The Relation Between Tree Burn Severity and Forest Structure in the Rocky Mountains[1]

Theresa B. Jain and Russell T. Graham[2]

Abstract
Many wildfire events have burned thousands of hectares across the western United States, such as the Bitterroot (Montana), Rodeo-Chediski (Arizona), Hayman (Colorado), and Biscuit (Oregon) fires. These events led to Congress enacting the Healthy Forest Restoration Act of 2003, which, with other policies, encourages federal and state agencies to decrease wildfire risks by evaluating, prioritizing, and implementing vegetation treatments across large landscapes. Land management agencies, and society, have high expectations that vegetation (fuel) treatments and forest restoration activities will moderate fire behavior (intensity) and its effects, resulting in the enrichment of forest values. However, the uncertainty of these relations is unknown, preventing forest managers from communicating their confidence in the effectiveness of fuel treatments in reducing risk of wildfires. To address this uncertainty, we observed the relation between pre-wildfire forest structure and burn severity across cold, moist, and dry forest types. We used a combination of collaborative studies and field data from 73 wildfire events in Idaho, Oregon, Montana, Colorado, Arizona, and Utah (which burned between 2000 and 2003) to obtain over 900 observations. We used a multiple spatial scale approach to provide insight into how physical setting, weather, and site-specific forest structures relate to tree burn severity, with conditional probabilities that provide an estimate of uncertainty. The burn severity classification we developed integrates fire intensity, fire severity, and the forest's response to wildfire. Forest and wildfire characteristics that determine tree burn severity are: a particular wildfire group, tree canopy base height, total forest cover, surface fuel amount, forest type, tree crown ratio, and tree diameter. Because of the study's wide breadth, results from it are applicable throughout the Rocky Mountains.

Introduction
In recent years, the Bitterroot (Montana), Rodeo-Chediski (Arizona), Hayman (Colorado), Biscuit (Oregon), and numerous other wildfire events have burned thousands of hectares (acres) across the western United States (Bitterroot National Forest 2000, Graham 2003, Graham et al. 2004). These events directed forest management activities towards developing and maintaining forests resilient and/or resistant to wildfire (Stephens and Ruth 2005). For example, the Healthy Forest Restoration Act of 2003, and the National Fire Plan, encouraged federal and state

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[2] Foresters, Fire Sciences Laboratory, Rocky Mountain Research Station, USDA Forest Service, 5775 Highway 10 West, Missoula, MT 59808.

agencies to evaluate, prioritize, and implement vegetation treatments across large landscapes, in order to decrease the risk of wildfires (USDA Forest Service 2004). The focus of these vegetation treatments will most likely occur in the wildland urban interface, municipal watersheds, habitats of threatened and/or endangered species, and other places that contain values important to forest users and stakeholders. Land management agencies and society have high expectations that vegetation (fuel) treatments and forest restoration activities will moderate fire behavior (intensity), and its effects, resulting in sustaining many cherished forest values.

Although canopy bulk density, fuel models, canopy base height, and other forest metrics have been related to fire behavior using physical laws, controlled experiments, and models (Graham et al. 2004, Peterson et al. 2005, Scott 1998, Scott and Reinhardt 2001), there is limited information to indicate how forest structure is related to fire behavior and burn severity (what is left and its condition) during a wildfire event (Broncano and Retana 2004, Loehle 2004, Weatherspoon and Skinner 1995). Moreover, the uncertainty of these relations is unknown, preventing forest managers from communicating their confidence in the effectiveness of fuel treatments in reducing the risk of wildfires and effects on forest values. Without these estimates, managers and forest stakeholders could have a false sense of security and a belief that if a wildfire occurs after a fuel treatment, the values they cherish (for example, homes, wildlife habitat, community water sources, sense of place) will be protected and maintained both in the short- (months) and long- (10s of years) term.

Our objective is to define and quantify the relation between forest structure and burn severity, and to determine the uncertainty of the relations (Jain and Graham 2004). Although other studies have quantified this relationship, they often were limited in scope and applicability (Carey and Schumann 2003, Martinson and Omi 2003). To avoid these shortcomings, we designed our study to sample many wildfires (73) that burned in different years throughout the inland western United States. Because of the study's scope, it incorporated a large amount of variation in forest structure as well as disparity in burn severity after extreme wildfires. The data we collected came from wildfires that burned in the moist, cold, and dry forests between 2000 and 2003. By studying wildfires that burned throughout the inland western United States (and in different years), we were able to include a variety of weather, which occurred during the fires, and physical settings in our sampling. The relations between forest structure and burn severity and the uncertainty of these associations after intense and severe wildfires will provide information that could be used in evaluating fuel management decisions throughout the moist, cold, and dry forests of the inland western United States.

Methods

Using intensive, extensive, and focused watershed sampling, we visited 73 wildfire events that burned between 2000 and 2003 in Montana, Idaho, Colorado, Oregon, Utah, and Arizona (*tables 1, 2, 3, fig. 1*). These wildfires occurred in the dry (ponderosa pine, *Pinus ponderosa* Dougl. ex Laws and Douglas-fir, *Pseudotsuga menziesii* [Mirb.] Franco), moist (western hemlock, *Tsuga heterophylla* [Raf.] Sarg., western redcedar, *Thuja plicata,* Donn ex D. Don grand fir, *Abies grandis* [Dougl. ex D. Don] Lindl., white fir, *Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), and cold (lodgepole pine, *Pinus contorta* Dougl. ex Loud., and subalpine fir, *Abies lasiocarpa*, [hook.] Nutt.) forests throughout the inland western United States. Since not all forest classifications burned in a single year, we included multiple years in our

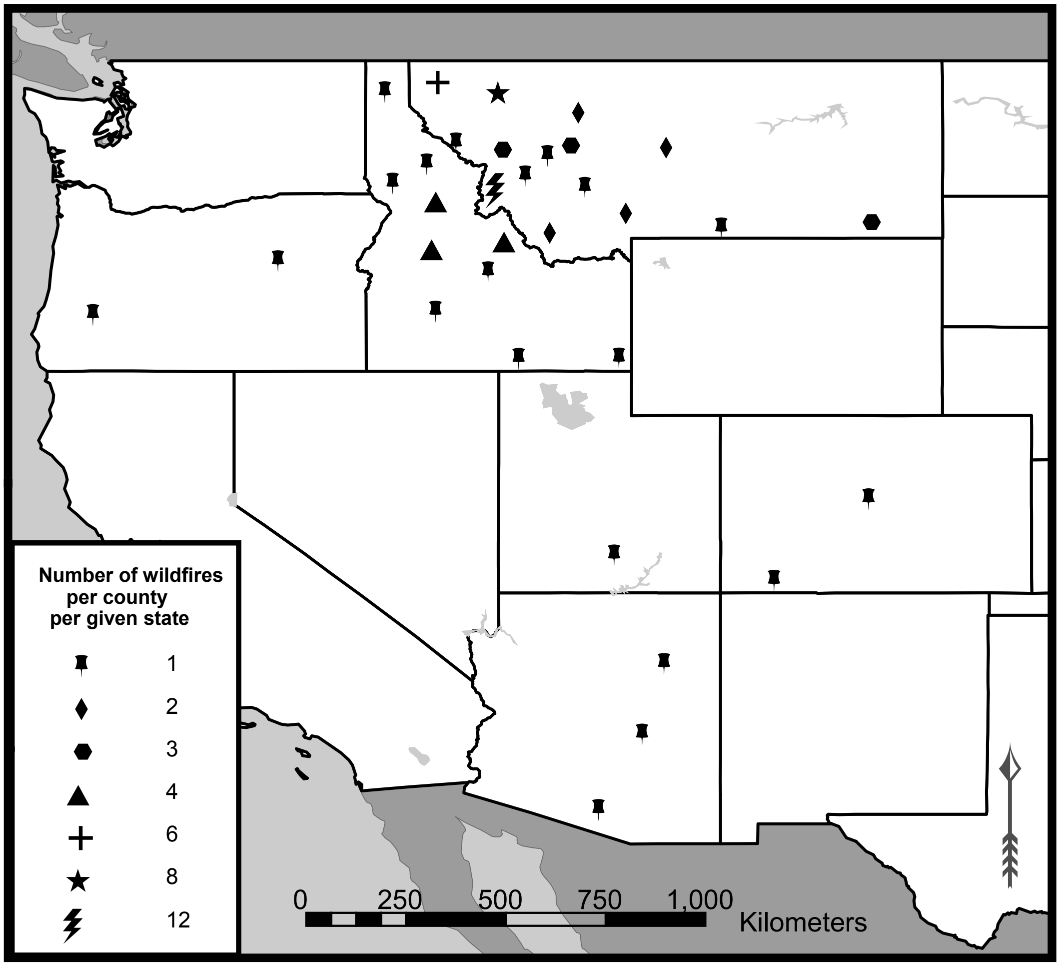

Figure 1—Distribution of the 73 fires that burned between 2001 and 2003. The symbol indicates the number of fires within a state's county. Counties and names of fires appear in *tables 1, 2, and 3*.

data collection. This enabled us to incorporate moist forest wildfires in our study, which tend to burn less frequently when compared to other forests. All areas were sampled the summer after they burned, except areas in Flathead and Lincoln counties in Montana and the Diamond Peak complex of fires in Idaho, which burned in 2000. These were sampled the second summer after they burned (*tables 1, 3*).

Sampling Designs

Fires were selected based on whether they occurred in moist, cold, or dry forests. Initially, all fires that burned in Idaho and Montana during 2000 and 2001 were sampled. We concentrated on wildfires in Colorado that burned in dry forests in 2002 to increase observations in these forest types. In 2004, we focused on wildfires that occurred only in moist forests that burned in 2003. We used three sampling designs to capture the variation in burn severity occurring at different spatial scales. The intensive sampling occurred in wildfires that burned between 2000 and 2003 and was led by Theresa Jain (US Forest Service, Rocky Mountain Research Station) (*table 1*). This extensive sampling revisited previously established Forest Inventory and Analysis (FIA) plots that burned in Montana and Idaho in 2000, in Montana in 2001, and in Arizona and Utah in 2002 (*table 2*). Using the FIA plots, we were able

Table 1—*The intensive sampling involved selecting a specific set of wildfires. The table describes the county and state where the fire occurred. For each fire, we included the fire name and number of observations (no. of obs.). We obtained daily weather for each fire, beginning with the fire weather start date (month/day/year) and continuing through to the end date. We also included fire start date, fire control date, the date the fire was out, and the estimated number of hectares each fire burned. In some places, we were unable to obtain specific dates (no date).*

			Fire weather		Wildfire			
County	**Fire name**	**No. of obs.**	**Start date**	**End date**	**Start date**	**Control date**	**Date out**	**Size (ha)**
				Colorado				
La Plata	Missionary Ridge	33	6/9/02	7/19/02	6/9/02	7/19/02	No date	29,591
Park	Hayman	62	6/8/02	6/28/02	6/8/02	6/28/02	7/7/02	55,749
				Idaho				
Bonner	Myrtle Creek	20	8/16/03	8/28/03	8/16/03	8/26/03	8/28/03	1,396
				Montana				
Beaverhead	Mussigbrod/ Maynard	5	7/31/00	10/6/00	7/31/00	10/6/00	11/6/00	18,891
Flathead	Fan Creek	7	8/10/00	8/16/00	8/10/00	8/16/00	8/20/00	318
Flathead	Moose	50	8/14/01	10/15/01	8/14/01	10/15/01	11/5/01	28,733
Flathead	Roberts	19	7/23/03	10/29/03	7/23/03	10/29/03	No date	23,178
Flathead	Taylor	4	8/10/00	10/31/00	8/10/00	9/20/00	10/31/00	531
Flathead	Young J	4	8/10/00	9/1/00	8/10/00	9/1/00	10/15/00	354
Lincoln	Cliff Point/ Lydia/Kelsey	26	8/11/00	9/13/00	8/11/00	9/13/00	10/30/00	5915
Lincoln	Stone Hill	29	8/11/00	9/13/00	8/11/00	9/13/00	10/30/00	4,498
Lincoln	Upper Beaver	31	8/11/00	9/25/00	8/11/00	9/25/00	10/30/00	3651
Mineral	Alpine Divide	16	8/3/00	9/22/00	8/3/00	9/22/00	10/27/00	1,503
Mineral	Landowner	1	8/11/00	9/12/00	8/11/00	9/12/00	No date	2,319
Missoula	Crazy Horse	20	8/6/03	10/17/03	8/6/03	10/17/03	11/21/03	4,573
Missoula	Ninemile	41	8/3/00	9/22/00	8/3/00	9/22/00	10/27/00	7,073
Missoula	Flat Creek	16	8/4/00	9/12/00	8/3/00	9/12/00	11/20/00	4,047
Ravalli	Bear	159	7/31/00	10/30/00	7/31/00	10/30/00	No date	58,696
Ravalli	Blodget	4	7/31/00	10/31/00	7/31/00	11/1/00	11/9/00	4,649
Ravalli	Coyote	8	7/31/00	9/2/00	7/31/00	9/2/00	12/1/00	8,903
Ravalli	Razor	14	8/5/00	10/23/00	8/5/00	10/23/00	11/6/00	5,342
Ravalli	Taylor Springs	2	7/31/00	10/23/00	7/31/00	10/23/00	11/6/00	8,696
Valley	Little Pistol	10	8/10/00	10/12/00	8/10/00	10/20/00	11/1/00	25,803
				Oregon				
Grant	Flagtail	45	7/15/02	9/4/02	7/15/02	9/4/02	No date	3,296

to sample several fires, but with few observations per fire (*table 2*). David Atkins (US Forest Service, Northern Region), Mike Wilson (Interior West Forest Inventory and Analysis Program, Rocky Mountain Research Station) and Theresa Jain led this effort. The focused watershed sampling quantified forest structure and burn severity within watersheds (142 ha to 6,475 ha, 350 to 16,000 ac) using remotely sensed data corroborated with ground-truth data (*table 3*). This sampling was led by David S. Pilliod (California Polytechnic State University), in collaboration with Theresa Jain.

