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Is Forest Structure Related To Fire Severity? Yes, No, and Maybe: Methods and Insights in Quantifying the Answer

Theresa Benavidez Jain[1] and Russell T. Graham[1]

Abstract—*Wildfires in 2000 burned over 500,000 forested ha in the Northern Rocky Mountains. In 2001, National Fire Plan funding became available to evaluate the influence of pre-wildfire forest structure on post wildfire fire severity. Results from this study will provide information on forest structures that are resilient to wildfire. Three years of data (558 plots) have been collected from forested areas that burned in 2000, 2001, and 2002. Forests used in this study include dry ponderosa pine/Douglas-fir, cold lodgepole pine/subalpine fir, and moist western larch forests. Probability sampling of all areas within a particular fire perimeter was used to locate study sites and a sampling matrix was used to capture variation in weather, topographic setting, and pre-wildfire forest structure of which the fires represented. Fire severity (current state of soils and vegetation after the wildfire) was quantified on adjacent paired plots, with each plot representing a different forest structure. Classification trees and cluster analysis identified relations among forest structure characteristics, physical setting, and fire severity. Probability of a particular forest structure relating to fire severity was computed. This paper describes methodology used in the project, discusses challenges associated with conducting this type of study, and uses preliminary results (probabilities) from the first two years of data collection to show how forest structure relates to both crown and soil surface fire severity.*

Introduction

Fire behavior (expressed as intensity) and severity are dependent on the interaction among forest structure and composition (fuel), weather, and physical setting (Robichaud and others 2003; Rothermel 1983, 1991; Ryan 1990; Wells and Campbell 1979). In general, fuels defined as canopy bulk density (canopy weight for a given volume), live crown base height, and surface fuel conditions (amount, composition, moisture content, compactness, continuity) are key forest characteristics related to fire behavior (Albini 1976; Agee 2002; Graham and others 1999; Rothermel 1983, 1991; Scott and Reinhardt 2001). Most often the objective when altering forest fuels is not to remove fire completely from a forest, but rather to make a forest more resilient to fire and decrease a fire's unwanted and detrimental effects by altering these key forest characteristics (Agee 2002; Graham and others 1999; Scott and Reinhardt 2001).

Because fire behavior and effects are highly complex, there is still uncertainty in knowing when and where forest structure characteristics influence both wildfire behavior and/or severity, particularly during large and extreme wildfire events (Albini 1976; Carey and Schumann 2003; Cruz and others 2003; Omi and Martinson 2001; Graham 2003). In fact, there is little empirical information determining when (under what weather conditions

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and physical settings) forest structure contributes to decreasing crown-fire occurrence (Carey and Schumann 2003; Cruz and others 2003; Omi and Martinson 2002).

Moreover, it is difficult to directly quantify fire behavior (e.g., not safe for persons to closely observe fire behavior) during extreme wildfire events; however, fire severity can be evaluated for its relation to forest structure after a fire has occurred and, to a certain extent, indicate how forest structure influenced a fire's behavior. Fire behavior characteristics include rate of spread, fire line intensity, residence time, transition to crown fire, and spotting, and they are usually associated with a flaming front (Rothermel 1972, 1983, 1991; Albini 1976; Van Wagner 1977). Fire severity is dependent on what is burned and the units used for its evaluation (Simard 1991). For example, wildfire severity describes the amount of organic material consumed, its flame length, torching index, and other indicators of fire risk and fire behavior. The wildfire severity in terms of its effects on the atmosphere describes the particulates and gasses a wildfire produces and its effects on sky clarity (Finney and others 2003). In economic terms, fire severity describes the value of homes damaged, timber destroyed, or water storage losses measured in dollars (Kent and others 2003). Fire severity in relation to vegetation and soils describes the extent of char on shrubs, forest floor, rotten wood, scorch height on tree boles and crown scorch, exposed mineral soil, and the amount of soil modification (fusing of soil particles, changes in color, etc.). These descriptors and quantification of fire severity can provide interpretive possibilities as to the effect a fire would have on processes such as soil erosion, tree growth, vegetation regeneration and succession, or nutrient cycling. In addition, fire severity can relate to the fire behavior—such as all black crowns (fire severity indicator) are caused by a crown fire (fire behavior indicator), mixed black and green crowns indicate a surface fire with some torching in the crowns and green crowns with abundant organic materials remaining on the forest floor would indicate a low intensity surface fire.

In general, forest management concentrates on desired conditions to meet a particular goal or objective ranging from timber production to maintaining wildlife habitat. As indicated by the passing of the Healthy Forests Restoration Act of 2003, the development of resilient fire dependent forests is also a national emphasis. These objectives singly or in combination can be met through silviculture prescriptions that describe forest composition and structure development through time. Attributes of resilient fire-dependent forests include appropriate species, live trees, seed sources, and intact soils. Presence of these elements are important after a wildfire (Debano and others 1998; Hungerford and others 1991; Jurgensen 1997; Robichaud 2003). Because of this importance we chose to describe and quantify fire severity as the condition of the vegetation and soils after a wildfire.

The wildfires that burned in the Rocky Mountains in 2000, 2001, and 2002 provided an opportunity to study the influence that pre-wildfire forest structure has on fire severity. In addition, this replicated study will add to our knowledge of describing and quantifying fire severity. This paper introduces the study, provides some preliminary results, and provides some "food for thought" on the relation between pre-wildfire forest structure and fire severity. In this paper we present methods used in data collection, show how pre-wildfire forest structure was reconstructed from post-fire characteristics, describe ways to classify fire severity, and determine if relations between forest structure and fire severity can be identified.

