CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2006, **15**, 557–566

Influence of topography and forest structure on patterns of mixed severity fire in ponderosa pine forests of the South Dakota Black Hills, USA

Leigh B. Lentile[A,C,D], *Frederick W. Smith*[A] *and Wayne D. Shepperd*[B]

[A]Department of Forest Sciences, Colorado State University, Fort Collins, CO 80523, USA.
[B]USDA Forest Service, Rocky Mountain Research Station, 240 West Prospect Road, Fort Collins, CO 80526, USA.
[C]Present address: Department of Forest Resources, University of Idaho, Moscow, ID 83844, USA.
[D]Corresponding author. Email: lentile@uidaho.edu

Abstract. We examined the influence of topography and stand structure on fire effects within the perimeter of the ~34 000 ha Jasper fire of 2000 in ponderosa pine (*Pinus ponderosa* Laws.) forests of the South Dakota Black Hills, USA. We used a remotely sensed and field-verified map of post-fire burn severity (accuracy 69%, kappa statistic 0.54), the Digital Elevation Model, and vegetation databases maintained by the Black Hills National Forest to empirically test relationships at 500 randomly located points in each of three severity classes. Burn severity was defined as the relative degree of post-fire change based on fire effects on soil, forest floor, and vegetation. This fire burned rapidly, yet created a patchy mosaic of effects (25, 48, and 27% low, moderate, and high severity). Stands burned by low and moderate severity fire had fewer trees (stand density index < 470 with fewer than 230 trees > 13 cm diameter at breast height ha^{-1}) and were found on less steep sites (slope < 18%). Denser stands (stand density index > 470) with larger trees (average stand diameter > 24 cm) or many small trees were more likely to burn with high severity effects. Our results suggest that managers should consider topography and stand structure together when making strategic decisions about which stands to thin or otherwise manage to reduce the severity with which forests will burn in wildfires.

Additional keywords: burn severity; mixed severity fire regime.

Introduction

Over the past two decades, the economic costs of fire management and suppression in the United States have been among the highest on record and, as a result, considerable effort has been focused on understanding how and why large fires burn. Long- and short-term weather patterns, topography, and fuels influence fire behavior and the subsequent effects of burning (Agee 1993). Whereas large, severe fires were historically common in many high-elevation forests, the size, occurrence, and severity of wildfires has increased in dry, low-elevation ponderosa pine (*Pinus ponderosa*) forests. Fire exclusion, grazing, and tree harvest have altered fuel and canopy structures, and combined with drought and frequent natural and anthropogenic ignitions, have led to many recent large and severe fires in ponderosa pine forests (Covington and Moore 1994; Swetnam *et al*. 1999; Allen *et al*. 2002; Schoennagel *et al.* 2004). In the present paper, we examine the relation between burn severity and topography and pre-fire stand structure in a large, mixed severity fire in a managed ponderosa pine forest to gain insight into where and under what forest conditions severe fire effects are likely to occur.

The relative contribution of forest structure, topography, and weather in many recent fires is of great interest to managers tasked with deciding where, when, and how restoration treatments are most likely to be effective (Allen *et al*. 2002; Agee and Skinner 2005; Hessburg *et al*. 2005; Raymond and Peterson 2005). The type, quantity, and spatial arrangement of fuels influence active fire properties (e.g. fireline intensity, flame length, and rate of spread) (Rothermel 1972; Van Wagner 1977) and the scale and severity of post-fire effects (Fulé *et al*. 2004; Agee and Skinner 2005). Pre-fire fuel patterns affect the way that fires burn, yet fuels cannot burn without an ignition source and conducive weather (Agee 1993). Burn severity is a measure of the magnitude of fire effects on vegetation and soil, and is largely driven by the dynamic interaction of fire behavior and fuels (Ryan and Noste 1985; DeBano *et al*. 1998). Although the physical manifestations of burn severity vary continuously, for practicality burn severity

 10.1071/WF05096 1049-8001/06/040557

is often broadly defined and partitioned into discrete classes ranging from low (less severe) to high (more severe).

Burn severity is related to fire intensity and behavior, but severe fire effects are not limited to crown fires (Lentile *et al*. 2006). Fuel characteristics such as canopy bulk density, live crown base height, and surface fuel conditions (amount, composition, moisture content, compactness, continuity) influence a stand's potential to sustain crown fire (Agee *et al.* 2002; Jain and Graham 2004). Severe fire effects such as high duff consumption, tree root damage, and reduced soil water infiltration have been associated with slow-moving, smoldering, surface fires (Ryan and Noste 1985; DeBano *et al*. 1998). Needle scorch, crown consumption, and tree cambial death are commonly associated with fast-moving, crown fires (DeBano *et al*. 1998; Brown and Smith 2000). Severe fire effects may lead to slower soil and vegetation recovery, accumulations of large woody fuels, and increased severity in future fires (Jurgensen *et al.* 1997; Agee 2003).

Contemporary management of many forests, particularly in low elevation ponderosa pine forests, is often designed to reduce fuels to modify effects of future wildfires or other disturbances (Arno *et al*. 1995; Brown *et al*. 2004). Many of these forests were historically burned by low or mixed severity fires, yet several recent fires (e.g. Hayman fire, CO; Rodeo-Chedeski fire, AZ) have been larger, and perhaps more severe, than previously recorded fires. Mixed severity regimes are complex and may include individual fires that create variable fire effects, including patches of stand-replacing fire, as well as surface fire with non-lethal effects (Arno *et al*. 2000; Agee 2005). Mixed severity fire regimes have been little studied, although Fulé *et al*. (2003) suggest that low and high severity fires burning in proximity may be the result of fine-scale, topographically influenced differences in vegetation and fuel moisture. Furthermore, there is little information on wildfire effects and how they vary with vegetation structure and topography in mixed severity fires.

