Stover and Keyes, J Biodivers Manage Forestry 2016, 5:2
http://dx.doi.org/10.4172/2327-4417.1000158

Journal of Biodiversity Management & Forestry

Research Article

A SCITECHNOL JOURNAL

Forest Fuels and Wildfire Hazard in Two Fire-Excluded Old-Growth Ponderosa Pine Stands: Contrasting Stand-Average Calculations with Measures of Spatial Heterogeneity

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Abstract

Forest managers in the northern Rocky Mountains are charged with conducting restoration treatments that will enhance the resilience of fire-dependent old-growth stands, and reduce their susceptibility to stand-replacing fire. Yet, stand-average metrics that are routinely used for prescription development poorly characterize the typically heterogeneous stand structure and forest fuels that are associated with old-growth forests. We conducted a proof-of-concept study to compare stand-average calculations of forest fuels and associated wildfire hazard to the within-stand spatial heterogeneity of those properties. We analyzed two fire-excluded old-growth ponderosa pine stands in western Montana, encompassing the moisture gradient across which the forest type occurs in this region. At one site, we also analyzed the effect of a restoration prescription to reduce fuels and abate wildfire hazards. Fixed-area plot sample data were analyzed to describe within-stand heterogeneity by analyzing the distributions of current and anticipated post-treatment plot conditions, and contrasting these with conventional stand-average calculations. Distributions of overstory structures, fuel loads, and modeled fire behaviors were typically non-normal, skewed, and varied widely. Generally, stand-average calculations poorly represented the range of within-stand conditions. The study's findings highlight the heterogeneity of stand structure, forest fuels, and wildfire fire hazard in old-growth ponderosa pine stands, and reveal the shortcomings of analytical methods that simplify spatially heterogeneous stand data.

Keywords

Ecological restoration; Late-successional forest; Silviculture; Rocky Mountains; Fire ecology; Canopy bulk density; Canopy base height; Torching index; Crowning index

Introduction

In the western United States, old-growth stands dominated by ponderosa pine (*Pinus ponderosa* Laws.) have been in a state of decline for decades [1]. Forest and fire management practices have substantially altered fire regimes, allowing uncharacteristic accumulations of shade-tolerant and more fire-sensitive tree species [2-7]. Such conditions predispose old-growth stands in the interior northwestern United States to wildfire intensities and severities that are atypical of historic behaviors [1].

To restore resilience to fire-excluded forests, silvicultural restoration treatments are frequently proposed and implemented [8-12]. They have generally been successful in remediating fire behavior and severity in managed and second-growth ponderosa pine stands [13-15]. Less frequently are they employed in old-growth stands. Yet, restoration treatments can promote structures typical of historic, fire-maintained systems for old-growth stands that have been subjected to decades of fire exclusion [16,17].

Accurately characterizing the fuel loads and potential fire hazard of fire-excluded ponderosa pine stands, and quantitatively communicating the value of restoration treatments, is an ongoing challenge for forest and fire managers in this region. Stand metrics used to analyze and convey fire hazard are customarily calculated at the whole-stand level, which frequently blur natural within-stand heterogeneity in forest fuel loads, including both surface and aerial fuels [18]. Fire behavior is not determined by stand-average values, but rather by that finer-scale spatial variation in the fuel complex that occurs within stands [19-21].

In this study, we conducted a proof-of-concept study to compare stand-average calculations of forest fuels and associated wildfire hazard to the within-stand spatial heterogeneity of those properties. We used contemporary wildland fire models to analyze stand structure, fuels, and crown fire hazard in two old-growth ponderosa pine stands of the northern Rocky Mountains. The sites represent the ends of the moisture spectrum across which ponderosa pine occurs in western Montana. Both stands are classified as 'old-growth' under the definitions established by Green et al. [22], which are the standards used by the United States Forest Service for old-growth forest identification in western Montana and northern Idaho. At one of the sites, we also evaluated a restoration prescription for its effectiveness in reducing crown fire hazard. Treatment goals were to reduce the hazard of stand-replacing wildfire and to restore health and dominance of old-growth ponderosa pine and western larch (*Larixoccidentalis* Nutt.) trees [23].

In addition to the conventional method wherein stand-average metrics are calculated to represent overall stand conditions (ground and surface fuel loads, canopy base height, canopy bulk density) and wildfire hazards (fire type, surface fire flame length and spread rate, we analyzed the within-stand fuel load variability via plot-by-plot analysis of distributions using common normality descriptors and tests. By characterizing fuels and stand structures in two representative old-growth ponderosa pine stands, the purpose of the study was to better understand the within-stand variability in those properties, and to help guide analytical practices contributing to their restoration.

Methods

Study areas

The Boulder Creek Research Natural Area (Boulder Creek -

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Received: January 18, 2016 **Accepted:** March 16, 2016 **Published:** March 26, 2016

doi:http://dx.doi.org/10.4172/2327-4417.1000158

BC) study site consists of 41 acres (17 ha) within a 200-acre (81-ha) treatment unit in the Bitterroot National Forest near Conner, Ravalli County, Montana, USA. The site is on a southwest aspect with a mean slope of 60% at 46°N latitude, between 4600 ft and 5600 ft (1402 to 1707 m) in elevation. Boulder Creek's mean annual precipitation is 15.8 in (401 mm), with yearly mean January minimum and July maximum temperatures of 18.1°F (-7.7°C) and 84.2°F (29°C) (Darby, MT NWS Station #242221) [24].The Meadow Smith Old-Growth Restoration Project (Meadow Smith - MS) study site is a 76-acre (31-ha) unit in the Flathead National Forest near Condon, Missoula County, Montana, USA. The MS site is within a broad glacial valley with gently undulating topography, at 47.5°N latitude, between 3600 ft and 3700 ft (1097 to 1128 m) in elevation. Meadow Smith's mean annual precipitation is 28.7 in (729 mm), with yearly mean January minimum and July maximum temperatures of 15.7°F (-9.1°C)and 81.0°F (27.2°C)(Swan Lake, MT NWS Station #248087) [24].