Methods

Study Areas

Although this study was conducted in Montana, Idaho, Colorado, and Oregon on fires occurring in 2000, 2001, and 2003, the analysis and results of this paper only encompass data collected on sites burned during 2000 and 2001 by fires on the Bitterroot, Lolo, Kootenai, and Flathead National Forests in Montana (figure 1). In this analysis a total of 19 separate fires were sampled within the cold (lodgepole pine *Pinus contorta* and subalpine fir *Abies lasiocarpa*) moist (western hemlock *Tsuga heterophyll;* western redcedar *Thuja plicata;* and grand fir *Abies grandis*), and dry (ponderosa pine *Pinus ponderosa* and Douglas-fir *Pseudotsuga menziesii*) forests. The Bitterroot fires (eight fires) burned 144,040 ha within the cold and dry forests from July 15 through September 1, 2000. On the Lolo National Forest, three fires totaling 15,662 ha were sampled that burned from August 5 through September 6, 2000. We sampled the Moose Creek Fire in the Flathead National Forest, which burned between August 16 and October 5, 2001 and encompassed 28,723 ha of cold forest. Eight fires burning a total of 14,000 ha between July 31, 2000, and August 30, 2000, were sampled in the moist forests within the Kootenai National Forest. All fires were sampled the summer after they occurred, except for the fires on the Kootenai National Forest, which were sampled the second summer after they occurred.

Study Design

Stratified random sampling of each fire was used to ensure that the variation in forest structure, physical setting, and weather were represented within each fire. It is the interaction of these characteristics that determine fire severity (Ryan 1990, Lohr 1999). In establishing the sampling frame,

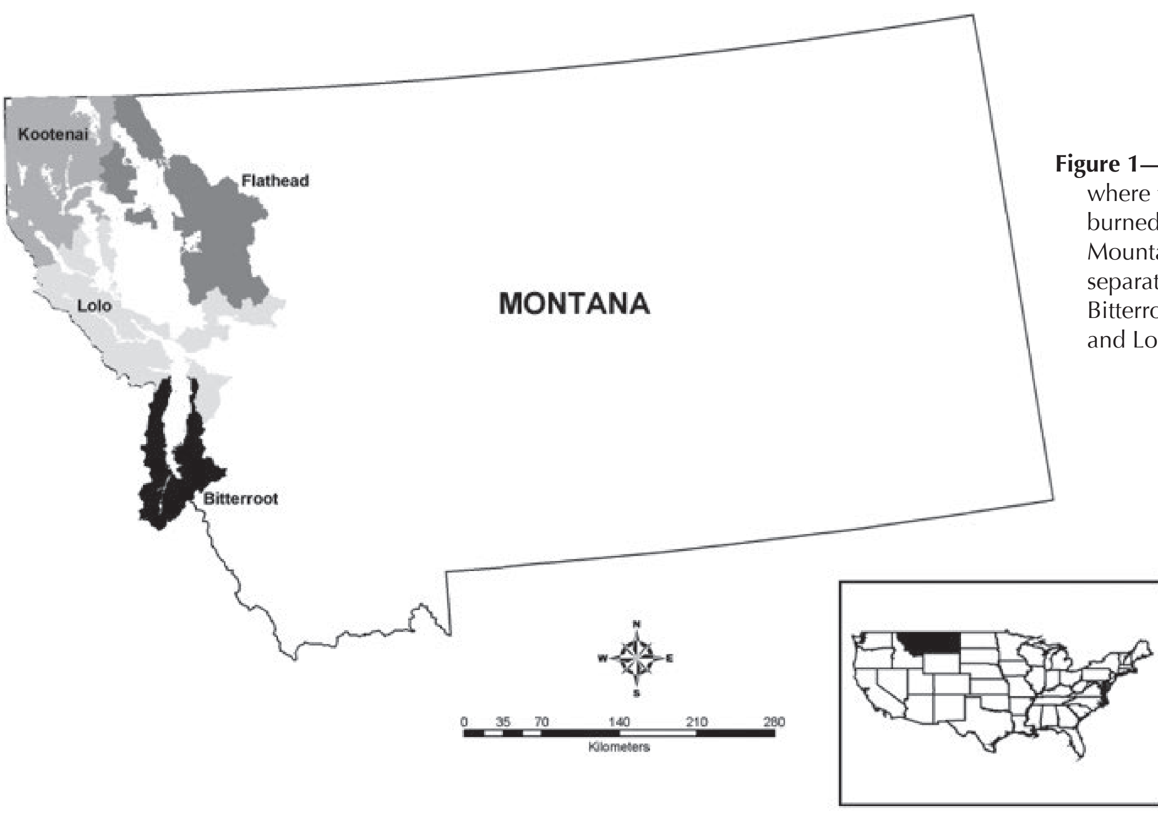

Figure 1—This map shows the area where the 2000 and 2001 fires burned in the Northern Rocky Mountains. We sampled 19 separate fires located on the Bitterroot, Kootenai, Flathead, and Lolo National Forests.

forest cover type was used to describe the broad-scale vegetation. Cover types included: ponderosa pine and/or Douglas-fir, (PP/DF), grand fir, western redcedar, and/or western hemlock (GF/C/WH), and lodgepole pine and/or subalpine fir (LPP/SAF). Within a specific cover type, burning index accounted for variation due to weather. Burning index describes the effort needed to contain a single fire within a particular fuel type within a given area. The index is based on the spread component (SC) and available energy release component (ERC) of a fire, which in turn are used to estimate flame length from which the burning index is computed (Bradshaw and others 1983, Bradshaw and Britton 2000). Wind speed, slope, fuel (including the effects of green herbaceous plants) and the moisture content of the fuels are used to determine the SC and ERC. The difference between the two components is that SC is determined on the moisture levels of the fine fuels while ERC requires moisture levels from the entire fuel complex.

