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Fuel variability following wildfire in forests with mixed severity fire regimes, Cascade Range, USA

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ABSTRACT

Fire severity influences post-burn structure and composition of a forest and the potential for a future fire to burn through the area. The effects of fire on forests with mixed severity fire regimes are difficult to predict and interpret because the quantity, structure, and composition of forest fuels vary considerably. This study examines the relationship between fire severity and post-burn fuel characteristics in forests with mixed severity fire regimes. We sampled live and dead canopy and surface fuels across four fire severity classes on three wildfires that occurred on the east side of the Cascade Range, USA, in 2007 and 2008. We used empirical fuels data and stand structure and composition characteristics to calculate potential surface fire behavior for the four fire severity classes. Post-burn average canopy cover is 25–30% in the low severity class and <10% in the high severity class and ranges from 0 to 50% for all fires. All variables representing post-burn canopy fuels differ by fire severity class. The average loading of dead and down woody fuels <7.6 cm diameter and litter is 0.9–1.1 kg m^{-2} in the low severity class and 0.6–0.8 kg m^{-2} in the high severity class. Values for fuel loading variables span a wide range of values within and among fires, and substantial overlap exists among severity classes. Fire severity generally does not influence post-burn dead and down woody fuel loading. Estimates of potential fire behavior also cover wide ranges of values, particularly among fires. Flame lengths average 0.4–0.8 m in the low severity classes and 0.3–1.1 m in the high severity classes. The range of potential flame length values, modeled with a 16.1 km h^{-1} midflame wind speed, varies by up to 2.0 m within a single severity class (0.6–2.6 m). Fire severity does influence potential fire behavior, but typically just one severity class differs from the other three classes. These results indicate that fire severity influences immediate (2–3 years) post-burn canopy fuels and potential fire behavior but does not influence dead and down surface fuel loading for the three fires studied. The wide ranges of values for the fuel components analyzed demonstrate the variability that is characteristic of forests with mixed severity fire regimes and emphasize the need to consider the natural heterogeneity of these forests in fire and fuels management. Quantification of post-burn fuel variability is critical for understanding the ecological significance of mixed severity fires and developing restoration strategies that emulate characteristics of the historical fire regime.

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1. Introduction

Climate and fuels vary considerably in forests with mixed severity fire regimes and affect fire frequency and severity (Agee, 1993; Schoennagel et al., 2004; Lentile et al., 2005). The effects of fire in these forests are difficult to predict and interpret because multiple factors interact to influence fire behavior. Fire effects in forests with mixed severity fire regimes include those common to low, moderate, and high severity fires. Low severity fires result in minimal overstory tree mortality (<20%) and variable surface fuel consumption (Agee, 1993). High severity fires cause near-complete mortality of overstory trees (>70%) and aboveground understory vegetation (Agee, 1993). Moderate severity fires result in a level of vegetative mortality and fuel consumption that is intermediate between low and high severity fires (overstory mortality 20–70%; Agee, 1993). Weather generally dictates fire behavior in forests with a high severity fire regime (Bessie and Johnson, 1995; Turner et al., 2003), whereas the abundance and continuity of fuels have the greatest effect on fire behavior in forests with a low severity fire regime (Swetnam and Baisan, 1996; Graham et al., 2004). Both weather and fuels influence fire behavior in forests with mixed severity fire regimes. The relative influence of each of these two

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factors varies across large landscapes, often within the perimeter of a single fire (Arno, 1980; Halofsky et al., 2011). A mosaic of fire effects and burn severity patterns results from the inconsistent and interacting influence of weather and fuels on fire behavior over time and space. Research that characterizes and quantifies both pre- and post-burn canopy and surface fuels in forests with mixed severity fire regimes will increase our understanding of these systems and the interactions and feedbacks among fire frequency, fire severity, and fuelbed variability.

Mixed severity fire regimes in western North America are complex and poorly understood because fires vary in severity, frequency, and extent at multiple scales (Agee, 2005). Combinations of low, moderate, and high severity fires occur over a range of frequencies and spatial extents, which influences ecosystem dynamics by creating an assortment of forest structures in patches of various sizes (Agee, 1981; Taylor and Skinner, 1998; Agee, 2003; Taylor and Skinner, 2003). The mean fire return interval for mixed severity fire regimes in the Pacific Northwest ranges from 25 to 75 years (Agee, 2002a,b) and is dependent on local site conditions.

Forests with mixed severity fire regimes occur throughout western North America, predominantly at mid-elevations, where the combination of complex topography, moisture gradients, and fire interact to create a diverse mixture of tree species and densities. Fire history studies in the Rocky Mountains (Arno, 1980; Arno et al., 1995; Brown et al., 1999) and the eastern Cascade Range (Everett et al., 2000; Wright and Agee, 2004) suggest that, on relatively dry sites in mid-elevation mixed conifer forests, low intensity surface fires encouraged dominance by fire-resistant species including ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), western larch (*Larix occidentalis* Nutt.), and Douglas-fir (*Pseudotsuga menzesii* (Mirb.) Franco) in variable densities. Frequent recurrence of low to moderate intensity fires on these dry sites perpetuated the dominance of fire-resistant species over thinner-barked species, such as grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), other fir species (*Abies* spp. Mill), and lodgepole pine (*Pinus contorta* Douglas ex Louden var. *latifolia* Engelm. ex S. Watson), which are more readily killed by fire. The thinner-barked fir species and lodgepole pine tended to exist in higher densities and occupy wetter locations with less frequent disturbance than the dry sites. Fires on these wetter sites were typically of moderate to high severity. A mosaic of even and uneven-aged stands resulted from the combination of low severity surface fires on dry sites, high severity stand-replacing fires on wet sites, and moderate severity fires at sites that are intermediate in climate and topography.

Spatial and temporal variations in the occurrence and severity of fires shape successional dynamics in forests with mixed severity fire regimes. Vegetation composition and fire history affect fire severity and result in a dynamic feedback between fire severity and forest fuel structure (Peterson, 2002; Collins and Stephens, 2010; Thompson and Spies, 2010). Fuel structure refers to the quantity, distribution, and horizontal and vertical arrangement of live and dead trees, understory vegetation, woody debris, litter, and humus (Brown and Bevins, 1986; Johnson, 1992). Historically, frequent fire maintained a relatively low tree density on dry sites, whereas infrequent fire and climatic conditions allowed higher density stands to develop on wet sites. Over the past century, vegetation density, fuel loading, and structural complexity have increased in many drier forests, due, in part, to fire exclusion (Arno et al., 1995; Kaufmann et al., 2000). In the absence of fire, live and dead fuels are more likely to persist on a site, and the species composition shifts from trees that are adapted to survive frequent surface fires to trees that are less adapted to frequent fire. Dry sites are more susceptible to relative changes in stand density and composition and to the ecological effects associated with those changes (Veblen and Lorenz, 1986; Arno et al., 1995; Kaufmann et al., 2000; Ehle and Baker, 2003) because the influence of fire exclusion is greater in areas that historically burned frequently. In the absence of fire, dry sites begin to resemble wetter sites in forest fuel structure and species composition. The homogenization of dry and wet sites influences the spatial and temporal patterns of fire severity and may result in a broad-scale decrease in the heterogeneity of forests with mixed severity fire regimes (Agee, 2002a; Hessburg et al., 2005; Perry et al., 2011).

At a local scale, prior fires affect the likelihood of subsequent fires and potential fire behavior by altering the structure and composition of fuelbeds (Stephens, 1998; Fernandes and Botelho, 2003; Raymond and Peterson, 2005; Stephens and Moghaddas, 2005). A fuelbed is defined as a relatively homogeneous unit of the landscape with a unique combustion environment that dictates potential fire behavior and effects (Ottmar et al., 2007). Prior fires affect both live and dead fuel structure. Fire consumes live fuels and can stimulate the post-burn growth of shrubs, herbaceous plants, and tree regeneration. Fire also consumes dead fuels and can increase coarse woody debris and litter as a result of direct and indirect mortality. Thus, the current fuelbed is a product of the timing and severity of the most recent fire. The structure and composition of the fuelbed determine the rate and amount of energy that will be released during favorable burning conditions in subsequent fires (Ryan, 2002). For example, a decrease in the loading of surface fuels and the vertical continuity between surface and crown fuels can inhibit crown fire initiation, and a reduction in the quantity and horizontal continuity of canopy fuels can prevent crown fire spread (Raymond and Peterson, 2005; Prichard et al., in preparation).

Empirical data for forests with mixed severity fire regimes are limited to a few geographic areas, such as southwestern Oregon (Thompson et al., 2007; Halofsky and Hibbs, 2008; Thompson and Spies, 2010; Halofsky et al., 2011) and the central Rocky Mountains (Schoennagel et al., 2004). These studies found that fuel structure was the predominant influence on fire behavior on days of low and moderate fire growth, but weather was the predominant influence during major spread events with high severity fire effects. These studies explore potential cause-and-effect relationships between fire behavior and canopy fuels, but consider only anecdotal information about surface fuels.