Mixed severity regimes are poorly understood (Agee 2005). The inherent variation in mixed severity fire regimes complicates the ability to retrospectively attribute causality, make inferences about the nature of these fire regimes, and adapt management decisions accordingly (Lentile *et al*. 2005). Topographic characteristics may interact with weather, but can also have direct effects on fire (Agee 1993). The influence of topography on fire behavior may be greater on steep slopes, ridgetops, and southerly aspects (Agee 1994), and we expected that these areas would burn more severely. Second, we expected that stands of higher density would burn more severely and experience higher tree mortality, but that under some burning conditions forest structure and topography would have little influence on subsequent fire effects. Many studies have shown that fire effects were less severe following thinning treatments in ponderosa pine forests (Weaver 1943; Cooper 1961; Biswell *et al*. 1973; Pollet and Omi 2002; Schoennagel *et al.* 2004); however, under some extreme weather conditions, and with increasing time since treatment, treatment effectiveness may be decreased (Agee and Skinner 2005; Finney *et al*. 2005). Furthermore, Raymond and Peterson (2005) emphasize that many retrospective wildfire studies, particularly in frequent fire regimes where surface fuel conditions are highly related to subsequent fire effects, may provide more reliable reconstruction and analyses of canopy fuels than surface fuels.

The Black Hills have a long history of intensive timber harvest of larger and more fire-resistant trees. Additionally, fire exclusion in the last century has lengthened fire return intervals and led to an increase in the amount and continuity of surface and canopy fuels. These forces in combination with favorable conditions for regeneration throughout the 20th century have increased the potential for large, severe fires (Shepperd and Battaglia 2002; Brown and Cook 2006). The largest of these fires was the Jasper fire, which burned ~7% of the USDA Forest Service Black Hills National Forest (BHNF) in 8 days in the late summer of 2000. With over half of the land base of the BHNF in the moderate to high departure fire regime condition class (USDA Forest Service 2005) and over 4000 ha scheduled for fuels reduction in the Wildland–Urban Interface (http://www.fs.fed.us/r2/blackhills/news/2005/11/30_prescribed_burning.shtml, accessed 3 October 2006), there is a great need to improve understanding of relationships between pre-fire and post-fire conditions and to provide support for strategic and science-based management decisions.

In the present study, we quantified topographic and pre-fire vegetation conditions in areas that subsequently burned under low, moderate, and high severity in the Jasper fire. We related a remotely sensed and field-verified map of post-fire burn severity to topographic and pre-fire stand conditions using Digital Elevation Model and vegetation databases. We used decision-tree regression analyses to identify topographic and pre-fire forest characteristics more likely to experience a particular suite of fire effects, i.e. burn severity. The Jasper fire, like other recent, large wildfires in managed ponderosa pine forests (see Schoennagel *et al*. 2004 and Agee and Skinner 2005), exhibited variable burn severity and at times appeared to be influenced by subtle differences in burning conditions. An understanding of pre-fire condition and burning patterns following the Jasper fire will provide valuable insight for adaptive management and restoration efforts in the Black Hills and other ponderosa pine systems prone to mixed severity burning.

Methods

Site description

On 24 August 2000, the human-caused Jasper fire originated in the interior forests of the south-central Black Hills in western South Dakota and north-eastern Wyoming (Fig. 1). Gusting winds quickly contributed to ~18 000 ha burned in

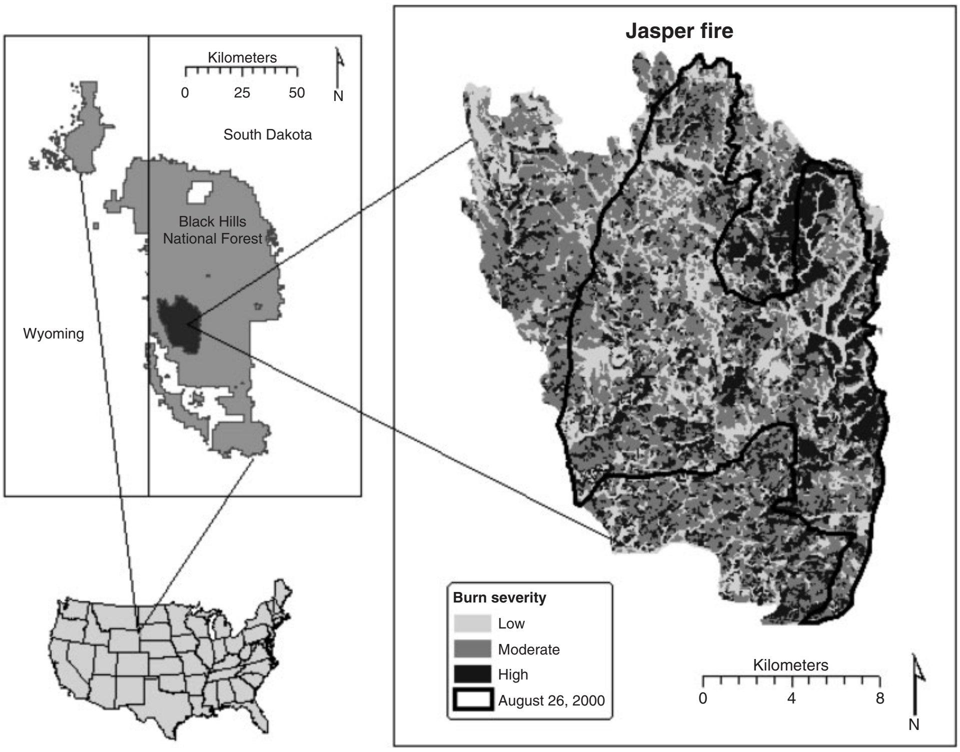

Fig. 1. The Jasper fire was located in western South Dakota on the Black Hills National Forest. The areas outlined in black burned on 26 August 2000. Jasper fire center latitude 43°48′56″N and longitude 103°52′37″W.

one afternoon. On this day, the closest Remote Automated Weather Station (43.8°N 103.6°W, ∼13 km from the fire) recorded a daily maximum temperature of 29°C, a relative humidity of 25%, a 10-h fuel moisture of 5%, and an average wind speed of 31 km h^{-1} out of the south-east. Weather conditions at sites within the fire most likely differed because of the sensitivity of fire behavior to local conditions of slope, aspect, elevation, and stand structure. The local Keetch Byram Drought Index, a measure of soil moisture deficiency on a scale of 0 to 800, was 195. The energy release component, a measure of seasonal fuel moisture conditions, was 67, indicating the potential for severe fire behavior. The Jasper fire was officially contained on 8 September 2000 after burning 33 795 ha or 7% of the BHNF land base and was ∼25% larger than any other recorded fire in Black Hills history (USDA Forest Service 2001).

