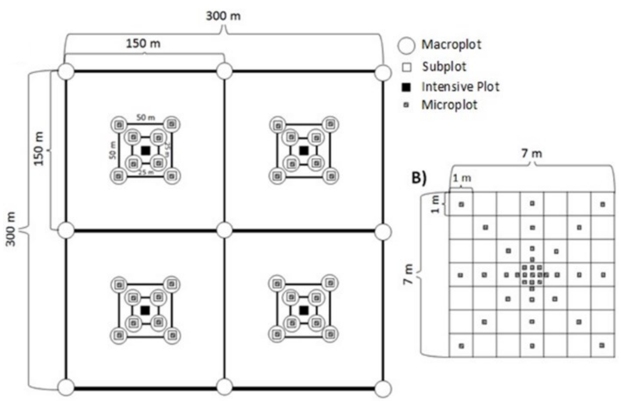

Figure 2. Nested cluster sampling design used to characterize surface fuel load variability.

D. Assessing changes in potential fire behavior following restoration treatments using the Wildland Urban Interface Fire Dynamics Simulator:

Model description and study design

Potential fire behavior for each site pre- and post-thinning was simulated using the Wildland Urban Interface Fire Dynamics Simulator (WFDS) under four different open wind speed scenarios. WFDS is a comprehensive physics based fire behavior model developed by the National Institute of Standards and Technology and the US Forest Service Pacific Northwest Research Station. WFDS employs computational fluid dynamics methods to solve the spatial and temporal evolution of fire using a three dimensional numerical grid. This approach allows for the three dimensional nature of fuels to be accounted for and predicts the evolution of the fire front through time and space. This model has been applied to a number of natural resource related questions including understanding the impact of bark beetle caused mortality on fire behavior (Hoffman 2012, Hoffman 2013) and characterizing fuel treatment efficacy (Skowronski et al. 2016, and this project). A more detailed description of the physical and mathematical formulations in WFDS can be found in Mell et al. (2007, 2009). WFDS is an extension of FDS, the Fire Dynamics Simulator (McGrattan et al. 2016a). Verification and evaluation studies of FDS and WFDS are described in Hoffman et al. (2015), McGrattan et al. (2016a, 2016b), Mell et al. (2007, 2009) and Mueller et al. (2015).

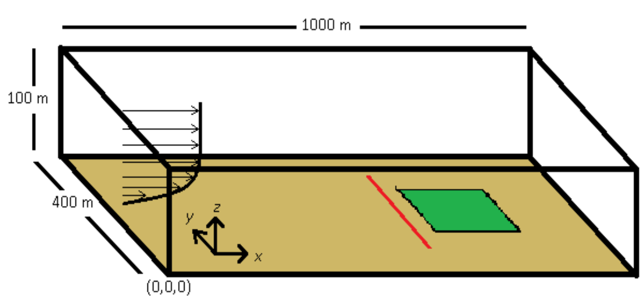

Figure 3. Schematic of WFDS simulation domains. Note the (a) inflow wind profiles originating at x=0 m, (b) the site located 700 to 900 m downwind of the inflow, and (c) the fireline origin at x=650 m.

All WFDS simulation used a simulation domain measuring 1000 m x 400 m x 100 m in the x, y and z dimensions (Figure 3). We input the measured stem-maps for each site, before and after thinning, with individual tree crowns simulated as right circular cones and a foliar moisture content of 100%. Surface fuels were modeled as a homogeneous fuel layer defined by each site's mean fine fuel load and mean fuelbed depth. The open wind flow was simulated following an atmospheric power law function with four different 10-m wind speeds, 2.2 m s-1, 4.0 m s-1, 9.0 m s-1, and 13.4 m s-1. We estimated the mean fire rate of spread, fireline intensity, and canopy consumption for each simulation. To exam the effect of restoration treatments on simulated fire behavior we used a mixed-effects (PROC GLIMMIX; SAS Institute Inc, Cary, NC, USA) three-way analysis of variance with status (pre-treatment or treated) and 10-m wind speed ($m\ s^{-1}$) as fixed effects and site as a random effect. Pairwise differences between status and wind speed levels of the three fire behavior parameters were determined using least squares means with a Tukey-Kramer adjustment.

To further evaluate the role of horizontal spatial pattern on potential fire behavior we conducted an additional numerical experiment using WFDS. The numerical experiment was set up as a randomized block design with a factorial treatment structure consisting of 7 different horizontal forest patterns, 2 levels of understory fuel loading, and 3 levels of 10-m open wind velocities.

E: Assessing restoration treatment longevity

To understand the impacts of regeneration on the longevity of forest fuel hazard reduction in restoration treatments we simulated combinations of seedling establishment densities and timing in stem-mapped sites across a range of ponderosa pine site productivities. Stand growth was simulated using the Central Rockies variant of the Forest Vegetation Simulator (FVS) (Dixon 2002), a distance-independent growth and yield model operating at the individual-tree level. FVS is commonly employed throughout the United States for forest planning and evaluating alternative treatment effects on forest stand development (Crookston et al. 2005). In order to mimic the range of potential regeneration pulses seen within ponderosa pine forest types (Bailey and Covington 2002), the post-treatment simulations had natural regeneration of ponderosa pine introduced through five different seedling densities (124, 371, 618, 1235, and 2470 seedling ha -1) and four temporal distributions starting in year 1 and varying in length to a maximum of 25 years (single long pulse, single narrow pulse, two narrow pulses, and constant regeneration; Figure 4). Fire hazard was modeled as the 10 m open wind speed (km hr−1) required to initiate crown fire (Torching) and to support crown fire spread (Crowning) by inputting the predicted stand structure and fuel loads from the FVS-FFE simulations into the Crown Fire Initiation and Spread model (CFIS) (Rothermel 1991, Crookston et al. 2005). CFIS was setup to incorporate the canopy bulk density (CBD; kg m−3) and potential surface fuel consumption (SFC; kg m−2) estimates from the FVS-FFE simulations. The utilization of CFIS within this study was largely decided upon because of the documented under-prediction bias and erratic nature of crown fire behavior modeling in FVS-FFE (Johnson et al. 2011, Cruz et al. 2002, Cruz and Alexander 2010).