Fire progression maps were used to estimate the day a particular stand burned. Using weather data for this day from the closest weather station and the most applicable fuel model for each fire, the burning index for each stand within the fire perimeter was calculated using Fire Family Plus (Bradshaw and Britton 2000). After forest cover type, the stands within the fire were stratified by high and low burning index (divided at the median burning index) for all stands burned by a particular fire. This stratification ensured that stands sampled were burned during the range of weather conditions that occurred throughout the fire.

Within each burning index class (high and low) the physical settings of the stands were placed into two strata: those with slope angles less than or equal to 35 percent and those with slope angles greater than 35 percent. In the Northern Rocky Mountains, settings with slope angles less than 35 percent usually occur on benches, within riparian areas, or along ridge tops. Settings with slope angles greater than 35 percent tend to occur on side slopes. Within a given slope class, the structure characteristics of stands were divided into those containing short, sapling- to medium-sized trees (≤13 m), and those containing tall, mature to old trees (>13 m). Within these size classes stands were divided into two density strata: those with canopy cover less than or equal to 35 percent and those with canopy cover greater than 35 percent. This stratification ensured that stands selected for sampling would have a range of horizontal structure. Therefore, the final sampling stratification contained forest cover (3 classes), burning index (2 classes), slope angle (2 classes), canopy height (2 classes), and stand density (2 classes). All stands occurring within a particular stratum and fire perimeter had an equal probability of being selected. Additional fire and physical setting characteristics not in the stratification but occurring regularly were recorded during sampling and included aspect, bole scorch height, and direction of the scorch as indicators of flame length (Van Wagner 1973) or ignition source (back fire, flank fire, or head fire).

Stand Selection

All stands within the fire perimeter contain a unique identification code. These codes were randomly assigned into the sampling matrix, which represented the designed stratification. The matrix was populated with the first 15 low-density stands that were randomly selected. Each stand was evaluated (in selection order) to determine if it (1) fit within the sampling criteria, (2) had an opportunity to burn (in some cases, stands along the fire perimeters had fire lines that prevented them from burning), (3) did not have any

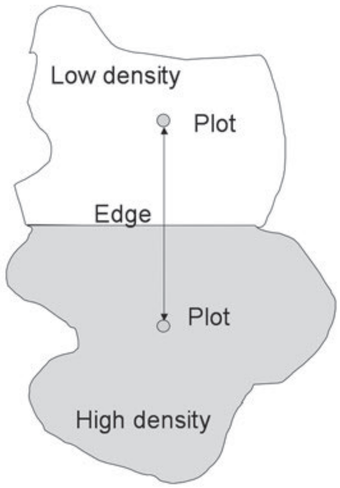

Figure 2—Illustration of paired plots between two stands. The low-density stands were paired to an adjacent stand that had a distinct change in forest structure. The adjacent stand required a change in horizontal structure (density defined by canopy cover), species composition, and/or vertical structure (number of stories). Plots were located a minimum of 50 m to plot center from stand edge.

confounding factors that may have influenced burning (e.g., fire retardant throughout, large fire lines splitting the stand), and (4) was at least 100 m by 100 m in size (large enough to establish the sample points).

In order to increase the number of stands sampled and to determine if changes in stand structure influenced fire severity in a given area, randomly selected low-density stands were paired with qualified adjacent stands (figure 2). To qualify as a paired stand it had to be adjacent to the randomly selected stand and contain a change in horizontal structure (density defined by canopy cover), species composition, and/or vertical structure (number of stories or vegetation layers). A change in stand density was defined as a differential between high and low canopy cover of at least 20 percent, (i.e., a stand with 25 percent cover was paired with a stand with no less than 45 percent canopy cover). A change in species composition was defined as a change in the cover type (e.g., lodgepole cover type to subalpine fir cover type). Vertical structure was a change in the number of stories (canopy layers) occurring in a stand, such as the selected stand containing a single story and the paired stand containing two or three stories or a selected multi-storied stand paired with a single storied stand.

Stand adjacency was determined by a rule set. The first choice for a paired stand with a different structure was downhill from the selected stand. Since fires predominantly burn uphill, this selection criteria would provide opportunities for sampling stands in which structure influenced either or both fire behavior and fire severity. If a major change in topography (such as 180^{o} aspect change, steep side slope to riparian setting, etc.) occurred downhill from the selected stand before a suitable adjacent stand was selected, an alternate selection process commenced. Beginning on the western edge of the selected stand and continuing in a clockwise direction, forest conditions were evaluated until an adjacent stand was located. Ideally, the paired stand would be similar in aspect and slope as the selected stand, but subtle changes in slope and aspect were allowed. If no suitable stand was located adjacent to the randomly selected stand, the low-density stand was not chosen and the next stand in the matrix was evaluated.

Plot Selection

The objective of this study was to quantify the relation between pre-wildfire forest structure and fire severity among stands and not to characterize fire severity within stands. Therefore, to maximize the number of stands sampled, only one plot was placed in each selected stand. The edge of a stand was defined where the forest structure changed between the paired stands (figure 2). An aerial photo or topographic map was used to obtain an azimuth intersecting the approximate center of both stands. At a minimal slope distance of 100 m from the stand edge along this azimuth, a random number between 1 and 6 was selected (using a die). This value was multiplied by 16 and an additional distance (meters) equaling this value along the azimuth was traversed before plot installation. If the stand was too small to use this additional distance, the plot was located at least 50 meters from the stand edge. The plot was monumented with a 1 m rebar stake, the location was recorded by a GPS, and distance from the stand edge was recorded.

Data Collection

Site descriptors (aspect, slope, topographic position, and elevation) and a general stand description (species composition, number of stories, stand origin, horizontal spacing) for each plot were recorded. Our intention was to post-classify or develop a continuous variable characterizing fire severity. Therefore descriptors of soils and vegetation were collected in considerable detail. Our approaches to data collection were developed or modified from past fire severity classifications (Key and Benson 2001; Ryan and Noste 1985; Wells and others 1979) (tables 1, 2, and 3). The characterization and

Table 1—Surface components, their definitions, and char classes for fire severity. Litter fallen since fire, litter prior to fire, and humus depth were measured in cm. All measurements were conducted on a 1/740th ha circular plot. Trees were less than 12.7 cm diameter breast height (DBH).