In the study area, latitudes range from 43°41′35″ to 43°55′48″N and longitudes range from 103°46′1″ to 104°0′47″W. Elevations range from ∼1500 to 2100 m. The BHNF manages 95% of the area burned by the Jasper fire. The climate is continental, and most precipitation falls in the summer months. Intensively managed ponderosa pine forms the dominant vegetation matrix, but scattered aspen (*Populus tremuloides*) clones and meadowland inclusions are found in the study area (Lentile 2004). Mean daily maximum and minimum temperatures are 13.2 and −3.3°C, and annual precipitation ranges from ∼45 to 48 cm (Froiland 1990).

Burn severity map

The current research directly builds on an initial burn severity classification (Gould 2003) of 30-m spatial resolution Landsat 7 imagery (acquired 24 September 2001). We selected this image as it was taken 1 year post fire and was free of cloud and smoke interference. Tree mortality was more evident and needle loss permitted a clearer satellite 'view' of ground conditions in the 1 year post fire image when compared with the imagery available immediately after the fire. Gould (2003) used the ISODATA (Ball and Hall 1965) algorithm to identify 10 classes of spectral reflectance. Three randomly selected plots were located within each of the 10 ISODATA classes and then sampled in the field. Gould (2003) assessed fire effects on forest canopy at each plot center and on ground cover in nine subplots (72 points per plot). Ground cover assessments refer to the cumulative percentage of protected soil (i.e. the proportion of the plot covered with vegetation and duff), as contrasted with unprotected soil (i.e. the proportion of the plot covered with rock, bare mineral soil, and litter without duff). Groups of pixels or plots exhibiting similar characteristics of fire effects were grouped into classes following Ryan and Noste's (1985) severity classification. Many studies have relied on Ryan and Noste's (1985) field-based characterization of fire effects to classify remotely sensed data because the discriminating features are detectable from satellite data (White *et al*. 1996; Ruiz-Gallardo *et al*. 2004; Lentile *et al*. 2006). Furthermore, our ability to robustly calibrate the imagery with field data and validate the fine-scale variation represented in the burn severity map resulted in a more accurate map than the standardized differenced normalized burn ratio (dNBR) techniques (Key and Benson 2006) developed for Glacier National Park, Montana.

Initial accuracy assessment was based on data collected in September 2000 and focused primarily on tree canopy scorch as an indicator of the immediate post-fire condition of vegetation. We performed an additional accuracy assessment during the summer of 2002, incorporating the same methods used to develop the initial severity classification. Ten plots were randomly located in each severity class with no prior knowledge of the classification. Sites were reselected if they coincided with areas influenced by post-fire salvage logging. Accuracy assessment of the remotely sensed outputs was evaluated using the measures of overall accuracy and kappa statistics through production of an error matrix (Congalton and Green 1988; Kundel and Polansky 2003).

We imported the burn severity map into ArcView geographic information system (GIS) to examine spatial patterns of burn severity. We obtained daily fire progression GIS layers from the BHNF. We used Patch Analyst to create, query, map, and analyze cell-based raster data. We created patches by dissolving boundaries between adjacent polygons of the same burn severity class.

Stand condition, structure, and topographical variables

We randomly selected 500 points from each of the low, moderate, and high burn severity classes within the ponderosa pine cover type. For these 1500 points (all selected independently from data used in the accuracy assessment), we compiled information about various topographic and vegetation characteristics from existing spatially explicit databases with comparable resolution. Individual burn severity patches included a range of topographic conditions and vegetation characteristics. Similarly, more than one class of burn severity was associated with each stand. For this reason, multiple points were located in some stands, and an individual patch of burn severity might contain more than one point.

The Resource Information System (RIS) database is maintained by the USDA Forest Service for the BHNF and provides the scientific and managerial knowledge base for virtually all decisions regarding the use of these public lands. In this 40-m resolution database, polygon coverages are developed from a combination of information sources and processes, including aerial photo interpretation, on-screen digitizing, and field surveys. The 2000 RIS database contained information including pre-fire forest cover type, tree density (trees ha^{-1}) in size classes >13 cm and <13 cm diameter at breast height (DBH), average stand diameter (ASD, cm), crown cover (percentage canopy closure), stand basal area (BA, m^2 ha^{-1}), stand density index (SDI), and habitat structural stage (HSS). The SDI value is the number of trees per hectare stands would have if the trees had an average size of 25.4 cm DBH. The premise of SDI is that if growing space is fully occupied, an increase in average stand diameter can only occur if there is a reduction in the number of trees per unit area (Long 1985). Application of the SDI method is biologically justifiable in even-aged stands, but may overpredict site occupancy in uneven-aged stands dominated by smaller diameter trees (as opposed to larger ones) (Woodall *et al*. 2003). HSS describes the existing dominant stand appearance or physiognomy for the ecosystem unit and is derived from the seral and stand structure classifications recommended by Oliver and Larson (1990). HSS includes five classes: grass-forb (stage 1), shrub-seedling (<2.54 cm DBH for pine seedlings) (stage 2), sapling-pole (2.54–22.86 cm DBH) (stage 3), mature (trees >22.86 cm DBH) (stage 4), old-growth forest (stage 5), and stages 3 and 4 are further divided into 3a/4a, 3b/4b, and 3c/4c for 10–40, 41–70, and 71–100% crown cover, respectively. Elevation, slope, and aspect were gathered from the 30-m resolution Digital Elevation Model for the Black Hills for each of the 1500 points.

Statistical analyses

We analyzed data from 500 randomly selected points from each of the three burn severity classes within the ponderosa pine cover type to test the strength of the relationship between the categorical response variables of burn severity (low, moderate, or high) and continuous predictor variables including SDI, the number of trees >13 cm DBH, the number of trees <13 cm DBH, ASD, and slope. These variables were selected based on both statistical and ecological rationales. We tested for correlation using PROC CORR (SAS Institute 2001). We compared values using analysis of variance (PROC GLM; SAS Institute 2001). Probabilities were computed to determine if means were significantly different from each other. Variables were tested for significance at the 95% confidence level ($\alpha = 0.05$). Results are reported in Lentile (2004), but not here. Graphical analysis suggested that many relationships were non-linear.