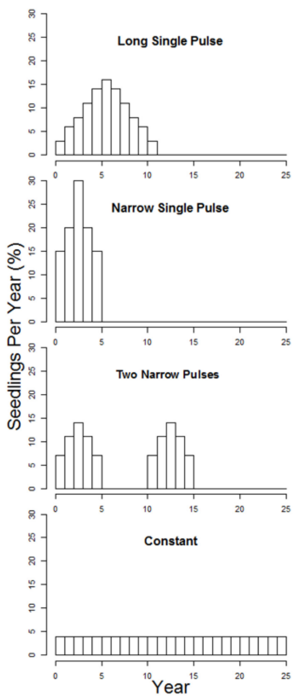

Figure 4. Temporal distribution of regeneration simulated following restoration treatments using FVS

The time required for a scenario to return to its pre-treatment fire hazard level was defined as the time when the Torching and Crowning Indices returned to within 10% of the pre-treatment indices. Tobit regression, or a censored regression model, was utilized for assessing the influence of regeneration pulse magnitude (seedlings ha-1), temporal distribution, and site index on the timing of when the stands returned to within 10% of their pre-treatment indices. The Tobit analysis is designed to estimate linear relationships between variables when the dependent variable is censored or has an artificial limitation imposed (Tobin 1958, McDonald and Moffitt 1980), which made it well suited for this study as some of the modelled scenarios failed to return to within 10% of the pre-treatment indices by the end of the 100 year simulations. For these cases the time to return was recorded as 100 years, with 100 years being set as the upper bound for the dependent variables (years to return to pre-treatment Torching and Crowning Indices) of the regression. In comparing the effect of the CRNMULT Keyword on the regression results, significant changes in coefficients between the simulation sets were tested at the $\alpha = 0.05$ level.

F: WFDS Model Evaluation

Although detailed physics-based models provide the user with a great deal of flexibility to investigate a variety of wildland fire behavior questions and a substantial amount of evaluation has been performed, there is a need to assess model performance, especially in terms of crown fire behavior, to identify potential model errors and establish model credibility. As a first step towards model evaluation, we also conducted a coarse assessment of crown fire rate of spread predictions from the WFDS results from the this study, as well as previously reported results from another comprehensive physics based fire model (FIRETEC) using previously published field scale data by developing an empirical relationship between the 10-m open wind speed and crown fire rate of spread and examining the proportion of simulated predictions that fall within our empirically derived 95% prediction bands. We assumed that reasonable model performance was achieved based on criteria proposed by Rykiel (1996) for dynamic ecological models. This approach is conceptually consistent with recommended standards for deterministic fire model evaluation in that we determined the degree to which ROS is an accurate representation of the real world from the perspective of the intended use (American Society for Testing and Materials 2005).

G: Development and refinement of methods to quantifying forest complexity and fuel load in dry western forests

To refine methods related to the quantification of forest complexity and fuel loads in dry western forests we conducted two different field studies aimed at improving characterizing surface woody fuels using the planer intercept method (Brown 1974) and the photoload method (Keane and Dickinson 2007).

The objective of the first study was to assess the use of photoload double sampling to improve fine woody debris fuel (0.0–0.6, 0.6–2.5, and 2.5–7.6 cm) load estimation accuracy and precision, while improving sampling efficiency. Specifically, the study evaluates: (1) the use of photoload sampling for fuel load estimation, (2) the use of ratio and regression estimators in correcting photoload double sampling fuel load estimates, and (3) the influence of double sampling rate (i.e. the percentage of plots being destructively sampled) on estimate accuracy and precision. To meet these objectives 512 sampled 1 m^2 photoload plots of fine woody debris (0–0.6 cm) were collected within ponderosa pine forests across the central and southern Rocky Mountains of the Colorado Front Range and northern New Mexico, USA. The photoload fuel loadings were visually estimated and then destructively sampled by field technicians, each of whom had received extensive training on the proper use of the technique as outlined by Holley and Keane (2010). Using the 512 double sampled photoload plots, six simulated fuel beds that represented a range of fuel loadings (0.016, 0.060, and 0.120 kg m-2) and fuel load variability (coefficients of variation of 42 and 85%) commonly seen in western United States dry forests were created (Keane et al. 2012). Each simulated fuel bed consisted of 100 of the double sampled plots. To determine the non-double sampling accuracy, 1000 Monte-Carlo simulations were drawn with samples from the size simulated fuel beds with sample sizes from 5 to 50 in increments of 5. Each Monte Carlo simulation was then compared against the 100 destructively sampled loadings. To determine whether a ratio or regression estimator was more appropriate for photoload double sampling, 1000 Monte Carlo simulations of each double sample size ranging from 5–50 in increments of 5 were drawn from each of the six simulated fuel beds by simple random sampling without replacement. Each of the 1000 sample sets then underwent a classical, jackknife, and bootstrap approach to calculate the percent bias and root mean squared error (RMSE) of the correction estimator for each fuel load using the ratio and regression estimators. Finally utilizing the preferred correction technique, 1000 Monte Carlo simulations of each sample size ranging from 10–60 in increments of 10 photoload plots were drawn from each population by simple random sampling without replacement, to evaluate the influence of double sampling rate.

The goal of the 2nd study was to provide the squared diameter (d^2) of dead down woody biomass in ponderosa pine stands on the eastern side of the continental divide in the Rocky Mountains of Colorado and New Mexico under three common scenarios: natural stands, stands that have been partially harvested to restore a more historic forest structure and composition and stands that have been underburned after a partial harvest. Currently there are no published values of d^2 for the Southern Rocky Mountains, especially d^2 values that reflect the previously mentioned current silvicultural practices in these systems. The d^2 estimates provided in this study should improve dead down woody fuel loading estimates produced using the planar intersect method in this region. In addition, we perform bootstrap analysis to determine the sample size required to produce reasonably accurate d^2 estimates at a local level. We collected fine dead down woody fuels from 12 ponderosa pine dominated stands on the eastern side of the continental divide across Colorado and New Mexico on the Roosevelt, Pike and San Isabel, Carson, and Cibola National Forests and in Boulder County Open Space. Overstory species composition ranged from 72–100% ponderosa pine by basal area, with other trees species including Douglas-fir, quaking aspen, and Rocky Mountain juniper (*Juniperus scopulorum*). Sampled stands ranged in elevation from 2000–2800 m, covering the elevational distribution of ponderosa pine forests in this region (Peet 1981; Dick-Peddie 1993), had slopes from 0–30%, and included all aspects. At each stand we randomly located a 9-ha plot such that it was completely contained within the treatment unit and had an average slope of less than 5%. Within each quarter of the plot we randomly placed 12 1-m^2 frames for a total of 48 per site and collected all woody fuels less than 7.62 cm in diameter. Because Brown (1974) requires the user to directly measure the diameter of 1000-h fuels and calculate the d^2, they were not included in this study. Following woody fuel collection at each site we sorted all fuel into timelag classes (i.e. 1-h, 10-h, and 100-h fuel classes), with 50 particles randomly selected from each timelag class and measured for endpoint and midpoint diameters. These measurements were used to calculate an arithmetic mean diameter for each particle and a stand-level quadratic mean diameter for each timelag class. From the stand-level quadratic mean diameters of each timelag class the arithmetic mean was calculated and squared to produce our d^2 estimate within each stand condition. Differences in the mean squared average quadratic diameter among different treatment types were tested using a generalized linear mixed model with treatment as a fixed effect, site as a random effect, and a random residual effect for each site to account for variance heterogeneity between treatments with a critical value (a) of 0.05. The assumed response distribution was lognormal.

