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Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado

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Abstract:

An important element of evaluating a large wildfire is to assess its effects on the soil in order to predict the potential watershed response. After the 55 000 ha Hayman Fire on the Colorado Front Range, 24 soil and vegetation variables were measured to determine the key variables that could be used for a rapid field assessment of burn severity. The percentage of exposed mineral soil and litter cover proved to be the best predictors of burn severity in this environment. Two burn severity classifications, one from a statistical classification tree and the other a Burned Area Emergency Response (BAER) burn severity map, were compared with measured 'ground truth' burn severity at 183 plots and were 56% and 69% accurate, respectively.

This study also compared water repellency measurements made with the water drop penetration time (WDPT) test and a mini-disk infiltrometer (MDI) test. At the soil surface, the moderate and highly burned sites had the strongest water repellency, yet were not significantly different from each other. Areas burned at moderate severity had 1·5 times more plots that were strongly water repellent at the surface than the areas burned at high severity. However, the high severity plots most likely had a deeper water repellent layer that was not detected with our surface tests. The WDPT and MDI values had an overall correlation of $r = -0{\cdot}64$ ($p < 0{\cdot}0001$) and appeared to be compatible methods for assessing soil water repellency in the field. Both tests represent point measurements of a soil characteristic that has large spatial variability; hence, results from both tests reflect that variability, accounting for much of the remaining variance. The MDI is easier to use, takes about 1 min to assess a strongly water repellent soil and provides two indicators of water repellency: the time to start of infiltration and a relative infiltration rate.

KEY WORDS forest fire; water repellent soils; erosion; burn severity; water drop penetration time (WDPT); mini-disk infiltrometer (MDI)

INTRODUCTION

One of the first and most significant tasks in evaluating a large wildfire is the development of a postfire soil burn severity map. For wildfires occurring mostly on Forest Service lands in the USA, these postfire maps are created by Burned Area Emergency Rehabilitation (BAER) teams from the US Department of Agriculture (USDA) Forest Service together with the USDA Remote Sensing Applications Center (RSAC, 2004). The burn severity map is used to identify the areas where fire-induced changes to soils have increased the potential for runoff and erosion (Parsons and Orlemann, 2002).

The burn severity map is developed using multi-spectral satellite imagery, such as the Moderate-Resolution Imaging Spectroradiometer (MODIS), the Système Pour l'Observation de la Terre (SPOT), or Landsat. This imagery is used to generate a burned area reflectance classification (BARC) map. The reflectance spectra are classified using existing algorithms that compare near-infrared values with mid-infrared values. Green vegetation is highly reflective in the near-infrared region of the electromagnetic spectrum, while mineral soil and rock are more reflective in the mid-infrared region. Hence, a ratio of the near-infrared and mid-infrared

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reflectance can be used to indicate burn severity (RSAC, 2004; van Wagtendonk *et al.*, 2004). As the relative percentage of green vegetation decreases and the amount of exposed soil and char (blackness) increases, the burn severity generally increases.

The goal of the BAER team is to measure and map burn severity based on ground and soil characteristics rather than canopy vegetation (Miller and Yool, 2002; Parsons and Orlemann, 2002). Unfortunately, the BARC maps often reflect the canopy, especially in a forest environment (Patterson and Yool, 1998). To the extent possible, the reflectance map is immediately validated to identify and refine the burn severity classes to create a burn severity map that classifies the area within the fire perimeter as unburned, low, moderate or high burn severity. However, the number of ground measurements that can be made is restricted by time and access, thus 'ground truthing' is often done from low-flying aircraft (Parsons and Orlemann, 2002).