Strata	Unburned (%)	Light char (%)	Moderate char (%)	Deep char (%)
		Surface		
Litter fallen onto surface since fire	Litter type (fir or pine, leaves) with no char classes			
Litter present prior to fire	No sign of char	Blackened but present	No moderate or deep char class	
Humus (decomposed organic matter)	No sign of char	Blackened but present	No moderate or deep char class	
Bare mineral soil	No sign of char	Blackened	Gray color	Orange color
Rock	No sign of char	Black edges	Black edges	White residue
Brown cubical rotten wood	No sign of char	Burned on surface	Charred but still present	Imprint on surface
Coarse woody debris ≤7.6 cm diameter	No sign of char	Burned on surface	Charred but still present	Not present
Coarse woody debris >7.6 cm diameter	No sign of char	Burned on surface	Charred but still present	Imprint on surface
Stumps	No sign of char	Burned on surface but intact	Completely charred	Stump hole
		Shrubs and Trees		
Shrubs – low <0.60 mm basal stem dia.	Stems intact	Stems present but charred	Base of stem present	Stump hole
Shrubs – medium 60-250 mm stem dia.	Stems intact	Stems present but charred	Base of stem present	Stump hole
Shrubs – tall >250 mm stem dia.	Stems intact	Stems present but charred	Base of stem present	Stump hole
Forbs and grasses	Growing on unburned litter	Growing on blackened surface	Growing on moderate charred soil	Growing on deep charred soil
New seedlings since fire	Growing on unburned litter	Growing on Blackened litter	Growing on charred soil	Growing on deep charred soil
Trees present prior to fire <12.7 cm DBH	No sign of char	Live trees needles present	No or brown needles	Stump hole

Table 2—Fire severity data taken on large trees (>12.7 cm diameter breast height (DBH) using a fixed (1/59th acre) and variable plot (8 m² ha⁻¹). Trees less than or equal to 45 cm DBH were measured on fixed plot, and trees greater than 45 cm DBH were measured on variable plot.

Strata	Un-compacted crown ratio	Green crown (%)	Brown crown (%)	Black crown (%)	Bole scorch height (ft) and direction scorch is facing (az)		Scorch at) base (%
					Low	High	
Trees >12.7 cm DBH	Total crown ratio	Green needles	Brown needles	Black stems, no needles	Scorch height and direction	Scorch height and direction	Circumference

Table 3—Forest structural characteristics derived from the FFE-FVS (Forest and Fuels Extension-Forest Vegetation Simulator) model (Reinhardt and Crookston 2003).

Density characteristics	Characteristics related to fire behavior	Biomass characteristics (Mg/ha)	Miscellaneous characteristics
Trees per ha	Height to base of crown (ft)	Foliage biomass	Average top height
Basal area (sq. m/ha)	Canopy bulk density	Live branches <7.6 cm	Number of stories
Stand density index		Live branches >7.6 cm	Species composition
Crown competition factor		Cubic volume	Dominant species
Total canopy cover (%)		Vertical distribution of crown versus stem	Quadratic mean diameter
Sum of the diameters (cm)			Dry, cold, or moist forest
			Average top height for plot

description of soils and vegetation were accomplished using five strata: (1) soil surface, (2) grass, forbs, small shrub, and seedlings, (3) medium and tall shrubs (4) saplings and large trees, and (5) woody debris (tables 1 and 2) (DeBano and others 1998).

All strata (surface and understory vegetation) except for the large trees and woody debris were measured on a 1/740th ha circular plot. For the large trees, a combination of fixed and variable radius plots was used to ensure enough trees representing all sizes were sampled. Trees greater than 45 cm diameter breast height (DBH) were sampled using a variable radius plot defined by an 8 m² ha⁻¹ angle gauge (40 ft² ha⁻¹). Trees between 12.7 and 45 cm DBH were measured using a 1/59th ha fixed plot.

Soil surface characterization included total cover and the proportion of total cover dominated by new litter (deposition since the fire), old litter (present previous to the fire), humus, brown cubical rotten wood (rotten wood at or above the soil surface), woody debris less than or equal to 7.6 cm in diameter, woody debris greater than 7.6 cm in diameter, rock, and bare mineral soil. Each of these cover characterizations were divided into char classes (table 1). The second stratum described the proportion of grass and forbs growing on a specific charred surface. Cover proportion and number of basal stems were used to quantify small shrubs (<0.5 m tall or <0.60 mm basal stem diameter) (Brown 1976) (table 1). The number of new tree seedlings regenerated since the fires (1-year post fire) were counted and if the species was identifiable it was recorded (table 1). The medium (0.5 to 2 m tall or 60 mm to 250 mm basal stem diameter) and tall shrubs (>2 m tall or >250 mm basal stem diameter) were quantified using the same protocol as the low shrubs (table 1) (Brown 1976). The fourth stratum included saplings (<2.7 cm DBH) established prior to the fire and large (>12.7 cm DBH) trees (tables 1 and 2). The total number, species, and height of saplings were recorded and classified as to their fire severity (saplings with no char, charred saplings with brown needles, charred saplings with no needles, and a burned stump (table 1). Species, height, diameter, and uncompacted crown ratio were recorded for each large tree. The proportion of the total crown containing green needles, brown needles, no needles, or black stem was determined for each large tree. Scorch height on the stem was recorded and the circumference of scorch at the base of the stem was measured (table 2). The amount of woody debris on the site was determined using three 37 m linear transects (0, 120, and 240 degree azimuths) starting at plot center (Brown 1974).