Table 2—*The extensive sampling involved revisiting forest inventory and analysis (FIA) plots that burned during the 2000 (Idaho and Montana) and 2001 (Montana) wildfires. The table describes the state and county where the fire occurred, the fire name, and number of observations (no. of obs.). We obtained daily weather for each fire, beginning with the fire weather start date (month/day/year) and continuing through to the end date. We also included the fire start date, fire control date, the date the fire was out, and the estimated number of hectares each fire burned. In some places, we were unable to obtain specific dates or estimates of size (no date, no est.). For the fires in Arizona, we did not obtain weather data.*

			Fire weather		Wildfire			
County	Fire name	No. of obs	Start date	End date	Start date	Control date	Date out	Size (ha)
				Arizona				
Gila	Packrat complex	1	No date	No date	8/15/02	9/2/02	9/2/02	1,404
Navajo	Rodeo/ Chediski	2	No date	No date	6/18/02	7/2/02	7/7/02	189,651
Pima	Bullock	1	No date	No date	5/21/02	6/2/02	6/10/02	12,368
				Idaho				
Cassia	STF Assist 5	3	7/15/00	10/10/00	7/15/00	10/15/00	No date	No est.
Clearwater	Elizabeth	1	8/3/00	10/10/00	8/3/00	10/10/00	10/13/00	1,318
Custer	Rankin	1	8/10/00	9/2/00	8/10/00	9/2/00	11/6/00	2,715
Elmore	Trail Creek	5	8/15/00	10/11/00	8/15/00	10/13/00	No date	14,081
Idaho	Burnt Flats	2	8/10/00	9/8/00	8/10/00	9/8/00	10/25/00	9,116
Idaho	Butts	2	7/31/00	10/14/00	7/31/00	11/1/00	11/27/00	10,538
Idaho	Fitz	1	7/15/00	10/15/00	7/15/00	10/15/00	No date	445
Idaho	Hamilton	3	7/15/00	10/15/00	7/15/00	10/15/00	No date	No est.
Idaho	Lonely	5	7/30/00	10/22/00	7/30/00	10/23/00	11/1/00	7,874
Idaho	Papoose	1	8/10/00	10/1/00	8/10/00	11/1/00	11/22/00	1,207
Idaho	Thirty	1	7/15/00	10/15/00	7/15/00	10/15/00	No date	No est.
Idaho	Three Bears	1	7/31/00	10/30/00	7/31/00	10/30/00	10/30/00	6,086
Lemhi	Clear Creek	3	7/8/00	11/01/00	7/8/00	12/1/00	12/11/00	69,661
Lemhi	Morse	1	8/10/00	10/9/00	8/10/00	10/10/00	10/16/00	2,329
Lemhi	Packer Meadow	1	8/6/00	11/1/00	8/5/00	11/1/00	11/27/00	2,226
Lemhi	Shellrock	5	8/10/00	10/31/00	8/10/00	11/1/00	11/27/00	30,042
Lewis	Maloney Creek	1	7/15/00	10/15/00	7/15/00	10/15/00	No date	No est.
Valley	Diamond Peak	9	8/10/00	10/31/00	8/10/00	11/1/00	11/27/00	30,042
Valley	Indian Creek	1	7/15/00	10/12/00	7/15/00	10/12/00	No date	1,133
				Montana				
Beaver-head	Bear/Maynard	2	7/31/00	10/30/00	7/31/00	10/30/00	No date	18,891
Beaver-head	Mussigbrod/ Maynard	7	7/31/00	10/6/00	7/31/00	10/6/00	11/6/00	18,891
Carbon	Willie	1	8/27/00	9/6/00	8/27/00	9/6/00	9/6/00	608
Flathead	Bald Hill	2	8/12/00	8/20/00	8/12/00	8/20/00	No date	No est.
Flathead	Chipmunk	1	8/11/00	10/1/00	8/11/00	10/1/00	10/1/00	1,267
Flathead	Helen Creek	2	7/23/00	10/31/00	7/23/00	10/31/00	12/6/00	666
Gallatin	Beaver Creek	2	8/10/00	9/2/00	8/10/00	9/2/00	10/16/00	4,371

Table 2 Continued—*The table describes the county and state where the fire occurred. For each fire, we included the fire name and number of observations (no. of obs.). We obtained daily weather for each fire, beginning with the fire weather start date (month/day/year) and continuing through to the end date. We also included the fire start date, fire control date, the date the fire was out, and the estimated number of hectares each fire burned. In some places, we were unable to obtain fire name, specific dates, or estimates of size (no date, no est.). For the fires in Utah, we did not obtain weather data.*

			Fire weather		Wildfire			
County	Fire name	No. of obs.	Start date	End date	Start date	Control date	Date out	Size (ha)
				Montana				
Gallatin	Maudlow/ Toston	6	7/15/00	10/15/00	7/15/00	10/15/00	No date	No est.
Granite	Alder	1	8/24/00	9/25/00	8/24/00	9/25/00	10/10/00	2,226
Granite	Cougar	1	7/23/00	9/25/00	7/23/00	9/25/00	No date	1,942
Granite	Ryan Gulch	3	7/23/00	10/15/00	7/15/00	10/15/00	No date	No est.
Jefferson	High Ore	1	7/15/00	8/19/00	7/15/00	10/15/00	No date	No est.
Judith Basin	Lost Fork Ridge	2	8/1/00	10/6/00	8/1/00	10/6/00	12/4/00	526
Lewis & Clark	Bunyan	1	9/15/00	11/10/00	9/15/00	11/10/00	11/10/00	479
Lewis & Clark	Cave Gulch	4	7/23/00	8/23/00	7/23/00	8/23/00	9/26/00	12,141
Lincoln	Cliff Point	1	8/11/00	9/13/00	8/11/00	9/13/00	10/30/00	No est.
Lincoln	Grambauer Face	1	8/11/00	8/20/00	8/11/00	8/20/00	10/30/00	321
Lincoln	Northwest Peaks	1	8/10/00	8/25/00	8/10/00	8/25/00	10/13/00	12
Lincoln	Stone Hill	2	8/11/00	9/13/00	8/11/00	9/13/00	10/30/00	4,498
Mineral	Alpine Divide	1	8/3/00	9/22/00	8/3/00	9/22/00	10/27/00	1,503
Mineral	Landowner	6	8/11/00	9/12/00	8/11/00	9/12/00	1/22/00	2,319
Missoula	Flat Creek	3	8/4/00	9/12/00	8/3/00	9/12/00	11/20/00	4,047
Missoula	Ninemile	2	8/3/00	9/22/00	8/3/00	9/22/00	10/27/00	7,073
Powder River	Stag	5	7/26/00	8/12/00	7/26/00	8/12/00	9/5/00	24,948
Powell	Monture/Spread	7	7/13/00	10/31/00	7/13/00	11/1/00	12/30/00	9,632
Ravalli	Bear	27	7/31/00	10/30/00	7/31/00	10/30/00	No date	58,696
Ravalli	Blodget	1	7/31/00	10/31/00	7/31/00	11/1/00	11/9/00	4,648
Ravalli	Boundary	1	7/15/00	10/13/00	7/15/00	10/15/00	No date	No est.
Ravalli	Coyote	3	7/31/00	9/2/00	7/31/00	9/2/00	12/1/00	8,902
Ravalli	Mink	1	7/31/00	8/30/00	7/31/00	8/30/00	11/6/00	271
Ravalli	Razor	1	8/5/00	10/23/00	8/5/00	10/23/00	11/6/00	5,342
Ravalli	Taylor Springs	4	7/31/00	10/23/00	7/31/00	10/23/00	11/6/00	8,695
Teton	Clear	8	7/15/00	10/15/00	7/15/00	10/15/00	No date	No est.
Teton	McDonald 2	1	7/21/00	7/30/00	7/21/00	7/30/00	11/10/00	1,758
Teton, Park	Unknown	3	No date	No date	No date	No date	No date	No est.
Flathead	Unknown	7	No date	No date	No date	No date	No date	No est.
Gallatin	Unknown	2	No date	No date	No date	No date	No date	No est.
Powell	Unknown	1	No date	No date	No date	No date	No date	No est.
				Utah				
Garfield	Sanford	1	No date	No date	6/1/02	7/1/02	No date	26,268

Table 3—*The focused watershed sampling design occurred within the Quartz fire and Diamond Peak complex. The table describes the county and state where the fire occurred. For each fire, we included the fire name and number of observations (no. of obs.). We obtained daily weather for each fire, beginning with the fire weather start date (month/day/year) and continuing through to the end date. We also included the fire start date, fire control date, the date the fire was out, and the estimated number of hectares each fire burned.*

County	Fire name	No. of obs.	Fire weather		Wildfire			
			Start date	End date	Start date	Control date	Date out	Size (ha)
				Oregon				
Douglas	Quartz	50	8/9/01	9/26/01	8/9/01	9/26/01	10/31/01	2,494
				Idaho				
Lemhi	Diamond Peak	79	8/10/00	10/31/00	8/10/00	11/1/00	11/27/00	30,042

Intensive Sampling

For each selected wildfire, we used stratified random sampling to represent the variation in forest structure, physical setting, and weather (*table 4*). In establishing the sampling frame, forest cover type (dry, moist, or cold) described the broad-scale vegetation. The stands burned within each wildfire were stratified first by forest cover type and then further stratified by high and low burning index (split at the median burning index for all stands burned by a particular wildfire). Fire progression maps were used to estimate the day a particular stand burned, and then weather data for that day was acquired from the closest weather station (*tables 1, 2, 3*). Using these weather data and the most applicable fuel model for each stand within a fire perimeter, we calculated the burning index[3] using Fire Family Plus for each stand (Bradshaw and Britton 2000). This stratification insured the stands we sampled were burned during the range of weather conditions that occurred throughout the wildfire event.

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 (*table 4*). 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. On the Hayman fire in Colorado and Flagtail fire in Oregon, we used a 25 percent slope angle to differentiate the two slope classes because the rolling topography burned by these fires tended to be moderately steep. Within a given slope class, the stands were divided into those containing short, sapling to medium sized trees ($\leq$ 12.2m, 40 ft), and those containing tall, mature to old trees (> 12.2m, 40 ft). Within these structural 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 insured that stands selected for sampling would have a broad range of horizontal

[3] Burning index describes the effort needed to contain a single fire within a particular fuel type within a given area. The index is a function of 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 et al. 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.

structures. Therefore, the final sampling stratification contained forest cover (three classes), burning index (two classes), slope angle (two classes), canopy height (two classes), and stand density (two classes) (*table 4*). Each area where a stand existed within a particular stratum and fire perimeter had an equal probability of being selected.

From the sampling frame (approximately 100s to 1000s of stands) for each wildfire, we randomly selected 15 stands. Each stand was evaluated (in selection order) to determine if (1) it met the sampling criteria, (2) had an opportunity to burn (in some cases, stands near the fire perimeters had control lines preventing them from burning), (3) did not have any confounding factors that may have influenced their burning (for example, evidence of fire retardant or other suppression activities), and (4) measured at least 100m by 100m (328 ft by 328 ft) in size (large enough to establish the sample points).

Table 4— *This sampling matrix was used to sample the 2000 Bitterroot National Forest fires for the dry forest type. Within each forest type, stands were stratified by burning index (two classes), slope angle (two classes), canopy height (two classes), and stand density (two classes L=low, H=high). This matrix was replicated between six to nine times. Similar matrices were created for each fire we sampled in the dry, moist, and cold forest types.*

Dry forest type																
Burning index	≤ 75								> 75							
Slope	≤ 35%				> 35%				< 35%				> 35%			
Height (ft)	≤ 40		> 40		≤ 40		> 40		≤ 40		> 40		≤ 40		> 40	
Density (cover) L= ≤ 35% H= > 35%	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H

The purpose of our intensive sampling was to quantify the relation between pre-wildfire forest structure and burn severity, not to characterize the variation of burn severity and forest structure within stands. Therefore, to maximize the number of stands sampled (including the full breadth of burn severity), only one plot was placed in each randomly selected stand. An aerial photograph or topographic map was used to obtain an azimuth of a line intersecting the approximate center of the stand. In stands two hectares (5 ac) and larger in size, a minimal slope distance of 100m (328 ft) from the stand edge along this azimuth and a random number between one and six was selected using a dice. This number was multiplied by 16, and additional distance (meters) equaling this value was traversed along the azimuth before plot installation. In stands less than two hectares (5 ac) in size, the plot was located 50m (164 ft) from the stand edge along the line intersecting the center of the stand. The plot was permanently located using a metal stake, and the distance from the stand edge was recorded, as were the global positioning system (GPS) coordinates.