At Boulder Creek the overstory was primarily composed of ponderosa pine, with high densities of small diameter Douglas-fir (*Pseudotsugamenziesii*var. *glauca* (Beissn.) Franco) occupying the mid-canopy and understory (Figure 1). Meadow Smith consisted of an overstory component of mainly relict ponderosa pine and western larch, and a mid-canopy and understory component of Douglas-fir, subalpine fir (*Abieslasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Piceaengelmannii* Parry ex. Engelm.), lodgepole pine (*Pinuscontórta* Dougl. var. *latifolia* Engelm.), and grand fir (*Abiesgrandis* (Dougl.) Lindl.) (Figure 1). Stand densities differed between Boulder Creek (382 trees ac^{-1}, 139 ft^2 ac^{-1} basal area) and Meadow Smith (295 trees ac^{-1}, 147 ft^2 ac^{-1} basal area).

At the time of the study, restoration treatment planning was incomplete at the Boulder Creek study area. At Meadow Smith, however, restoration treatment planning was complete and the stand was marked in preparation for implementation of the prescribed treatment. The prescription consisted of a low thinning to a residual basal area of 80 ft^2 ac^{-1}, with a focus on removing understory and mid-story trees (ladder fuels) and retaining the stand's component of large ponderosa pines and western larches.

Data collection

In 2008 and 2009, monitoring plot networks were installed at Boulder Creek (40 plots) and Meadow Smith (37 plots). Sampling protocols were dictated by the USFS Region 1 common stand exam manual, with plot sizes and transect lengths determined by USFS planning staff from pilot data. The plot design consisted of nested circular tree plots of 3 sizes: 1/4-ac or 1/5-ac (depending on within-stand variability from pilot data) for trees 19 in dbh and above, 1/24-ac for trees 3.0 - 18.9 in dbh, and 1/300-ac for trees ≤ 2.9 in dbh. Species and diameter were recorded for each tree. One tree per each 5-in diameter class per species was sampled for age, total height, and height to live crown. Within the 1/24-acre plot, percent cover (by ocular estimation) and average height were measured for woody shrubs and herbaceous vegetation.

Downed woody fuels were sampled via two perpendicular 50-ft line intercept transects established at each plot according to USFS FIREMON protocols [25]. On each transect, 1000-hr time-lag (≥ 3 in) fuels were individually measured for diameter and decay class along the full 50 ft length, 100-hr (1-3 in) fuels were tallied along the last 15 ft from plot center, and 1-hr (< 1/4 in) and 10-hr (1/4 – 1 in) fuels were tallied for the last 6 ft. Litter/duff depths were taken at transect midpoints and endpoints. Percent slope of each transect was measured.

Analysis of stand structure and forest fuels

Stand descriptor metrics were processed using the Forest Vegetation Simulator (FVS) [26]. Only live trees above 1 in. dbh were used in the analysis. Descriptive statistics included mean, median, min, max and coefficient of variation (CV). Structure metrics included stem density (trees acre^{-1}), basal area (ft^2 ac^{-1}), and quadratic mean diameter (QMD). Species composition (live trees) was calculated in terms of both trees ac^{-1} and basal area (ft^2 ac^{-1}).

Ground and surface fuels data were processed using the FIREMON computer software to calculate fuel loads in tons ac^{-1} (t ac^{-1}) for duff, litter, 1-hr, 10-hr, 100-hr, 1000-hr, live herbaceous fuels, and live shrub fuels [25]. Canopy fuels were calculated from plot tree data using FVS-FFE, which utilizes all geometric equations and adjustment factors for Brown's equations in order to calculate canopy bulk density (CBD) and canopy base height (CBH) from measured tree attributes [27,28].

To generate within-stand distributions, descriptive metrics were calculated at the plot level. For stand structure metrics, individual FVS tree list files and stand files were created for each plot. For fuels, plot-level descriptive statistics were calculated for key fuel attributes, including ground and surface fuel loads, CBD, and CBH. From these plot values, frequency distributions were constructed with subjectively predetermined class widths. Range, kurtosis, and skewness were calculated to describe the distributions, and Shapiro-Wilk tests of normality were applied to each descriptive statistic (α = 0.05) [29].

Fire behavior modeling

We used the NEXUS computer software to simulate surface fire behavior under 95th percentile weather conditions and to identify critical thresholds for crown fire types to occur [19,30]. We developed custom surface fuel models based on stand level (conventional method) or plot level (distributional method) 1-hr, 10-hr, and 100-hr, live herbaceous fuel loads and live shrub fuel loads. We initialized fuel models with the Timber Understory model 1 (TU1) for Boulder Creek, and TU3 for Meadow Smith [31]. Litter loads were added to the 1-hr fuels for modeling purposes (M. Harrington, 2010 personal communication). We used published packing ratios from standard models and a standard particle density (32 lbs ft^{-3}) with the custom fuel loads to determine fuel bed depth [31].

Wildfire scenario inputs included 95th percentile local fire weather and fuel moisture contents, utilizing data from remote weather

Figure 1: Stand conditions on the xeric, steep slopes of the Boulder Creek Research Natural Area (left), andthe mesic, gentle topography of the Meadow Smith restoration project area (right))(Montana, USA). Photos by Kyle Stover.

doi:http://dx.doi.org/10.4172/2327-4417.1000158

stations nearest to each site. For Boulder Creek, data from the Little Rock Creek Remote Automatic Weather Station (RAWS) (Station #242914, elev. 5507 ft, lat. 46.038, long. -114.262) was used due to its proximity and similar elevation. Meadow Smith fire weather was assigned from the USFS Condon Work Center RAWS (Station # 241502, elev. 3684 ft, lat. 47.5361, long. -113.7172) approximately 3 miles away. The Fire Family Plus software was used to calculate the 95th percentiles of each attribute to represent locally severe wildfire conditions (Table 1) [32]. Mid-flame windspeed adjustment factors were determined in FVS-FFE from the tree list data. Wind direction was uniformly set at 90° cross slope for Boulder Creek and upslope (0°) for Meadow Smith, based on general prevailing wind patterns, local topography, and similar plot aspect throughout each stand [33].