Discussion

Fire behavior most often is described at the stand level with at least an elementary understanding of how forest structure, weather, and physical setting interact to create a given fire behavior (Albini 1976; Rothermel 1972, 1983, 1991; VanWagner 1977). In contrast, there is little understanding how these same characteristics interact to provide a specific fire severity where each fuelbed and combustion environment can create a different fire severity (Ryan and Noste 1983). In this study we described fire severity, forest structure, weather, and topographic characteristics across three forest types. The fires we sampled were all large (2000 to 144,000 ha) and burned dry fuels during extreme weather events. The variation in fire severity and fire behavior captured in these fires was beneficial since the inferences derived from the data will reflect a wide range of conditions. However, large amounts of variation can be detrimental because it often masks relations and makes the analysis challenging.

In general, fire models were developed to predict fire behavior and effects within "normal" burning conditions; however, fires used in this study burned outside "normal" weather conditions, limiting fire model use in the analysis (Albini 1976, Bitterroot National Forest 2000). To be effective, the analysis needs to maintain simplicity but be robust enough to answer a suite of questions useful to both managers and the scientific community: For example, how should forest structure be characterized when related to fire severity? How should fire severity be defined to provide ecological understanding as well as analytical power? Can relations between forest structure and fire severity be determined and if so, which combinations of variables best describe these relations? Is there a relation between fire severity observed on tree canopies and those associated with the soil surface and lower vegetation?

Characterizing Forest Structure

The Fire and Fuels Extension (FFE: Reinhardt and Crookston 2003) to the Forest Vegetation Simulator (FVS: Wykoff and others 1982) was used to characterize pre-wildfire forest structure. The Northern Rocky Mountain variant of FFE-FVS provided relative values of forest structure characteristics using the data collected at each sample point (e.g., tree DBH, crown ratio, total height, and species). Forest structure characteristics derived from FFE-FVS included stand density indices (basal area per ha, stand density index, trees per ha, etc.), characteristics associated with fire behavior (canopy bulk density and height to the base of the live crown), biomass estimates of foliage and branches, and other miscellaneous stand characteristics (number of stories, dominant species, etc.) (table 3).

Describing pre-wildfire forest structure based on post wildfire conditions has proven to be effective but limited. From a forest stand and tree perspective, at least in relative terms, different forest structures can be described using post wildfire data, because live tree branches and boles were seldom completely consumed in our data even during the most intense and severe fire. These post wildfire standing tree data along with FFE-FVS provided consistent data summaries within and across regions. These techniques can also be repeated within both a research and management framework and FFE-FVS provides stand structural characteristics linked to models describing fire behavior. Even with these benefits, FFE-FVS estimates of needle, branch, total biomass, canopy bulk density, number of stories, and horizontal structure are limited (Reinhardt and Crookston 2003). Subsequently, it is unknown how well they reflect true values (Cruz and others 2003). However, these relative values are extremely useful for understanding forest structure changes across sites and with the information added from this study, the capability of FFE-FVS for predicting fire severity as a function of forest structural characteristics can be improved.

Although we have good confidence in describing pre-wildfire standing tree and stand characteristics using post wildfire data, describing pre-wildfire soil surface characteristics post wildfire is problematic. Only in very limited circumstances are soil surface conditions described before a wildfire, and even recurring forest inventories such as those conducted by Interior West Forest Inventory and Analyses (e.g., USDA 1997) do not regularly describe forest floor conditions. To definitively describe or predict both fire intensity and fire severity requires pre-wildfire biomass estimates of shrub and herbaceous layers, fine and coarse surface fuels, litter, and duff. In general, fine-scale sampling is required to estimate these surface fuel characteristics, and extrapolating existing prediction equations across different regions is questionable (Brown 1976). Using habitat type, successional stage, overstory structure, or other stand or site characteristics for estimating surface fuels is limited in scope (e.g., Covington and Fox 1991, Mitchell and others 1987). A possible estimate of surface fuel conditions that existed pre-wildfire might be achieved by using scorch heights on boles of standing trees post wildfire as an indicator of flame length. In turn these data could be used to identify potential fuels and fuel loadings that could have produced these flame lengths. However, this approach for estimating pre-wildfire surface fuel conditions is highly speculative and needs thorough investigation.

Classifying Fire Severity

In our study we had the ability to describe fire severity using either continuous or categorical variables. Initially we used canonical correlation analysis using continuous variables that described soil surface fire severity such as amount of mineral soil exposed, amount of charred litter, etc. (table 1). The results from this analysis identified variables describing forest structure (e.g., basal area per ha, height, and number of stories) and the variation in fire severity on the soils and crowns and determined whether these sets of variables were related to each other. The unfortunate aspect of canonical correlation is that, although it is mathematically elegant, results are difficult to interpret (Tabachnick and Fidell 2001) because they express the data in multi-dimensional space. However, from an exploratory perspective, the analysis did reveal that the relations between soil surface fire severity and forest structure are multivariate. The variability in these data is best described in three dimensions (up to 97 percent). Because the relations between soil surface fire severity and stand structure are multivariate, there are many soil and overstory variables that describe the relations among tree and stand characteristics and soil surface fire severity. This finding quickly showed that no single overstory characteristic such as tree density controls the impact wildfires have on soil surface fire severity; rather, combinations of structural characteristics interact to determine how a wildfire impacts the soil surface.

Soil characteristics relevant to fire severity included the mineral and litter components within the unburned, light char, and moderate char classes. Deep soil char did not appear to be as related to forest structure, most likely because it only occurred in isolated areas. Similarly, shrub, grass, and herbaceous cover were not important for describing fire severity because they too were not present throughout the burned areas. Therefore, it was difficult to evaluate the importance of these variables as to their relations with forest structure. Crown severity variables included percent crown scorch within the green, brown, and black scorch classes and scorch height (table 2). Variables important for describing forest structure included those associated with tree density, total biomass, biomass distribution, and vertical crown distribution (table 3).