Extensive Sampling

Interior West Forest Inventory and Analysis staff randomly located permanent forest sample points on a grid throughout the forests of the western United States (Interior West Forest Inventory and Analysis 2006). By chance, a number of the plots established by FIA burned in 2000 and 2001 wildfires. After the 2000 wildfires, all plots that burned in Idaho and Montana had burn severity quantified. After the 2001 wildfires, all fires that burned in Montana had burn severity quantified. Wildfires that burned in Utah and Arizona in 2002 were visited and burn severity was quantified as part of the annual FIA sampling (*table 2*). The FIA plots were established on different spatial grids and burned areas varied in size and location. Therefore, the number of FIA plots we could visit after a wildfire varied considerably depending on the wildfire and the sampling design established by FIA. Nevertheless, we visited all previously established FIA plots that burned in 2000 and 2001. As a result, some burned areas had multiple FIA plots sampled after a wildfire, while other areas only had one plot revisited.

Focused Watershed Sampling

The focused watershed sampling occurred within forests burned by the Quartz and Diamond Peak fire complexes in Idaho and Oregon in 2000 and 2001 (*table 3*). In contrast to other post-wildfire sampling we completed, this sampling was designed to ensure that the structure and burn severity observations we collected occurred equally in both upland and riparian areas. Using maps (GIS based), we delineated the watersheds burned by these two wildfire events and subsequently defined a 60m (197 ft) riparian zone along each side of the stream reaches. Areas outside the riparian zone within each watershed were defined as the upland zone. A minimum of twenty-five plots were randomly located within both the upland and riparian zones using a complete spatial randomness (CSR) Poisson process (Diggle 2003). By using this sampling approach, we avoided spatial autocorrelation among the plots and insured their spatial independence (Cressie 1991).

Data Collection

Intensive and focused data collection

For each randomly located plot, physical setting descriptors (aspect, slope angle, topographic position, elevation), a general stand description (species composition, number of stories, horizontal spacing), and stand origin (past harvest evidence, regeneration treatment) were recorded. Our intention was to develop a continuous variable or post-classify burn severity for both the vegetation and the forest floor. To do so, a variety of fine resolution descriptors of soil and vegetation burn severity were used or developed from past burn severity characterizations (DeBano et al. 1998, Key and Benson 2001, Ryan and Noste 1985, Wells et al. 1979) (*tables 5, 6*). However, in contrast to these classifications, our characterization concentrated on what was left after the wildfire and not on what was consumed. The characterization and description of soils and vegetation were accomplished using four strata: (1) soil surface, (2) grass, forbs, shrubs, and seedlings, (3) saplings and large trees, and (4) woody debris.

Forest floor (soil surface) characterization included total cover and the proportion of total cover dominated by the different char classes on a 1/741 ha (1/300 ac) fixed radius plot. These included new litter (deposition since the fire), old litter (present previous to the fire), humus, brown cubical rotten wood (at or above soil surface), woody debris less than or equal to 7.6 cm (3.0 in) in diameter, woody debris greater than 7.6 cm (3.0 in) in diameter, rock, and exposed mineral soil. The amount of char occurring in each of these cover characterizations was estimated using color (unburned, black, grey, or orange) (*table 5*).

Using a fixed radius plot (1/741 ha, 1/300 ac), the proportion of grass and forbs, the number of new seedlings (species recorded, if identifiable) regenerated since the

Table 5—*Surface components (strata) and char classes for quantifying burn severity are displayed. In addition to proportion of cover and char class, depths (cm) were measured for litter fallen since fire, litter prior to fire, and humus. All measurements were conducted on a 1/741 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	Not present	Not present
Humus (decomposed organic matter)	No sign of char	Blackened but present	Not present	Not present
Bare mineral soil	No sign of char	Blackened	Grey color	Orange color
Rock	No sign of char	No sign of char	Black edges	White residue
Brown cubical rotten wood	No sign of char	Burned on surface	Charred but still present	Imprint on surface
Woody debris ≤ 7.6 cm diameter	No sign of char	Burned on surface	Charred but still present	Not present
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	Charred but still charred	Stump hole
		Ground level vegetation and small trees		
Shrubs – low 0 - 0.5 cm basal stem diameter	Stems intact	Stems present but charred	Base of stem present	Stump hole
Shrubs – medium 0.51 - 2 cm stem diameter	Stems intact	Stems present but charred	Base of stem present	Stump hole
Shrubs – tall 2.1 - 5 cm stem diameter	Stems intact	Stems present but charred	Base of stem present	Stump hole
Forbs and grasses	Growing on unburned litter	Growing on blackened litter	Growing on grey charred soil	Growing on orange charred soil
New seedlings since fire	Growing on unburned litter	Growing on blackened litter	Growing on grey charred soil	Growing on orange 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

fire, and both proportion and number of basal stem diameters for shrubs were estimated. Shrubs were placed into three size classes. Low shrubs were defined as those less than 0.5 cm (0.2 in) basal stem diameters, medium shrubs from 0.51 cm to 2 cm (0.2 to 0.8 in), and tall shrubs from 2.1 to 5 cm (0.8 to 1.9 in) (Brown 1976). For grass, forbs, and new (post-fire) seedlings, the proportion growing on a specific charred surface was recorded, while the char class was defined by their condition (*table 5*).

Small trees (saplings), those less than 12.7 cm (5.0 in) diameter breast height (1.4m, 4.5 ft), were quantified using a 1/741 ha (1/300 ac) circular plot. The total number, species, and height were recorded and classified as to burn severity. Char class was defined by the condition of the saplings (*table 5*). To quantify large tree burn severity, we used a combination of fixed and variable radius plots. A 1/59 ha (1/24 ac) fixed plot was used for trees 12.7 cm (5.0 in) and greater. However, fixed plots tend to insufficiently quantify very large trees and in these situations a variable radius plot based on tree size is preferred (Avery 1967). To insure we quantified large trees, we used a variable radius plot where plot size is proportional to tree size. On the Missionary Ridge, Hayman, and Flagtail wildfires, we used a 4 m^2/ha (20 ft^2/ac) angle gauge. In these places all trees greater than 30.5 cm (12.0 in) dbh were sampled within this variable plot. On the rest of the wildfires a 9 m^2/ha (40 ft^2/ac) angle gauge was used and all trees greater than 45 cm (18.0 in) were sampled (*table 6*). Species, height, diameter, and uncompacted crown ratio (*fig. 2*) 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 (low and high) on the stem was recorded and the circumference of scorch at the base of the stem was estimated (*table 6*).

Table 6—*Burn severity data taken on large trees (≥ 12.7 cm diameter breast height (dbh) using a fixed (1/59 ha, 1/24 ac) and variable plot (9 m^2/ha or 4 m^2/ha). Trees greater than 45 cm (18 in) dbh were measured on 9 m^2/ha (40 ft^2/ac) variable plot. Trees greater than 30.5 cm (12 in) dbh were measured on 4 m^2/ha (20 ft^2/ac) variable plot on the Hayman and Missionary Ridge fires in Colorado and Flagtail fire in Oregon. Trees with diameters less than these were measured on the fixed plot.*

Strata	Uncompacted crown ratio	Green crown (%)	Brown crown (%)	Black crown (%)	Bole scorch height (cm) and direction (azimuth) scorch is facing		Scorch at tree base (%)
					Low	High	
Trees ≥ 12.7 cm dbh	Total crown ratio	Green needles	Brown needles	Black stems, no needles	Lowest extent of scorch	Highest extent of scorch	Circumference

The amount of woody debris on the site and proportion in each decay class (no decay, decayed wood present, majority decayed wood, and completely decayed) was determined using three 37m (120 ft) linear transects radiating from the plot center at 0, 120, and 240 degree azimuths (Brown 1974, Maser et al. 1979).

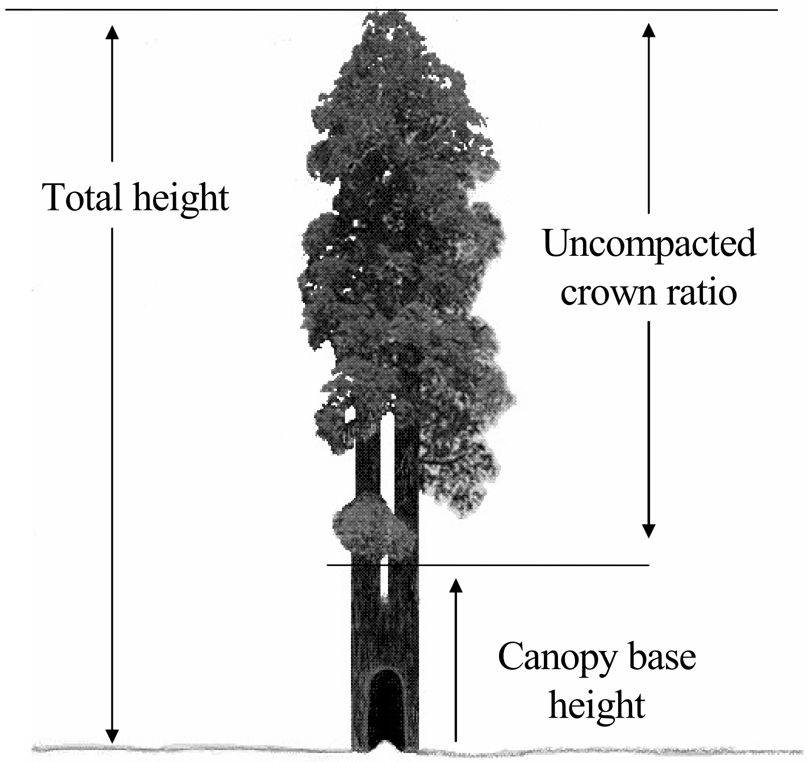

Figure 2—Illustration of how we measured uncompacted crown ratio and canopy base height (total height minus length of uncompacted crown ratio).

Extensive data collection

The extensive sampling occurred on previously established FIA plots that burned in wildfires. The plot design depended on when the plot was established (*table 7*, *fig. 3*). There were five different plot designs used for the extensive sampling: a single-plot, four-plot, six-plot, seven-plot, and ten-plot design. A fixed, variable, or a combination of fixed and variable plots (1/59 ha fixed circular and 9 m^2/ha variable), often of different sizes (1/59 or 1/741 ha fixed circular), were used for collecting post-wildfire data (*table 7, fig. 3*).

The aspect, slope, topographic position, and elevation of each plot were recorded at the time the FIA plot was established. Although different plot designs were used, the burn severity estimates and forest structure characterizations were similar to those obtained by the intensive and focused watershed designs (*tables 5, 6*). However, for small trees, shrubs, forbs, and grass, cover was quantified by species and the number of shrub stems was not recorded. All trees, including saplings and large trees, were tallied and burn severity was recorded using the proportion of crown containing green, brown, or black stems with no needles (*table 6*).

Physical setting, fire weather, and forest structure

Fire behavior and burn severity, for the most part, are determined by physical setting (location, topography, juxtaposition, and so forth), fuels (live and dead vegetation), and weather (both short- and long-term). We included these factors into

Table 7—*FIA plot designs varied depending upon when the plot was established (Interior West Forest Inventory and Analysis 2006). This table provides the plot design, establishment date for each fire, and shows whether it was a woodland plot (oak, juniper, or pinyon) or forested plot. Variable radius plots used a 9 m^2/ha (40 ft^2/ac) basal area factor, fixed radius plot number 1 (No. 1) were 1/59 ha (1/24 ac), fixed radius plot number 2 (No. 2) were 1/741 ha (1/300 ac), and woodland fixed radius plots were 1/25 ha (1/10 ac).*

County	Fire	Date established	Plot design	Number of plots			
				Variable	Fixed no. 1	Fixed no. 2	Woodland fixed
			Arizona				
Gila	Packrat complex	Unknown	4-plot woodland	-	4	4	-
Navaho	Rodeo/ Chediski	Unknown	4-plot woodland	-	4	4	-
Pima	Bullock	Unknown	4-plot woodland	-	4	4	-
			Idaho				
Cassia	STF Assist 5	1990-1997	4-plot woodland	-	4	4	-
Cassia	STF Assist 5	1980-1981	1-plot woodland	-	-	1	1
Clearwater	Elizabeth	1997-Present	4-plot forest	-	4	4	-
Custer	Rankin	1997-Present	7-plot forest	7	-	7	-
Elmore	Trail Creek	1997-Present	5-plot forest	5	-	5	-
Idaho	Butts	1997-Present	4-plot forest	-	4	4	-
Idaho	Papoose	1997-Present	4-plot forest	-	4	4	-
Idaho	Burnt Flats	1997-Present	5-plot forest	5	-	5	-
Idaho	Fitz	1997-Present	5-plot forest	5	-	5	-
Idaho	Hamilton	1997-Present	5-plot forest	5	-	5	-
Idaho	Lonely	1997-Present	5-plot forest	5	-	5	-
Idaho	Thirty	1997-Present	5-plot forest	5	-	5	-
Idaho	Three Bears	1997-Present	5-plot forest	5	-	5	-
Lemhi	Shellrock	1997-Present	4-plot forest	-	4	4	-
Lemhi	Clear Creek	1997-Present	4-plot forest	-	4	4	-
Lemhi	Clear Creek	1988-1989	10-plot forest	10	-	10	-
Lemhi	Morse	1997-Present	7-plot forest	7	-	7	-
Lewis	Maloney Ck	1997-Present	5-plot forest	5	-	5	-
Valley	Diamond Peak	1997-Present	4-plot forest	-	4	4	-
Valley	Indian Ck	1997-Present	4-plot forest	-	4	4	-
			Montana				
Beaverhead	Bear/Maynard	1993-1998	5-plot forest	5	-	5	-
Beaverhead	Mussigbrod/ Maynard	1993-1998	5-plot forest	5	-	5	-
Carbon	Willie	1993-1998	5-plot forest	5	-	5	-
Flathead	Bald Hill	1988-1989	10-plot forest	10	-	10	-
Flathead	Chipmunk	1993-1998	7-plot forest	7	-	7	-
Flathead	Helen Creek	1993-1998	7-plot forest	7	-	7	-
Missoula	Flat Creek	1993-1998	5-plot forest	5	-	5	-
Gallatin	Beaver Creek	1988-1989	10-plot forest	10	-	10	-
Gallatin	Beaver Creek	1993-1998	5-plot forest	5	-	5	-