Windspeed is a critical determinant of fire behavior; yet, it is inherently variable and therefore difficult to characterize in wildfire hazard analysis. Short-duration wind gusts (rather than prevailing windspeeds) are powerful determinants of fire behavior, so use of normal windspeeds in hazard analysis can result in overly-conservative estimates of fire behavior [20,34]. Therefore, to accommodate high wind gusts and events, we also analyzed fire behaviors using 20-ft windspeeds at double (38 mi hr^{-1}) that of Boulder Creek's 95th percentile, and at double (16 mi hr^{-1}) and triple (24 mi hr^{-1}) Meadow Smith's 95th percentile (tripling was modeled because the 95th percentile was a notably low 8 mi hr^{-1}).

Surface fire flame length (ft) and rate of spread (chains hr^{-1} or 'ch hr^{-1}') were modeled using NEXUS with the values described above utilized as input assignments. Foliar moisture content was set at 90% for Boulder Creek and 100% for Meadow Smith based on the range of published Douglas-fir foliar moisture contents and climatic differences between the two study areas [35,36]. Canopy bulk density (CBD; lbs ac^{-1} ft^{-1}) and canopy base height (CBH; ft) calculations from FVS-FFE were used with surface fuel and weather scenario inputs to determine the modeled fire behavior type (surface fire, conditional surface fire, passive crown fire, or active crown fire) as well as Torching Index (TI) and Crowning Index (CI). Torching Index is the threshold 20-ft windspeed (mi hr^{-1}) above which crown ignition occurs and surface fire transitions to passive crown fire; Crowning Index is the threshold above which an active crown fire can spread through the canopy.

For the conventional method of analysis, we utilized one stand-average custom surface fuel model for each site. For the distributional method, we characterized each plot's potential fire behavior with custom fuel models developed separately from each plot's measured surface fuel load. Similarly, windspeed adjustment factors, canopy bulk densities, and canopy base heights were assigned from FVS-FFE via each plot's measured tree data; each plot's measured slope was also utilized. Surface fire flame length, surface fire rate of spread, Torching Index, and Crowning Index were modeled for each plot. Each modeled output per plot was sorted into pre-determined classes and expressed as a frequency distribution. Class widths were determined subjectively by the range and observed variation of each fire behavior and crown fire hazard metric. For each parameter, mean, median, min, max, CV, kurtosis, skewness, and Shapiro-Wilk test of normality p-values were calculated.

Evaluation of restoration treatment effects

Because restoration treatments were not yet completed at the time of this study, their effects at Meadow Smith were simulated by removing from the tree lists those trees designated for harvest. Both the conventional and distributional methods of analysis were applied to stand structure, canopy fuels, and potential fire behavior. The ability to model activity surface fuels, down and woody fuel decomposition, and shrub responses associated with treatment are limited and carry additional modeling assumptions. In order to reduce assumptions we only evaluated structural changes to the canopy and held surface fuel loads constant at current conditions. Surface fuel loads do change as a result of treatment but in ways that very greatly by logging system specifics. The logging method was as yet undefined at the time of this study; lacking any quantitative basis for altering surface fuel loads we instead elected to maintain them as constant rather than select numbers arbitrarily. Similarly, weather input assumptions and foliar moisture contents were unchanged from the pretreatment scenario (with the exception of windspeed adjustment factors, which were calculated by FVS-FFE based on the simulated post-treatment tree lists). We used NEXUS to assess the change in Torching Index and Crowning Index compared to current conditions.

Results

Stand structure

Boulder Creek stem density averaged 382 trees ac^{-1}, with 139 ft^2 ac^{-1} of basal area (Table 2). Stand QMD was 11.3 inches. Species composition was primarily a two species mix of Douglas-fir (64% trees ac^{-1}) and ponderosa pine (36% trees ac^{-1}). However, ponderosa pine dominated the basal area composition (68%) due to its larger average size (7.3 in QMD, vs. 4.8 in QMD for Douglas-fir). Meadow Smith stems density averaged 295 trees ac^{-1}, with 147 ft^2 ac^{-1} basal area, and QMD was 10.4 inches. MS species composition was mixed, consisting of Douglas-fir (50% trees ac^{-1}), true firs and Engelmann spruce (26% trees ac^{-1}), western larch (10%), lodgepole pine (9% trees ac^{-1}), and ponderosa pine (5% trees ac^{-1}). Basal area composition was composed of Douglas-fir (38%), western larch (21%), ponderosa pine (20%), true firs and Engelmann spruce (12%), and lodgepole pine (9%). At both study sites, trees ac^{-1} was the most variable of all structural metrics based on differences between means and medians, and exhibited the highest CV (1.11for BC, and 0.55 for MS; Table 2).

Distributions of stem density at both sites were non-normal (Table 2). At Boulder Creek, plots ranged widely (24 to 2,340 trees ac^{-1}); the mean was skewed high (skewness value = 2.75). Meadow Smith's density range was smaller (73 to 843 trees ac^{-1}) with a mode of 175 trees ac^{-1} (27% of plots). Basal areas were normally distributed at both sites (MS p-value = 0.050, BC p-value = 0.870). They ranged 28 to 258 ft^2 ac^{-1}at Boulder Creek, and 51 to 310 ft^2 ac^{-1} at Meadow Smith. Distributions of plot QMD were non-normal for Boulder Creek (p-value = 0.020) and ranged 2.9 to 26.7 in. Meadow Smith's

Table 1: 95th percentile fire weather and fuel moisture conditions. Weather stations: Boulder Creek - Little Rock Creek RAWS #242914; and Meadow Smith - Condon RAWS #241502. Date range: 1 May - 31 Oct, 2003-2009.

Attribute	Boulder Creek	Meadow Smith
Temp max (°F)	86	95
Wind (mi hr^{-1})	19	8
Woody fuel moisture (%)	70	70
Herb fuel moisture (%)	30	30
Dead fuel moisture (%)		
1-hr	3	3
10-hr	4	4
100-hr	6	9
1000-hr	8	11

QMD distribution was normal (p-value = 0.661) with a range of 4.8 to 16.5 inches.