We used standard with-replacement bootstrapping techniques (Efron and Tibshirani 1993) to estimate the optimal sample size required to create accurate local estimates of d^2 for each size class and treatment combination. For each fuel size class and treatment combination we created 1000 bootstrapped samples ranging in size from 5–200 samples in increments of 5 and calculated the variance between the mean d^2 of each of the 1000 bootstrap observations at each sample size. For each fuel class and treatment type we visually evaluated changes in the d^2 variance across the range of sample sizes to determine the point where the decrease in variance was minimal compared with the increase in sample size (Jalonen et al. 1998). We considered the recommended sample size to be the visually estimated inflection point in the graph (Sikkink and Keane 2008).

IV. Key Findings

The key findings presented in the final report represent an abbreviated set of findings completed to date in this project. As our analysis and write up of the datasets and simulations completed during this project continues we expect additional findings to be added to this list.

A: Restoration treatment effects spatial and non-spatial measures of stand structure

Following treatment tree densities, basal areas and canopy fuel loads were all decreased consistent with several non-spatial expectations of the fuel hazard reduction treatments and previous studies in dry forest types across the western U.S. (Covington et al. 1997, Agee and Skinner 2005, Hudak et al. 2009, Stephens et al. 2009, Fulé et al. 2012, Churchhill et al. 2013). However, we did not find an increase in CBH contradicting the results reported by Fulé et al. (2012) and violating one of the principle objectives in fuel hazard reduction treatments outlined by Agee and Skinner (2005). The lack of effect on canopy base height and surface fuel loading is likely due to an increased emphasis on maintaining vertical structural complexity rather than emphasizing the preferential selection of smaller diameter trees and the lack of prescribed fire following treatments. All post-treatment stands were classified as having an aggregated spatial pattern of trees consisting of a matrix of individual trees, clumps and openings (Table 2; Figure 5) similar to descriptions of historical dry forests (Harrod et al. 2009, Abella and Denton 2009, Larson and Churchill 2012, Brown et al. 2016). However, pre- to post-treatment comparisons suggest that treatments did not necessarily result in increased levels of aggregation (Table 2).

Table 2. Univariate pair correlation function results describing the spatial tree patterns pre-treatment, $g_{pre}(r)$, post-treatment, $g_{post}(r)$, and the bivariate pair correlation function, $g_{post}(r) - g_{pre}(r)$, results comparing degree of aggregation from post- to pre-treatment.

Site	$g_{pre}(r)$		$g_{post}(r)$		$g_{post}(r) - g_{pre}(r)$	
	Pattern	*P*	Pattern	*P*	Difference	*P*
HB	Unif.	0.002	Agg.	0.001	More agg.	0.001
LC	Agg.	0.001	Agg.	0.001	Less agg.	0.001
MG	Agg.	0.001	Agg.	0.001	More agg.	0.003
PC	Agg.	0.001	Agg.	0.001	More agg.	0.001
DL	Agg.	0.001	Agg.	0.001	More agg.	0.001
UM	Agg.	0.001	Agg.	0.001	Less agg.	0.026
BW	Agg.	0.001	Agg.	0.001	None	0.138

Potential patterns are uniform (unif.), aggregated (agg.) or random

We found no clear effect of restoration treatments on vertical structure and that a wide diversity of vertical heterogeneity existed on these sites before and after treatment (Figure 6). Given that silvicultural prescriptions for our sites did not directly address manipulation of vertical structure, the lack of a consistent effect of treatments may simply reflect the prioritization of various objectives at each site (e.g. wildlife habitat vs. crown fire hazard). These results suggest that while contemporary restoration treatments in the southern Rocky Mountains are not always increasing spatial complexity they are producing horizontal patterns that closely mimic historical reference conditions.

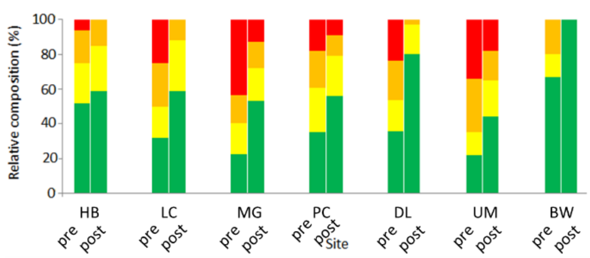

Figure 5. Changes in clump size distributions following restoration treatments.

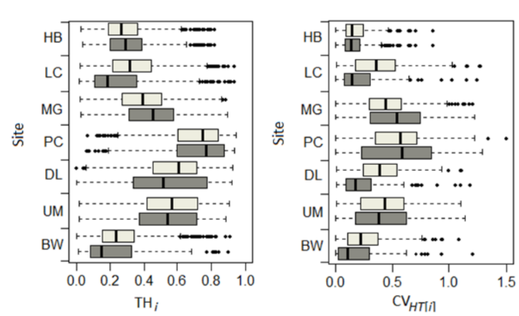

Figure 6. Distributions of height differentiation index values (THi) and of coefficients of variation of tree heights (CVHT[i]) among each site before (light grey) and after (dark grey) mechanical treatments. Larger values represent greater degrees of height differentiation.