Table 7 Continued—*FIA plot designs varied depending upon when the plot was established (Interior West Forest Inventory and Analysis 2006). This table provides the plot design, establishment date for each fire, and shows whether it was a woodland plot (oak, juniper, or pinyon) or forested plot. Variable radius plots used a 9 m^2/ha (40 ft^2/ac) basal area factor, fixed radius plot number 1 (No. 1) were 1/59 ha (1/24 ac), fixed radius plot number 2 (No.2) were 1/741 ha (1/300 ac), and woodland fixed radius plots were 1/25 ha (1/10 ac).*

County	Fire	Date established	Plot design	Number of plots: Variable	Fixed no. 1	Fixed no. 2	Woodland fixed
			Montana				
Gallatin	Maudlow/Toston	1988-1989	4-plot woodland	-	-	4	4
Gallatin	Maudlow/Toston	1988-1989	10-plot forest	10	-	10	-
Gallatin	Maudlow/Toston	1993-1998	5-plot forest	5	-	5	-
Gallatin	Maudlow/Toston	1993-1998	4-plot woodland	-	4	4	-
Granite	Alder	1993-1998	5-plot forest	5	-	5	-
Granite	Cougar	1993-1998	5-plot forest	5	-	5	-
Granite	Ryan Gulch	1988-1989	10-plot forest	10	-	10	-
Jefferson	High Ore	1988-1989	10-plot forest	10	-	10	-
Judith Basin	Lost Fork Ridge	1988-1989	10-plot forest	10	-	10	-
Lewis & Clark	Bunyan	1993-1998	5-plot forest	5	-	5	-
Lewis & Clark	Cave Gulch	1993-1998	5-plot forest	5	-	5	-
Lincoln	Cliff Point	1993-1998	7-plot forest	7	-	7	-
Lincoln	Grambauer Face	1993-1998	7-plot forest	7	-	7	-
Lincoln	Northwest Peaks	1993-1998	7-plot forest	7	-	7	-
Lincoln	Stone Hill	1993-1998	7-plot forest	7	-	7	-
Mineral	Alpine Divide	1993-1998	5-plot forest	5	-	5	-
Mineral	Landowner	1993-1998	5-plot forest	5	-	5	-
Missoula	Ninemile	1993-1998	5-plot forest	5	-	5	-
Powder River	Stag	1993-1998	5-plot forest	5	-	5	-
Powell	Monture/Spread	1993-1998	7-plot forest	7	-	7	-
Powell	Monture/Spread	1993-1998	5-plot forest	5	-	5	-
Ravalli	Bear	1988-1989	10-plot forest	10	-	10	-
Ravalli	Bear	1993-1998	5-plot forest	5	-	5	-
Ravalli	Bear	1993-1998	4-plot woodland	-	4	4	-
Ravalli	Blodget	1993-1998	5-plot forest	5	-	5	-
Ravalli	Boundary	1993-1998	5-plot forest	5	-	5	-
Ravalli	Coyote	1993-1998	5-plot forest	5	-	5	-
Ravalli	Mink	1993-1998	5-plot forest	5	-	5	-
Ravalli	Razor	1993-1998	5-plot forest	5	-	5	-
Ravalli	Taylor Spring	1993-1998	5-plot forest	7	-	5	-
Teton	McDonald 2	1993-1998	5-plot forest	5	-	5	-
Flathead	Unknown	1988-1989	10-plot forest	10	-	10	-
Flathead, Park	Unknown	1993-1998	7-plot forest	7	-	7	-
Gallatin	Unknown	1988-1989	10-plot forest	10	-	10	-
Gallatin	Unknown	1993-1998	5-plot forest	5	-	5	-
Teton	Unknown	1993-1998	5-plot forest	5	-	5	-
			Utah				
Garfield	Sanford	unknown	4-plot woodland	-	-	4	4

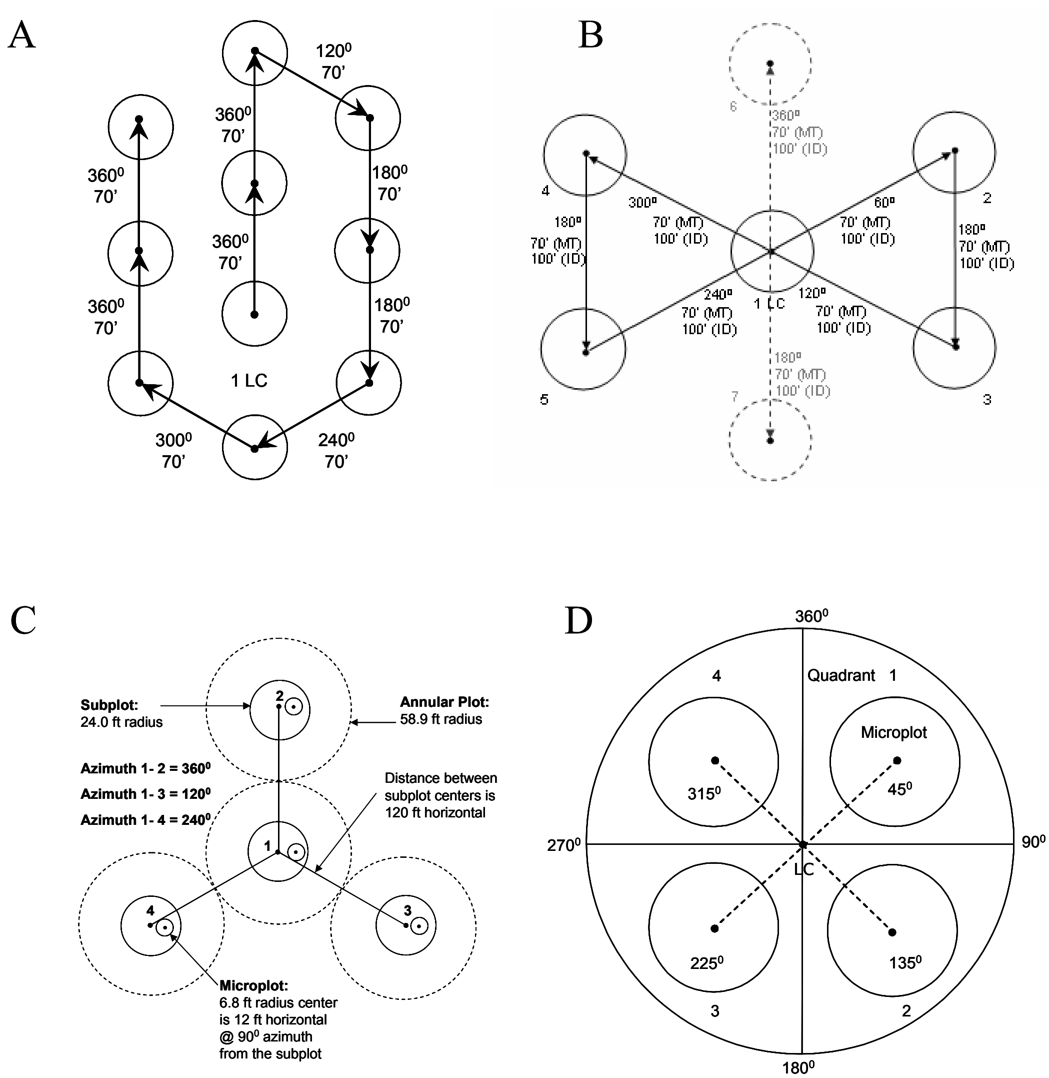

Figure 3—Illustrations showing different plot designs for the forest inventory and analysis (FIA) plots (Interior West Forest Inventory and Analysis 2006). Depending upon when a plot was established, FIA used a ten-plot (A), seven-plot (B where plot 6 and 7 are shown above and below the bowtie), five-plot (B without plots 6 and 7), 4-plot (C), and the one-plot woodland (D).

our study in addition to quantifying burn severity of the different vegetative strata. To describe the physical setting, we used the location of each plot in combination with a digital elevation model to develop several physical setting indices. Common attributes, such as aspect, slope angle, and elevation of each sample point, were obtained along with other descriptors, including slope curvature, compound topographic index (steady-state wetness index) (Gessler et al. 1995), landform index (McNab 1993), and topographic solar index (McCune and Keon 2002).

For each burned area we visited, we obtained hourly weather observations of the conditions under which the wildfire burned (*tables 1, 2, 3*). Data from remote automatic weather stations (RAWS) located in the county where each wildfire burned were summarized into daily reports using Fire Family Plus 2.0 (Bradshaw and McCormick 2000) (*table 8*). Because the exact day and time a specific plot burned is unknown, we summarized the weather data to the specific fire. In limited circumstances, we did not know the fire name and therefore were unable to obtain weather data for that particular fire.

Table 8—*Weather data were obtained from the nearest remote automated weather station (RAWS) in the county where the fire was located. Burning index is the effort needed to contain a single fire within a particular fuel type (Bradshaw et al. 1983, Bradshaw and Britton 2000). The index is a function of the spread component and energy release component of a fire. Wind speed, slope angle, fuel (including the effects of green herbaceous plants), and the moisture content of the fuels are used to determine the spread component and energy release component. The spread component is determined by the moisture levels of fine fuels while energy release component requires moisture levels from the entire fuel complex. We used Fire Family Plus 2.0 to summarize the weather into daily reports (Bradshaw and McCormick 2000). The Keetch-Byram drought index is a soil drought index that ranges from 0 (no drought) to 800 (extreme drought) and is based on soil capacity of 20.3 cm (8 in) of water. Factors in the index are maximum daily temperature, daily precipitation, antecedent precipitation, and annual precipitation (Burgan 1993). The Haines index (HI) was obtained from the Wildland Fire Assessment System (2006), where we selected for the particular day and location. The index is composed of a stability term and a moisture term. The stability term is derived from the temperature difference at two atmosphere levels. The moisture term is derived from the dew point depression at a single atmosphere level (Haines 1988). The indices range from 2 to 6, indicating potential for large fire growth.*

Weather variable definition	Units of measurement or range of index
Date of occurrence	Month, day, year
Maximum temperature	F ^{0}
Minimum relative humidity	Percent
Maximum relative humidity	Percent
Wind speed	Miles per hour
Wind direction	One of eight cardinal points
Precipitation	Inches
One hour fuel moisture	Percent
Ten hour fuel moisture	Percent
One thousand hour fuel moisture	Percent
Energy release component	British thermal units per square foot
Burning index	0-100
Keetch-Byram drought index	0-800
Haines index	2-6

We used the Forest Vegetation Simulator (FVS) and its Fire and Fuels Extension (FFE) to characterize pre-wildfire forest structure (Dixon 2004, Reinhardt and Crookston 2003, Wykoff et al. 1982). FFE-FVS is an excellent tool for forest structure characterization, as it can summarize data from a variety of plot designs and the metrics it produces can be adjusted using model variants reflecting regional forest conditions. For example, data from sites within northern Idaho and western Montana were summarized using the Inland Empire Variant. The Central Rockies Variant was used to summarize data collected in Colorado and Utah. In addition, FFE-FVS produces a variety of forest metrics associated with fire behavior, wildlife habitat, and forest development, and is supported by the U.S. Forest Service, Forest Management Service Center (Dixon 2004). The system is used by federal, state, and private entities throughout the western United States to summarize forest data, thereby making our data compatible, repeatable, and understandable by many forest managers and researchers of the western United States.

Forest structure characteristics derived from FFE-FVS included stand density indices (basal area per unit area, stand density index, trees per unit area, and so forth), characteristics associated with fire behavior (canopy bulk density and canopy base height) (*fig. 4*), and other miscellaneous stand characteristics (number of canopy layers, dominant species, and so forth) (Reinhardt and Crookston 2003) (*table 9*). In addition to these FFE-FVS derived forest characteristics, we estimated canopy base height directly from our data and described total cover, which included canopy overlap as suggested by Crookston and Stage (1999). Also, rather than using quadratic mean diameter (QMD) to describe stem dimensions, we used stem diameter weighted by basal area because it gives a better representation of tree diameters, especially when abundant small trees are present (*table 9*).