Evidence suggests that past fires in low to mixed severity fire regimes limited the extent and severity of future fires (Everett et al., 1997; Heyerdahl, 1997; Everett et al., 2000; Heyerdahl et al., 2001; Taylor and Skinner, 2003). Variability in fire effects and local site characteristics likely influence the duration over which past fires affect subsequent fire spread. Some forests experience an increase in fuel loading and potential fire behavior immediately after a fire (Greenlee and Greenlee, 2002), but other forests require adequate time for fuel to accumulate after a fire before fire will burn through the same area (Wright and Agee, 2004; Collins et al., 2009). These examples highlight the importance of understanding post-burn fuel dynamics with respect to their influence on future fire behavior and severity.

In this study, we characterized and quantified post-burn fuels in forests with mixed severity fire regimes. We collected fuels data in four burn severity classes from three wildfires in the Cascade Range to quantify variability for post-burn canopy fuels, surface fuels, and potential fire behavior and to determine if relationships exist between fire severity and post-burn canopy fuels, surface fuels, and potential fire behavior. We compiled summary statistics for three characteristics of post-burn canopy fuels, three categories of post-burn dead and down woody fuel loading, and three measures of potential surface fire behavior for each fire. We hypothesize that high levels of surface fuel variability exist within and among severity classes and that fire severity is not a good indicator of reburn potential in forests with mixed severity fire regimes. Results from this study can help determine reburn potential, guide

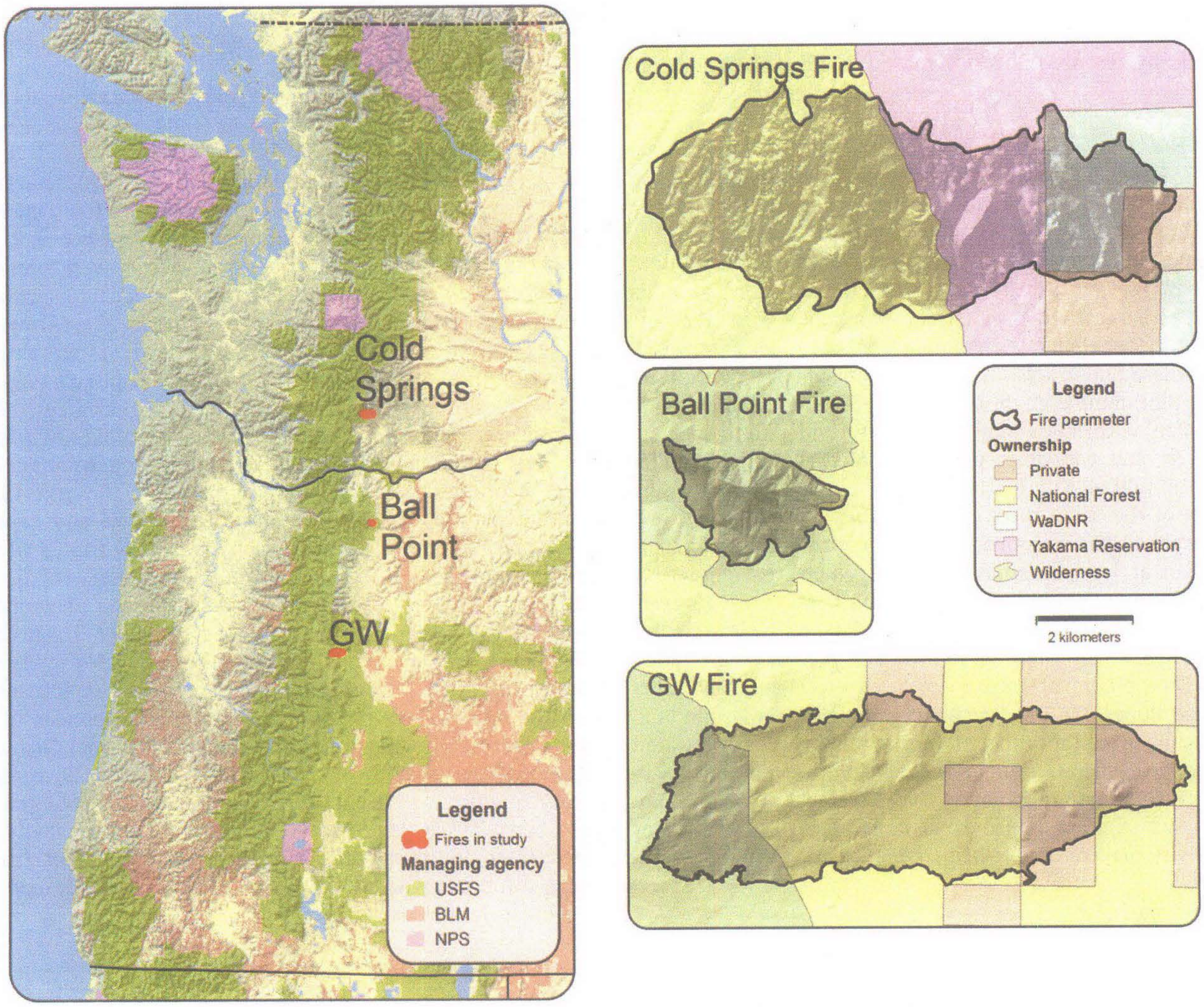

Fig. 1. Location of the study area and the three fires sampled in Oregon and Washington, USA.

future restoration efforts that aim to emulate the effects of naturally-ignited mixed severity fire in similar ecosystems, and serve as a starting point to measure post-burn fuels over time.

2. Methods

2.1. Study area

We studied three lightning-caused fires on the near east side of the Cascade Range in Oregon and Washington that burned in 2007 and 2008. The Ball Point, Cold Springs, and GW Fires each covered a minimum of 500 ha, and at least half the area of each fire burned with mixed severity (low, moderate, and high severity patches within a single fire perimeter). Vegetation was dominated by mature mixed conifer forest ($\geqslant$70 years old) that consisted of ponderosa pine, Douglas-fir, and grand fir located between 800 and 1600 m elevation. The area had abundant herbaceous cover, low shrub cover, and variable understory tree densities both within the fire perimeter and in surrounding forest stands. At least 75% of the area burned by each fire is on National Forest System lands. All study plots are within 1 km of a road or trail.

2.1.1. Ball Point Fire

The Ball Point Fire was located 25 km southwest of Dufur, Oregon, in the Badger Creek Wilderness in the Mt. Hood National Forest. Lightning started this 500 ha fire in August 2007. Ponderosa pine and Douglas-fir-dominated mixed conifer forests occupied the north- and west-facing slopes, while Douglas-fir and Oregon white oak (*Quercus garryana* Douglas ex Hook.) forests occupied the south- and east-facing slopes. All plots were established in the ponderosa pine and Douglas-fir-dominated forest between 800 and 1300 m with 30–60% slope. We avoided the drier south- and east-facing slopes with Douglas-fir and Oregon white oak forest and areas where cattle were actively grazing or had recently grazed.

2.1.2. Cold Springs Fire

The Cold Springs Fire was located 15 km north of Trout Lake, Washington. Lightning started the fire on the south side of Mt. Adams in the Gifford Pinchot National Forest in late June 2008. The fire spread eastward and burned 3230 ha of land managed by the Gifford Pinchot National Forest, the Confederated Tribes and Bands of the Yakama Nation, Washington Department of Natural Resources, and Hancock Timber Company. A grand fir-Douglas-fir-ponderosa pine forest dominated the area below 1500 m, while subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and lodgepole pine forest dominated the area above 1500 m. The higher elevation area burned predominantly with high severity. All plots were established below 1500 m on National Forest land with 0–30% slope. The sampled portion of the fire is part of a roadless area managed primarily for recreation with no evidence of other management actions. Pockets of vegetation have been affected by western spruce budworm (*Choristoneura occidentalis* Freeman) and mountain pine beetle (*Dendroctonus ponderosae* Hopkins), but locations with obvious pre-fire insect mortality were excluded from sampling.

2.1.3. GW Fire

The GW Fire is located 10 km northwest of Sisters, Oregon, on the east side of Mt. Washington. Lightning ignited the 2980 ha GW Fire in the Mt. Washington Wilderness in August 2008. The fire burned eastward across the Deschutes National Forest and onto heavily managed and privately-owned lands. Regeneration units planted after harvest were scattered throughout the eastern portion of the fire, where lands were managed for timber and recreation and where public and private land parcels were intermixed. Ponderosa pine dominated the overstory of the low elevation forest (below 800 m) with grasses and sedges in the understory. Douglas-fir, grand fir, and ponderosa pine dominated the mixed conifer overstory at mid-elevations (800–1500 m). The understory was comprised of the same three species, in variable densities, and the herbaceous layer was greater in richness and structural complexity than at low elevations. Species composition shifted to lodgepole pine, subalpine fir, and mountain hemlock (*Tsuga mertensiana* (Bong.) Carrière) above 1500 m. Plots were restricted to mature stands in the mid-elevation mixed conifer forest (800–1500 m). The predominant aspect of the fire was east, and plots have gentle slopes (0–20%). The areas sampled were within land allocations managed for timber and recreation and were dissected by roads and regeneration units. Locations with evidence of harvest or fire suppression activities that affected the desired site characteristics (mature mixed conifer forest ⩾70 years old) or added activity fuels to the fuelbed were avoided.