We applied a non-linear, non-parametric statistical model to the dataset to explore relationships between burn severity and the significant topographic and structural variables. Decision tree regression analysis generally relies on fewer assumptions than parametric statistical methods. There is no assumption of a linear model or the need to pre-specify a probability distribution for the errors, and these models are suited to a wide variety of data structures. Furthermore, decision trees are particularly useful when the predictors may be associated in some non-linear fashion (Breiman *et al.* 1984). We used S-PLUS (version 6.2; Insightful Corporation, Seattle, WA, USA) to construct a decision tree regression analysis

Table 1. Description of pre-fire forest characteristics within the area burned in the Jasper fire
Data were summarized from the 2000 Black Hills National Forest Resource Information System database. DBH, diameter at breast height

Variable	Stand size (ha)	Stand diameter (cm)	Density (trees ha^{-1})			Basal area (m^2 ha^{-1})	Stand density index	Site index (base age = 100)
			<3 cm DBH	3–13 cm DBH	>13 cm DBH			
Mean	15.8	25.3	884.1	654.4	388.3	17.7	345	57
s.e.	0.3	1.9	299.7	178.2	86.9	3.1	208	10

in which an overall accuracy of classification was assigned to each burn severity class in the model. The model creates a tree structure from the data in which each branch is split into mutually exclusive subsets. Each branch of the tree corresponds to a decision rule for splitting the data into subsets that yield predictions of low, moderate, or high burn severity given the values of the dependent variables. Forest structure or topographical characteristics occurring at the top of a classification tree indicate a stronger relation to severity, relative to characteristics that appear further down the tree (Jain and Graham 2004).

Results

Burn severity map

Burn severity classes ranged from low (surface fire) to moderate (mixed surface fire and torching) to high (stand-replacing fire). Low severity had low tree mortality with predominantly green tree canopies (<25% canopy scorch), and >70% ground cover. Moderate severity had mixed tree mortality and survival, extensively scorched tree canopies (>25% scorch), and 30–70% ground cover. High severity was characterized by complete tree mortality (100% blackened canopies) and less than 30% ground cover, although typically 10% or less. For full details, please see Gould (2003). The 2-year post-fire accuracy assessment indicated that the burn severity map was accurate 56, 88, and 73% of the time in low, moderate, and high burn severity. The overall accuracy of the burn severity map was 69%, whereas the kappa statistic value was 0.54, indicating moderate agreement between the field data and remotely sensed outputs (Smith *et al*. 2002).

Pre-fire forest structure

Before the Jasper fire, ponderosa pine stands of varying densities were found on 87% of the burned area. Stands were occupied by saplings, mature pole-sized trees, and small sawtimber. Pre-fire ASD (s.e.) was 25.3 (1.9) cm. Sixty-one percent of ponderosa pine forests were in a mature HSS (4a, 4b, and 4c). These forests had moderate to high canopy cover, and 29% of forests had canopy cover >70%. On average, there were 388 trees ha^{-1} >13 cm DBH, 654 trees ha^{-1} between 3 and 13 cm DBH and 884 saplings <3 cm DBH. For all stands in the study area, average basal area was ~18 m^2 ha^{-1}. Average SDI was 345 or ~30% of maximum stand density. Mean site index for ponderosa pine stands within the burned area was 57 (base age = 100 years) (Table 1).

Table 2. Description of pre-fire vegetation and post-fire burn severity patches within the ponderosa pine cover type in the Jasper fire
Values are the number of pre-fire vegetation patches in each burn severity class and the mean size of burn severity patches within each severity class

Burn severity	No. pre-fire vegetation patches	Mean burn severity patch size (ha)	
		Mean	s.e.
Low	323	10.4	2.7
Moderate	1210	24.1	7.1
High	506	7.5	1.0
Total	2039	12.5	2.0

In the study area before the fire, there were 2039 stands of ponderosa pine (Table 2) with a mean size (s.e.) of 15.8 (0.3) ha (Table 1). Points were randomly located in 900 of these stands (44%). Of the sampled stands, 59% contained only one sample point, 25% were sampled twice, 10% were sampled three times, and 6% more than three times.

Post-fire analysis

Although the Jasper fire was large and occurred under extreme weather conditions, the burn mosaic was complex. Spatial analysis of the burn severity map indicated 25, 48, and 27% of the landscape was burned by low, moderate, and high severity fire, respectively. Patch size averaged 10, 24, and 8 ha for low, moderate, and high burn severity, respectively (Table 2). The proportion of the Jasper fire that burned at low, moderate, and high severity was related to vegetation structure and topography. In the decision tree regression analysis, stand density index was the most important variable in predicting burn severity (Fig. 2). At SDIs <470, it was possible to correctly classify burn severity as either low or moderate 78% of the time. Eighty-five percent of all the observations of low or moderate severity occurred at low stand densities. In stands with lower density, we incorrectly classified high severity 22% of the time, which accounted for 47% of high severity observations. Conversely, when SDI exceeded 470, we correctly classified high burn severity 63% of the time. Fifty-three percent of all the observations of high severity occurred at high stand densities. Thirty-seven percent of the time, we incorrectly classified low or moderate severity, which accounted for only 15% of low or moderate observations.

The second most important variable identified in the decision tree was either the number or size of trees (Fig. 2). When stand density was low and there were fewer than ~230 trees

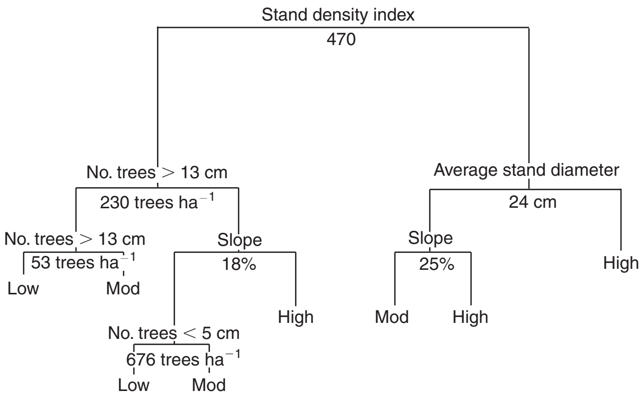

Fig. 2. Results for decision tree regression analysis for low, moderate, and high burn severity on 1500 randomly selected points, predicted by stand density, tree size, and slope. Values greater than the presented value classify to the right, lesser values classify to the left.