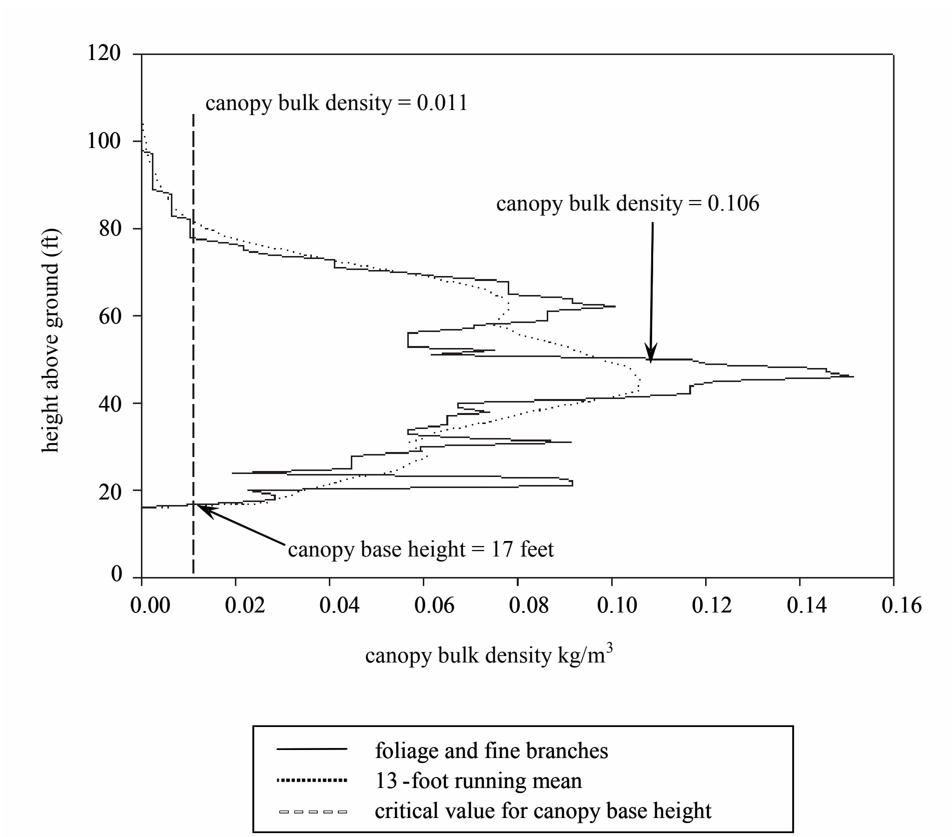

Figure 4—An illustration of how canopy bulk density and canopy base height are calculated in Fire and Fuels Extension of the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003). FFE-FVS does not include trees two meters and under. In the calculation, they are considered surface fuels.

FFE-FVS provides a suite of characteristics based on our data that describes different elements of forest structure. For example, there are several ways to characterize overstory density, such as basal area per unit area, trees per unit area, percent cover, canopy bulk density, relative stand density index, total cubic volume per unit area, and total standing biomass (*table 9*). We wanted to avoid using multiple correlated variables as predictors. Therefore, we used canonical correlation for data mining and used our expertise to determine which of these variables had promise for identifying the relation between forest structure and burn severity. This process was well-suited, as it decreased the number of variables that we used to characterize forest structure. For density, we used total canopy cover with overlap, for tree size we used basal area weighted diameter and average height, and we used dry, moist, and cold forests to reflect broad variation in species composition. To describe the forest canopy, we used canopy base height (total height minus uncompacted crown length, averaged for plot) and uncompacted crown ratio (*fig. 2*). Because the amount of surface fuel available for burning is frequently used in predicting fire behavior, we included the amount of biomass of these fuels using FFE-FVS algorithms in our analysis.

Classifying Burn Severity

When we started the study, we wrongly assumed an established burn severity classification existed. However, it became obvious that burn severity was variable in application and inconsistently used and defined (Jain et al. 2004). Although there were clearly defined burn severity classes in several publications, the rationale supporting the classes was not provided. Upon comparing many definitions of burn severity, we discovered severity classes were either "lumped" or "split" and most often the classification focused on a "selected" severity condition. As a result, there appears to be no consistent way to communicate burn severity to the scientific community, managers, or to society at large. In fact, both in the scientific literature and lay publications, fire severity, burn severity, fire behavior, and fire intensity are often used interchangeably and inconsistently, leading to confusion and misinformation as to the impact wildfires have on forests and elements important to society. Yet, forest stakeholders are asking managers and policy makers to make decisions on manipulating vegetation to alter "wildfire severity" in forest ecosystems (USDA Forest Service 2004).

In our attempt to alleviate some of the inconsistency in severity definitions and classifications, we investigated and synthesized the literature to develop a burn severity classification with specific objectives. The classification needed to be useful and applicable to managers, scientists, and society. Also, the classes used in the system needed sufficient flexibility as to whether they could be grouped or used individually, depending upon the need or interest of the person or persons using the classification.

To develop a soil burn severity classification, we synthesized fire intensity, fire severity, and the response literature (*fig. 5*). Fire science has provided the knowledge on fire intensity by describing the variation in heat pulse into the soil (Baker 1929, Debano et al. 1998, Hare 1961, Hungerford et al. 1991, Levitt 1980, Lyon et al. 1978, Wells et al. 1979, White et al. 1996, Wright and Bailey 1982). However, in many circumstances, it is important to understand the amount of fuel consumed by a fire event. Therefore, we also incorporated fire severity into our rationale (Debano et al. 1998, Dyrness et al. 1989, Key and Benson 2001, Morgan and Neuenschwander 1988, Ryan and Noste 1985, White et al. 1996).

Finally, we included what responses might be important to society and provided a link in the burn severity classes (what is left) to management and ecological values (for example, wildlife, soil productivity, erosion) (Debano et al. 1998, Neary et al. 1999) (*fig. 5*).

Table 9—*Forest structural characteristics derived from the Fire and Fuels Extension-Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003) and directly from our data.*

Density characteristics	Characteristics related to fire behavior	Biomass characteristics (Mg/ha)	Miscellaneous characteristics
Trees/ha	Canopy base height from FFE-FVS	Foliage	Average top height
Basal area (m^2/ha)	Canopy bulk density	Live branch < 7.6 cm	Number of stories
Stand density index	Canopy base height direct measure (CBH)[1]	Live branches > 7.6 cm	Species composition
Crown competition factor		Surface	Dominant species
Total canopy cover (TCC) (%)[2]		Total	Quadratic mean diameter
Cubic volume (m^3/ha)			Dry, cold, or moist forest
Average canopy cover (ACC)(%)[3]			Uncompacted crown ratio
			Basal area weighted diameter[4]

[1] CBH is total height minus uncompacted crown length.
[2] TCC is $C' = 100(p_i a_i)A^{-1}$ where: C' = percent canopy cover without accounting for overlap, p_i = trees per acre for the *ith* sample tree, a_i = projected crown area for the *ith* tree in ft^2/acre, and A = ft^2/acre (43560) (Crookston and Stage 1999).
[3] ACC is $C = 100\,[1 - \exp(-.01\,C')]$ where: C = percent canopy cover that accounts for overlap, and C' from TCC (Crookston and Stage 1999).
[4] Basal area weighted diameter breast height (dbh-in) is ∑ ((dbh*individual tree basal area (ft^2) * number of trees for each dbh class) divided by (∑ (number of trees * individual tree basal area (ft^2)).

The classification included six levels of soil burn severity based on factors that link fire intensity, fire severity, and the response (*fig. 6*). The factors in the soil burn severity include proportion of litter, mineral soil, and exposed rock present after a fire and the dominant char class, defined as unburned, black, grey, and orange char specific to mineral soil (Debano et al. 1998, Ryan and Noste 1985, Wells et al. 1979).

Level 1 describes places where there is evidence of fire, but not enough to consume litter. Thus, there is greater than 85 percent litter cover for all char classes. Level 2 describes places that have between 40 and 85 percent litter cover for all char classes. Places with less than 40 percent litter cover, with mineral soil exhibiting black char, are represented by level 3, while level 4 represents places with less than 40 percent litter cover and the exposed mineral soil is dominated by grey or white char. Levels 5 and 6 reflect very little litter cover (0 to 5 percent), with level 5 characterized by exposed mineral soil dominated by black char and level 6 characterized by exposed mineral soil dominated by either grey or white char.

For defining tree burn severity, we used an approach similar to the one we used when developing the soil burn severity levels. However, instead of using temperature

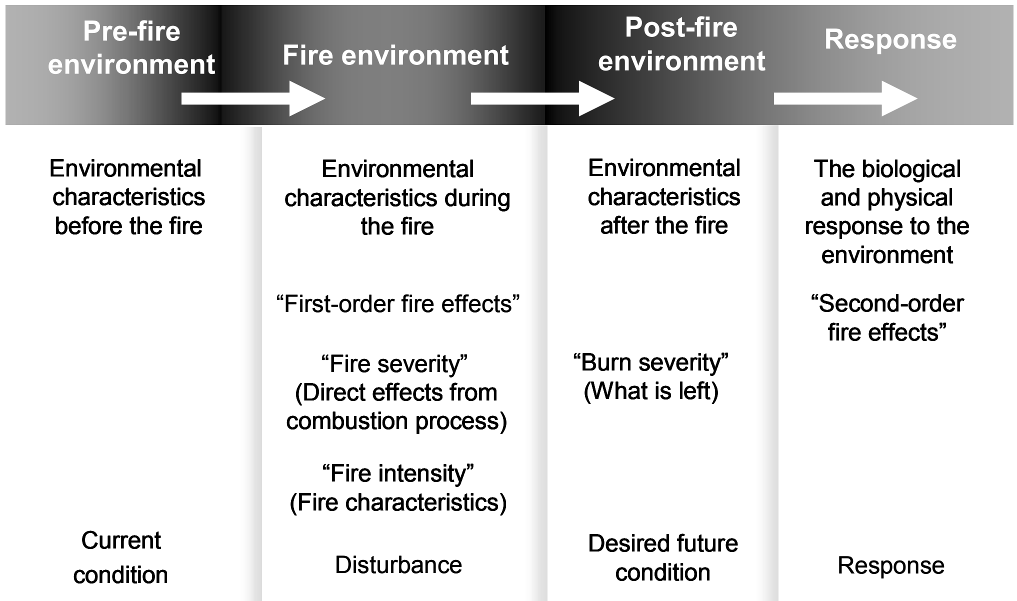

Figure 5—The fire disturbance continuum, of which there are four components, describes the interpretation of different factors involved in fires (Jain et al. 2004). The first component the pre-fire environment, includes forest vegetation and state of the environment (moisture levels, amount of biomass, and species composition). This can also be referred to as the condition just prior to the fire event. The second component, the fire environment, is the environment during the fire event, where fire intensity and fire behavior are characterized in addition to fire severity. Changes to forest components from the fire are also referred to as first-order fire effects. The third component is the environment after the fire is out, referred to as the post-fire environment. This is the environment created by the fire but is also a function of the pre-fire environment and is characterized by what is left after the fire. We refer to this as burn severity. In some cases when fuel treatments are being applied to create a more resilient forest, this could be referred to as the desired condition. The last component is the response, often referred to as second-order fire effects.

to guide the classification, we used flame length to represent fire intensity (Ryan and Noste 1985, VanWagner 1973). Levels of fire severity are dependent upon the amount of tree bole killed or the amount of tree crown scorched or burned by the fire (Peterson and Arbaugh 1986, Ryan and Reinhardt 1988, Weatherspoon and Skinner 1996, Wyant et al. 1986). Tree burn severity is dependent upon the condition of the tree after a fire and, in particular, the portion of the crown and the amount of bole left alive after the fire (*fig. 7*).

The perceived "goodness" of burn severity, or lack there of, depends on the values at risk, the biophysical setting, and/or the management objectives. Therefore, levels of both soil and tree burn severity do not depict a value but rather describe a continuum from a totally unburned forest to a forest in which fire has appreciably altered its pre-fire condition (soil, forest floor, ground level vegetation, trees, and so forth).

Soil and Tree Burn Severity

We combined our six levels of soil burn severity into three levels because we have very few observations of soil burn severity in levels 1 and 6. Level 2 burn sever-

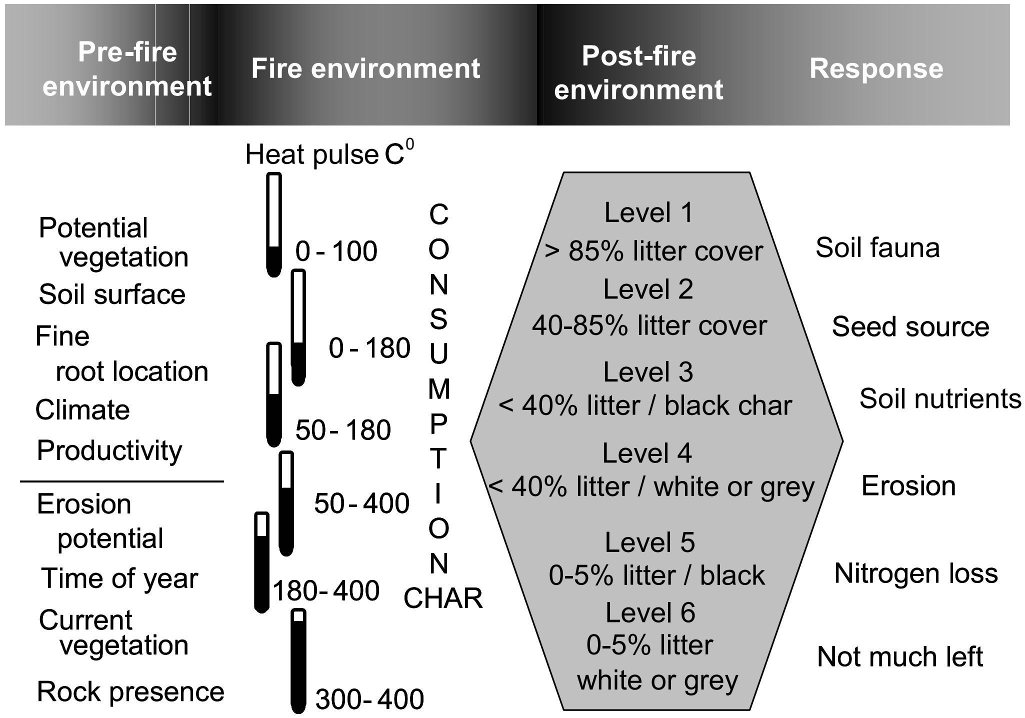

Figure 6—Within the post-fire environment, the soil burn severity classification includes six levels. Going from left to right, a range of temperatures associated with the fire event correspond to the probable indicator of what is left after a fire. For example, to maintain litter cover, the heat pulse into the ground had to be between 0 and 100°C. When surface litter remains, soil fauna are often still alive (level 1). A fire severity description would assume 15 percent litter is consumed. By level 6, the heat pulse into the ground had to exceed 300°C in order to create white ash or a grey charred soil appearance (Hungerford et al. 1991). In a fire severity description, surface nutrients would no longer be present. The char in each burn severity level refers to the dominant char present after the fire.

ity (combined levels 1 and 2, *fig. 6*) consisted of areas with greater than 40 percent litter cover. The forest floor could vary from unburned to areas exhibiting black char, although abundant litter cover existed. Level 4 soil burn severity (combined levels 3 and 4, *fig. 6*) described areas where less than 40 percent litter cover existed and the exposed mineral soil was either black or grey in color. Level 6 soil burn severity (combined levels 5 and 6, *fig. 6*) described sites where there was 0 to 5 percent litter cover and the exposed mineral soil was black, grey, and/or orange colored, or there was an abundance of exposed rock.