B: Characterizing spatial variability and the scale of spatial autocorrelation in surface fuels following restoration treatments

Surface fuel loadings in Southern Rocky Mountain ponderosa pine forests of potential management are highly variable across and within surface fuel types and components. Coefficients of variation were above 100% for all fuel components and estimated range values varied across fuel components from less than 1 to 47 m (Table 3). Surface fuel load variability increased as a function of mean fuel load following a power-law relationship with a doubling in fuel load resulting in a 3.3-fold increase in the variability.

***Table 3**: Fitted semivariance parameter (sill and range) by fuel component and treatment type. Values in parentheses represent standard errors.*

Fuel Component	Rx	Sill $(kg\ m^{-2})^{-2}$	Range (m)
1-hr	None	0.0254 (0.0030) [a]	14.50 (1.88) [a]
	Thin	0.0054 (0.0003) [b]	0.91 (0.11) [b]
	Thin and burn	0.0041 (0.0003) [c]	1.81 (0.22) [c]
10-hr	None	0.0403 (0.0022) [a]	1.47 (0.11) [a]
	Thin	0.1586 (0.0114) [b]	1.32 (0.13) [a]
	Thin and burn	0.0331 (0.0030) [a]	1.44 (0.20) [a]
100-hr	None	0.0558 (0.0026) [a]	0.89 (0.07) [a]
	Thin	0.3226 (0.0249) [b]	1.53 (0.15) [b]
	Thin and burn	0.0777 (0.0051) [c]	1.23 (0.10) [b]
1,000-hr	None*	0.3998 (0.0418) [a]	
	Thin	0.3026 (0.0579) [a]	47.59 (13.10) [b]
	Thin and burn	0.3558 (0.0686) [a]	46.89 (13.21) [b]
Litter	None	0.4789 (0.0255) [a]	1.13 (0.08) [a]
	Thin	0.5518(0.0398) [a]	0.93 (0.11) [a]
	Thin and burn	0.1701 (0.0136) [b]	0.99 (0.12) [a]
Duff	None	5.9616 (0.3165) [a]	1.18 (0.08) [a]
	Thin	5.1888 (0.3857) [a]	1.02 (0.10) [a]
	Thin and burn	0.9112 (0.0744) [b]	1.16 (0.13) [a]
Shrub	None*	0.0717 (0.0002)	
	Thin**		
	Thin and burn	0.0133 (0.0008)	1.00 (0.09)
Herbaceous	None**		
	Thin*	0.0041(0.0002)	
	Thin and burn**		

* Pure nugget model; value given in sill column is nugget value.
** MLE fit not possible due to distribution of data.

In addition, we found that the scale of spatial autocorrelation increased as a function of fuel component diameter following a power-law relationship with smaller diameter fuel particles having a smaller spatial autocorrelation scales than and larger diameter fuels. A doubling of fuel particle diameter resulted in a 3.6-fold increase in spatial autocorrelation length scale.

Both surface fuel variability and the scale of spatial autocorrelation were altered following thinned and thin-and-burned treatments. However, the effect of treatments on heterogeneity was inconsistent among fuel components (Table 3), with these differences possibly arising for a variety of reasons. First, the preferential removal or death of certain trees during thinning and prescribed fire activities may disproportionately influence fuel components because branch diameter size distributions differ by species and position in the canopy (Brown 1978). In addition, complex spatial and temporal interactions between the pre-treatment stand characteristics and patterns of treatment disturbance may ultimately control spatial arrangement and distribution of wildland fuels.

These findings provide insight that could help address a number of fuels management and ecological questions by informing the approaches used in fuels inventory, fuel mapping, and fire behavior and effects modeling. Because each wildland fuel component not only varies at a unique scale but also exhibits a different level of population variance optimal fuel inventory, approaches may need to adopt different sampling strategies for each fuel component. For example, a hierarchically nested sampling design where each fuel component is measured within differently sized plots corresponding to the estimated range parameter would be a logical approach to designing a fuels inventory. For a more complete description of the findings see Vakili et al. (In Press).

C: Restoration treatment effects on potential fire behavior

Our results indicate that restoration treatments resulted in decreased fire ROS, fireline intensity and canopy fuel consumption compared to pretreatment forests across all wind scenarios tested (Figure 7). These results provide additional support to a growing body of literature that has suggested that restoration treatments do result in reduced fire behavior (Fulé et al 2012). In addition our simulated canopy consumption suggest that following restoration treatment these forests exhibit low to moderate levels of fire severity (20-35% canopy consumption) which are in line with several estimates of historic fire severity in these systems (Sheriff et al 2014; Brown et al 2016.).

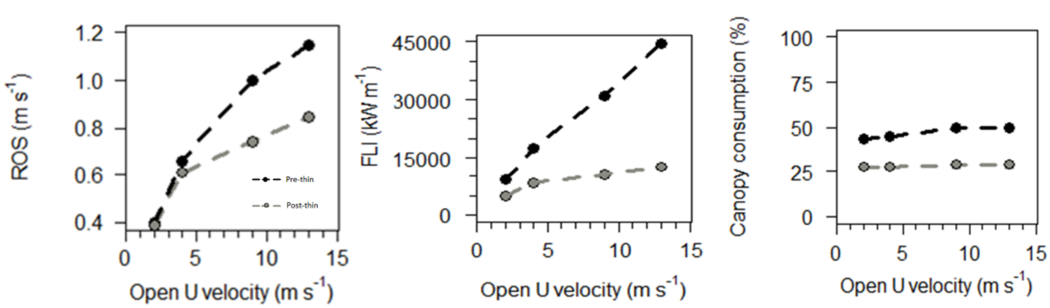

Figure 7. Predicted changes in fire behavior metrics following restoration treatments in the Southern Rocky Mountains.

D: Do restoration treatments simultaneously reduce potential fire behavior and maintain or restore structural complexity in the southern Rocky Mountains?

Implementation of forest restoration in dry conifer ecosystems are often designed to modify both spatial and non-spatial aspects of forest structure while simultaneously reducing the potential for uncharacteristic wildfires (Schultz et al. 2012; Underhill et al. 2014). Our results suggest that the range of conditions created by restoration treatments in the southern Rocky Mountains are at least qualitatively meeting non-spatial and spatial stand structure objectives and reducing fire rate of spread, intensity and severity.