$>$13 cm DBH ha^{-1}, we correctly classified low and moderate severity 83% of the time. Lower stand density and fewer large diameter trees accounted for ~55% of low and moderate observations. When stand density was not high and a greater number of larger diameter trees were present (trees ha^{-1} > 230), at slopes <18%, we correctly classified low and moderate severity 76% of the time. When there were fewer small trees (DBH < 5 cm), we were more likely to observe low than moderate severity fire. This classification related to ~20% of low and moderate burn severity observations. Conversely, at slopes >18%, we correctly classified high severity 42% of the time, which accounted for 11% of observations of high severity. If SDI exceeded 470, and average stand diameter was <24 cm and slope >25%, we correctly classified high severity 53% of the time. This scenario of a high density stand of smaller diameter trees on steep slopes accounted for ~25% of all high severity observations. When SDI was >470, ASD < 24 cm and slopes were <25%, we were more likely to observe moderate than high severity fire. In higher density stands with larger trees (ASD > 24 cm), high burn severity was correctly classified 80% of the time. Again this scenario accounted for ~25% of all high severity observations.

Predictor variables, ranked in order of importance, were SDI, the number of large trees (DBH > 13 cm), ASD, slope, and the number of small trees (DBH < 5 cm). We were able to correctly classify fire effects 74, 64, and 76% of the time under low, moderate, and high severity, respectively. Overall classification accuracy was ~71%.

Discussion

Despite extreme weather conditions, fire effects in the Jasper fire varied with differences in pre-fire forest structure and landscape position. This observation was surprising because most of the area burned by the Jasper fire contained mature, moderate to high density second-growth ponderosa pine. The homogeneity of forest structure and vegetation composition,

Table 3. Summary of fire size (USDA Forest Service 2000) and proportion burned within each burn severity class for the 8 days of active burning during the Jasper fire, 2000

Date	Daily area burned (ha)	Proportion of daily area burned (%)		
		Low	Moderate	High
24 Aug	1479	14	59	28
25 Aug	3414	17	49	33
26 Aug	19 768	27	45	27
27 Aug	1707	21	64	15
28 Aug	1925	15	59	26
29 Aug	2986	34	51	15
30 Aug	2133	24	37	39
31 Aug	348	43	38	19

combined with extremely low fuel moistures and high winds (USDA Forest Service 2000; Benson and Murphy 2003) created ideal conditions for a running crown fire with high spread potential. Although the Jasper fire burned ~60% of the hectares in <12 h, fire effects were heterogeneous (Fig. 1), and we found many small patches of low, moderate, and high burn severity on the landscape (Lentile *et al*. 2005).

The Jasper fire was not dominated by high severity fire effects, even though the Jasper fire occurred under drought conditions on one of the most intensively logged national forests in the west that had also been subjected to over a century of fire exclusion. The summer of 2000 had been dry, and when the fire started, daytime relative humidities were very low. Fuel moisture levels of 10-h fuels were ~60% lower and 100- and 1000-h fuels were 18–26% lower than the 10-year average (1993–2002) for the June to September fire season in the Black Hills (Benson and Murphy 2003). Very strong and gusting winds caused the Jasper fire to grow from ~5000 to nearly 20 000 ha in one day (Table 3), creating firestorm conditions, and raining ash on urban areas ~50 km to the east (USDA Forest Service 2000).

Several interesting similarities exist between the Jasper fire and the 2002 Hayman fire in Colorado's Front Range. Prolonged drought conditions led to abnormally low fuel moisture contents (5–10%) of woody fuels of all sizes in the Hayman fire area. During the Hayman fire, high winds (32–80 km h^{-1}) with gusts to 135 km h^{-1}, and low humidity (~10%) resulted in extensive runs and widespread crown fire with long-range spotting (Graham 2003). The Haines Index was 6, the highest level of atmospheric instability, on the day when each fire experienced large crowning runs (USDA Forest Service 2000; Graham 2003). Extreme fuel and weather conditions and steep terrain combined to severely burn ~28 000 ha, roughly half of the landscape burned by the Hayman fire, within a 24-h period (Graham 2003). In contrast, in the Jasper fire, even when daily fire size was large, our estimates indicate a relatively even distribution of burn severities (Table 3).

Many of the variations in effects and response to fire result from variation in burn severity and patch size (Pickett and

White 1985). Patch sizes in the Jasper fire were small relative to daily area burned, and the largest patches of low and moderate severity burned over multiple days (Lentile *et al.* 2005). High severity fire burned >9000 ha during the Jasper fire; however, the proportion of area burned by high severity fire varied little from day to day (Table 3). The largest high severity patch burned in a few hours, but was much smaller than the largest burned patches of low and moderate severity. In the Hayman fire, 33% of the area burned was classified as high severity and the largest patch of complete mortality was ~3500 ha (Graham 2003). Small 'escapes' or narrow 'tree crown streets' were embedded within large patches of crown fire in the montane ponderosa pine and Douglas-fir (*Pseudotsuga menzensii*) forests on the Hayman fire. The proportion and patch sizes of high severity fire were much smaller in the Jasper fire than in the Hayman fire. A matrix of surviving vegetation was interspersed with patches of crown fire on the Jasper landscape (Fig. 1).

Many studies (e.g. Callaway and Davis 1993; Cram *et al.* 2003; Odion *et al.* 2004) have found that patterns of fire effects (i.e. severity) and post-fire vegetation recovery may be predisposed by topographical position and pre-fire vegetation structure. SDI, the number of large trees, and slope were the variables most closely associated with low and moderate burn severity under the severe weather conditions during the Jasper fire. Many stands in the Jasper fire were dense (mean SDI ~345) and approached full site occupancy for Black Hills ponderosa pine. Forest stands with low numbers of large trees on gentle slopes were most likely to burn at low or moderate burn severity. Similarly, ponderosa pine stands treated with tree density reduction or prescribed burning practices experienced less severe canopy and ground char damage following the Rodeo-Chedeski fire in Arizona in 2002 (Cram *et al.* 2003; Finney *et al.* 2005). Even with very low fuel moisture conditions and extreme fire behavior, basal area, tree density, and canopy bulk density were positively related to burn severity, whereas ASD was negatively related to severity (Cram *et al.* 2003).

In less dense stands, we found tree size and density were important in predicting burn severity at steeper slopes. Slopes can influence fire similarly to the effects of wind by pushing flames to the ground surface and pre-heating fuels ahead of the flame front or by increasing rates of spread (DeBano *et al.* 1998). In the Jasper fire, stands with lower density composed of a greater number of large trees (trees $ha^{-1} > 230$) were less likely to burn under high severity when slopes were <18%. However, on steeper slopes, the crowns of large trees are effectively 'stacked' in a multi-layered arrangement that facilitates fire spread from crown to crown, resulting in more severe fire effects.