The fire severity variables identified by the canonical correlation were used in cluster analysis to determine if the fire severity descriptors could be grouped into distinct classes. Results from the cluster analysis were disappointing in that concise clusters of fire severity (low, medium, and high) were not identified. To address this challenge, we are pursuing several avenues, such as using ordination techniques to determine if fire severity can be analytically classified. In addition to attempting to classify fire severity analytically, we also are attempting to identify meaningful thresholds noted in the scientific literature (e.g., Hungerford and others 1991; Johansen and others 2001; Niwa and others 2001; Jurgensen and others 1997).

Relationship Between Forest Structure and Fire Severity

To evaluate whether a relation between forest structure and fire severity could be determined, we post-classified fire severity using variables identified in the canonical correlation analysis and supplemented these classifications with information on fire effects on soils and vegetation (Omi and Kalaokidis 1991; Ryan and Noste 1980; Wells and others 1979). However, the classifications we developed are preliminary and may change depending on further investigation. The purpose for using our current fire severity classifications is to investigate ways to identify relations between forest structure and fire severity.

The fire severity classification for tree crowns used four classes: (1) entire crown contained green needles (no sign of fire), (2) crown dominated by green needles but with the presence of brown needles and/or blackened crowns (charred branches with all needles consumed by the fire), (3) crown dominated by brown needles but with the presence of some green and/or black branches, and (4) crown dominated by black branches with only a trace of brown needles. We separated scorched trees from totally black trees because when brown needles fall to the forest floor they decrease soil erosion and provide organic matter to the soil (Jurgensen and others 1997, Pannkuk and Robichaud 2003). Therefore, fire severity was considered less severe on sites with brown needles present on trees compared to trees where all needles were consumed. After each tree was assigned a fire severity class, these data were summarized to an average crown fire severity for the plot. These values were placed into a severity class and used in the analysis. An average

Table 4—Cross-validation matrix showing how well the overall model correctly classified tree severity. The values on the diagonal provide the probability of correctly classifying the actual fire severity given the forest structure variables used in the model.

	Predicted class			
Actual class	**No fire**	**Green crowns**	**Brown crowns**	**Black crowns**
No fire	0.62	0.17	0.10	0.11
Green crowns	0.05	0.40	0.39	0.16
Brown crowns	0.08	0.39	0.35	0.48
Black crowns	0.11	0.28	0.26	0.34

crown severity between 1 and 1.50 was classified as green (class 1), average crown severity between 1.51 and 2.50 was classified as green to brown (class 2), an average crown severity between 2.51 and 3.50 was classified as brown (class 3), and an average crown severity >3.50 was classified as black.

The results from the canonical correlation indicated that litter and mineral soil in all char classes were related to soil surface fire severity. Moreover, surface organic matter (litter, humus, and brown cubical rotten wood) plays many roles in forest nutrition (Jurgensen and others 1997). Therefore, soil severity classes were based on the presence or absence of surface organic materials and their level of burning. The soil surface fire severity classes were defined as follows: unburned litter dominated the plot (class 1), lightly burned litter dominated the plot (class 2), unburned or lightly burned mineral soil dominated plot with litter present (class 3), moderately burned mineral soil dominated plot with litter present (class 4), and 100 percent of plot exhibited burned mineral soil with no litter present (class 5).

To identify relations between forest structure (only overstory forest structure characteristics were used) and both crown and soil surface fire severity, we used a nonparametric classification and regression tree (CART) technique (Steinberg and Colla 1997). CART does not require the normalization of data through transformations, making the results readily interpretable; it identifies interactions, maximizes homogeneity within a particular classification, and can conduct internal cross-validation (checks how a model generalizes to new data) among classes (see table 4 for cross-validation matrix). Most of our forest structure data were continuous (table 3) and our fire severity data categorical, which can be problematic for many analytical techniques that attempt to relate the two. However, CART partitions data using a binary decision process making it appropriate for both categorical and continuous data. CART produces trees with "nodes" showing where splits in the classifications occurred. Based on decision rules, CART classifies observations until either (1) every observation in the outcome is classified correctly or (2) the outcome contains equal proportions of classes or contains the minimum number of observations specified. In this particular analysis, we specified a minimum number of 30 observations left in the node. Forest structure characteristics occurring at the top of a classification tree provide an indication that they were clearly related to fire severity, compared to characteristics that appear later in the tree. CART can also identify thresholds in relations. For example, when crown base height was identified as an important characteristic for describing crown severity, it occurred at the top of the tree; CART then identified the crown base height at which the greatest number of observations were classified correctly (figure 3a). In addition, CART provides a probability of this relationship (figure 3b).