E: Assess forest restoration treatment longevity

We found a significant relationship between the number of seedlings on a site, the temporal pattern of regeneration and site index all influence the length of time before a stand will return to an undesirable fire hazard condition. More specifically we found that passive and active crown fire treatment longevity were reduced five years for every 550 and 150 seedlings ha^{-1}, respectively and that regeneration occurring over a short time period further reduces passive crown fire longevity by 10 years compared to delayed regeneration patterns (see Figure 4 for example temporal patterns simulated). Our results also suggest that for every 6 m increase in site index the time before a stand will return to an undesirable fire hazard condition increased by 4.5 years. For a more complete description of the findings of this study see Tinkham et al. (2016a)

F: WFDS model evaluation

Overall, 86% of all simulated ROS values using WFDS or FIRETEC fell within the 95% prediction interval of the empirical data, which was above the goal of 75% for dynamic ecological modeling (Figure 8). This suggests reasonable agreement between WFDS and FIRETEC predictions and the experimental data. In cases where WFDS and FIRETEC did not predict rates of spread within our predictive bounds, both models appear to over-predict the crown fire rate of spread. As suggested by Alexander and Cruz (2008), under-predictions have severe implications for public and firefighter safety and fire operations planning; whereas over-predictions can be easily dealt with.

Although our comparisons provide some indication that detailed physics-based models produced reasonable estimates of crown fire rates of spread, further evaluation of these models remains limited by: 1) the scarcity of available empirical data, 2) insufficient data regarding the spatial and temporal nature of environmental conditions and fuels, and 3) a lack of response variables, besides fire rate of spread. The lack of empirical data that has been collected with the intention to assess detailed physics-based models is currently acting as a bottleneck for further assessment of model performance and development. Additional experiments that are specifically designed to assess a broader array of detailed physics-based model outputs combined with a wider range of statistical analysis of model performance could help identify any potential errors and limitations, enhance model credibility, and expand the robustness of model assessment and model application. For a more

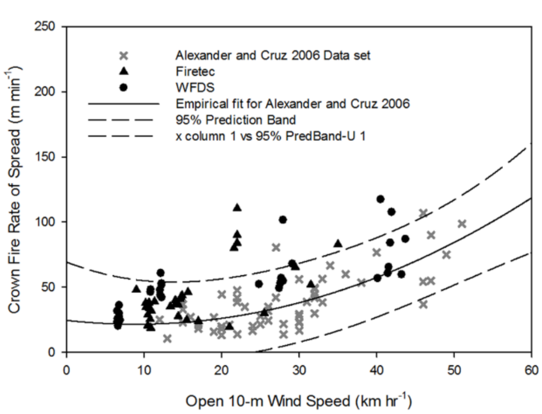

Figure 8: Comparisons of crown fire rate of spread predictions from WFDS and FIRETEC compared to empirical crown fire rates of spread.

complete description of this study including additional results see Hoffman et al. 2016.

G: Development and refinement of methods to quantifying forest complexity and fuel load in dry western forests

Standard photoload visual estimation for the six fuel beds provided consistent and biased estimates of the destructively sampled fuel loads with the standard error for all sample sizes, except for sample sizes of 5, less than 10% of the mean destructively sampled fuel load. The sample bias varied with fuel loading between the different fuel beds with the high and moderate fuel loadings (0.120 and 0.060 kg m2) being consistently underestimated in fuel load by 20% and the low fuel loading (0.016 kg m2) being overestimated by 10%. Regardless of the application, when the photoload technique is implemented as described by Holley and Keane (2010), useful estimates of fine woody material loading can be achieved. However, interpretation of standard photoload fuel loading estimates will be contingent on the user bias that is introduced during sampling. This study further shows that with only a moderate level of (20–40%) double sampling, a substantial reduction in estimation bias (5–15%) and the width of the confidence interval (approximately halved) can be achieved by applying a regression estimation correction factor to photoload sampling. This technique shows promise for improving the accuracy and efficiency of fine woody fuel loading estimation over the traditional planar intercept methods.

Table 4. Regional d^2 estimates of dead down woody fuel classes for ponderosa pine dominated forest of the southern Rocky Mountains.

Diameter Class (cm)		Southern Rockies	Brown 1974 (Brown 1974)
[0–0.63]	Natural	0.268	0.221 (−18%)
	Thin	0.258	0.160 (−38%)
	Thin-and-burn	0.195	–
[0.63–2.54]	Natural	1.746	1.54 (−12%)
	Thin	1.871	2.05 (+10%)
	Thin-and-burn	1.821	–
[2.54–7.62]	Natural	15.698	20.13 (+28%)
	Thin	18.387	18.26 (−7%)
	Thin-and-burn	14.778	–

In our 2nd study we found that local squared diameter (d^2) values for the southern Rocky Mountains generally result in greater estimates of the 1- and 10-h timelag fuel loadings and a lower estimate of 100-h timelag fuel loading compared to previously reported values by Brown 1974 (Table 4). Because, fuel loading estimates calculated using equations from Brown (1974) are directly proportional to the d^2 values using a value 10% higher for d^2 results in a 10% higher estimate of fuel loading. In evaluating fuel treatment effectiveness within southern Rocky Mountain ponderosa pine forests, the d^2 values presented here would thus result in a sizeable increase in post-treatment fuel loading of 1- and 10-h fuels compared with estimates using d^2 values from Brown (1974), assuming all other parameters in the model were held constant. This work also shows that a sample size of 35 diameters is need to produce local d^2 estimates. Such an effort can easily be collected and measured in under an hour using basic equipment, and the related calculations can be performed on a standard calculator, requiring no special software or expertise and could reduce potential biases associated with regional differences.

For a more complete description of these studies see Tinkham et al. (2016B) and Vakili et al. (2016).

V**. Management Implications:**

The overall objective of this research was to examine the influence of forest restoration treatments on vertical and horizontal fuel heterogeneity and the effect of altered forest heterogeneity on potential fire behavior. To address these overall objectives we used a combination of intensive field-sampling, and numerical modeling to: 1) examine changes in horizontal and vertical heterogeneity following restoration treatments in the southern Rocky Mountains; 2) characterize changes in surface fuel variability and the scale of spatial autocorrelation in surface fuels following restoration treatments; 3)

Simulate changes in potential fire behavior following restoration treatments using the Wildland Urban Interface Fire Dynamics Simulator and operational fire behavior models; 4) develop and refine methods of quantifying forest complexity and fuel load in dry western forests.