2.2. Fuel measurements

We measured 20 initial plots in the Cold Springs Fire in July 2009, and an additional 160 plots across the three fires from July through September 2010. We stratified the fires into four burn severity classes based on basal area (BA) loss as indicated on the Rapid Assessment of Vegetation Condition after Wildfire (RAVG) maps created by the U.S. Forest Service Remote Sensing Application Center (RSAC). In the RAVG analysis, BA loss refers to the percentage change in BA or tree cover (relative number of live trees on the site) from the pre-fire condition (USDA and USGS, 2011). The assessment uses two Landsat Thematic Mapper (TM) images captured before and after a wildfire and the relative differenced normalized burn ratio (RdNBR; Miller and Thode, 2007) to assess BA loss. The RdNBR algorithm is sensitive to vegetation mortality that results from the wildfire event (Miller and Thode, 2007). The four severity classes are (1) low (LL): 0–25% BA loss, (2) moderate-low (ML): 25–50% BA loss, (3) moderate-high (MH): 50–75% BA loss, and (4) high (HH): 75–100% BA loss (Fig. 2).

We identified 20 points in each fire from a set of computer-generated random latitude and longitude coordinates. The random points were the plot centers for the first 20 plots in each fire and were distributed equally across the four fire severity classes. After data were collected from the initial sample of 20 plots in each fire, additional plots were established systematically along transects that originated from the randomly established points. Additional plots were located 61 m from the random starting point in a cardinal direction chosen at random. Plot locations that did not meet the sampling criteria (e.g., skid roads, areas with evidence of logging or fire suppression, regeneration units, meadows, near creeks or drainages, etc.), were either skipped or, where possible, offset an additional 15.2 m in the same cardinal direction. We sampled systematically from a random starting point to minimize sampler bias. Plots were established in this fashion until at least 15 plots in each severity class were measured for each fire. We used the percentage change in BA or tree cover to ground-verify the remotely sensed fire severity classifications.

Each sample consisted of a 400 m^2 fixed-area tree plot for trees ⩾10.2 cm diameter at breast height (DBH; 1.37 m above ground) with one nested subplot for trees <10.2 cm DBH and ⩾1.5 m in height and another nested subplot for trees <10.2 cm DBH and <1.5 m in height. Subplot size varied based on tree density; subplots were 100 m^2 when fewer than two trees per species were present, 10 m^2 when >100 trees per species were present, and 40 m^2 otherwise. In addition, four 20-m planar intersect transects for measuring dead and down woody fuel loading (Brown, 1974) radiated from each plot center. The first transect was oriented at an azimuth of 90 degrees and consecutive transects were placed 45 degrees counterclockwise from the first (45 degrees, 0 degrees, 315 degrees; Lutes et al., 2006). If a transect could not be sampled because of terrain features, such as a cliff or large boulder, the transect at the designated aspect was placed on the next 45 degree interval. Woody fuel and ground fuel coverage and depth were estimated on 5, 2-m diameter subplots equally spaced along each of the four planar intersect transects with centers at 1.5, 4.6, 7.6, 10.7, and 13.7 m (20 subplots total). Shrub and nonwoody fuels and litter, lichen and moss data were collected on 3, 2-m diameter subplots evenly spaced along each of the four planar intersect transects with centers at 6.1, 12.2, and 18.3 m (12 subplots total).

The measurements taken at each plot corresponded to the inputs necessary to characterize a fuelbed in the Fuel Characteristic Classification System (FCCS; Ottmar et al., 2007; Riccardi et al., 2007a), which we used in later analyses to predict potential surface fire behavior. The FCCS captured the structural complexity of fuelbeds by compiling and analyzing the data from six fuel strata: canopy, shrub, nonwoody, litter, dead and down woody, and ground fuel (e.g., humus or duff).

2.2.1. Canopy fuels

We measured and tagged (except in wilderness areas) all live and dead trees ⩾10.2 cm DBH within each 400 m^2 plot. For each live tree, we recorded species, DBH, height, height to live crown, canopy class, total canopy cover, and canopy cover for each crown class. Height to live crown was defined as the first point where branching occured in at least two quadrants. We divided the canopy into three canopy classes: (1) overstory, comprised of canopy emergents and dominants; (2) midstory, comprised of canopy codominants and intermediates; and (3) understory, comprised of suppressed canopy trees and all trees <10.2 cm DBH. For each dead tree, we recorded species, DBH, height, and snag class. We divided snags (standing dead trees) into four classes: (1A) recently dead, foliage present; (1B) recently dead, foliage and fine twigs absent; (2) coarse branches and bark mostly present, top may be out; and (3) very few branches, no bark, top out, may be rotten. Live understory trees <10.2 cm DBH were tallied by species in two size classes: 0–5.1 cm and 5.1–10.2 cm at the base off the tree. Height and height to live crown were averaged by species for each size class.

Canopy coverage was estimated for 12, 2-m diameter cylindrical subplots. The subplots were evenly spaced with centers at 6.1 m, 12.2 m, and 18.3 m along each of the four planar intersect transects. Estimates were made from a vertical projection of tree foliage and branches to a single plane and excluded all spaces in the tree crowns (Lutes et al., 2006). We measured the maximum and minimum heights of ladder fuels and made visual observations regarding the vertical continuity and type of fuel (dead branches, arboreal lichens and moss, tree regeneration, or leaning snags). Ladder fuels were considered any potentially flammable material that provides an avenue for surface fire to spread into tree crowns. Vertical continuity existed when fuel strata extended from the

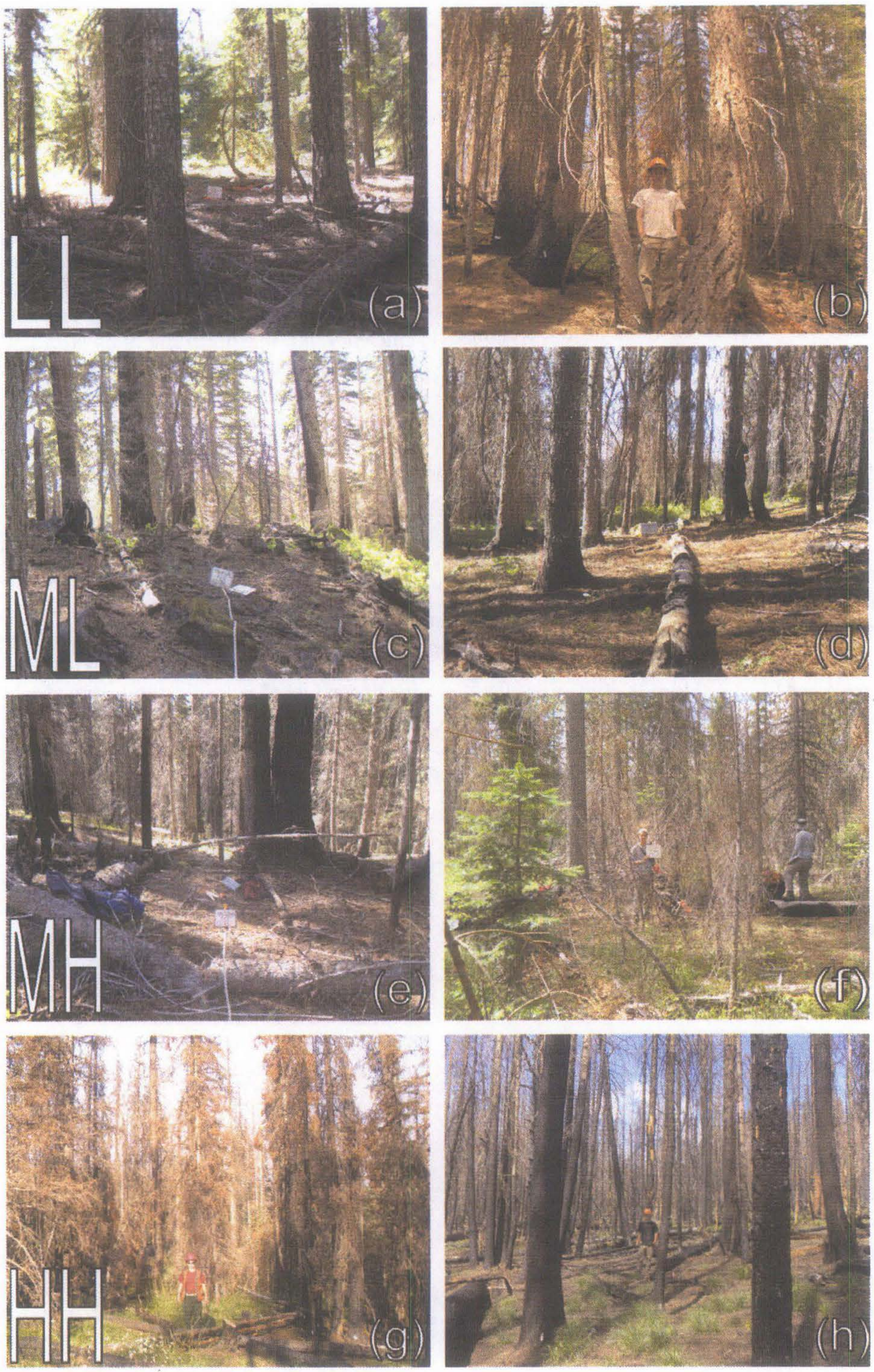

Fig. 2. High levels of variability in post-burn fuels and vegetation exist within each of the severity classes: (a) LL plot with high fuel loading and little evidence of fire; (b) LL plot with low woody fuel loading but high litter loading from post-burn needle cast; (c) ML plot with ladder fuels and moderate woody fuel and litter loadings; (d) ML plot with low woody fuel loading and high litter loading; (e) MH plot with high woody fuel and litter loadings; (f) MH plot in a patchy burn area with low woody fuel loading, variable herb cover, and ladder fuels; (g) HH plot with high scorch-related mortality, fine fuels still on trees, and high herb cover; (h) HH plot with high consumption, low fuel and litter loadings, and low herb cover.

ground to the base of the tree crowns for a majority of the plot. We included dead understory trees (<10.2 cm diameter) in ladder fuel measurements.