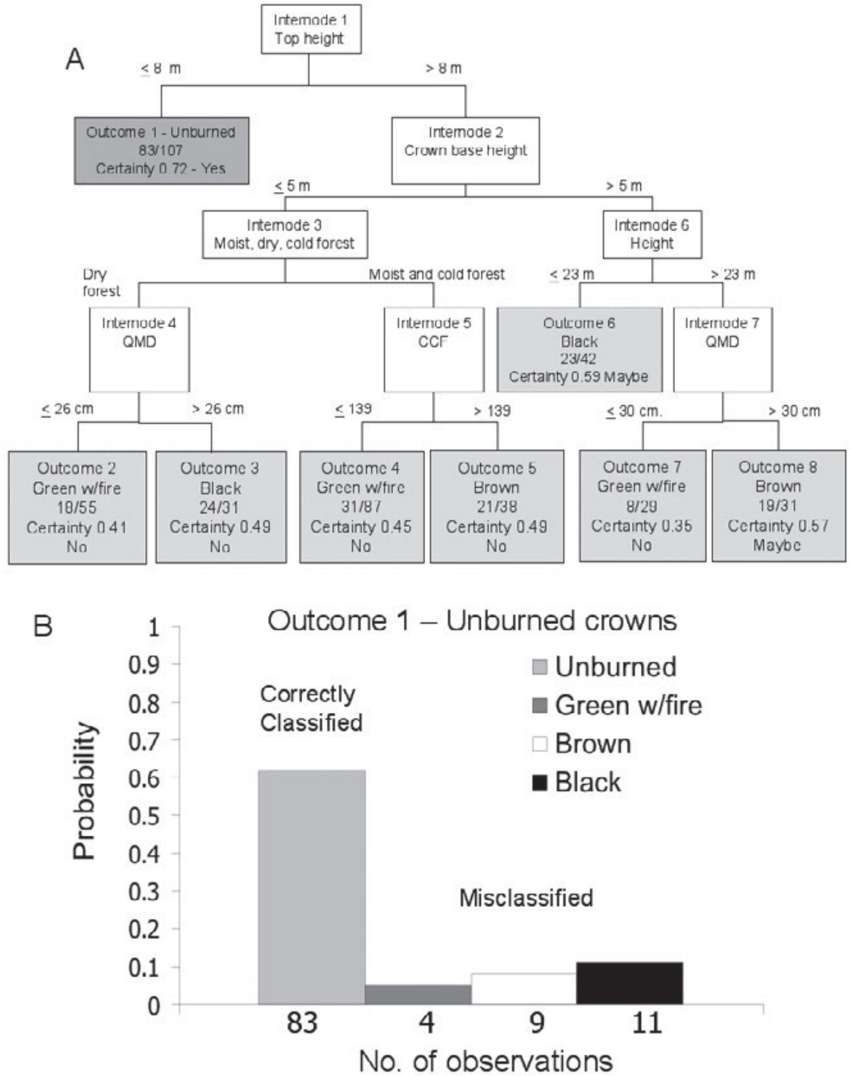

Figure 3—Figure 3a shows an eight-outcome-node classification tree used for predicting crown scorch as a function of pre-wildfire forest structure. Outcomes (shaded, 1 through 8) show number of observations correctly classified, total number of observations, probability of certainty, and whether or not the forest structure characteristic is related to crown scorch (yes, no, or maybe). The lower the probability of certainty the more likely there is no relationship. Internodes (non-shaded, 1 through 7) show the forest structure characteristics used in the split and the threshold where the split occurred (e.g., top height ≤8 m went left to outcome 1). Forest structure characteristics used to split the data at the internodes included top height (m), crown base height (m), forest type (dry, moist, and cold), quadratic mean diameter (QMD), and crown competition factor (CCF). **Figure 3b** illustrates the probabilities after cross-validation associated with predicting unburned crowns (Outcome 1, figure 3a). In this outcome, there is a 0.62 probability that trees less than ≤8 m tall were correctly classified as having unburned crowns (83 of 107 observations). Twenty-four observations were misclassified that actually contained green crowns with fire, brown crowns, or black crowns. Crown severity was placed into four classes. Unburned class was where the crown had green needles and no sign of fire. The green crown with fire class was where green needles dominated the entire crown, with the presence of scorched brown needles and/or black branches. Brown crown class was where entire crown was dominated by scorched brown needles but may have had green or no needles left. Black crown class was where the entire crown was scorched with no needles left or the crown had very few scorched needles.

There are several ways to measure forest density; for example, basal area per hectare, crown competition factor (CCF), total cubic feet per ha, trees per ha, and canopy bulk density. Both in CART and in canonical correlation analysis, canopy bulk density (key variable used in fire models) as calculated by FFE-FVS when included with other density measurements was never involved in any relations with fire severity. However, when canopy bulk density was the only density measurement used, it was included in the relationships. Similar results where noted by Omi and Martinson (2001) when they related canopy bulk density to fire severity. We inferred from this result that canopy bulk density might not reflect variation in density among sites as well as other density measurements such as CCF or basal area per ha.

Forest Structure and Crown Severity

The results from CART were encouraging because they identified forest structure characteristics that were related to fire severity, plus they provided an indication of the strength and weaknesses of these relations. When predicting crown severity as a function of pre-fire overstory forest structure, the model explained 36 percent of the variation in the data. This particular model performed fairly well at classifying sites with no evidence of fire in tree crowns versus areas that tended to contain trees with burned crowns. Sites containing non-burned tree crowns had a 0.62 probability of being correctly classified. In contrast, the model showed a 0.40 probability of classifying burned sites with green crowns present, a 0.35 probability of classifying trees with brown crowns, and a 0.34 probability of classifying trees with no needles left after the fire (table 4).

The classification tree contained eight outcomes as a function of forest structure (figure 3a). Outcomes (shaded) show the number of observations correctly classified, total number of observations, and the outcome's certainty (the probability of correctly classifying the fire severity on a new observation not included in the CART model). Internodes show the forest structure characteristics used in the split and the threshold where the split occurred (e.g., top height ≤8 m went left to outcome 1). The first split in the tree was top height at 8 m tall (figure 3a). There were 107 observations in outcome 1, which contained trees ≤8 m tall, 83 of the plots were correctly classified as containing unburned crowns resulting in a 0.72 probability of certainty. Outcome 1 indicates that, yes, there is a relationship between top height and fire severity.