Our findings provide very actionable and useful knowledge to land managers and expand general theories used in fuels and fire management. To date few studies have explicitly evaluated the effect of restoration treatments on structural complexity or accounted for this in potential fire behavior assessments. Yet, previous studies have suggested that structural complexity can influence potential fire behavior by altering local thresholds for crown fire ignition and spread, and the within canopy wind speed and turbulence (Hoffman et al. 2012; Pimont et al. 2011) and thus may not result in reductions of potential fire behavior. Our research suggests that despite current treatments not meeting all of the principles of fuel hazard reduction (i.e. increased crown base height, and decreased surface fuel loads) they are capable of maintaining structural elements of historical forests and reducing potential wildfire behavior. Furthermore, our findings indicate that the long-term efficacy of restoration treatments depends upon the amount and timing of future regeneration.

In addition, our results regarding the spatial nature of surface fuels have direct impacts on fuel mapping which has become a pivotal tool within wildland fire management. Our results suggest that current fuel mapping efforts are too coarse and likely do not capture the inherent scale of fuel spatial variability. This bias is particularly important if such maps will be used in fire behavior and effects modeling as fine scale variability in fuel load can have significant implications for fire spread and intensity as well as on the subsequent post fire plant response and residue composition. To assist fuels inventory and mapping we quantified local values to assist in planer intercept sampling and assessed the ability for newer fuel inventory approaches such as the photoload method combined with double sampling. These studies provide critical methodological information that should improve the accuracy and efficiency of fuel inventory within the southern Rocky Mountains.

To further assist managers in designing and implementing restoration treatments we developed a visualization tool of forest structure following restoration treatments. This tool was designed to assist managers in linking quantitative and visual descriptions of forest structure to assist in the identification and communication of silvicultural targets relate to spatial forest structure. This tool was developed in direct response to concerns we have heard from local managers regarding the difficulty to communicate and visualize spatial objectives.

Finally although models such as WFDS are currently not designed or intended for management purposes due to computational demands, the work completed during this project have helped enhance model credibility, and expand the robustness of model assessment and model application.

VI. Relationship to other recent findings and ongoing work

The research conducted during this project builds on a number of recent research projects related to fuels treatment effectiveness and fuels inventory and management. For example our findings that current restoration treatments can simultaneously reduce fire behavior and maintain horizontal and vertical complexity provide additional support to a growing body of literature that has suggested treatments do result in reduced fire behavior (Fulé et al. 2012, Hudak et al. 2011, Stephens et al. 2009). Furthermore, our work was one of the first attempts to quantify surface fuel spatial autocorrelation and semivariance in dry-forest types of the western U.S. and the only study that has assessed the effects of forest management on surface fuel spatial variability. This work builds on a growing body of literature regarding the spatial variability of surface fuels and provides new methods and tools to improve fuels inventory and mapping.

In addition, we have developed several successful proposals that directly build upon the work completed during this project.

1) Assessing factors that influence fuels treatment effectiveness. This project is funded by JFSP (Project number: 14-1-01-18) and seeks to increase our understanding of the mechanisms that influence the effectiveness of landscape scale fuels treatments. This project expands upon the stand level research conducted in this project to evaluate how the amount, size and configuration of treatments across influence landscape scale fire behavior.

2) Quantifying tradeoffs among potential fire behavior and spatial heterogeneity to enhance fuel hazard reduction and restoration treatment design. This project is funded through the National Fire Plan and Rocky Mountain Research Station. The overall objective of this proposal is to investigate the influence different forest treatments have on vertical and horizontal fuel heterogeneity and the effect of forest heterogeneity on the likely range of potential fire behavior. This research directly address knowledge gaps identified during this project by explicitly evaluating the role of vertical heterogeneity and the interaction between vertical and horizontal heterogeneity on potential fire behavior.

3. Establishment of a large scale permanent forest dynamics plot to characterize forest health and resiliency in Colorado. This project is funded through Colorado State University and seeks to establish a large scale long-term forest dynamics plot within the Rocky Mountains to assess the impacts of current forest mitigation strategies on forest stand dynamics, fuels ecology and forest health. This work will provide long-term study site to address multiple knowledge gaps related to spatial and temporal controls of fuel loading.

VII. Future work needed

While this project has provided new insights into forest restoration and the effect of spatial heterogeneity on fire behavior there remains a number of related unanswered questions. These questions include furthering our understanding of the spatial and temporal controls of fuels following forest restoration and a deeper understanding of the effects of horizontal and vertical forest heterogeneity on fire behavior and effects. In addition, there remains a need to further develop new methods to quantify and map the spatial and temporal variability of surface fuels and to continue to develop and assesses fire behavior models.

VIII. Deliverables Crosswalk

Proposed	Delivered	Status
Conference presentation	See Additional reporting section	Completed – related documents available on JFSP website
Refereed publication	See Additional reporting section	Completed – related documents available on JFSP website
M.Sc. Thesis	See Additional reporting section	Completed
Manager guide to structural heterogeneity	See Additional reporting section	Completed, In Press
Manager Briefs	See Additional reporting section	Completed
Manager Presentations	See Additional reporting section	Completed – related documents available on JFSP website

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X. Additional Reporting

A: JFSP Final Report

Hoffman, C.M., Battaglia, M.A., Cheng, A, Ziegler, J. 2016. Assessing the effectiveness of spatially heterogeneous fuel reduction restoration treatments.

B. Refereed Publications

1. Vakili, E, Hoffman, C.M., Keane, R.E., Tinkham, W.T. Dickinson, Y. Spatial variability of surface fuels in treated and untreated ponderosa pine forests of the southern Rocky Mountains. *International Journal of Wildland Fire (In press)*.
2. Vakili, E., Hoffman, C.M., Keane R.E. 2016. Fuel particle diameters of southern Rocky mountain ponderosa pine forests. *International Journal of Wildland Fire* 25(7): 780-784.
3. Tinkham, W.T., Hoffman, C.M., Ex, S., Battaglia, M., Saralecos, J.D. 2016a. Ponderosa pine forest restoration treatment longevity: Implications of regeneration on fire hazard. Forests 7, 137.
4. Tinkham, W.T., Hoffman, C.M., Canfield, J.M., Vakili, E., Reich, R.M. 2016b. Using double sampling with photoload technique to improve surface fuel loading efficiency and accuracy. International Journal of Wildland Fire 25(2): 224-228.
5. Hoffman, C.M., Canfield, J., Linn, R.R., Mell, W. Sieg, C.H., Pimont, F., Ziegler, J. 2016. Evaluating crown fire rate of spread predictions from physics-based models. Fire Technology 52(1): 221-237.