The canopy data were summarized into three components of canopy fuels: canopy bulk density, canopy base height, and canopy cover. Canopy bulk density (CBD) is the weight of available canopy fuel per unit volume of canopy space (Reinhardt et al., 2006). Calculations of CBD measure the arrangement and amount of fuels in the canopy based on species-specific crown biomass equations and characterize an entire stand rather than an individual tree (Snell and Brown, 1978; Scott and Reinhardt, 2001). We used the program FUELCALC (Reinhardt et al., 2006) to compute CBD. FUELCALC uses regression equations developed from destructively sampled trees and distributes fuel vertically throughout the tree canopy with more biomass occurring higher in the canopy. A canopy profile is created by summing fuel loading in 0.3-m increments for all

Table 1
Fuel particle timelag class, associated diameter, and sampling location along each transect.

Timelag class (h)	Diameter (cm)	Transect length (m)	Transect placement along the tape (m)
1	<0.64	1.8	1.5–3.4
10	0.64–2.54	3.1	1.5–4.6
100	2.55–7.62	20	0–20
1000	>7.62	20	0–20

trees in the stand. The profile is smoothed with a 4.8-m running mean, and CBD is considered the maximum value of that running mean.

Canopy base height (CBH) is an important contributor to crown fire initiation (Van Wagner, 1977). CBH is calculated at the stand scale to capture its influence on potential crown fire behavior. CBH is defined in terms of its contribution to crown fire initiation as the lowest height above the ground where sufficient canopy biomass (CBD) exists to support vertical fire spread (Van Wagner, 1993). Beukema et al. (1997) suggested that the threshold of CBD necessary to propagate vertical fire spread is at least 0.012 kg m^{-3} (used by Scott and Reinhardt, 2001; based on Sando and Wick, 1972; Brown, 1978). We used FUELCALC to compute CBH as the lowest point at which the running mean of CBD exceeded 0.012 kg m^{-3}. Use of this arbitrary threshold value to identify the point at which CBD affects fire behavior avoids visual estimation and interpretation that might result in inconsistent outputs and allows calculations to be performed quickly for multiple stands (Reinhardt et al., 2006). Limitations to the use of this arbitrary threshold include a null CBH value for a stand if the CBD never exceeded the threshold value for the stand.

FUELCALC consistently calculated canopy coverage (CC) values greater than those we measured in the field. We used the canopy coverage values from field measurements rather than the computed values from FUELCALC in both the FCCS analysis and the compilation of summary statistics.

2.2.2. Shrubs and nonwoody fuels

Coverage, average height, percentage live, and relative coverage of major species were measured in 12, 2-m diameter subplots, evenly spaced with centers at 6.1, 12.2, and 18.3 m along each of the four planar intersect transects. We measured shrubs and nonwoody fuels separately in each subplot. Coverage was estimated from a vertical projection of the foliage and/or branches on the subplot to a single plane, excluding spaces (Lutes et al., 2006). Average height was calculated from a sample of at least three representative specimens on each subplot. Percentage live and relative species coverage were estimated visually. We calculated nonwoody fuel loading using an equation that estimates oven-dry plant weight from coverage and plant height from a study that sampled shrubs and herbs in central Washington Douglas-fir stands (Olson and Martin, 1981). Many of the same major species were common to both studies.

2.2.3. Dead and down woody fuels

Woody fuel coverage was estimated on 20, 2-m diameter subplots equally spaced along each transect with centers at 1.5, 4.6, 7.6, 10.7, and 13.7 m. Estimates were made by vertically projecting all dead and down biomass <7.6 cm diameter and <1 m above the ground to a single plane, excluding spaces (Lutes et al., 2006). Woody fuel depth was measured as the highest particle height of woody fuels <7.6 cm diameter in a 0.3-m planar intersect transect segment originating at the center of each woody fuel coverage plot (Brown, 1974). Woody fuel particles that were >0.8 m above all other dead and down woody fuels in each transect segment were excluded. The number of pieces of sound woody debris <7.6-cm diameter was tallied by size class (Brown, 1974) using modified transect lengths (Table 1). Large woody fuels >7.6 cm diameter were measured on an initial subset of 20 plots in the Cold Springs Fire. We compared the measured large woody fuel loadings to the most representative predefined FCCS fuelbed (fuelbed #208, grand fir/Douglas-fir (fire exclusion) forest).[1] Large woody fuel loadings from the 20 measured plots were typically equal to or less than the default values for the selected, representative FCCS fuelbed. Therefore, we accepted the default values from the FCCS rather than collecting data on large woody fuels on all plots to increase sampling efficiency and maximize the number of plots sampled overall. Furthermore, surface fire calculations performed are not sensitive to large woody fuel loading (Sandberg et al., 2007b; Prichard et al., in preparation) so large woody fuels are of minimal concern regarding the questions addressed in this study. Rotten woody debris, stumps, and accumulations of dead and down woody debris (e.g., piles and jackpots) were recorded as "not present" because we observed the post-burn loadings of these fuels to be very light or non-existent. Fuel loading was calculated separately for 1-h, 10-h, and 100-h fuels (Table 1) based on equations in Brown (1974). We separated dead and down fuel loadings into three categories for subsequent analyses: (1) fine fuel (sum of 1-h and 10-h woody fuel and litter, does not include fine herbaceous fuels) (2) 100-h woody fuel, and (3) total loading of fuel <7.6 cm diameter (sum of 1-h, 10-h, and 100-h woody fuel and litter loadings).

2.2.4. Litter/lichen/moss

Coverages of litter, lichen, and moss were estimated on the same 12, 2-m diameter subplots as the shrubs and nonwoody fuels. Estimates were made by vertically projecting each type of biomass on the subplot to a single plane, excluding spaces (Lutes et al., 2006). We averaged lichen and moss depths from a sample of at least three representative specimens at each of the subplots. Litter depth was measured at two locations on each planar intersect transect, directly below the tape at 9.1 and 18.3 m. We visually estimated the dominant litter arrangement (normal, fluffy, or compact) and the relative amounts of each type (grass, long needle pine, and other conifer) for the entire plot. Litter loading was calculated in the FCCS from field observations of coverage, depth, type, and arrangement.

2.2.5. Ground fuels

Ground fuels, including duff and accumulations of duff around the bases of trees were assessed on the same subset of 20 plots as the large woody fuel loading. Duff and basal accumulations were rare following the wildfires and recorded as "not present" for all plots, because the potential surface and crown fire calculations performed are not sensitive to these inputs (Sandberg et al., 2007b; Prichard et al., in preparation).

2.3. Potential fire behavior estimates

Field data were used to create a unique FCCS fuelbed for each plot. FCCS converts the quantitative descriptions of fuel characteristics to estimates of potential surface fire behavior. For each unique fuelbed, the FCCS generates metrics of the potential surface fire behavior. Surface fire behavior predictions are based on a modification of the Rothermel (1972) fire spread model, which calculates the potential spread rate of a quasi-steady state head fire (a fire moving upslope with the wind) through homogeneous surface

[1] The FCCS provides a set of 216 predefined fuelbeds covering a variety of vegetation types and compiled from published and unpublished literature, fuels photo series, fuels datasets, and expert opinion (Ottmar et al., 2007).