The spatial continuity and density of tree canopies combine with fuel moisture and wind to determine rate of fire spread and severity (Rothermel 1983, 1991). Graham *et al.* (2004) reported that the potential for crown fires was high in many western forests with homogeneous and continuous horizontal and vertical stand structures. We found high stand density presented the most likely scenario for high severity fire. High density stands (SDI > 470) with either large trees (ASD > 24 cm) or many small trees were likely to burn under high severity. Stands with many small trees tend to have low crown base height and a high degree of vertical and horizontal continuity in fuel structure. In contrast, branches of larger trees in dense stands self-prune, raising crown base height. The potential for surface fire to transition to crown fire is decreased in stands with higher crown base height that have less vertical continuity between surface and canopy fuels (Van Wagner 1977). However, there is high potential for fire to pass from crown to crown in dense stands, particularly in wind-driven fire events. Raymond and Peterson (2005) found that raising crown base height without addressing resultant surface fuels did not decrease the potential for crown fire initiation in mixed-evergreen forests in south-western Oregon. Canopy bulk density is the foliage contained per unit volume of a forest stand (Scott and Reinhardt 2001) and effectively represents crown fire hazard (Peterson *et al.* 2003). Cram *et al.* (2003) found that crown fire initiation was more likely in stands with canopy bulk densities $>0.10\ kg\ m^{-3}$ and slopes >5%. High burn severity during the Jasper fire was probably more likely in dense stands with large trees owing to high canopy bulk density. The interspersion of small meadows or grasslands within forests may have provided natural fuel breaks; however, dense forests with multiple canopy layers and age cohorts are a more common component of the landscape burned by the Jasper fire. Shelterwood harvest techniques create age and structural diversity, which may reduce the spread of fire under most burning conditions; however, where fire has been excluded for some time, wildfire may easily transition from surface to canopy via ladder fuels.

The imprint of mixed severity fire effects following the Jasper fire resulted in a landscape mosaic with many small burned patches (~0.01–500 ha) with varying proportions of surviving trees and fire-killed trees, interspersed with some young, even-aged large forest patches (~1000 ha), and some small openings (Lentile *et al.* 2005). Patches of dense trees, shrub fields or grassy openings may develop where stand-replacing fire occurred within what was overall a mixed severity fire event. Black Hills ponderosa pine forests are dense and multi-storied with high canopy cover, and regeneration is prolific (Shepperd and Battaglia 2002). These conditions increase the probability of surface fires developing into crown fires. Fine surface fuels associated with productive overstories and vertical ladder fuels in the form of dense regeneration and understory thickets with a high degree of horizontal continuity are common on the Black Hills landscape and may favor mixed severity burning.

In the present study, we evaluated a single fire event in one location. Black Hills ponderosa pine forests have a different ecological and management history than most other ponderosa pine forests, and are thus likely not directly comparable with other ponderosa pine forests or with other forest types. In ponderosa pine forests, there is much literature to suggest that it may be practical and ecologically consistent to manage surface fuels as a means to mitigate burn severity (see Weaver 1943; Cooper 1961; Biswell *et al*. 1973; Pollet and Omi 2002; Cram *et al*. 2003; Schoennagel *et al.* 2004; Agee and Skinner 2005; Finney *et al*. 2005; Raymond and Peterson 2005). The data available for the present study did not contain any variables that would be related to different surface fuel conditions at the time of the fire. Additionally, spatially explicit weather data corresponding to the fire's known progression were unavailable. Thus, in the current study, some of the primary determinants of fire behavior and burn severity were not evaluated in the stands that burned. Having data on wind, temperature, and relative humidity, as well as local fuels, could improve predictive power and enhance our understanding of the complex interplay between fuels, topography, weather, and fire effects. Lastly, we did not evaluate stand treatments or time since treatment, nor were treatments designed to reduce severity of future fires.

Managers are greatly interested in strategic and effective placement of restoration and fire mitigation treatments. Our expectations that steep slopes, ridgetops, and southerly aspects would burn more severely were partially confirmed, as were our expectations that stands of higher density would burn more severely. Steep slopes burned more severely when stands were dense, but topography otherwise had little influence on burn severity given the relatively gentle terrain found in the South Dakota Black Hills. To our surprise, even under extremely dry and windy burning conditions, subtle variations in forest structure and slope influenced subsequent fire effects. Our results generally agree with other studies that suggest that modification of forest canopy and surface fuel structure may reduce the severity of future fires, and at the very least, suggest that forest managers should consider both the spatial arrangement and size of harvest and other management units, as well as topographic characteristics, when planning for fuel treatments and other fire mitigation measures.

Conclusion

There has been much debate surrounding historical conditions and the effects of fire exclusion in western forests. In particular, many ponderosa pine forests are currently described as uncharacteristic, at risk of severe wildfire and in need of restoration treatments. The present study and others (Graham *et al*. 1999; Pollet and Omi 2002; Cram *et al*. 2003; Jain and Graham 2004; Raymond and Peterson 2005) suggest that elements of forest structure likely influence fire behavior and, in some cases, forest treatments may reduce crown fire hazard and burn severity even when fires burn during extremely dry and windy conditions. A consensus has not been reached regarding the potential for fuel treatments to create more sustainable and resilient structures and restore processes within fire-dependent forests. In recent decades, mixed severity fires have become increasingly common, yet the influences of pre-fire forest structure, topography, and weather are poorly understood. Understanding where and under what conditions severe fire effects are likely to occur will help managers strategize the location and design of fuel management and restoration treatments.

Acknowledgements

This study was funded by the Black Hills National Forest through In Service Agreement #0203-01-007, Monitoring Fire Effects and Vegetation Recovery on the Jasper Fire, Black Hills National Forest, South Dakota, to Rocky Mountain Research Station and Colorado State University and by McIntire-Stennis funding to the Department of Forest Sciences. The authors would like to thank B. Cook, J. Gould, M. Bobbitt, M. Williams for their support of the Jasper Fire Monitoring Project, and R. Reich for his assistance with statistical analysis. We would like to thank W. Romme, E. Kelly, W. Jacobi, T. Jain, A. M. S. Smith, and P. Morgan for review of early drafts. Comments from two anonymous reviewers greatly improved the paper.

References

Agee JK (1993) 'Fire ecology of Pacific Northwest forests.' (Island Press: Washington, DC)

Agee JK (1994) 'Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades.' USDA Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-320. (Portland, OR)

Agee JK (2003) Monitoring post-fire tree mortality in a mixed-conifer forests of Crater Lake, Oregon. *Natural Areas Journal* **23**, 114–120.