Fuel loads

Total surface and ground fuel loads averaged 24.1 t ac^{-1} at Boulder Creek and 38.3 t ac^{-1} at Meadow Smith, primarily consisting of dead fuels (Table 3). 1000-hr fuels represented the greatest share of the average loads at both BC (36%, 8.66 t ac^{-1}) and MS (44%, 17.00 t ac^{-1}). Averages differed substantially from the median loads, particularly in the 1000-hr class, which had the greatest range (BC 0 to 68 t ac^{-1}, MS 0 to 77 t ac^{-1}). Considering median loads, duff comprised the greatest share, accounting for 32% (5.22 t ac^{-1}) of the load at BC and 41% (14.00 t ac^{-1}) at MS. High variance was not unique to the 1000-hr fuels class but was common to all fuel classes, as exhibited by high coefficients of variation (range 0.46 to 3.23). Live herbaceous and shrub fuel loads averaged 0.27 t ac^{-1} for Boulder Creek and 1.27 t ac^{-1} for Meadow Smith, and were dominated by the live shrub loads (Table 3). Median live herbaceous and shrub fuel loads were 0.14 t ac^{-1} for BC, and 0.82 t ac^{-1} for MS.

Surface fuel distributions were non-normal for nearly all fuel types and classes (except BC 1-hr, MS litter, and MS total surface fuels), based on visual inspection, kurtosis and skewness values, and the results of the Shapiro-Wilk tests (Table 3). In all the dead surface fuel loads, distributions were skewed right (positive skewness values as high as 2.58), a result of plots with outlying loads considerably higher than the rest of the distribution (Table 3). Duff loads at Boulder Creek ranged 0 to 55 t ac^{-1}, but were clustered (94% of plots) in the smallest three classes below 15.0 t ac^{-1}. At Meadow Smith the distribution ranged 2.5 to 43.7 t ac^{-1}, with a 12.5 t ac^{-1} mode (5 t ac^{-1} class widths) accounting for 23% of plots. In the litter load, BC's distribution range was 0 to 10.5 t ac^{-1} and was platykurtic (i.e. distributed broadly or 'flat'), as exhibited by a kurtosis value of -0.92. The average 4.28 t ac^{-1}

Table 2: Stand structure metrics at Boulder Creek and Meadow Smith: stem density (trs ac^{-1}), basal area (ft^2 ac^{-1}), and quadratic mean diameter (in). 'Pre-trt' and 'Post-trt' refer to stand conditions immediately preceding and following (respectively) restoration treatment. P-values are from Shapiro-Wilk tests of normality.

Study site	Statistic	Pre trs ac^{-1}	Post trs ac^{-1}	Pre BA ft^{2}ac^{-1}	Post BA ft^{2}ac^{-1}	Pre QMD in	Post QMD in
Boulder Creek	mean	382	-	139	-	11.3	-
	median	216	-	127	-	10.5	-
	min	24	-	28	-	2.9	-
	max	2340	-	258	-	26.7	-
	CV	1.11	-	0.39	-	0.50	-
	skewness	2.75	-	0.21	-	0.89	-
	kurtosis	9.19	-	-0.34	-	1.09	-
	p-value	<0.001	-	0.870	-	0.020	-
Meadow Smith	mean	295	43	147	80	10.4	19.0
	median	246	31	132	73	10.4	19.5
	min	73	13	51	2	4.8	4.1
	max	843	165	310	286	16.5	29.8
	CV	0.55	0.80	0.35	0.70	0.28	0.28
	skewness	1.42	2.13	0.96	1.75	0.20	-0.57
	kurtosis	2.48	4.74	1.73	4.41	-0.32	0.46
	p-value	0.001	<0.001	0.050	<0.001	0.661	0.593

Table 3: Attributes of ground and surface fuel loads (t ac^{-1}) at Boulder Creek and Meadow Smith. P-values are from Shapiro-Wilk tests of normality.

		Ground Fuels	Dead Surface Fuels					Live Surface Fuels			Ground+ Surface
Study site	Statistic	Duff	Litter	1-hr	10-hr	100-hr	1000-hr	Herb	Shrub	Herb+ Shrub	Total
Boulder Creek	mean	8.47	4.28	0.18	1.2	0.99	8.66	0	0.27	0.27	24.06
	median	5.22	3.78	0.16	1.09	0.87	2.04	0	0.14	0.14	16.26
	min	0	0	0.02	0.16	0	0	0	0.01	0.01	2.56
	max	54.53	10.54	0.45	5.19	3.7	68.02	0.02	1.47	1.47	92.28
	CV	1.25	0.68	0.6	0.79	0.98	1.87	3.23	1.14	1.13	0.86
	Kurtosis	8.98	-0.92	-0.41	7.05	0.57	6.07	12.57	5.56	5.56	2.19
	Skewness	2.7	0.38	0.61	2.08	1	2.58	3.48	2.24	2.24	1.61
	P-value	<0.001	0.052	0.071	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Meadow Smith	mean	15.85	1.59	0.24	0.9	1.45	17	0.03	1.24	1.27	38.31
	median	14	1.7	0.21	0.61	1.45	11.47	0.01	0.81	0.82	34.17
	min	2.5	0	0	0	0	0	0	0.09	0.11	7.94
	max	43.7	4.5	0.95	2.28	5.81	76.6	0.33	6.85	6.87	90.13
	CV	0.55	0.59	0.81	0.77	0.84	0.98	2.11	1.2	1.17	0.46
	Kurtosis	1.6	1.49	3.83	-1.04	3.11	3.25	22.13	6.21	6.25	1.32
	Skewness	1.1	0.69	1.7	0.54	1.37	1.57	4.43	2.51	2.51	0.88
	P-value	0.019	0.133	<0.001	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	0.069

doi:http://dx.doi.org/10.4172/2327-4417.1000158

fell near the middle of this distribution (4.5 t ac^{-1} class). At MS, the distribution of litter loads had a mode of 1.5 t ac^{-1} (45% of plots). 1000-hr fuels had roughly 10% of plots at both study sites in classes in excess of 35 t ac^{-1}, compared to the 8.66 t ac^{-1} average at BC and the 17.00 t ac^{-1} average at MS, though the CV's for 1000-hr fuel loads were the highest of all the dead fuels (1.74 at BC, and 0.98 for MS). Live herbaceous and shrub fuel loads were concentrated in the lowest class (0.25 t ac^{-1})for 88% of plots for BC. MS's mode was 0.75 t ac^{-1} (41% of plots). The range was much larger at MS (range 0.09 to 6.85 t ac^{-1}) than at BC (range 0.01 to 1.47 t ac^{-1}).