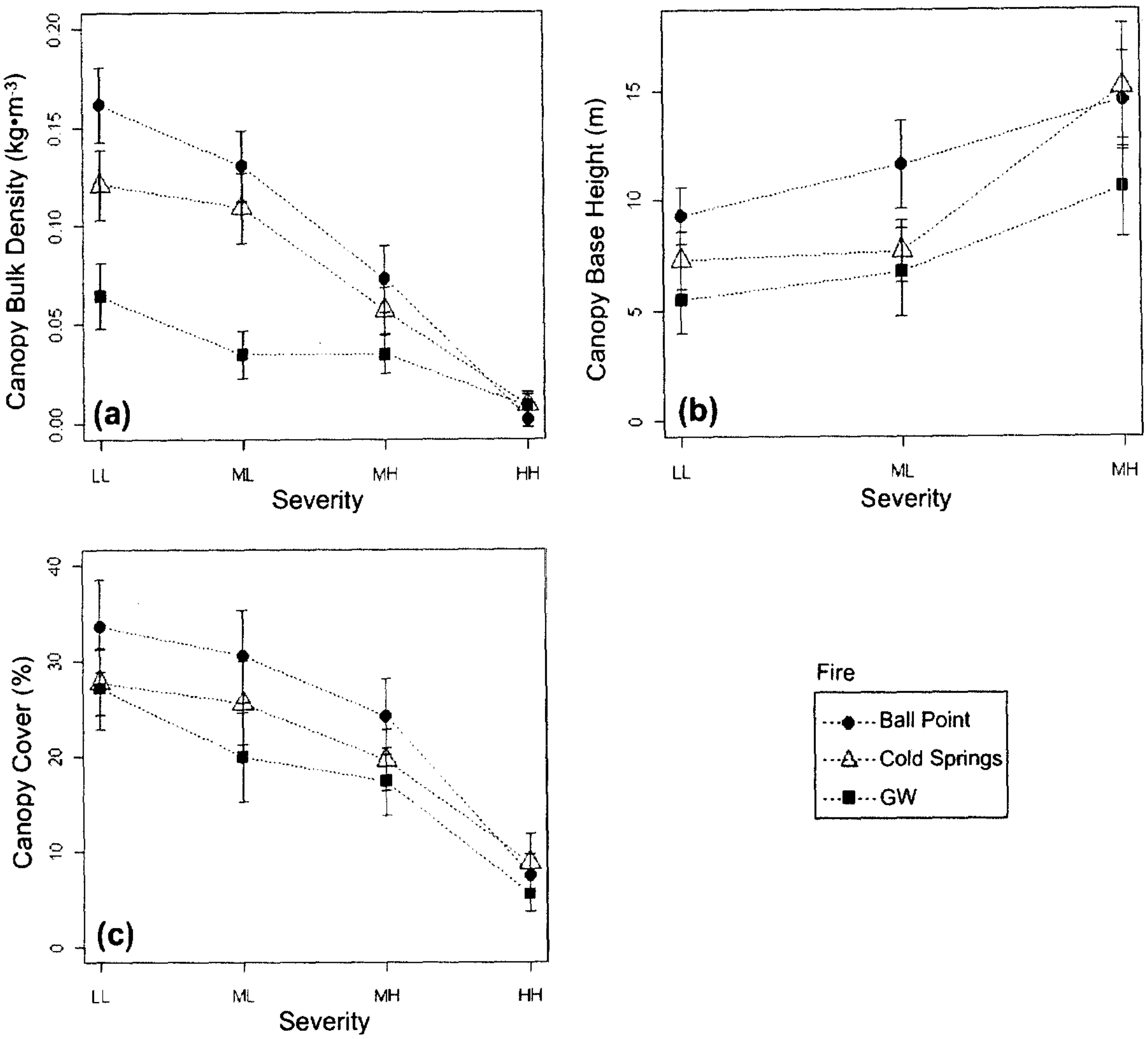

Fig. 3. Means with standard errors for (a) canopy bulk density, (b) canopy base height, and (c) canopy coverage. The connecting lines are provided to assist with visual interpretation and do not represent trends.

fuels under uniform conditions with respect to fuel loading and arrangement, fuel moisture, wind, and slope. Rate of spread calculations describe fire behavior in the flaming front of the fire, which is influenced primarily by fine fuels. Sandberg et al. (2007b) reformulated the Rothermel model to allow input of multiple fuelbed strata into the surface fire behavior model. Potential fire behavior outputs were generated based on the default fuel moisture scenario and midflame wind speeds of 6.4 km h^{-1} and 16.1 km h^{-1}. Use of a constant fuel moisture scenario facilitated comparisons among severity classes and among fires rather than local percentile weather, which varies by site. Based on local knowledge, the default fuel moisture scenario corresponds to dry conditions in which fuels ignite readily but extreme fire behavior is not expected (1 h = 9%, 10 h = 10%, 100 h = 11%, 1000 h = 15%, nonwoody = 90%, shrub = 120%, crown = 120%, duff = 100%). Slope was assumed constant at 0%.

FCCS calculates reaction intensity (RI), rate of spread (ROS), and flame length (FL) based on Sandberg et al.'s (2007b) reformulation of the Rothermel fire spread model. The RI (kW m^{-2}) is derived from the reactive volume of fuels per unit of ground surface, surface fuel depth, heat of combustion (Sandberg et al., 2007a). The ROS (m min^{-1}) is a function of the RI, propagating energy flux, and radiant heat sink (Sandberg et al., 2007a). The FL (m) is derived from the product of RI, ROS, and flame residence time (Byram, 1959; Albini, 1976; Sandberg et al., 2007a).

2.4. Data analysis

Summary statistics were compiled for the variables of concern (dependent variables, described below) including minimum, maximum, median, mean, and standard deviation per severity class per fire. We calculated differences among severity classes for the fuel and fire behavior variables measured using analysis of variance (ANOVA) and covariance (ANCOVA; where site characteristics have a significant influence on the dependent variables) in R version 2.10.1 (R Development Core Group, 2009). Nearly all of the dependent variables are right-skewed; therefore, we natural log or square-root transformed the data where necessary to meet the assumptions of ANOVA and ANCOVA (Zar, 1999). Levene's test ($\alpha = 0.20$) was used to compare variances among groups (Levene, 1960).

We also analyzed the influence of aspect, slope, and elevation on the dependent variables. The distribution of aspects is unbalanced for each fire. The majority of plots occur on a single, dominant aspect (Ball Point: SW, Cold Springs: SE, GW: NE). The lack of balance limits the inferences that can be drawn about the influence of aspect on variables of concern; therefore, aspect was analyzed only in an exploratory manner. We analyzed the relationship between the dependent variables and slope and elevation using linear regression ($\alpha = 0.10$). If no relationships were identified, we performed an ANOVA with fixed effects for the dependent variables, grouped by fire severity class. If a relationship was present between a dependent variable and slope or elevation, the topographic variable was combined with severity in an ANCOVA to identify potential interactions, relationships, and/or confounding influences. We verified the normality of the data and the fits of the models for each statistical test by ensuring even distribution of the residuals and no patterning in the q-q plots. Finally, if significant differences existed among severity classes after accounting for the influence of slope and elevation, pairwise comparisons were done by re-ordering factor levels in R and repeating the ANOVA or ANCOVA to determine which severity classes differed with respect to the variable of concern.

3. Results

We grouped the results into three categories of interest: canopy fuels, dead and down woody fuels, and potential surface fire behavior. We did not specifically analyze the influence of fire severity on shrubs and nonwoody fuels, litter/lichen/moss, or ground fuels, but the data from these fuelbed components were included in the potential fire behavior estimates.

3.1. Canopy fuels

The range of CBD values was similar for the LL, ML, and MH severity classes and smaller in the HH class for all three fires sampled (Fig. 3). The mean CBD decreased as severity class increased. A difference in post-fire CBD existed among severity classes (Ball Point: $p < 0.001$, Cold Springs: $p < 0.001$, GW: $p = 0.007$). The exploratory analysis of aspect suggested that, in the Cold Springs Fire, CBD was higher on west-facing slopes than on south- and east-facing slopes. No plots were established on north-facing slopes in the Cold Springs Fire.

FUELCALC did not produce a CBH value for many of the HH severity plots because the running mean of available canopy biomass never exceeded 0.012 kg m^{-3}, so the HH severity plots were excluded from CBH analyses. The range of CBH values was large within and among severity classes. The smallest within-class range was 9.1 m (Ball Point Fire, LL severity class) and the largest was 21.7 m (Cold Springs Fire, MH severity class). Mean CBH increased as severity class increased (Fig. 3). A difference in CBH existed among severity classes (Ball Point: $p = 0.009$, Cold Springs: $p < 0.001$, GW: $p = 0.005$). For all fires, the MH severity class differed from the LL and ML severity classes, which did not differ from one another. In the Ball Point Fire, CBH declined significantly with increasing elevation ($p = 0.007$).

In all fires, the range of canopy coverage was similar in the LL, ML, and MH severity classes and smaller in the HH severity class (Fig. 3). Mean canopy coverage decreased as severity increased. Differences in canopy coverage existed among severity classes (Ball Point: $p < 0.001$, Cold Springs: $p < 0.001$, GW: $p < 0.001$). Elevation also influenced canopy coverage in the Cold Springs Fire ($p = 0.03$); higher elevations had lower canopy coverage values.

3.2. Dead and down woody fuels

Each fire differed with respect to ranges of variability for dead and down woody fuel loading and relationships among fuel loading, fire severity, and other independent variables. Mean post-fire fine fuel loading was typically highest in the LL severity class, except in the Ball Point Fire, in which the highest mean fine fuel loading was in the MH severity class (**Fig. 4**). Mean fine fuel loading was typically lowest in the HH severity class, except in the Cold Springs Fire. The mean fine fuel loading for the HH severity class in the Cold Springs Fire was nearly equal to the mean for the ML severity class and slightly higher than the mean for the MH severity class (Fig. 4). Fine fuel loading differed significantly among severity classes in the Ball Point Fire ($p < 0.001$) and the GW Fire ($p = 0.001$), but not in the Cold Spring Fire. Pairwise comparison of fine fuel loading by severity classes in both the Ball Point and GW Fires revealed that the HH severity class differed from the three other classes, but no significant differences in fine fuel loading existed among the LL, ML, and MH classes. Slope influenced fine fuel loading in the Cold Springs Fire ($p = 0.03$); lower fine fuel loading occurred on steeper slopes.