C. Non-refereed Publications

1. Tinkham, W.T., Dickinson, Y., Hoffman, C.M., Battaglia, M.A., Ex, S., Ziegler, J.P., Underhill, J. In Press. Visualization guide to heterogeneous forest structures following treatment in the southern Rocky Mountains*. USDA F.S. RMRS General Technical Report RMRS-GTR-XXX, Fort Collins, CO.*
2. *Tinkham, W., Ziegler., Hoffman, C.M., Battaglia, M. 2016. Changes in Forest Structure and Fire Behavior on the Heil Valley Ranch Forest Restoration Project, Colorado Forest Restoration Institute CFRI-TB-1602, Colorado State University, Fort Collins, CO.*
3. *Tinkham, W., Ziegler., Hoffman, C.M., Battaglia, M. 2016. Changes in Forest Structure and Fire Behavior on the Lookout Canyon Forest Restoration Project, Colorado Forest Restoration Institute CFRI-TB-1603, Colorado State University, Fort Collins, CO.*

4. *Tinkham, W., Ziegler., Hoffman, C.M., Battaglia, M. 2016. Changes in Forest Structure and Fire Behavior on the Long John Forest Restoration Project, Colorado Forest Restoration Institute CFRI-TB-1608, Colorado State University, Fort Collins, CO.*
5. *Tinkham, W., Ziegler., Hoffman, C.M., Battaglia, M. 2016. Changes in Forest Structure and Fire Behavior on the Messenger Gulch Forest Restoration Project, Colorado Forest Restoration Institute CFRI-TB-1605, Colorado State University, Fort Collins, CO.*
6. *Tinkham, W., Ziegler., Hoffman, C.M., Battaglia, M. 2016. Changes in Forest Structure and Fire Behavior on the Phantom Creek Forest Restoration Project, Colorado Forest Restoration Institute CFRI-TB-1606, Colorado State University, Fort Collins, CO.*
7. *Tinkham, W., Ziegler., Hoffman, C.M., Battaglia, M. 2016. Changes in Forest Structure and Fire Behavior on the Red Feather Forest Restoration Project, Colorado Forest Restoration Institute CFRI-TB-1607, Colorado State University, Fort Collins, CO.*
8. *Tinkham, W., Ziegler., Hoffman, C.M., Battaglia, M. 2016. Changes in Forest Structure and Fire Behavior on the Unc Mesa Forest Restoration Project, Colorado Forest Restoration Institute CFRI-TB-1608, Colorado State University, Fort Collins, CO.*
9. *Tinkham, W., Ziegler., Hoffman, C.M., Battaglia, M. 2016. Changes in Forest Structure and Fire Behavior on the Bluewater Forest Restoration Project, Colorado Forest Restoration Institute CFRI-TB-1609, Colorado State University, Fort Collins, CO*
10. Vakili, E., 2015. Improving assessments of fuel treatment effects on surface fuels in ponderosa pine forests of the southern Rocky Mountains. MSc thesis, Colorado State University, Fort Collins, CO
11. Ziegler, J.P., 2014.Impacts of treatments on forest structure and fire behavior in dry western forests. MSc thesis, Colorado State University, Fort Collins, CO

D. Oral Presentations

1. Hoffman, C.M**.**, Ziegler, J., Battaglia, M., Mell, W. 2016. Assessing restoration treatment effectiveness in the Southern Rocky Mountains. WESTFIRE Center Spring Seminar Series, Colorado State University, March 2, Fort Collins, CO. **(Invited)**
2. Hoffman, C.M**.**, Ziegler, J., Battaglia, M., Mell, W. 2016. How are Front Range CFLR treatments altering structure and fire behavior? An assessment. Front Range Roundtable, Landscape Restoration Monitoring Team, May 23, Golden, CO. **(Invited)**
3. Hoffman, C.M**.**, Ziegler, J., Battaglia, M., Mell, W. 2016. Assessing restoration treatment effectiveness in the Southern Rocky Mountains. WESTFIRE Center Spring Seminar Series, Colorado State University, March 2, Fort Collins, CO. **(Invited)**
4. Hoffman, C.M., Linn, R.R., Mell, W., Battaglia, M., Sieg, C., Winterkamp, J., Canfield, J., Ziegler, J. 2016. Predicting the spread of wildland fires: The importance of fire interactions with the atmosphere, ecosystems and topography. Colorado State University Department of Atmospheric Sciences Colloquia. Feb. 5th, Fort Collins, CO. **(Invited)**
5. Battaglia, M.A., Fornwalt, P.J., Gannon, B., Brown, P., Hoffman, C., Chambers, M., Cheng, A.S., Malone, S. 2016. Front Range Collaborative Forest Landscape Restoration Project: Research efforts, historical reconstruction of forest stand structure, and associated fire behavior. Watershed Wildfire Protection Group, Denver, CO.
6. Hoffman, C.M**.**, Ziegler, J., Battaglia, M., Mell, W. 2015. Restoration and fire behavior in ponderosa pine dominated forests of the southern Rocky Mountains. 6th International Fire Ecology and Management Congress: Advancing Ecology in Fire Management. Nov 16-20, San Antonio, TX.