We combined our five burn severity levels into four levels to describe trees post-wildfire because we had only a few observations in level 3 tree burn severity (*fig. 7*). The lowest tree burn severity described burned settings in which the trees contained dominantly green crowns (level 1 referred to as containing green crowns, *fig. 7*). The mixed-green tree burn class typified settings in which the trees had greater than 30 percent residual green crown ratio (level 2 referred to as containing mixed green crowns). The mixed brown tree class described stands where all trees had less than 30 percent residual green crown ratio (level 3) and a brown tree class for stands with scorched crowns (level 4). In this study, we combined levels 3 and 4 and referred to these observations as containing brown crowns (*fig. 7*). When black stems and branches were the only tree components left after a wildfire, we used a level 5 tree burn severity to describe these conditions (referred to as containing black crowns (*fig. 7*).

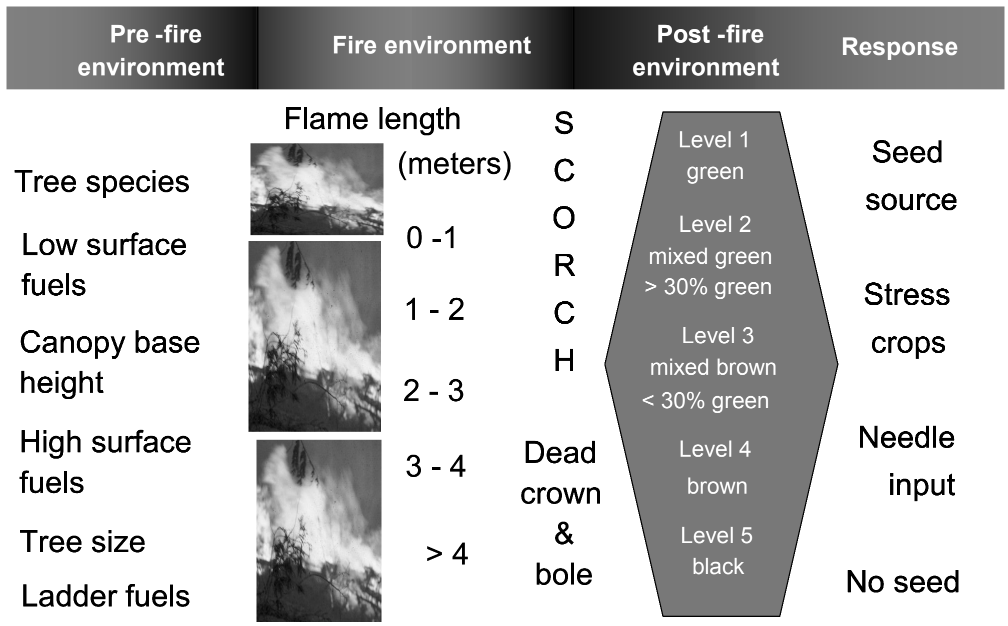

Figure 7—The tree burn severity classification links flame length and amount of crown scorch to burn severity, which indicates the portion of the tree left alive. Ryan and Noste (1985) discussed a conceptual model that described the relation between flame length and crown scorch. We used this model to develop our tree burn severity classes. The lowest tree burn severity class describes settings in which the trees contained dominantly green crowns (level 1). To distinguish between mixed green (level 2) and mixed brown (level 3), we used the proportion of residual crown left alive as an indicator. Greater than 30 percent green indicates this portion of the crown is alive. Trees with a crown ratio greater than 30 percent have a high chance of survival and respond with increased growth after the disturbance (Ryan and Reinhardt 1988, Smith 1986). In contrast, with trees with less than 30 percent of the crown left alive, there is a chance the tree will not survive after the fire. Only a portion of the remaining trees had to contain green crowns to be placed either into the mixed green or mixed brown classes. Brown indicates all trees contained brown needles and no green needles remained (level 4). Black indicates no needles were left on the tree and only black stems and branches remained (level 5).

Analysis and Interpreting Results

The sampling stratification we used was intended to insure the variation in burn severity and forest structure was obtained. The stratification was not used in the analysis, rather, individual fires (categories) and forest structure characteristics (continuous values) were used to predict tree burn severity (categories). A nonparametric classification tree technique (CART) (Breiman et al. 1984, Steinberg and Colla 1997) was used to identify the relation between the predictors and tree burn severity. CART does not require normalizing data through transformations making the results readily interpretable. It identifies interactions, maximizes homogeneity within a particular classification, and can conduct internal cross-validation among classes (a measure of overall performance). The forest structure data were continuous and the burn severity data were categorical, which can be problematic for many analytical techniques that attempt to relate the two (for example, linear regression and analysis of variance). In addition, neither of these techniques identifies thresholds of performance for a given variable.

CART partitions the data using a binary decision process, making it appropriate for both categorical and continuous data. CART produces trees with "nodes" showing where splits (differentiation of the values of a variable into two classes) in the classifications occurred. Based on decision rules, CART classifies observations until all observations are placed in one class, all observations in the node are the same, the node contains equal proportions in the classes, or, as with this analysis, there were 10 observations left to be classified. *Figure 8* shows a 16-outcome classification tree predicting tree burn severity as a function of pre-wildfire forest structure. Outcomes 1 through 16 (shaded) show number of observations correctly classified, total number of observations, and probability of certainty.

Forest characteristics occurring at the top of a classification tree provide an indication that they were clearly related to burn severity compared to characteristics that appear later in the tree. For example, in the classification tree used to predict tree burn severity, wildfire groups (groups of individual fires) were commonly used in the splits, followed by canopy base height, forest type (cold, dry, or moist), and/or total cover and weighted basal area dbh (*fig. 8*). In addition, it identified thresholds of forest structure characteristics that have the strongest relation to a burn severity level. For example, in predicting outcome 1, trees with canopy base height ≤ 1.7m (5.6 ft) split to the left in the classification tree and trees with canopy base heights > 1.7m (5.6 ft) split to the right and went to internode 3.

The value given for a probability of certainty in the CART analysis is a conditional probability (*fig. 8*). An example of a conditional probability is demonstrated by asking the question: what are the chances of a person visiting a particular tire store? Under normal driving situations, the probability of visiting a particular store when four are available is approximately 25 percent. Having a flat tire, however, can dramatically change this probability. If the flat occurs in the neighborhood of a particular store, the probability of visiting that store will likely increase. If the flat tire occurs in the home driveway, the probability of patronizing a store that provides timely home repair will likely increase. These probabilities are conditional upon whether a flat tire has occurred (condition A) and upon the location (condition B) where the flat tire occurred. The CART analysis we performed displays such conditional probabilities of an event happening predicated on a particular situation. For example, if canopy base height in a particular plot averaged less than 1.7m (5.6 ft) (condition B) and occurred in fire group 1 (condition A), there is a 0.52 probability the trees would have green crowns (tree burn severity level 1) (outcome 1, *fig. 8*).

Results and Discussion

Our results suggest that soil burn severity and tree burn severity resulting from wildfires are independent. All three of the soil burn severity levels we identified occurred with all four of the tree burn severities (*fig. 9*). These results indicate that when wildfires burn, there are different pre-fire conditions and fire environments (for example, intensity or behavior) that result in particular soil and tree burn severities.

For example, a low intensity surface fire (slow rate of spread and short flame lengths) can create a level 6 soil burn severity (consume all of the organic forest floor components and change mineral soil color) if a large amount of heat is transferred to the mineral soil for an extended period of time (approximately 10s of minutes to hours). In these situations, because of the short flames (10s of cm, 10s of inches), little crown or bole scorch may occur on the standing trees. An example of such burning could occur in ponderosa pine forests accustomed to frequent low intensity surface fires where, because of fire exclusion, large amounts of surface fuels may have accumulated (Graham 2003, Graham et al. 2004). In contrast, an intense wildfire burning tree crowns, combined with moist soil conditions (for example, lower duff moisture content exceeding approximately 100%), can lead to a level 2 soil burn severity (surface organic layers charred but a large portion of them intact), but leave only blackened stems and branches (level 5 tree burn severity) (*fig. 9*). Fires burning in the boreal forests often typify these burning conditions resulting in different tree and soil burn severities (Dahlberg 2002, Debano et al. 1998). These findings indicate that a composite burn severity integrating both soil and tree burn severity would be difficult. Such a composite could contain many combinations of soil and tree burn severities.

As no two forests in the western United States are identical, the wildfires that burn in them are highly variable in both behavior and burn severity. Nevertheless, we were able to identify seven groups of fires related to tree burn severity (*tables 10, 11*). The grouping of fires in the analysis most likely reflected broad scale attributes such as vegetation type, locale, geography, weather, or other physical setting attributes. Fire group 1 contained the largest number of fires showing similar relations as to how forest structure influenced burn severity. As canopy base height and total cover became relevant to classifying tree burn severity, fire group 1 broke into two additional fire groups (groups 2 and 3) (*table 10, fig. 8*).

The Missionary Ridge wildfire near Durango, Colorado and the Hayman wildfire near Colorado Springs, Colorado occurred in relatively the same geographic area and under similar weather conditions. However, they expressed uniqueness as they classified into separate fire groups early in the CART analysis (*tables 1, 10, 11, fig. 8*). The area burned by the Hayman wildfire (*table 11*) contained rolling topography and was primarily characterized by Douglas-fir/common juniper (*Juniperus communis* L.) or other dry vegetation types (average precipitation 25 cm, 10 in), and was located on the Colorado Rocky Mountain Front Range. In contrast, the area burned by the Missionary Ridge wildfire (*table 10*), located in the San Juan Mountains in southwest Colorado, contained highly variable topography, and tended to be dominated by mixed conifer and/or ponderosa pine, Douglas-fir, and/or oak (*Quercus gambelli* Nutt.) woodlands (average precipitation 48 cm, 19 in) (Casey et al. 1996). Also, these classifications of the wildfires most likely reflected the weather during the fire event. For example, the Keetch-Byram drought index (Keetch and Byram 1988) for the Hayman wildfire averaged 272 while the index for the Missionary Ridge wildfire averaged 382. However, further analysis is needed to evaluate and determine which factor or combinations of factors reflect the different fire groups. These findings indicated that the most telling wildfire characteristic affecting tree burn severity is the wildfire itself and summation of the attributes that determine its occurrence and propagation. These results emphasize the importance of observing burn severity in many different wildfires occurring in different years (weather), forest types (species, potential vegetation), and across geographical areas (for example, northern Rocky Mountains, central Rocky Mountains) (van Mantgem et al. 2001). Our analysis indicated a set of wildfires more than likely had similar characteristics, such as duration, heat produced, physical setting, and geographic location.

Canopy base height, uncompacted crown ratio, and surface fuel conditions are important forest structure characteristics that determine whether a fire will transition from a surface fire to a crown fire (Graham et al. 2004, Peterson et al. 2005, Scott and Reinhardt 2001). Our study indicated that canopy base height was the most important forest characteristic associated with tree burn severity within individual fire groups. However, high canopy base heights, as we surmised, did not always result in green crowns after a wildfire. In fact, we discovered that relatively low canopy base heights of 1.1m (3.5 ft) in fire group 7 (outcome 15), 2.0m (6.5 ft) in fire group 4 (outcome 5), and 1.7m (5.5 ft), in fire group 1 (outcome 1) were important break points in determining tree burn severity (*figs. 8 and 10a*). For example, green tree burn severity (level 1) occurred with a conditional probability of 0.52 for stands occurring in fire group 1, even if they had low canopy base heights (≤ 1.7m, 5.6 ft) (*fig. 8*, outcome 1). With a comparable probability (0.55), a similar green tree burn severity occurred in fire group 4 when canopy base heights were≤ 2.0m (6.6 ft) (*fig 8*, outcome 5). Stands exhibiting these burn characteristics tended to be relatively dense (2100 trees/ha, 850 trees/ac) and relatively short (<12m, 39 ft) compared to many stands we sampled (*figs. 10 b, c*).

In both of these fire groups, thinned stands, plantations, and other stands exhibiting management typified this outcome. The forest floor conditions exhibited in these fire groups could be associated with stand initiation structural stages which frequently contain moist and robust layers of ground-level vegetation. Because these stands were managed, the surface fuel matrix was modified through slash disposal and site preparation activities resulting in a discontinuous fuel bed. Crown fires would burn around these areas and most often there was evidence that firebrands landed in these stands. However, surface fuel conditions prevented sufficient fire from developing that could burn or scorch the tree crowns. These results indicate that high stand densities and low canopy base heights do not necessarily lead to a crown fire or black stems.