Canopy bulk density averaged 256.9 lbs ac^{-1} ft^{-1} at Boulder Creek and 247.5 lbs ac^{-1} ft^{-1} at Meadow Smith. Canopy base heights were 6 ft at BC and 12 ft at MS. Coefficients of variation (range 0.64 to 0.77) were moderate compared to surface fuels. Canopy bulk density distributions and mode/median values were similar between sites, although distributions were non-normal (Figure 2). However, skewness was high for both sites (skewness values of 2.2 at BC, and 2.51 at MS) as result of plot CBD in excess of 500 lbs ac^{-1} ft^{-1} class and greater (10% of plots at BC, 8% of plots at MS); three percent of plots at both sites had loads exceeding 950 lbs ac^{-1} ft^{-1}. Canopy base height distributions at both sites lacked central tendency (kurtosis of -0.41 and -0.68 for BC and MS respectively) and were non-normal (p-values of 0.0002 and 0.0078 respectively) (Figure 2). Approximately one third of each site's CBH distribution was at the low end of the range, including the 3 ft class at BC (33% of plots; class width is 2 ft) and the 1 ft class at MS (30% of plots). Meadow Smith's CBH average was 12 ft, though only 8% of plots actually fell in that class.

Modeled fire behavior

Modeled surface fire at 95th percentile weather conditions (Table 1) and site-average fuel loads (Table 3) resulted in surface fire projections of a 6 ft flame length and a 15 ch hr^{-1} spread rate for Boulder Creek, and a 3 ft flame length and 3 ch hr^{-1} spread rate for Meadow Smith (Table 4). At BC, the Torching Index was 14 mi hr^{-1} and the Crowning Index was 27 mi hr^{-1}; at MS the Torching and Crowning Indexes were 72 mi hr^{-1} and 28 mi hr^{-1}, respectively. At the 95th percentile weather conditions, stand-average projections are for passive crown fire behavior at BC and surface fire at MS. At BC, windspeed at double (24 mi hr^{-1}) the 95th percentile conditions indicated an active crown fire type. At MS, windspeeds at double (16 mi hr^{-1}) and triple (24 mi hr^{-1}) the 95th percentile conditions indicated surface fire and passive crown fire types, respectively.

Distributions of modeled surface fire flame lengths at BC were normal according to the Shapiro-Wilk test (p-value = 0.083; Table 4). Nearly a third of the distribution (30%) had high flame lengths in excess of 8 ft (definition of high-low referenced from Scott and Burgan fuel models) (Figure3a) [31]. Meadow Smith's flame length distribution was non-normal (p-value = 0.001). Distributions were in accordance with the litter load frequency distribution (litter was an important contributing fine fuel model input; data not shown). Surface fire spread rate distributions were non-normal at both sites (p-values < 0.001; Figure 3b). Boulder Creek's range was 1.1 to 33.5 ch hr^{-1} (Table 4) though 27% of plots produced rates of spread that are relatively high (above 20 ch hr^{-1}) [31]. Meadow Smith's range was less (0.9 to 10.7 ch hr^{-1}) and was low- to medium-intensity fire behavior.

Torching Index distributions at both sites demonstrated no evidence of normality from visual inspection (Figure 4a), kurtosis, skewness, or the Shapiro-Wilk tests (p-values < 0.0001). Crowning Index distributions at both sites were skewed right (skewness = 1.4 and 0.5 respectively) (Figure 4b). Meadow Smith Crowning Index was one of the few distributions observed that showed moderate evidence of normality (p-value = 0.54).

Conventional analysis at Boulder Creek had suggested the potential for passive crown fire. This proved to be the most common fire type in our distributional (plot-by-plot) method of analysis as well (63% of plots) (Table 5). However, a large portion (25% of plots) revealed the potential for active crown fire. Conventional analysis at Meadow Smith had indicated surface fire. Using the distributional method, just 76% of plots modeled surface fire; the remainder 24% exhibited potential for passive crown fire (Table 5). At BC, doubling windspeeds resulted in 13% of plots shifting from surface fire to conditional crown fire. At MS, doubling and tripling windspeeds resulted in modeled conditional crown fire (5% and 38% respectively) and active crown fire (5% and 32% respectively) (Table 5).

Restoration treatment effect

As marked for cutting, the restoration thinning at Meadow Smith would result in a post-treatment basal area averaging 79.5 ft^2 ac^{-1}, effectively meeting the prescription's target residual basal area of 80 ft^2 ac^{-1} (Table 2). The thinning would reduce average trees ac^{-1} by 86% (from 295 to 43 trees ac^{-1}), assuming 100% cutting efficiency and no unintended losses to residual trees from either logging or burning. By attrition, this would elevate stand QMD by 56% (from 10.4 in to 19.0 in), and increase the dominance of western larch (10% to 41% trees ac^{-1}), and ponderosa pine (5% to 29% trees ac^{-1}). Conversely, species composition of fire-sensitive species including Douglas-fir (50% to 22% trees ac^{-1}), and true fir and Engelmann spruce (26% to 1% trees ac^{-1}) would be reduced. The component of lodgepole pine would decrease as well (9% to 6% trees ac^{-1}).

The distributional analysis of stand structure revealed that the stem density and basal area distributions would be non-normal following the treatment (p-value < 0.0001 and p-value = 0.0003, respectively). Meadow Smith basal area is normal prior to treatment (Table 2). All plots experience stem density reduction to a post-treatment range of 13 to 165 trees ac^{-1} with a mode class of 25 trees ac^{-1} (80% of plots). The post-treatment basal area distribution ranges from 2 to 286 ft^2 ac^{-1} concentrated below the 90 ft^2 ac^{-1} class (65% of plots). The treatment increases plot QMD to a post-treatment range of 4.1 to 29.8 inches and remains normal.