7. Tinkham, W., Hoffman, C.M., Battaglia, M., Ex, S. 2015. Treatment longevity of ponderosa pine forest restoration: implications of regeneration on fire hazard. 6th International Fire Ecology and Management Congress: Advancing Ecology in Fire Management. Nov 16-20, San Antonio, TX.
8. Vakili, E., Hoffman, C.M., Keane, R., Tinkham, W. 2015. Fuel treatment effects on spatial variability of surface fuels in ponderosa pine forest of the southern Rocky Mountains. 6th International Fire Ecology and Management Congress: Advancing Ecology in Fire Management. Nov 16-20, San Antonio, TX.
9. Dickinson Y, Tinkham W, Hoffman CM, Battaglia M, Underhill, J. 2015. Rocky Mountain Dry Mixed Confer Restoration: Visual Guide to Silvicultural Prescription Development. Society of American Foresters National Convention, Nov 3-7, Baton Rouge, LA.
10. Battaglia M, Hoffman CM, Ziegler J, Mell W. 2015. Restoration and Fire Behavior in Ponderosa Pine Dominated Forest. Society of American Foresters National Convention, Nov 3-7, Baton Rouge, LA.
11. Ziegler, J. 2015. Beyond traditional forest sampling: Techniques for measuring structural heterogeneity. Boulder County Parks & Open Spaces. Oct 8. Longmont, CO.
12. Hoffman, C.M., Battaglia, M., Ziegler, J., Mell, W. 2015. Fire behavior and fuel treatment effectiveness: Theory and current knowledge. Ignite Talk Sponsored by the Colorado Forest Restoration Institute and the Southern Rockies Fire Science Network, November 2nd, Boulder, CO. **(Invited)**
13. Hoffman, C.M. 2015. Fuel complex characterization and numerical modeling in support of improved forest operations planning: An overview of ongoing research at the CSU fire science laboratory. Wildland fire, air quality and health workshop. August 12-13, Longmont, CO. **(Invited)**
14. Hoffman, C.M., Ziegler, J.Z., Battaglia, M., and Mell, W. 2015. Characterizing heterogeneous fuels and simulating fire behavior following forest treatments in dry-forest types. 3rd Annual NIST/USFS WUI Seminar Series. January 6. Gaithersburg, MD. **(Invited)**
15. Hoffman, C.M., Linn, R.R., Mell, W.E., Sieg, C.H., Pimont, F., Ziegler, J. 2014. Evaluating Crown Fire Rate of Spread from Physics Based Simulations to Field Data. VII International Conference on Forest Fire Research. November 14-21. Coimbra, Portugal.
16. Vakili, E., Hoffman, C.M., Keane, R., Dickinson, Y., Rocca M. 2014. Spatial Variability of Surface Fuels in Dry Ponderosa Pine Forests. Society of American Foresters National Convention, October 8-11, Salt Lake City, Utah.
17. Hoffman, C.M., Battaglia, M., Dickinson, Y., Ziegler, J., Vakili, E., Mell, W. 2014. Evaluation of forest management objectives: creating spatially heterogeneous structure and reducing fire behavior. Northern Front Range Forest Health Working Group Annual Meeting. July 8th. Boulder, CO. **(Invited)**
18. Ziegler, J.P., Hoffman, C.M., Battaglia, M., Mell, W.E. 2014. Evaluating restoration treatment objectives: creating spatially heterogeneous structure and reducing fire behavior. Large Wildland Fires: Social, Political and Ecological Effects Conference. May 19-23. Missoula, MT.
19. Hoffman, C.M., and Dickinson, Y. 2014. Evaluating forest restoration treatments in Colorado. Colorado State Forest Service Annual Meeting, May 6, Fort Collins, CO. **(Invited)**
20. Ziegler, J.P., Hoffman, C.M., Battaglia, M. 2014. Spatially explicit evaluation of restoration thinning: Structural complexity enhancement and fire behavior mitigation. Department of Forest and Rangeland Stewardship Departmental Seminar, Warner Collage of Natural Resources, Colorado State University. April 1, Fort Collins, CO. **(Invited)**
21. Hoffman, C.M., Ziegler, J.P., Battaglia, M. 2014. Evaluating spatial heterogeneous fuels complexes created through restoration treatments on fire behavior using WFDS. NIST WUI Workshop. January 6, Gaithersburg, MD **(Invited)**

22. Ziegler, J., Hoffman, C.M., Battaglia, M. 2012. Evaluating fuel treatment effects on structure and spatial pattern in fire-frequent forests of Colorado. 5th International Fire Ecology and Management Congress. December 3-7. Portland, OR.

E. Poster Presentations

1. Vakili, E., Hoffman, C.M., Keane, R., Dickinson, Y., Rocca, M. 2014. Evaluating fuel treatment effects on the spatial scale of surface fuels in front range ponderosa pine forests. Large Wildland Fires: Social, Political and Ecological Effects Conference. May 19-23. Missoula, MT. (2nd place in student poster competition)
2. Hoffman, C.M., Mell, W.E., Bova, A.S., Maranghides, A., Simeoni, A., Mueller, E., Forney, G. 2014. Development and Evaluation of the physics-based Wildland-Urban Interface Fire Dynamics Simulator. Large Wildland Fires: Social, Political and Ecological Effects Conference. May 19-23. Missoula, MT.
3. Vakili, E., Hoffman, C.M., Keane, R., Dickinson, Y., Rocca, M. 2014. Evaluating fuel treatment effects on the spatial scale of surface fuels in front range ponderosa pine forests. 20th Front Range Student Ecology Symposium, February 18-19. Fort Collins, Colorado.
4. Bova, T., Mell, W., Hoffman, C.M., Weise, D., Mahalingham, S., Simeoni, A., Mueller, E. 2013. Development and evaluation of the physics based wildland-urban interface fire dynamics simulator. 4th Fire Behavior and Fuels Conference. February 18-22. Raleigh, NC.
5. Ziegler, J.P., Hoffman C.M., Battaglia, M.A. 2013.Investigating heterogeneous fuels and fire behavior in the Uncompahgre Mesas Project. Uncompahgre Plateau Collaborative Forest Landscape Restoration Stakeholder Meeting. March 1. Montrose, CO.
6. Ziegler, J.P., Hoffman C.M., Battaglia, M.A. 2013. Evaluating fuel treatment effects on structural heterogeneity in fire-frequent forests of Colorado. 19th Annual Front Range Student Ecology Symposium. February 18-19. Fort Collins, CO
7. Ziegler, J.P., Hoffman C.M., Battaglia, M.A. 2012. Investigating heterogeneous fuels and fire behavior in the Uncompahgre Mesas project. Uncompahgre Partnership Annual Meeting, March 21, Montrose, CO.
8. Bova, T., Mell, W., Hoffman, C.M., Weise, D., Mahalingham, S., Simeoni, A., Mueller, E. 2012. Development and evaluation of the physics based wildland-urban interface fire dynamics simulator. 5th International Fire Ecology and Management Congress. December 3-7. Portland, OR.