The certainty of other outcomes is much less when compared to outcome 1. Moreover, a combination of forest structure characteristics is required to obtain one or more of these other outcomes (outcomes 2 through 8). For example, two outcomes (6 and 8) might (maybe) have a relation between forest structure (combination of top height, crown base height, and tree diameter) and crown severity (figure 3a). In outcome 6, trees were between 8 and 23 m (internode 1 and 6) tall and have crown base heights >5 m (internode 2), which resulted in a 0.59 probability of certainty where 23 of the 42 observations were classified correctly. Outcome 8 contains trees taller than 23 m that have crown base high heights >5 m and have a diameter >30 cm with a 0.57 probability of certainty. These outcomes either contained black or brown crowns indicating these characteristics tend to favor high fire severities in the crowns.

The other outcomes (2, 3, 4, 5, and 7) all have certainty probabilities <0.50 and can either contain black, green crowns with fire present, or brown crowns (figure 3a). Several observations were misclassified, indicating a substantial amount of variation in these outcomes. Outcome 7 was classified as containing green trees with an indication of fire; it contained crown base heights >5 m with diameters <30 cm but its probability of certainty was only 0.35. Upon further investigation, seven observations contained green trees with no sign of fire, and the residual observations contained either brown or green crowns. This ambiguous outcome may be a function of our fire severity classification and probabilities may improve with different breaks in our crown severity rating.

The strength of this model is identifying that young stands (short) with top heights less than 8 m have a low crown severity rating (green crowns) (figure 3b). After cross-validation, there is a 0.62 probability that areas with short trees (<8 m tall) were fairly resilient to fire; however, 20 observations still experienced moderate to high (brown or black) fire severities (figure 3b). There were several observations that were correctly classified and 24 of the 107 observations were misclassified.

Another important aspect of the model is to observe the entire classification tree to determine which forest structure characteristics were related to fire severity and which characteristics have either no relationship or a weak relationship to fire severity. Based on location of splits (figure 3a) (top versus bottom) and which structure characteristics were used in the splits, this model indicates that top height and crown base height play more of a role in relating to fire severity than density or size (QMD)—particularly top height, since it was the first variable used in the tree and was related to sites that contained no fire.

Forest Structure and Soil Severity

The relation of soil surface fire severity to forest structural characteristics was weak at best. The overall model explained 20 percent of the variation, and the only factor that was somewhat related to soil surface fire severity was tree height (figure 4). Observations with trees ≤15 m tall, tended to have unburned litter, but there were many observations that were incorrectly classified (139 observations) (figure 4). If sites contained trees >15 m tall,

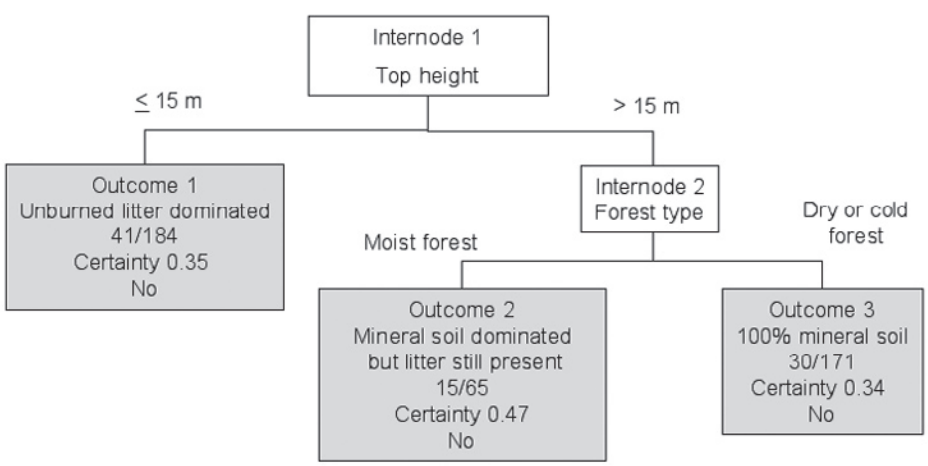

Figure 4—A three-outcome-node classification tree used for predicting soil fire severity as a function of pre-wildfire forest structure. Outcomes (shaded, 1 through 3) show number of observations correctly classified, total number of observations, probability of certainty, and whether or not the forest structure characteristic is related to crown scorch (yes, no, or maybe). The lower the probability of certainty the more likely there is no relationship. Internodes (non-shaded, 1 and 2) show the forest structure characteristics used in the split and the threshold where the split occurred (e.g., top height ≤15 m went left to outcome 1). Forest structure characteristics used to split the data at the internodes included top height (m) and forest type (dry, moist, and cold). Soil fire severity was defined as (1) unburned litter dominated the plot, (2) lightly burned litter dominated the plot, (3) unburned or lightly burned mineral soil dominated plot, litter still present, (4) moderately burned mineral soil dominated plot, litter still present, and (5) 100 percent of plot is mineral soil no litter present.

the classification tree split the difference in soil surface fire severity based on forest cover type (moist versus dry and cold forests). If sites occurred on moist forests they tended to have less severe soil surface fire severity (<100 percent mineral soil exposure with litter present) than when they occurred on either dry or cold forests (100 percent mineral soil exposure). Because of the low estimates of certainty (<0.47) and the misclassification of many observations, we inferred from this analysis that a relation between overstory forest structure and soil surface fire severity may not exist. Several factors may have contributed to these results: (1) overstory trees have little or no relation to soil surface fire severity, (2) fire severity for the soils is poorly classified, and (3) structural characteristics as currently defined are not related to soil surface fire severity.

Conclusion

Although these results are preliminary, they do provide an indication that data from this study will provide information on the relation between forest structure and wildfire severity. It will: (1) provide key structural characteristics related to fire severity, (2) identify thresholds in structural characteristics so they can be applied when treating forest stands, 3) provide useful results that can be incorporated into models, (4) give an estimate of risk or certainty of a particular fire severity within a stand containing identified structural characteristics, and (5) provide empirical probability distributions showing the relations between fire severity and forest structure, which we currently lack.

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