Loading of 100-h woody fuel was light, compared to fine fuel loading, and the ranges were smaller (**Appendix A**). The trend for mean 100-h woody fuel loading showed a slight increase as severity class increased in the Ball Point and GW Fires, except in the HH severity class of the GW Fire, which had a lower mean 100-h woody fuel loading than the MH severity class (**Fig. 4**). The trend for mean 100-h woody fuel loading showed a decrease as severity increased in the Cold Springs Fire. Statistically, the 100-h fuel loading did not differ significantly by severity class in the Ball Point Fire, and we did not identify any relationships between 100-h fuel loading and elevation, aspect, or slope. In the Cold Springs Fire, mean 100-h woody fuel loading did not differ significantly by severity class, but was related to slope ($p = 0.007$); steeper slopes had a lower loading. In the GW Fire, the LL severity class differed from the other three classes ($p = 0.01$); no significant differences existed among the ML, MH, and HH severity classes.

The total loading of fuel <7.6 cm diameter (total fuel loading) is a summation of fine fuel loading and 100-h woody fuel loading. Fine fuel loading was generally higher than 100-h woody fuel loading. Therefore, fine fuel loading contributed more to the range of variability of the total fuel loading and relationships between total fuel loading and the independent variables. For all fires, the mean total fuel loading tended to decrease as severity increased (**Fig. 4**). An exception was mean total fuel loading for the MH severity class of the Ball Point Fire, which was more than mean total fuel loading of the LL, ML, and HH severity classes. This relationship was similar to that in the fine fuel loading, but greater in magnitude. In the Ball Point Fire, no significant difference in total fuel loading existed among severity classes, and none of the other independent variables had a significant influence on total fuel loading. In the Cold Springs Fire, slope influenced total fuel loading ($p = 0.001$); lower total fuel loading occurred on steeper slopes. A significant difference in total fuel loading existed among severity classes when severity was considered alone, but the relationship was not significant when slope and severity were considered together. In the GW Fire, total fuel loading differed among severity classes ($p = 0.004$), and the HH severity class was lower than the other three classes. No significant difference existed among the LL, ML, and ML severity classes.

3.3. Potential fire behavior

Relationships between fire severity and measures of potential fire behavior were similar for the 6.4 km h^{-1} and the 16.1 km h^{-1} midflame wind speed scenarios. The range of potential RI values and relationship between fire severity and RI differed for each fire (Fig. 5). RI differed among severity classes ($p < 0.001$) in the Ball Point Fire. The Ball Point Fire had the largest range and the highest mean RI value in the HH severity class and the smallest range and the lowest mean value in the LL severity class. Pairwise comparison revealed that the RI for the HH and LL severity classes differed from the RI for the ML and MH classes and from each other, but the RI values for the ML and MH severity classes did not significantly differ from one another. For the Cold Springs Fire, RI differed among severity classes ($p = 0.06$), and the range of RI was relatively small. The largest range and highest mean RI occurred in the MH severity

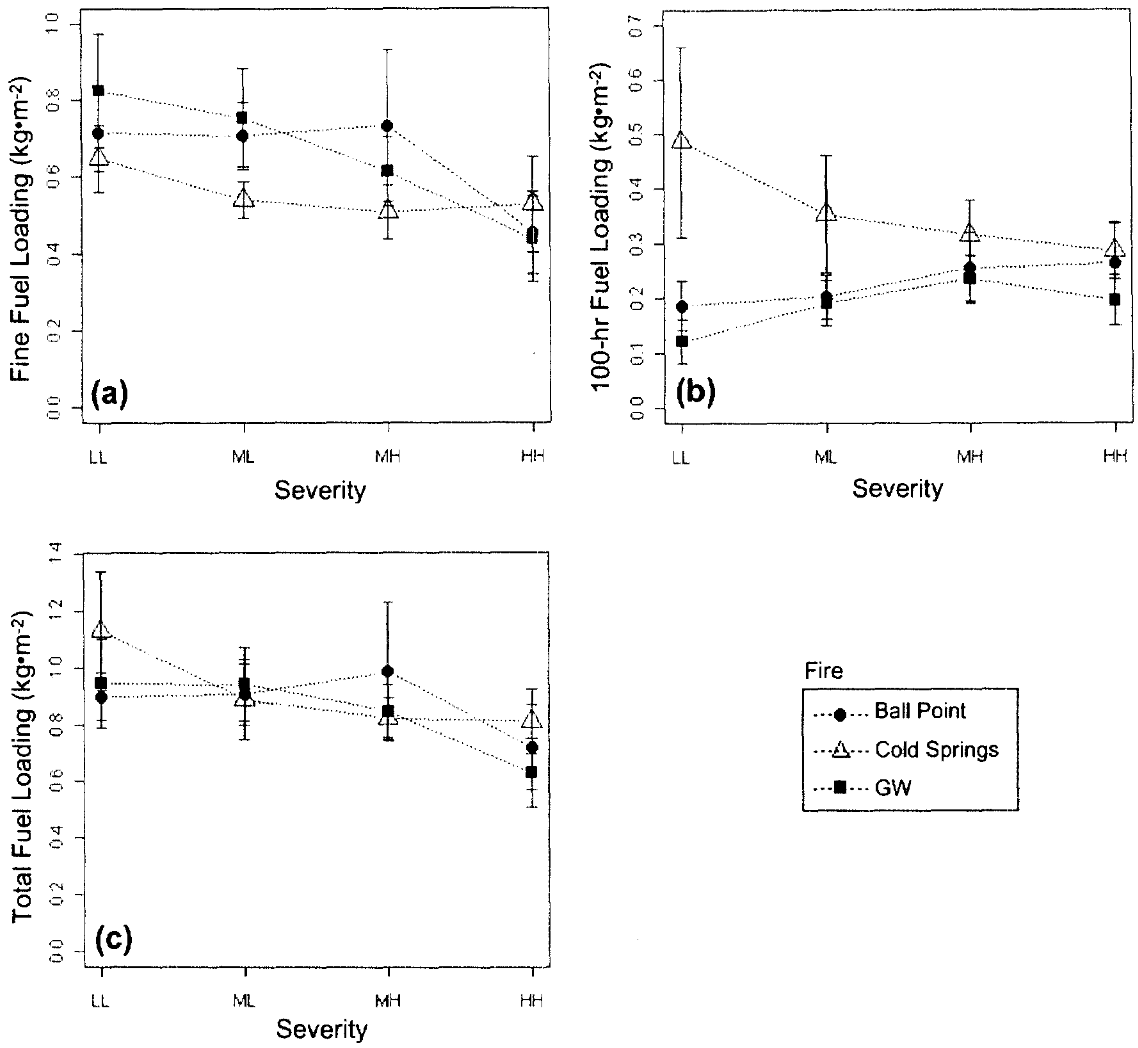

Fig. 4. Means with standard errors for (a) fine fuel loading (sum of 1-h and 10-h woody fuel and litter loading), (b) 100-h woody fuel loading, and (c) total loading of fuel <7.6 cm diameter (sum of 1-h, 10-h, and 100-h woody fuel and litter loadings). The connecting lines are provided to assist with visual interpretation and do not represent trends.

class. The RI values for the LL, ML, and HH severity classes did not differ from one another. In the GW Fire, mean RI was significantly higher in the MH severity class than in the other three severity classes ($p = 0.02$), and the range of RI outputs within each severity class was relatively large. The smallest range occurred in the LL severity class, and the highest range occurred in the ML severity class. The mean RI values did not differ among the LL, ML, and HH severity classes.

For all fires, a wide range of potential ROS values existed within each severity class, particularly for the 16.1 km h^{-1} wind speed scenario (**Appendix A**). The trend for mean ROS for the Ball Point Fire showed an increase as severity increased (Fig. 5), but no significant differences in ROS existed among severity classes. In the Cold Springs and GW Fires, the trend for mean ROS showed an increase from the LL to the MH severity class and then a decrease to a low point in the HH severity class for both the 6.4 and 16.1 km h^{-1} wind speed scenarios (Fig. 5). A significant difference in ROS existed among fire severity classes for both fires (Cold Springs: $p = 0.07$, 0.05; GW: $p = 0.008$, 0.02; for the 6.4 and 16.1 km h^{-1} wind speed scenarios, respectively). The HH severity class differed from the other severity classes, which did not differ from one another.

For all fires, a wide range of potential FL values was modeled within each severity class for both the 6.4 and 16.1 km h^{-1} wind speed scenarios (**Appendix A**). The within-group range exceeded 0.5 m in nearly every severity classes in all fires and reached as high as 2.0 m. A significant difference in FL existed among severity classes for all fires at both 6.4 and 16.1 km h^{-1} wind speeds (Ball Point: $p = 0.009$, 0.001; Cold Springs: $p = 0.02$, 0.02; GW: $p = 0.003$, 0.007, respectively). In the Ball Point Fire, the mean FL increased as severity class increased (Fig. 5). In the Cold Springs and GW Fires, mean FL increased from the LL to the MH severity class and decreased to the lowest value in the HH severity class (Fig. 5). In the Ball Point Fire, the LL severity class differed from the other three classes, but no significant difference existed among the ML, MH, and HH severity classes. For the Cold Springs and GW Fires, the HH severity class differed from the other three classes, and no significant difference existed among the LL, ML, and MH severity classes.