Agee JK (2005) The complex nature of mixed severity fire regimes. In 'Mixed severity fire regimes: ecology and management symposium proceedings', 17–19 November 2004, Spokane, WA, USA. (Eds L Taylor, J Zelnik, S Cadwallader, B Highes) MISCO3. (Association of Fire Ecology)

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83–96.

Agee JK, Wright CB, Williamson N, Huff MH (2002) Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. *Forest Ecology and Management* **167**, 57–62. doi:10.1016/S0378-1127(01)00690-9

Allen CD, Savage M, Falk DA, Suckling KF, Swetnam TW, Schulke T, Stacey PB, Morgan P, Hoffman M, Klingel JT (2002) Ecological restoration of South-western ponderosa pine: a broad perspective. *Ecological Applications* **12**, 1418–1433.

Arno SF, Scott JH, Hartwell MG (1995) 'Age-class structure of old growth ponderosa pine/Douglas-fir stands and its relationship to fire history.' USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper, INT-RP-481. (Ogden, UT)

Arno SF, Parsons DJ, Keane RE (2000) Mixed-severity fire regimes in the Northern Rocky Mountains: consequences of fire exclusion and options for the future. In 'Proceedings of the wilderness science in a time of change conference, Vol. 5: wilderness ecosystems, threats and management'. (Compilers DN Cole, SF McCool, WT Borrie, J O'Loughlin) pp. 225–232. USDA Forest Service, Rocky Mountain Research Station RMRS-P-15-VOL-5. (Ogden, UT)

Ball GH, Hall DJ (1965) 'A novel method of data analysis and pattern classification.' Technical Report AD-699616. (Stanford Research Institute: Menlo Park, CA)

Benson RP, Murphy MP (2003) Wildland fire in the Black Hills. In 'Proceedings: Second international wildland fire ecology and fire management congress and fifth symposium on fire and forest meteorology', November 2003, Orlando, FL. (American Meteorological Society: Boston) Available at http://ams.confex.com/ams/pdfpapers/65402.pdf [Verified 3 October 2006]

Biswell HH, Kallander HR, Komerek R, Vogl RJ, Weaver H (1973). 'Ponderosa pine fire management: a task force evaluation of controlled burning of ponderosa pine forests in central Arizona.' Tall Timbers Research Station Miscellaneous Publication 2. (Tallahassee, FL)

Breiman L, Friedman JH, Olshen RA, Stone CJ (1984) 'Classification and regression trees.' (Wadsworth International Group: Belmont, CA)

Brown JK, Smith JK (Eds) (2000) 'Wildland fire in ecosystems: effects of fire on flora.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-42-vol. 2. (Ogden, UT)

Brown PM, Cook B (2006) Early settlement forest structure in Black Hills ponderosa pine forests. *Forest Ecology and Management* **223**, 284–290. doi:10.1016/J.FORECO.2005.11.008

Brown RT, Agee JK, Franklin JF (2004) Forest restoration and fire: principals in the context of place. *Conservation Biology* **18**, 903–912. doi:10.1111/J.1523-1739.2004.521_1.X

Callaway RM, Davis FW (1993) Vegetation dynamics, fire and the physical environment in central California. *Ecology* **74**, 1567–1578. doi:10.2307/1940084

Congalton RG, Green K (1988) 'Assessing the accuracy of remotely sensed data: principles and practices.' (Lewis Publishers: New York)

Cooper CF (1961) Controlled burning and watershed condition in the White Mountains of Arizona. *Journal of Forestry* **59**, 438–442.

Covington WW, Moore MM (1994) South-western ponderosa pine forest structure: changes since Euro-American settlement. *Journal of Forestry* **92**, 39–47.

Cram DS, Baker TT, Boren J, Edminster C (2003) Inventory and classification of wildland fire effects in silviculturally treated *v.* untreated forest stands of New Mexico and Arizona. In 'Proceedings: Second international wildland fire ecology and fire management congress and fifth symposium on fire and forest meteorology', November 2003, Orlando, FL. (American Meteorological Society: Boston) Available at http://ams.confex.com/ams/pdfpapers/65363.pdf [Verified 25 February 2005]

DeBano LF, Neary DG, Ffolliott PF (1998) 'Fire's effects on ecosystems.' (John Wiley and Sons: New York)

Finney MA, McHugh CW, Grenfell IC (2005) Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. *Canadian Journal of Forest Research* **35**, 1714–1722. doi:10.1139/X05-090

Froiland SG (1990) 'Natural history of the Black Hills.' (Center for Western Studies, Augustana College: Sioux Falls, SD)

Fulé PZ, Heinlein TA, Covington WW, Moore MM (2003) Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data. *International Journal of Wildland Fire* **12**, 129–145. doi:10.1071/WF02060

Fulé PZ, Cocke AE, Heinlein TA, Covington WW (2004) Effects of an intense prescribed forest fire: is it ecological restoration? *Restoration Ecology* **12**, 220–230. doi:10.1111/J.1061-2971.2004.00283.X

Gould JJ (2003) Hydrologic modeling of high-intensity, short-duration rainfall on burned ponderosa pine forested watersheds existing in highly permeable geology within the Black Hills of South Dakota. MS Thesis, South Dakota School of Mines and Technology, Rapid City, SD.

Graham RT (Tech. Ed.) (2003) 'Hayman fire case study.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-114. (Ogden, UT)

Graham RT, Harvey AE, Jain TB, Tonn JR (1999) 'The effects of thinning and similar stand treatments on fire behavior in western forests.' USDA Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-463. (Portland, OR)

Graham RT, McCarthy S, Jain TB (Tech. Eds) (2004) 'Science basis for changing forest structure to modify wildfire behavior and severity.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-120. (Fort Collins, CO)

Hessburg PF, Agee JK, Franklin JF (2005) Dry forests and wildland fires of the inland Northwest USA: contrasting the landscape ecology of the pre-settlement and modern eras. *Forest Ecology and Management* **211**, 117–139. doi:10.1016/J.FORECO.2005.02.016

Jain TB, Graham RT (2004) Is forest structure related to fire severity? Yes, no, and maybe: methods and insights in quantifying the answer. In 'Silviculture in special places: proceedings of the National Silviculture Workshop', 8–11 September 2003, Granby, CO. (Comps WD Shepperd, LG Eskew) pp. 217–234. USDA Forest Service, Rocky Mountain Research Station Proceedings RMRS-P-34. (Fort Collins, CO)

Jurgensen MF, Harvey AE, Graham RT, Page-Dumroese DS, Tonn JR, Larsen MJ, Jain TB (1997) Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland Northwest forests. *Forest Science* **43**, 234–251.