The previous examples, because they show that canopy base height impacts tree burn severity at relatively low heights (< 2.0m, 6.6 ft), contradict to some degree what we would expect (Cruz et al. 2002, Graham et al. 1999, Graham et al. 2004, Scott and Reinhardt 2001, Van Wagner 1977). Nevertheless, outcome 6 in our present study reflects the more common notion that high canopy base heights result in low burn severity (*fig. 8*). This outcome illustrates that relatively high canopy base heights (> 6m, 19 ft), occurring on tall trees (22m, 70 ft), with greater than 62 percent cover, results in green tree burn severity (*figs.10a, b, 11*). Although outcome 6 had high tree density (3500 trees/ha, 7413 trees/ac), there was substantial variation. This result may indicate that high overstory tree density shaded out the ground-level vegetation and the high canopy base height prevented the fire from transitioning into a crown fire. This outcome was relegated to one fire group, and it had a high (0.81) conditional probability of occurring. Outcome 7 also illustrates that tall trees with high canopy base heights and very low canopy cover (10 percent), with very low amounts of surface biomass, can result in green tree burn severity (*figs. 10, 11*). This outcome had a high (0.70) conditional probability of occurring and typified the common view that low density forests with high canopy base heights and very little

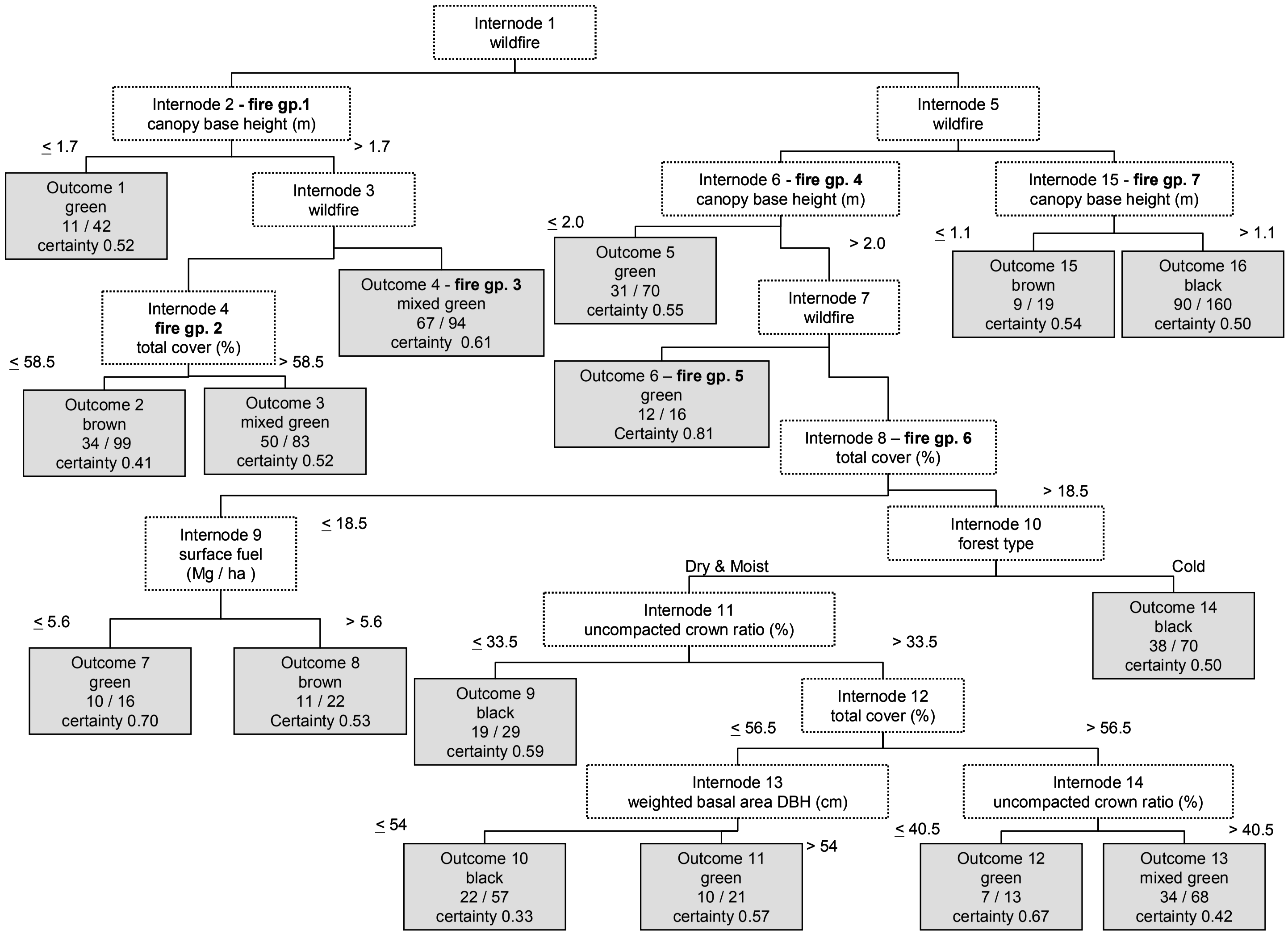

Figure 8—Classification tree for predicting tree burn severity resulting from CART analysis. Shaded areas reflect different predicted outcomes. Each outcome contains the tree burn severity, the number of correctly classified observations versus the total number of observations in the outcome, and a conditional probability referred to as "certainty." The internodes identify the fire group or the forest structural threshold used in predicting a particular outcome.

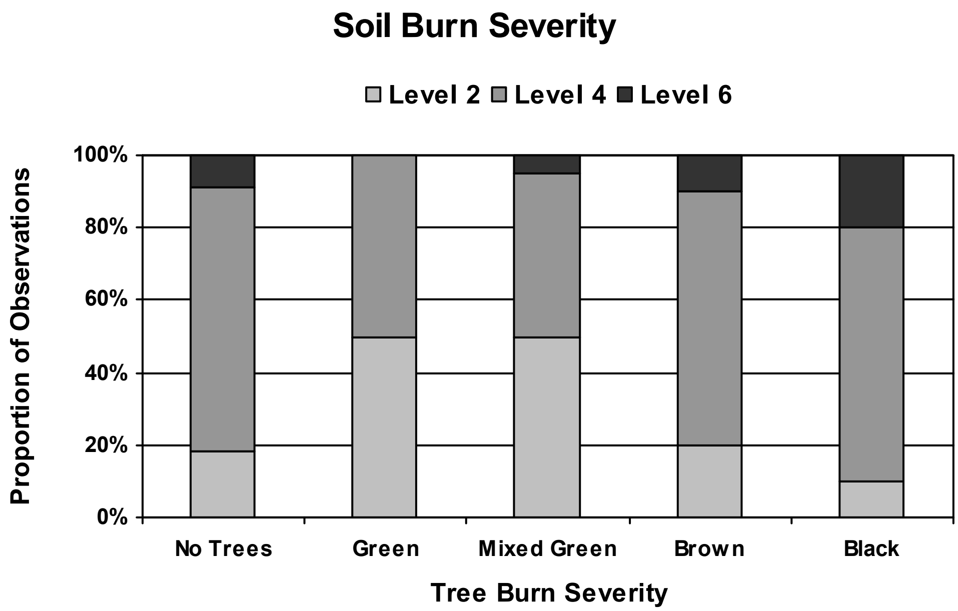

Figure 9—The relation between tree burn severity and soil burn severity is relatively independent. All soil burn severities can occur beneath all tree burn severity classes.

surface fuels are highly resistant to crown fire (Cruz et al. 2002, Graham et al. 1999, Graham et al. 2004, Scott and Reinhardt 2001, Van Wagner 1977).

The winds driving fires in group 7 had the highest minimum and median wind speeds of the wildfires we examined (*fig. 12*). In this fire group, canopy base height was related to tree burn severity, especially within wildfires that tended to burn under extreme conditions (for example, high air temperatures, strong winds, low humidity), such as with the Hayman fire in Colorado (Graham 2003). In this fire group, there was a 0.54 probability of classifying plots with brown tree severity when trees within the plots had mean canopy base heights ≤ 1.1m (3.5 ft.) (*fig. 8*, outcome 15*, fig. 10a*). Within this outcome (15), the tree density was relatively high (1929 trees/ha ± 180 trees/ha, 780 trees/ac ± 73 trees/ac), but there was also considerable variation. Most likely because of this variation and the burning conditions that typified fire group 7, the classified tree burn severity resulted in brown rather than green, which occurred with similar canopy base heights in fire groups 1 and 3. However, in group 7 fires, stands containing trees with a mean canopy base height of > 1.1m (3.6 ft) were classified as having black tree burn severity (probability 0.50) (*fig. 8*, outcome 16). Most likely the relatively high (5m, 16 ft) canopy base heights occurring in these stands allowed sufficient (63.6 Mg/ha, 28.4 tons/ac) live and dead surface fuels to accumulate. These aspects, combined with other factors associated with this group of fires, led to the creation of conditions favoring a crown fire, resulting in black crowns.

Another outcome typifying black tree burn severity occurred in the cold forests, where total cover exceeded 18.5 percent (*fig. 8*, outcome 14). In the burned plots, the trees were relatively tall (15m plus, 50 ft) with canopy base heights exceeding 8m (26.2 ft) (*fig. 10a,b)*. In such dense subalpine fir dominated forests (cold), tree crowns tend to intercept precipitation and evapotranspiration tends to deplete forest

Table 10—*CART uses a hierarchical classification. For predicting tree burn severity, individual fires were placed into seven fire groups. This table shows which fires were placed into fire groups 1 through 3, the forest types that dominated that particular fire group, and the outcome where observations occurred for a particular fire. Within these fire groups, individual forest structure characteristics were identified that related to a tree burn severity.*

Fire-group	Out-come	Forest type C=cold D=dry M=moist	Fire-group	Out-come	Forest type C=cold D=dry M=moist	Out-come	Forest type C=cold D=dry M=moist
1	-	-	2	2	C	3	C
1	-	-	2	2	D	3	M
1	-	-	2	2	C	-	-
1	1	D	2	2	D	-	-
1	-	-	2	2	D, C	3	D, C
1	-	-	2	2	M, C	3	C
1	1	D, M	2	2	D, M, C	3	D, M
1	-	-	2	2	C	-	-
1	-	-	2	2	D	3	D
1	1	D, C	2	2	D, C	3	D, C
1	1	D	2	2	D, M	3	D, M
1	-	-	2	-	-	3	D
1	-	-	2	2	D	-	-
1	-	-	2	-	-	3	C
1	1	C	2	2	D, M, C	3	C
1	-	-	2	2	M	3	M
1	-	-	3	4	C	-	-
1	1	C	3	4	D, C	-	-
1	-	-	3	4	C	-	-
1	-	-	3	4	C	-	-
1	-	-	3	4	C	-	-
1	-	-	3	4	C	-	-
1	1	C	3	4	M, C	-	-
1	-	-	3	4	C	-	-
1	-	-	3	4	D	-	-
1	1	C	3	4	C	-	-
1	-	-	3	4	D	-	-
1	1	M	3	4	D	-	-
1	1	C	3	4	D, C	-	-
1	-	-	3	4	D, C	-	-
1	-	-	3	4	D	-	-
1	1	C	3	4	D	-	-
1	-	-	3	4	M	-	-
1	1	C	3	4	M, C	-	-
1	-	-	3	4	C	-	-
1	-	-	3	4	C	-	-
1	1	D	3	4	D	-	-
1	-	-	3	4	D	-	-
1	1	M	3	4	D, M	-	-
1	1	D	3	4	D	-	-
1	-	-	3	4	D	-	-
1	1	M	3	4	M, C	-	-

Table 11—*CART uses a hierarchical classification. For predicting tree burn severity, individual fires were placed into seven fire groups. This table shows which fires were placed into fire groups 4 through 7, the forest types that dominated that particular fire group, and the outcome where observations occurred for a particular fire. Within these fire groups, individual forest structural characteristics were identified that related to a tree burn severity.*

Fire name	Fire Group	Outcome	Forest type C=cold D=dry M=moist	Fire group	Outcome	Forest type C=cold D=dry M=moist	Outcome `	Forest type C=cold D=dry M=moist	Outcome	Forest type C=cold D=dry M=moist	Outome	Forest type C=cold D=dry M=moist
Bald Hill	4	-	-	5	6	D	-	-	-	-	-	-
Grambauer Face	4	-	-	5	6	D	-	-	-	-	-	-
Little Pistol	4	5	D, C	5	6	D, C	-	-	-	-	-	-
Maloney	4	-	-	5	6	M	-	-	-	-	-	-
McDonald 2	4	-	-	5	6	C	-	-	-	-	-	-
Mink	4	-	-	5	6	D	-	-	-	-	-	-
Thirty	4	-	-	5	6	D	-	-	-	-	-	-
Young J	4	-	-	5	6	M, C	-	-	-	-	-	-
Unknown	4	-	-	6	-	-	8	C	9, 10, 12, 13	D	14	C
Bear	4	5	C	6	7	D	8	D, C	9, 10, 11, 12, 13	D	14	C
Coyote	4	5	C	6	-	-	-		13	D	14	C
Flagtail	4	5	D, M	6	7	D	9, 10, 11, 13	D, M	12	M	14	C
Landowner	4	-	-	6	-	-	8	D, C	9	D	14	C
Maudlow/Toston	4	5	D	6	-	-	-		10, 13	D, M	-	-
Myrtle	4	-	-	6	7	D, M	8, 9	D, M	10, 12	D	11, 13	M
Shellrock	4	5	D, C	6	7	D	8, 9, 11, 12	D	13	D, M	14	C
Taylor Springs	4	-	-	6	-	-	8	D	10, 13	D	14	C
Trail Creek	4	5	C	6	-	-	-	-	13	D	14	C
Blodget	7	15	D	-	16	D, C	-	-	-	-	-	-
Buckskin, Cave G	7	-	-	-	16	D	-	-	-	-	-	-
Clear Creek	7	15	C	-	16	D, C	-	-	-	-	-	-
Crazy H	7	15	M	-	16	M	-	-	-	-	-	-
Diamond Peak	7	-	-	-	16	D, C	-	-	-	-	-	-
Hayman, Moose	7	15	D	-	16	D	-	-	-	-	-	-
Morse,	7	-	-	-	16	C	-	-	-	-	-	-
Mussigbrod, Willie	7	-	-	-	16	C	-	-	-	-	-	-
Razor	7	-	-	-	16	D, C	-	-	-	-	-	-