4. Discussion

4.1. Canopy fuels

The post-burn CBD, CBH, and CC differed by severity class. For all fires, CBD and CC decreased as severity class increased, and CBH increased as severity class increased. A decrease in live BA, which was used in this study to categorize fire severity, was correlated with a decrease in CBD and CC, probably because both BA and

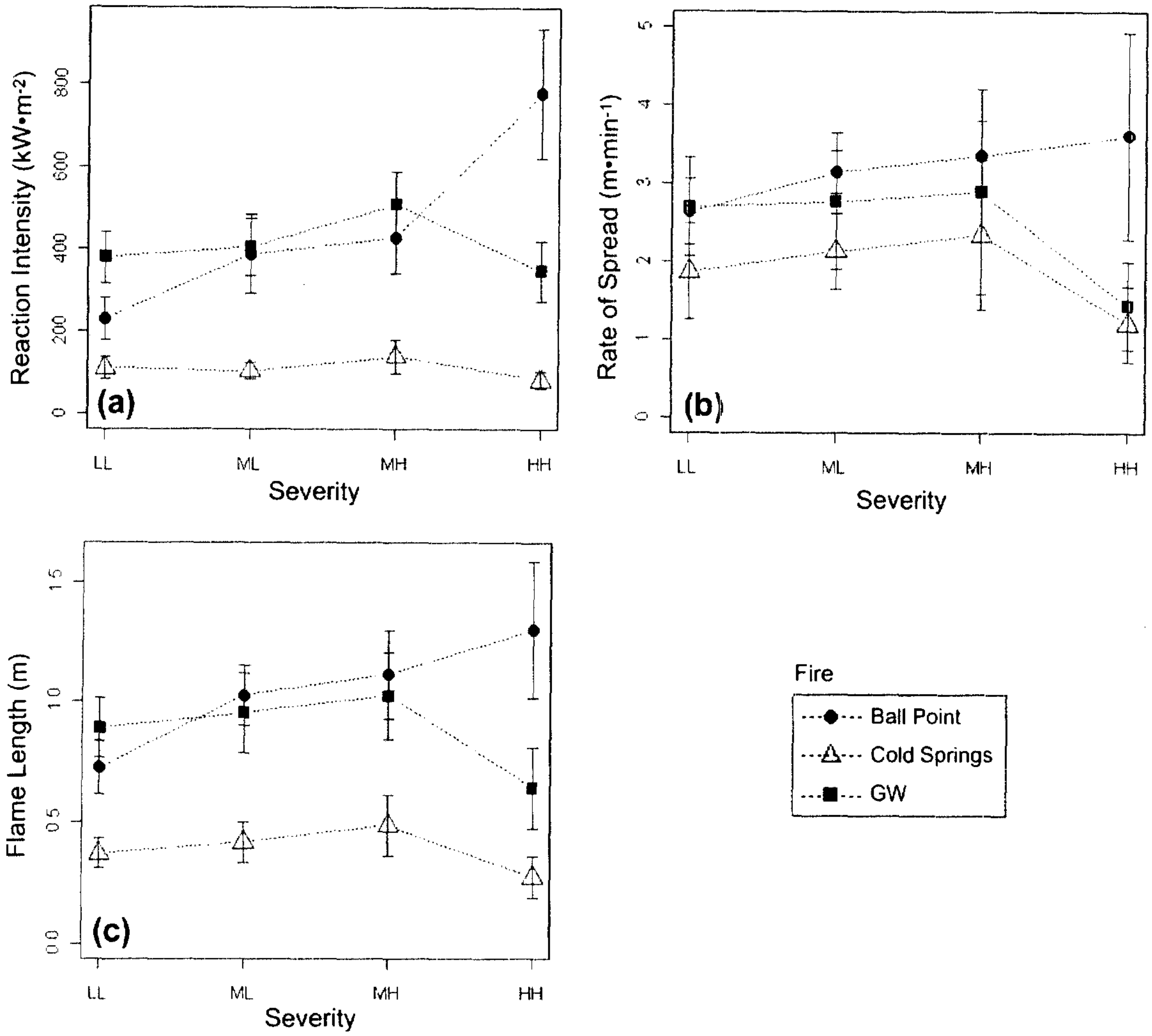

Fig. 5. Means with standard errors for (a) reaction intensity, (b) rate of spread, and (c) flame length with a 16.1 km h^{-1} midflame wind speed. The connecting lines are provided to assist with visual interpretation and do not represent trends.

the crown projection of an individual tree are functions of DBH (Tabbush and White, 1988; Farr et al., 1989; Smith et al., 1992). These variables behave differently when increasing the spatial scale from the individual tree to the plot because plot BA is the sum of individual tree BA, but canopy coverage is not necessarily the sum of individual tree crown coverage, owing to overlap among neighboring trees. Furthermore, tree spacing and growth rates influence the strength of the relationships among individual tree-scale crown characteristics, plot-scale canopy characteristics, and BA (Larocque and Marshall, 1994; Larocque, 2002).

In post-burn forests, the species composition and residual fuels vary within and among fire severity classes. In the present study, species-specific biomass equations were used to calculate CBD and CBH; however, residual post-fire canopy fuels may be misrepresented because the calculations for CBD and CBH assumed all trees were alive. In some fires, mortality occurs but canopy fuel consumption is low, leaving sufficient dead canopy biomass to contribute to future fire behavior, at least initially. Our inventory methods failed to adequately account for the dead crown component, because all dead tree biomass was recorded qualitatively as ladder fuels. By definition the HH severity class plots contained mostly dead canopy fuels, so the live canopy biomass rarely exceeded the minimum threshold value (0.012 kg m^{-3}) for FUELCALC to report a CBH value.

Crown fire cannot be considered independently of surface fire (Van Wagner, 1977; Alexander, 1988), but predictions can be made about the likelihood of crown fire based on canopy fuel characteristics. For the three fires sampled in this study, the post-burn probability of crown fire decreased as severity class increased. The decrease in CBD and CC that occured as fire severity class increased reduced the biomass available to carry fire horizontally through the canopy (Raymond and Peterson, 2005). Furthermore, the increase in CBH that occurred as fire severity class increased enlarged the size of the gap between the surface and canopy fuel strata, reducing the likelihood that fires could transition from the surface fuel layer to the canopy (Raymond and Peterson, 2005). Given the similarity among the three fires studied, the observed inverse relationship between fire severity and post-burn CBD and CC is probably consistent across all forested areas where tree mortality is used to determine fire severity, making the results of the canopy fuel analyses from this study applicable to other mixed conifer forests in the Cascade Range with a similar species composition. The post-fire canopy fuel data presented here help fill an existing data gap for canopy fuel characteristics in the Cascade Range. These data can enhance studies that analyze potential crown fire behavior by adding quantitative statistics to descriptive crown characteristics (e.g., Cruz et al., 2003).

4.2. Dead and down woody fuels

Fire severity did not influence the three categories of dead and down woody fuel loading analyzed in this study. Trends were inconsistent among the fires sampled. For example, total fuel loading (<7.6 cm diameter) was significantly lower in the HH severity class than in the LL, ML, and MH severity classes in the GW Fire, but no relationships were observed between fire severity and total fuel loading (<7.6 cm diameter) in the other two fires. Pre-fire fuel loading, level of fuel consumption during the fires, and post-fire blowdown all affected our measurements of post-fire fuel loading. Some of the LL plots are in >80-year old stands with accumulated surface fuels that the fire did not consume (Fig. 2a); whereas, other LL plots in the same type of stand experienced underburns that consumed the majority of fine surface fuels and some of the 100-h woody fuels (Fig. 2b). The ML and MH severity plots were also highly variable with respect to persistent pre-existing fuel loading and the effects of patchy fuel consumption. In some plots, dead and down woody fuel accumulated post-burn from crown scorch, needle cast, and the blowdown of dead branches (Fig. 2e). Conversely, in other ML and MH plots, fire consumed most of the surface fuel and understory trees and left only large, fire-resistant overstory trees and minimal surface fuels (Fig. 2d). In the HH severity plots, most pre-existing fine surface fuel and many of the fine canopy fuels were consumed (Fig. 2h), however, scorch-related or indirect mortality did contribute to surface fuel accumulation in some plots (Fig. 2g). Multiple factors interacted to create unpredictable, highly variable, post-fire dead and down woody fuel loading, which limits our inferences about the influence of fire severity on fuel loading. Furthermore, we did not measure coarse (>7.6 cm diameter) woody debris loading because our primary interest was to assess fire behavior, but a more comprehensive assessment and analysis of change could have been performed had we included coarse woody debris in our measurements. Coarse woody debris data would also allow evaluations of the effects of fire severity on additional fuel-related variables, such as an assessment of post-fire carbon flux. Periodic re-measurement of fuels on these sites could be used to monitor changes in various fuel characteristics over time and identify successional trends and interactions between fuelbed properties and fire severity.

4.3. Potential fire behavior

Fire severity did not consistently influence potential surface fire behavior or dead and down woody fuel loading. We did not quantitatively analyze the influence of herbaceous and shrub fuel loadings on fire behavior, but the results of an exploratory analysis suggested that high dead and down woody fuel loading in combination with high herbaceous fuel loading results in the highest potential surface fire behavior values. Nonwoody and shrub fuel loadings are listed in Appendix B. Both dead and down woody fuel loading and herbaceous fuel loading were highly variable, which resulted in a wide range of potential fire behavior values. Potential fire behavior may be misrepresented where fuel cover is not continuous because FCCS assumes continuity of the fuelbed components used to calculate fire behavior characteristics (Riccardi et al., 2007b). Field observations or local knowledge is needed to verify whether sufficient continuous fuels exist to propagate fire spread.