Key CH, Benson NC (2006) 'Landscape assessment: sampling and analysis methods.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-164-CD. (Ogden, UT)

Kundel HL, Polansky M (2003) Measurement of observer agreement. *Radiology* **228**, 303–308.

Lentile LB (2004) Causal factors and consequences of mixed-severity fire in Black Hills ponderosa pine forests. PhD Dissertation, Colorado State University, Fort Collins, CO.

Lentile LB, Smith FW, Shepperd WD (2005) Patch structure, fire-scar formation and tree regeneration in a large mixed-severity fire in the South Dakota Black Hills, USA. *Canadian Journal of Forest Research* **35**, 2875–2885. doi:10.1139/X05-205

Lentile LB, Holden ZA, Smith AMS, Falkowski MJ, Hudak AT, Morgan P, Lewis SA, Gessler PE, Benson NC (2006) Remote sensing techniques to assess active fire and post-fire effects. *International Journal of Wildland Fire* **15**, 319–345. doi:10.1071/WF05097

Long JN (1985) A practical approach to density management. *Forestry Chronicle* **61**, 23–27.

Odion DC, Frost EJ, Strittholt JR, Jiang H, Dellasala DA, Moritz MA (2004) Patterns of fire severity and forest conditions in the western Klamath mountains, California. *Conservation Biology* **18**, 927–936. doi:10.1111/J.1523-1739.2004.00493.X

Oliver CD, Larson BC (1990) 'Forest stand dynamics.' Biological Resource Management Series. (McGraw-Hill: New York)

Peterson DL, Johnson MC, Agee JK, Jain TB, McKenzie D, Reinhardt ED (2003) Fuels planning: managing forest structure to reduce fire hazard. In 'Proceedings: Second international wildland fire ecology and fire management congress and fifth symposium on fire and forest meteorology', November 2003, Orlando, FL. (American Meteorological Society: Boston) Available at http://ams.confex.com/ams/pdfpapers/74459.pdf [Verified 3 October 2006]

Pickett STA, White PS (1985) 'The ecology of natural disturbance and patch dynamics.' (Academic Press: New York)

Pollet J, Omi PN (2002) Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* **11**, 1–20. doi:10.1071/WF01045

Raymond CL, Peterson DL (2005) Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. *Canadian Journal of Forest Research* **35**, 2981–2995. doi:10.1139/X05-206

Rothermel RC (1972) 'A mathematical model for predicting fire spread in wildland fuels.' USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper INT-RP-115. (Ogden, UT)

Rothermel RC (1983) 'How to predict the spread and intensity of forest and range fires.' USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-GTR-143. (Ogden, UT)

Rothermel RC (1991) 'Predicting behavior and size of crown fires in the Northern Rocky Mountains.' USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper INT-RP-115. (Ogden, UT)

Ruiz-Gallardo JR, Castano S, Calera A (2004) Application of remote sensing and GIS to locate priority intervention areas after wildland fires in Mediterranean systems: a case study from southeastern Spain. *International Journal of Wildland Fire* **13**, 241–252. doi:10.1071/WF02057

Ryan KC, Noste NV (1985) Evaluating prescribed fires. In 'Proceedings of the symposium and workshop on wilderness fire', 15–18 November 1983, Missoula, MT. (Tech. Coords JE Lotan, BM Kilgore, WC Fischer, RW Mutch) USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-GTR-182. (Ogden, UT)

SAS Institute (2001) 'SAS user's guide: statistics, V. 8.02.' (SAS Institute: Cary, NC)

Schoennagel TL, Veblen TT, Romme WH (2004) The interaction of fire, fuels and climate across Rocky Mountain forests. *Bioscience* **54**, 661–676. doi:10.1641/0006-3568(2004)054[0661:TIOFFA]2.0.CO;2

Scott JH, Reinhardt ED (2001) 'Assessing crown fire potential by linking models of surface and crown fire behavior.' USDA Forest Service, Rocky Mountain Research Station Research Paper RMRS-RP-29. (Fort Collins, CO)

Shepperd WD, Battaglia MA (2002) 'Ecology, silviculture, and management of Black Hills ponderosa pine.' USDA Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-9. (Fort Collins, CO)

Smith AMS, Wooster MJ, Powell AK, Usher D (2002) Texture-based feature extraction: application to burn scar detection in Earth Observation satellite imagery. *International Journal of Remote Sensing* **23**, 1733–1739. doi:10.1080/01431160110106104

Swetnam TW, Allen CD, Betancourt J (1999) Applied historical ecology: using the past to manage for the future. *Ecological Applications* **9**, 1189–1206. doi:10.2307/2641390

USDA Forest Service (2000) 'Jasper Fire rapid assessment team report.' USDA Forest Service, Black Hills National Forest. Supervisor's Office. (Custer, SD) Available at http://www.fs.fed.us/r2/blackhills/fire/history/jasper/00_11_09_JRAT_Report.pdf [Verified 3 October 2006]

USDA Forest Service (2001) 'Jasper Fire value recovery final environmental impact statement FEIS.' USDA Forest Service, Black Hills National Forest, Supervisor's Office. (Custer, SD)

USDA Forest Service (2005) Natural disturbance processes. In 'Black Hills National Forest Phase II Amendment'. pp. 336–381. USDA Forest Service, Rocky Mountain Region, Black Hills National Forest. (Custer, SD) Available at http://www.fs.fed.us/r2/blackhills/projects/planning/amendments/phase_II/feis/04_chapt3_2005_1028_p336-381.pdf [Verified 3 October 2006]

Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* **7**, 23–34.

Weaver H (1943) Fire as an ecological and silvicultural factor in the ponderosa pine region of the Pacific slope. *Journal of Forestry* **41**, 7–15.

White JD, Ryan KC, Key CC, Running SW (1996) Remote sensing of forest fire severity and vegetation recovery. *International Journal of Wildland Fire* **6**, 125–136. doi:10.1071/WF9960125

Woodall CW, Fiedler CE, Milner KS (2003) Stand density index in uneven-aged ponderosa pine stands. *Canadian Journal of Forest Research* **33**, 96–100. doi:10.1139/X02-168