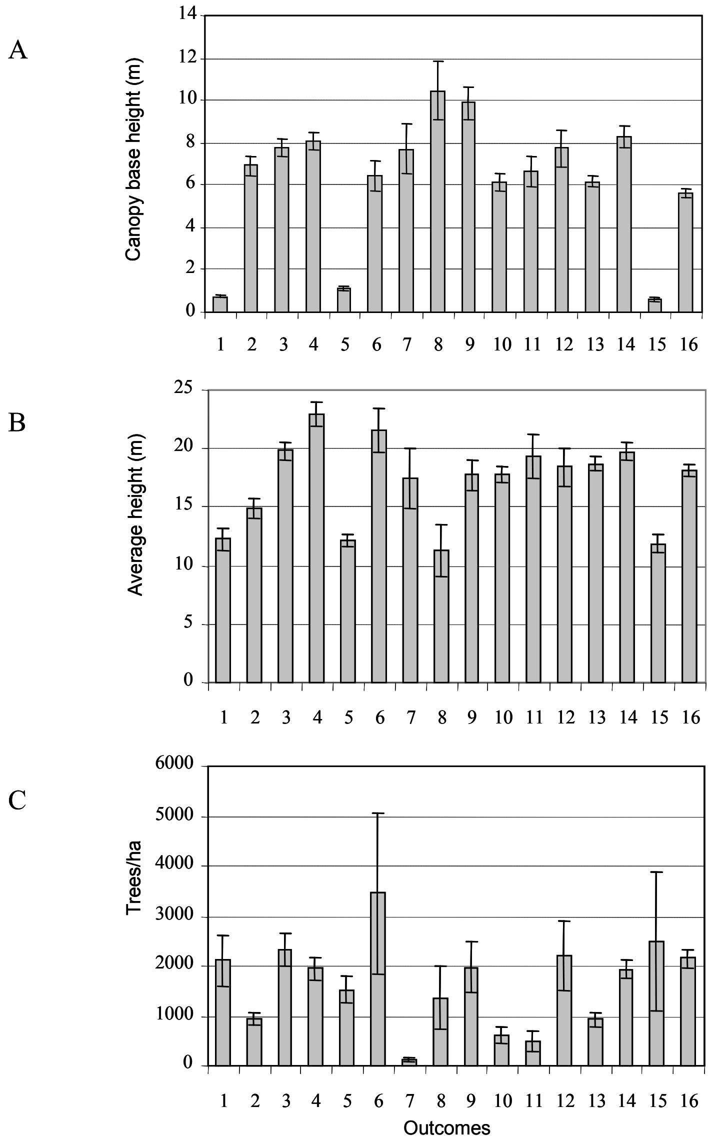

Figure 10—Sixteen outcomes resulted from predicting tree burn severity as a function of forest structure and wildfires. Average canopy base height (A), height (B), and trees/ha (C) are associated with each outcome. Standard error bars are presented to illustrate the variation within and among outcomes.

floor moisture, which can result in dry forest floor conditions (Rutter 1968). These dry surface conditions, coupled with our estimated pre-fire surface fuel loadings exceeding 70.6 Mg/ha (31.5 tons/ac), were probably prime contributors to facilitating surface fire ignitions and the development of sufficient fire intensities to create black crowns. These results indicate that although canopy base height is very important in determining tree burn severity, high canopy base heights may not always protect the needles from being consumed during a fire.

As stated earlier, the forests of the inland western United States are rather complex, both in composition and structure, and the wildfires that burn them are highly variable (Agee 1993, Burns and Honkala 1990, Graham et al. 2004, Hann et al. 1997). Even with this complexity, we were able to show that hierarchal relations exist among forest structure and tree burn severity (*fig. 8*). In this hierarchy (CART tree), the probability of a given forest characteristic influencing a particular tree burn severity is conditional on the previous characteristics occurring in the CART tree. In addition, the characteristics occurring earlier in the classification indicate they are more important in predicting tree burn severity than those listed later. These characteristics are: a particular wildfire group, tree canopy base height, total forest cover, surface fuel amount, forest type, uncompacted tree crown ratio, and tree diameter.

These variables were not only hierarchically related to tree burn severity, but together they predicted green, mixed green, and black tree burn severities very readily. Because we identified four levels of tree burn severity, a random probability of a given severity occurring would be 0.25. Therefore, any probability exceeding 0.25 indicates the additions of forest structural characteristics within a fire group were significantly related to tree burn severity in the cross-validation matrix (*table 12*). The variables, in order of importance, and the relations we identified, classified green crowns with a 0.46 probability, mixed green crowns with a 0.42 probability, and black crowns with a 0.55 probability. However, this same model only predicted brown tree severity with a 0.19 probability (*table 12*).

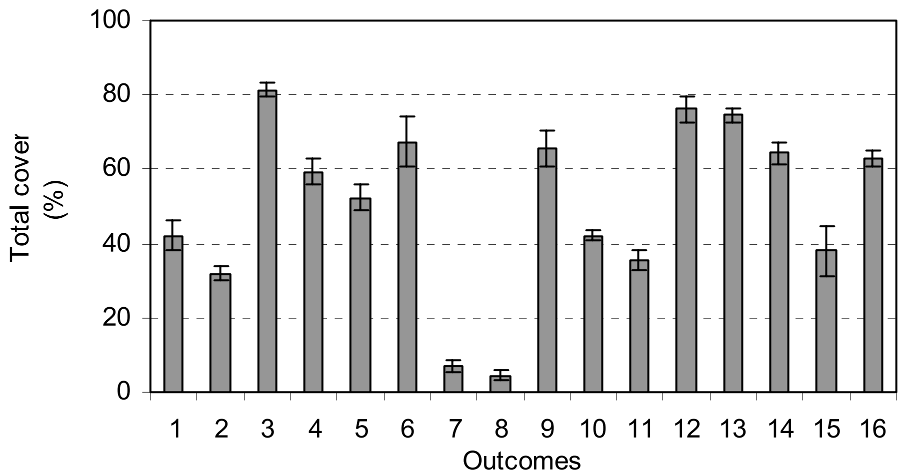

Figure 11—Average total cover in percent for the sixteen tree burn severity outcomes resulting from the classification tree (CART) analysis. Standard error bars are presented to illustrate the variation in total cover within and among outcomes.

These results indicate that wildfire and fuel conditions that create green or mixed green crowns and black crowns tended to be somewhat simpler than those creating brown crowns. For brown crowns to occur, a set of specific conditions needed to exist, such as in outcome 2 and outcome 8 (*fig. 8*). In both these outcomes, observations contained low overstory densities, with less than 35 percent cover for outcome 2 and 10 percent or less cover for outcome 8 (*fig. 11*). Moreover, the difference between outcome 7 (green) and outcome 8 (brown) was a result of very low surface fuels (*fig. 7*). The combination of these conditions could be relatively rare, or there was simply substantial variation when these conditions occurred. This was exemplified in outcome 2, where the probability of certainty was 0.41 (*fig. 8*).

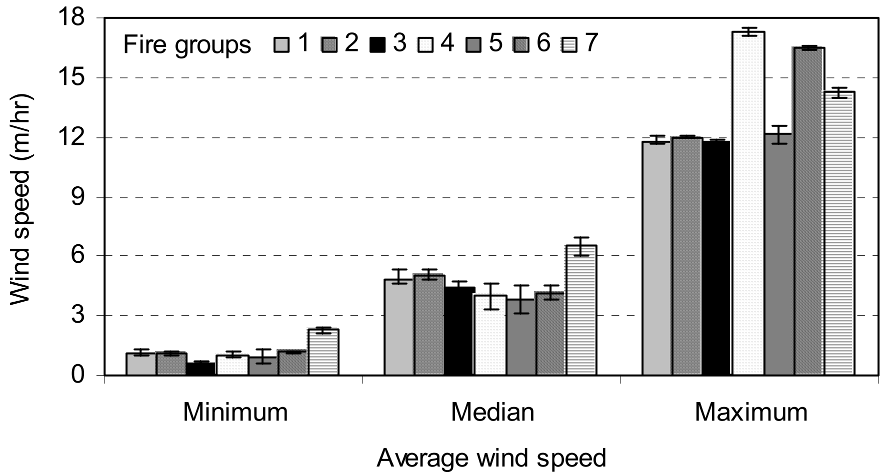

Figure 12—Average wind speeds for three classes: minimum, median, and maximum among fire groups. Standard error bars are presented to illustrate the variation in wind speed within and among the fire groups.

Table 12—*A cross-validation matrix showing how the overall model correctly classified tree burn severity. The highlighted values on the diagonal provide the probability of correctly classifying the actual burn severity given the forest structure characteristics and wildfires used in the classification. Standard errors are presented in parenthesis.*

Actual class	Predicted class			
	Green crowns	Mixed green crowns	Mixed brown & brown crowns	Black crowns
Green crowns	**0.46 (0.04)**	0.14	0.13	0.27
Mixed green crowns	0.20	**0.42 (0.03)**	0.13	0.25
Mixed brown and brown	0.25	0.20	**0.19 (0.03)**	0.36
Black crowns	0.21	0.13	0.10	**0.55 (0.03)**

Conclusion

There are several factors (for example, weather, types of vegetation, fuel moisture, atmospheric stability, physical setting, ladder fuels, surface fuels) that influence fire behavior and burn severity. Forest structure is but one factor (Agee 1996, Graham et al. 2004). Therefore, we did not expect forest structure characteristics to fully explain all of the variation present in burn severity after a wildfire. However, through our study and subsequent analysis, we were able to predict tree burn severity as a function of pre-wildfire forest structure with probabilities far greater than what would have occurred randomly (*table 11*). Throughout the literature, canopy base height has always strongly been associated with fire behavior and with burn severity (Agee 1996, Graham et al. 1999, Graham et al. 2004, Peterson et al. 2005, Scott and Reinhardt 2001). What surprised us was the strong association that canopy base height had with tree burn severity at heights less than 2m (6.4 ft). This is far lower than we expected and, most likely, these low canopy base heights reflect surface fuel moistures, stand structural stages, and past forest management activities. This finding also shows that canopy base height is a forest structure element related to many different forest characteristics. Thus, it relates to fire behavior and tree burn severity in many different ways.

Undoubtedly, intense fire behavior is a primary concern for forest management throughout the western United States. Consequently, fuel treatment to modify this fire behavior becomes a primary consideration (Graham et al. 2004). However, in most circumstances, what a fire leaves behind in terms of soils, homes, and trees is as important, if not more so, than fire behavior. Therefore, fuel treatments need to be designed and implemented to modify burn severity, and the traditional thinned forest with high canopy base heights may not result in the desired burn severity. In fact, the stands with the highest canopy base heights we sampled (10m, 32 ft) had brown or black crowns after a wildfire (*figs. 8*, *10*). Stands with canopy base heights less than 1.7m (5.5 ft) had green crowns.

One size does not fit all. Therefore, we would suggest that fuel treatments be designed to consider burn severity as well as fire behavior. In particular, physical setting (forest type, locale, potential vegetation type, and so forth) needs to provide context for planned fuel treatments. Secondly, although high canopy base heights do not always result in reduced burn severity, tree canopy base height needs to be considered when designing fuel treatments. Similarly, reducing total forest cover does not necessarily reduce burn severity. Instead, its interactions with the biophysical setting, canopy base height, and surface fuel amounts and conditions most likely determine burn severity. The last characteristics that we identified as having a relation with tree burn severity, subsidiary to those already mentioned, were forest type, tree crown ratio, and tree diameter. Wildfires burning in the cold forests (subalpine fir) exemplify that high canopy base heights can result in black crowns, especially if the crowns intercept rain and snow, resulting in relatively dry forest floor conditions.

The robust data we accumulated from wildfires that burned throughout the western United States in recent years did not greatly simplify our understanding of the relations between forest structure and burn severity. Nevertheless, we did identify several interactions between forest characteristics and burn severity that have fuel treatment management applications. A significant factor of this work is the estimate of the certainty a forest structure (fuel treatment) will have in modifying burn severity. In addition, the approach we took in identifying the relations between forest structure and burn severity, and the level of certainty we provided, was conditional on the circumstances in which the forest characteristic occurred. This kind of information will be of value when communicating the importance forest structure (fuel treatments) has on determining the aftermath of wildfires. This paper and the analysis and results we reported are a continuation of our work in understanding how forest structure interacts with wildfires, their physical setting, and burning conditions to create a particular burn severity.

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