Consistent use of the default fuel moisture scenario, corresponding to dry conditions in which fuels ignite readily but extreme fire behavior is not expected, reduced weather-related variability among fires and facilitated comparison among severity classes. However, specific fire planning efforts may find it more useful to use local weather and fire business thresholds of concern (energy release component, burning index, etc. used by government agencies) when modeling potential fire behavior for fire management purposes. Modeled constant wind speeds and fuel moisture scenarios do not account for differences in surface wind speeds, fuel moistures, and potential fire behavior related to canopy density. Dense forest canopies shade fuels more than open canopies, which results in higher relative humidities, lower temperatures, and higher surface fuel moistures under dense canopies (Andrews, 1986). Dense forest canopies may retard surface winds that dry fuels more than open canopies (Agee, 2002c), which contributes to higher fuel moistures under dense canopies (Weatherspoon, 1996). Higher surface fuel moistures under dense canopies may reduce the probability of ignition in these forest stands (Graham et al., 2004), but probability of ignition was assumed constant for this study. Additional factors, such as slope (Chandler et al., 1991), influence potential fire behavior; however, the FCCS default setting assumes no slope (0%) for surface fire behavior predictions. The assumption of no slope is appropriate for predicting fire behavior for the GW and Cold Springs Fires, because these two fires occurred on relatively flat terrain; but this assumption underestimates ROS for the Ball Point Fire, which occurred on relatively steep terrain. Accounting for slope would influence the potential ROS, but probably would not affect the relationship between fire severity and ROS because sites in each severity class were distributed evenly across the range of slopes.

Conditions analyzed represent fuel conditions at a single point in time, 2–3 years post-burn. Fuel conditions are expected to change over time as new vegetation develops and woody fuels and litter fall accumulate from the dead overstory. Therefore, quantitative data from this study provide valuable insight regarding immediate fuel conditions following naturally ignited wildfire, but further analyses are required to derive future fire hazard as fuel loads change over time. Furthermore, the fuel moisture scenario used in this analysis assumed a universal nonwoody fuel moisture of 90%. Species, phenology, and local site factors influence moisture content (Agee et al., 2002). Potential post-burn fire behavior may be misrepresented in stands with high herbaceous fuel loading comprised of species with a range of fuel moisture levels, or with characteristic fuel moisture levels that differ from the default value of 90% that we used.

4.4. Applicability to fire and fuels management

Fire management plans and fire control strategies and tactics rely heavily on estimates of predicted fire behavior. The potential fire behavior estimates from this study can be used to assess the likely characteristics of a reburn in this fuel type and under the environmental conditions specified. Predicted flame lengths and rates of spread can be used to inform fire control options, and predicted RI can help forecast fire effects. The ability to predict fire effects is necessary to manage planned or unplanned ignitions safely and effectively for resource benefits such as wildlife habitat or hazardous fuels reduction. Descriptions of post-fire canopy and surface fuels can provide a basic quantitative baseline useful for defining goals for fuel treatments that aim to replicate the effects of wildfire (Perera and Buse, 2004). These data can also inform estimates of potential fire behavior and fire effects of a subsequent fire when using fire behavior models (e.g., Rothermel, 1972; Sandberg et al., 2007b).

The results of this study emphasize the inherent variability of forests with mixed severity fire regimes and illustrate the need to consider the natural heterogeneity of fuelbeds in fuel and fire management. Variability of these forests makes them difficult and costly to manage for multiple resource goals while maintaining the mosaic of structural and compositional conditions that historically characterized mixed severity fire regimes. In some situations, characteristics of the historical fire regime may be either difficult to reproduce or undesirable with respect to a particular resource objective. For example, in an area where the goal is to reduce fire hazard, a mixed severity fire will not result in uniformly low fuel loadings; rather, fire effects will be both spatially and structurally complex. In addition, an area that experiences a high severity burn may have little potential for canopy fire, but increased potential for high-intensity, high-severity surface fire because of post-fire fuel accumulation and a vigorous herbaceous response after the fire. Post-burn accumulation of fuels may lead to a reburn of this stand that would jeopardize tree reproduction and inhibit reforestation. Although an open canopy may be desirable for certain ecosystem processes and functions, it may negatively affect other ecosystem components that rely on forest cover and structural complexity.

Regional differences may exist in fuelbed variability, factors that influence fire behavior, and the relationship between fire severity and post-fire fuels. One difference between the three fires sampled in the Cascade Range for this study and the Biscuit Fire, a relatively well-studied fire in the Klamath-Siskiyou region, is the variability of post-fire fuels. Post-fire fuel loading was highly variable in all three fires in the Cascade Range. In contrast, fuel consumption was relatively uniform and nearly complete for all fuel categories, except the 10-h fuels, in the Biscuit Fire (Campbell et al., 2007). This distinction could be a function of pre-fire fuel loading or the variable influence of weather and fire behavior on fuels. The combination of weather, pre-fire fuel, and fire behavior produce distinct post-fire fuel characteristics, which, in turn, feedback on potential subsequent fire behavior and severity.

Current management policy emphasizes fuel reduction in dry forests of the western United States, many of which are characterized by mixed severity fire regimes, in order to reduce the likelihood of large, uniformly high severity wildfires (e.g., Healthy Forests Restoration Act of 2003 (HFRA, 2003), National Fire Plan (USDA and DOI, 2001), and 10-Year Comprehensive Strategy Implementation Plan (USDA and DOI, 2002)). Fuel reduction treatments may decrease forest heterogeneity by applying uniform prescriptions over large areas. Likewise, large areas of forest with high fuel loadings due to fire exclusion are more likely to experience high severity, weather-driven fire; and large, high severity fires may also lead to a decrease in forest heterogeneity. Changes in spatial and temporal patterns of fire severity would alter the variability that typically defines mixed severity fire regimes. That variability provides habitat for many plant and animal species; moreover, many species require the shifting mosaic of post-fire habitats caused by different levels of fire severity (Smucker et al., 2005).

More recent direction from the Federal Land Assistance, Management, and Enhancement (FLAME) Act of 2009 (USDA and DOI, 2009) and the National Cohesive Wildland Fire Management Strategy (Cohesive Strategy) of 2011 (USDA and DOI, 2011) emphasize forest restoration to improve ecosystem health and create resilient forests based on the parameters of historical fire regimes. Additional empirical data on variability in mixed severity fire regimes will inform future efforts to emulate this historical disturbance regime (Perera et al., 2004) and build resilience to a warmer climate and increased area burned (McKenzie et al., 2004) by restoring or maintaining forest heterogeneity.

5. Conclusions

We quantified the range of variability for post-burn canopy fuels, surface fuels, and potential fire behavior for three mixed severity wildfires in the eastern Cascade Range. Based on the data from these three fires, we suggest that fire severity influences post-burn canopy fuels and potential surface fire behavior, but not dead and down woody fuel loading (<7.6 cm diameter) in mixed-severity fires in this region. Although fire severity influences structure and composition of post-burn surface fuels, high variability within and among fire severity classes limits our ability to draw explicit conclusions about these complex relationships. Furthermore, categorization of fire severity by the effects of fire on canopy fuels does not allow us to make inferences about the surface fuel loadings within those severity classes because surface fuel loadings vary independently of canopy fuels. Inferences from this study align with other studies that suggest fire severity cannot be generalized across different components of an ecosystem (Jain and Graham, 2007; Safford et al., 2009; Perry et al., 2011). In this case, fire severity in canopy fuels does not indicate a particular condition of post-burn surface fuels.

The Ball Point, Cold Springs, and GW Fires represent a wide range of geographic, topographic, and vegetative characteristics. The fuel characteristics observed within and among these three mixed severity fires suggest that variations in fire severity can produce a diversity of post-fire fuelbeds. Differences in management practices and local site conditions likely affected our results and highlight the need to consider site differences when applying the results of this study to other locations.

Our conclusions about the relationship between fuelbed variability and fire severity may be applicable to other forests with mixed severity fire regimes in the Cascade Range and beyond, but additional data are needed for verification. This baseline dataset from the Cascade Range can be included in an analysis of regional similarities and differences among mixed severity fire regimes. Furthermore, these data provide a starting point for future research that measures changes in post-fire fuels over time. It may be possible to identify additional differences in fuel characteristics among severity classes if another metric for fire severity is used, if fire severity is classified at a finer scale, or if more plots within each severity class are sampled. Analysis of additional fuel properties, such as fuel coverage, fuel continuity, or herbaceous fuel loading may reveal other important relationships.

Variability is both a historical norm and a future restoration goal in many forests with mixed severity fire regimes. Management objectives that aim to capture that variability within and among fuelbeds can guide future restoration efforts. Scale of variability for all fuels strata is an important consideration in the planning and layout of restoration activities. Therefore, additional data on scale of variability as well as species richness and structural complexity might be particularly valuable for restoration in forests with mixed severity fire regimes.

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Appendices A and B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2012.04.008.

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