The thinning would reduce stand-average canopy bulk density by 67% (from 157.7 lbs ac^{-1} ft^{-1} to 51.8 lbs ac^{-1} ft^{-1}) and raise the canopy base height more than 6-fold (from 7 ft to 43 ft). This translates to a substantial increase in the Torching Index from 19 mi hr^{-1} to 120 mi hr^{-1}, and Crowning Index from 33 mi hr^{-1} to 72 mi hr^{-1}. Even at windspeeds up to three times the 95th percentile wind conditions (24

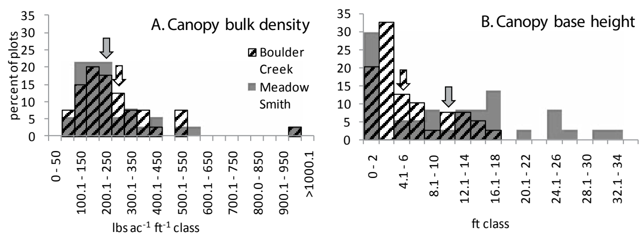

Figure 2: Distributions of canopy fuel attributes at Boulder Creek and Meadow Smith (percent of plots within each class). Canopy bulk density (A) in lbs ac^{-1}ft^{-1}; canopy base height in ft. Arrows denote the class encompassing the stand average.

Table 4: Attributes of modeled fire behaviors. Flame length (FL) in ft; Rate of spread (ROS) in chains hr^{-1}; Torching Index (TI) and Crowning Index (CI) in mi hr^{-1}. P-values are from Shapiro-Wilk tests of normality.

Study site	statistic	FL	ROS	TI	CI
Boulder Creek	mean	6.0	14.5	13.9	27.4
	median	5.8	14.6	0.0	25.7
	min	0.7	1.1	0.0	8.3
	max	12.5	33.5	177	69.4
	CV	0.6	0.7	3	0.5
	Kurtosis	-1.0	-0.9	8.7	2.8
	Skewness	0.2	0.3	3.1	1.4
	P-value	0.083	0.031	<0.001	0.002
Meadow Smith	mean	2.8	3.2	72.1	28
	median	2.5	2.6	34.5	27.3
	min	1.1	0.9	0	8.2
	max	7.9	10.7	355.3	54.6
	CV	0.5	0.7	1.3	0.4
	Kurtosis	2.8	3.3	3.0	0.5
	Skewness	1.5	1.9	1.9	0.5
	P-value	0.001	<0.001	<0.001	0.540

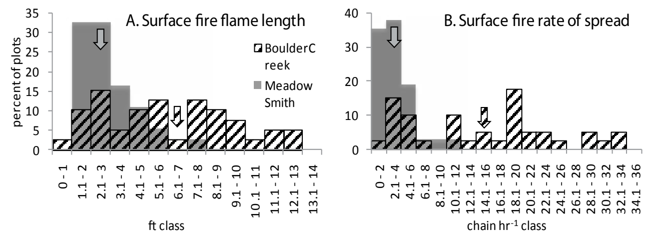

Figure 3: Distributions of within-stand modeled surface fire behaviors at Boulder Creek and Meadow Smith (percent of plots within each class). Flame length (A) in ft; rate of spread (B) in chains hr^{-1}. Arrows denote the class encompassing the stand average.

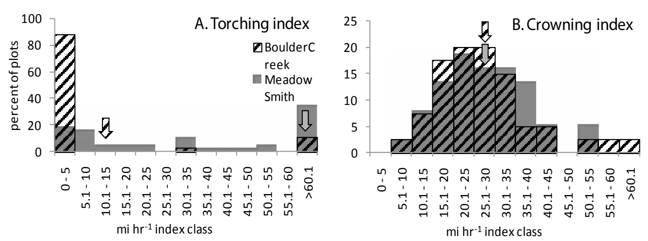

Figure 4: Distributions of within-stand modeled Torching Index (A) and Crowning Index (B) at Boulder Creek and Meadow Smith (percent of plots within each class). Indexes refer to the threshold 20-ft windspeed that ignites a passive crown fire (Torching Index) or facilitates active crown fire spread (Crowning Index). Arrows denote the class encompassing the stand average.

mi hr^{-1}), the predicted MS fire type is surface fire following treatment (Table 5).

The distributional analysis of canopy fuels shows a post-treatment Torching Index above 60 mi hr^{-1} for 86% of plots (Figure 5a); we interpret TI values above 60 mi hr^{-1} as unlikely to see conditions that will initiate crown fire behavior. The remaining 14% of plots would be more susceptible to torching, at 30.1 to 45 mi hr^{-1}. The Torching Index median would increase from 35 to 155 mi hr^{-1} with a distribution range of 32 to 754 mi hr^{-1}. Treatment would increase the projected median Crowning Index from 27 to 78 mi hr^{-1}, with a value range of 32 to 264 mi hr^{-1} (Figure 5b). After thinning, 100% of plots would experience surface fire behavior at 95th percentile weather conditions, compared to 76% of the plots prior to treatment. Doubling and tripling the windspeeds produced no effect on modeled fire type: all plots modeled a post-treatment surface fire behavior type (Table 5).

Discussion

The old-growth ponderosa pine stand structures, fuel complexes, and wildfire hazards studied here were heterogeneous, with plot distributions that were non-normal, skewed, and wide-ranging. Results show that stand-average metrics failed to adequately represent these actual within-stand conditions. This study's plot-level fire hazard analysis approach revealed that the two observed sites exhibited a threshold for crown fire hazard that was spatially discontinuous and non-uniform within stands, and poorly represented by stand means. In operational management settings, variance metrics such as coefficient of variation, standard error, or inter-quartile range are sometimes used in this capacity to quantify stand heterogeneity, but in those cases they are often noted only briefly, if presented at all. Moreover, variation metrics carry an assumption of a normal distribution, which was rarely found at each of our study sites, making these metrics of limited interpretive value.

We are not the first to report or demonstrate this phenomenon. Other researchers, including Fulé et al. [37] and Roccaforte et al. [14] in southwestern ponderosa pine old-growth stands, and Ritchie et al. [38] in Sierra Nevada ponderosa pine stands, concluded that average stand conditions do not recognize the spatially heterogeneous nature of ladder fuels. Those researchers computed canopy fuels at the plot level and ranked canopy base height data by quintiles (20th percentile categories), while holding other parameters constant.

In our study, descriptions of plot-level fire hazards provided a more comprehensive and informative depiction of wildfire risks and silvicultural prescription effectiveness than either means alone or with variation metrics. Perhaps this is most underscored by the distributions of discrete modeled fire types at the two sites. Under 95th percentile weather conditions, we observed that the majority (63% of plots) of Boulder Creek are prone to passive crown fire, yet, a significant portion of stand area (25% of plots) exhibited local fuel conditions that suggest an active crown fire (Table 5). Similarly, at 95th percentile weather conditions at Meadow Smith, the predominant modeled fire type was just surface fire (76% of plots), but the remainder of the stand (24% of plots) was predicted to burn as passive crown fire. Increasing windspeeds to values beyond the 95th percentile revealed more variations in fire behavior as crown fire was predicted to increase. When we evaluated treatment effects on canopy

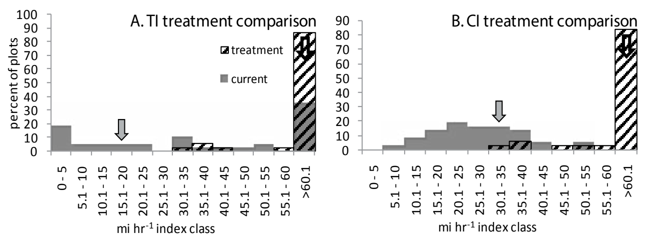

Figure 5: Pre-treatment and post-treatment distributions of within-stand modeled Torching Index (A) and Crowning Index (B) at Meadow Smith (percent of plots within each class). Indexes refer to the threshold 20-ft windspeed that ignites a passive crown fire (Torching Index; TI) or facilitates active crown fire spread (Crowning Index; CI). Arrows denote the class encompassing the stand average.

doi:http://dx.doi.org/10.4172/2327-4417.1000158

Table 5: Distributions of within-stand modeled fire behavior types at Boulder Creek and Meadow Smith. For Boulder Creek, 20-ft windspeeds are set at the local 95th percentile (19 mi hr-1) and doubled. For Meadow Smith, 20-ft windspeeds are set at the local 95th percentile (8 mi hr-1), doubled, and tripled. At Meadow Smith, the projected post-treatment fire types are also presented ("Treatment Effects").

	Current Conditions					**Meadow Smith**		
	Boulder Creek		**Meadow Smith**			**Treatment Effects**		
Fire type	19 mi hr^{-1} winds	38 mi hr^{-1} winds	8 mi hr^{-1} winds	16 mi hr^{-1} winds	24 mi hr^{-1} winds	8 mi hr^{-1} winds	16 mi hr^{-1} winds	24 mi hr^{-1} winds
Active	25%	75%	0%	5%	32%	0%	0%	0%
Passive	63%	15%	24%	27%	11%	0%	0%	0%
Conditional	0%	10%	0%	5%	38%	0%	0%	0%
Surface	13%	0%	76%	62%	19%	100%	100%	100%

fuels at Meadow Smith, those treatments appeared to homogenize stand structure and reduce variance in canopy structure, resulting in a stand of lessened structural complexity, but also one of substantially reduced crown fire behavior potential for all plots across the stand area.

We note several qualifications about interpreting the modeling results produced by this study. First, the original Van Wagner [39] and Rothermel [40,41] fire models were developed from semi-empirical data assessed at the stand scale. Second, Cruz and Alexander [42] contend that Van Wagner's crown fire ignition models often demonstrate under-prediction bias when assessing crown fire hazard under field conditions. Third, several concerns have been expressed over the CBD and CBH canopy fuel algorithms that are employed by FVS-FFE program [42-44]. Yet we also note that these exact fire behavior models continue to experience widespread use by fire managers, perhaps for lack of any better decision-support tool. Therefore, we suggest that the primary value of our analysis lies in the comparison of analytical approaches, rather than in the absolute values that the modeling exercise produced. Used in that manner, they shed light on the implications that heterogeneous stand conditions present to fuels planners seeking to perform meaningful wildfire hazard analysis.

An important consideration is determining when this analysis-intensive approach to fuels planning is warranted on an operational basis by forest managers prescribing restoration treatments, due to the additional analysis required. In the case of this study, there was a solid research basis for restoring complexity in old-growth stands. Additional analysis steps were indeed required, but we note that no additional or more complicated data collection methods (e.g., stem mapping for spatial analysis) were necessary. We believe this strategy can serve as a useful model for managers seeking to gain greater interpretive value from the analysis of stand and fuel data, and – as this study has illustrated – with inferential value that far exceeds that provided by stand-average metrics, while yet retaining the virtue of efficiency in data collection.

Acknowledgements

This was a study of the Applied Forest Management Program at the University of Montana, a research and outreach unit of the Montana Forest and Conservation Experiment Station. Dr. Michael G. Harrington (retired Research Forester, USDA Forest Service) was instrumental in making this research possible. Funding was provided by the USDA Forest Service Rocky Mountain Research Station (Missoula Fire Sciences Laboratory). We thank Thomas Perry, Emily Garlough, and Woongsoon Jang for their assistance.

References

1. Spies TA, Hemstrom MA, Youngblood A, Hummel S (2006) Conserving old-growth forest diversity in disturbance-prone landscapes. Conserv Biol 20: 351-362.
2. Cooper CF (1960) Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. Ecol Monogr 30: 129-164.
3. Agee JK (1993) Fire Ecology of Pacific Northwest Forests. Island Press, Covelo, Canada.
4. Arno SF, Smith HY, Krebs MA (1997) Old growth ponderosa pine and western larch stand structures: Influences of pre-1900 fires and fire exclusion. INT-RP-495, USA.
5. Arno SF, Scott JH, Hartwell MG (1995) Age-class structures of old growth ponderosa pine/Douglas-fir stands and its relation to fire history. USDA Forest Service INT-RP-481, USA.
6. Leonzo CM, Keyes CR (2010) Fire-excluded relict forests in the southeastern Klamath Mountains, California, USA. Fire Ecol 6: 62-76.
7. Jain TB, Battaglia MA, Han H-S, Graham RT, Keyes CR, et al. (2012) A comprehensive guide to fuel management practices for dry mixed conifer forests in the northwestern United States. USDA Forest Service RMRS-GTR-292, USA.
8. Arno SF, Ottmar RD (1994) Reintroduction of fire into forests of eastern Oregon and Washington. In: Everett R L tech Eds. Volume 4: Restoration of stressed sites, and processes. USDA Forest Service PNW-GTR-330.
9. Fiedler CE (1996) Silvicultural applications: restoring ecological structure and process in ponderosa pine forests. In: Hardy C C, Arno S F Eds. The Use of Fire in Forest Restoration. USDA Forest Service INT-GTR-341.
10. Allen CD, Savage M, Falk DA, Suckling KF, Swetnam TW (2002) Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecol Appl 12: 1418-1433.
11. Youngblood A, Max T, Coe K (2004) Stand structure in eastside old-growth ponderosa pine forests of Oregon and northern California. For Ecol Manage 199: 191-211.
12. Kolb TE, Agee JK, Fulé PZ, McKowell NG, Pearson K (2007) Perpetuating old ponderosa pine. For Ecol Manage 249: 141-157.
13. Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. For Ecol Manage 211: 83-96.
14. Roccaforte JP, Fulé PZ, Covington WW (2008) Landscape-scale changes in canopy fuels and potential fire behavior following ponderosa pine restoration treatments. Int J Wildland Fire 17: 293-303.
15. Fieldler CE, Metlen KL, Dodson EK (2010) Restoration treatment effects on stand structure, tree growth, and fire hazard in a ponderosa pine/Douglas-fir forest in Montana. For Sci 56:18-31.
16. Fielder CE, Friederici P, Petruncio M, Denton C, Hacker WD (2007) Managing for old-growth in frequent-fire landscapes. Ecol Soc 12: 20.
17. Larson AJ, Stover KC, Keyes CR (2012) Effects of restoration thinning on spatial heterogeneity in mixed-conifer forest. Can J For Res 42: 1505-1517.
18. Varner JM, Keyes CR (2009) Fuels treatments and fire models: Errors and corrections. Fire Manage Today 69: 47-50.
19. Scott JH, Reinhardt ED (2001) Assessing crown fire potential by linking models of surface and crown fire behavior. USDA Forest Service RMRS-RP-29.
20. Harrington MG, Noonan-Wright E, Doherty M (2007) Testing the modeled effectiveness of an operational fuel reduction treatment in a small western Montana interface landscape using two spatial scales. In: Butler B W, Cook W, comps., USDA Forest Service RMRS-P-46CD.
21. Kreye JK, Varner JM, Dugaw CJ (2014) Spatial and temporal variability of forest floor duff characteristics in long-unburned *Pinuspalustris* forests. Can J For Res 44: 1477-1486.

doi:http://dx.doi.org/10.4172/2327-4417.1000158

22. Green P, Joy J, Sirucek D, Hann W, Zack A, et al. (1992) Old-growth forest types of the northern region. USDA Forest Service. Internal Publication. R-1 SES 4/92.
23. United States Forest Service (2008) Detailed silvicultural prescription summary of the Meadow Smith timber sale. Flathead National Forest, USDA Forest Service, USA.
24. Western Regional Climate Center (2005) Montana climate summaries. URL: http://www.wrcc.dri.edu/summary/climsmmt.html.
25. Lutes DC, Keane RE, Caratti JF, Key CH, Benson NC et al. (2006) FIREMON: Fire effects monitoring and inventory system. USDA Forest Service RMRS-GTR-164CD.
26. Crookston NL, Dixon GE (2005) The Forest Vegetation Simulator: A review of its structure, content, and applications. Comput Electron Agric 49: 60-80.
27. Reinhardt ED, Crookston NL (2003) The Fire and Fuels Extension to the Forest Vegetation Simulator. USDA Forest Service INT-GTR-116.
28. Brown JK (1978) Weight and Density of Crowns of Rocky Mountain Conifers. USDA Forest Service INT-RN-197.
29. Shapiro SS, MB Wilk (1965) An analysis of variance test for normality (complete samples). Biometrika 52: 591-611.
30. Scott JH (1999) NEXUS: A system for assessing crown fire hazard. Fire Manage Notes 59: 20-24.
31. Scott JH, Burgan RE (2005) Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service RMRS-GTR-153.
32. Bradshaw L, McCormick E (2000) Fire Family Plus user's guide, Version 2.0. USDA Forest Service RMRS-GTR-67-WWW.
33. Albini FA, Baughman RG (1979) Estimatingwindspeeds for predicting wildand fire behavior. USDA Forest Service INT-RP-221.
34. Crosby JS, Chandler CC (2004) Get the most from your wind speed observation. Fire Management Today 64: 53-55.
35. Philpot CW, Mutch RW (1971) The seasonal trends in moisture content, ether extractives, and energy of ponderosa pine and Douglas-fir needles. USDA Forest Service INT-RP-102.
36. Keyes CR (2006) Role of foliar moisture content in the silvicultural management of forest fuels. West J Appl For 21: 228-231.
37. Fulé PZ, Covington WW, Smith HB, Springer JD, Heinlien TA, et al. (2002) Comparing ecological restoration alternatives: Grand Canyon, Arizona. For Ecol Manage 170: 19-41.
38. Ritchie MW, Skinner CN, Hamilton TA (2007) Probability of tree survival after wildfire in an interior pine forest of northern California: Effects of thinning and prescribed fire. For Ecol Manage 247: 200-208.
39. Van Wagner CE (1977) Conditions for the start and spread of crown fire. Can J For Res 7: 23-34.
40. Rothermel RC (1972) A mathematical model for predicting fire spread in wildand fuels. USDA Forest Service INT-RP-115.
41. Rothermel RC (1983) How to predict the spread and intensity of forest and range fires. USDA Forest Service INT-GTR-143.
42. Cruz MG, Alexander ME (2010) Assessing crown fire potential in coniferous forests of western North America: a critique of current approaches and recent simulation studies. Int J Wildland Fire 19: 377-398.
43. Parsons RA (2007) Spatial variability in forest fuels: Simulation modeling and effects on fire behavior. University of Montana PhD Dissertation. Missoula, USA.
44. Keyser T, Smith FW (2010) Influence of crown biomass estimators and distribution on canopy fuel characteristics in ponderosa pine stands of the Black Hills. For Sci 56: 156-165.

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