In areas burned at low severity, the fine fuels such as litter cover and small woody debris will be partially charred and consumed. The larger fuels may be blackened, but are not consumed. Soil heating is minimal, the soil structure is largely unaltered, and there is little mineral soil exposure (Wells *et al.*, 1979; Robichaud *et al.*, 2000). Consequently, the potential runoff response is essentially unchanged from the pre-burn condition (Robichaud and Waldrop, 1994). In moderate severity burns, the fine fuels are mostly consumed and larger fuels are charred and partially to completely consumed (Robichaud *et al.*, 2000). Soil heating extends through the top 100 or 200 mm of the soil, and the surface humus and small roots are destroyed (Ryan and Noste, 1983). High severity burns generally consume all surface litter cover, plants, and branches (large woody debris), and stumps, logs, and trees will be deeply charred and black, often with 100% tree mortality (Ryan and Noste, 1983). Characteristically, an area burned at high severity has extensive exposed mineral soil, often greater than 80% (Wells *et al.*, 1979; Robichaud *et al.*, 2000). The soil surface is visibly altered to a yellow or reddish colour. High severity burns have an elevated potential for runoff, erosion and sedimentation due to decreased infiltration capacity, increased exposed mineral soil and disturbed soil structure (Ryan and Noste, 1983; Morris and Moses, 1987; Robichaud and Waldrop, 1994; Robichaud and Brown, 1999; DeBano, 2000b; Robichaud, 2000; Shakesby *et al.*, 2000; Wang *et al.*, 2000; Moody and Martin, 2001; Mataix-Solera and Doerr, 2004).

A forest fire's above-ground, large-scale effects, such as the destruction of vegetation, are clearly evident and relatively easy to evaluate. The alteration of soil structure and development of soil water repellency, however, are more difficult to determine (Giovannini and Lucchesi, 1997). Fire-induced water repellency is generally within the top 50 mm (sometimes up to 100 mm) of the soil profile, and has high spatial variability (Clothier *et al.*, 2000; DeBano, 2000a; Doerr *et al.*, 2000; Doerr and Moody, 2004).

Increasing burn severity is often assumed to be positively correlated with increasing soil water repellency (Doerr *et al.*, 2000). Yet, pre-fire soil texture, the amount and depth of litter cover, soil water, soil organic matter (OM), and the temperature and residence time of the fire all affect the degree of soil modification and the resulting soil water repellency (Giovannini and Lucchesi, 1997; DeBano, 2000a; Doerr *et al.*, 2000; Wondzell and King, 2003). As the organic material, such as litter and duff on the soil surface, is consumed in a fire, the volatilized organic compounds are transferred into the soil profile (DeBano *et al.*, 1976). As these organic vapours cool and condense, soil particles are coated by a hydrophobic organic layer, consisting primarily of aliphatic hydrocarbons (Savage *et al.*, 1972; Doerr *et al.*, 2000). Temperatures up to 280 °C facilitate the formation of hydrophobic conditions, whereas temperatures above this point may produce a lesser degree of soil water repellency due to a more complete combustion of the aliphatic compounds in the litter (DeBano, 2000b; Robichaud and Hungerford, 2000; Letey, 2001). High temperatures at the soil surface during a fire may preclude the formation of water repellent soil at the soil surface; yet a water repellent layer may be formed in the cooler subsurface which will hinder infiltration and increase runoff and erosion (Giovannini and Lucchesi, 1997). Because the temperatures of forest fires and soil properties have high spatial variability, the connection between burn severity and soil water repellency is neither universally consistent nor well defined in existing studies (Doerr *et al.*, 2000).

The extent and degree of soil water repellency soil is an important consideration in the evaluation of postfire runoff and erosion potentials. Current methods for determining soil water repellency include: (1) water drop penetration time (WDPT; DeBano, 1981); (2) critical surface tension (CST; Watson and Letey, 1970); (3) time to start of infiltration and infiltration rate using a mini-disk infiltrometer (MDI; Decagon Devices Inc., 1998). The WDPT and CST are well-established tests, whereas the MDI has not been extensively tested. A goal and challenge with any of the tests is to make the point measurements meaningful at a watershed or landscape scale. Consequently, these tests, which typically require several seconds to several minutes to complete, must be repeated many times within an area of interest (DeBano, 1981; Letey *et al.*, 2000; Huffman *et al.*, 2001).

In the WDPT test, water drops are placed on the soil surface. If the drops 'bead up' and do not infiltrate within 5 s, then the soil is classified as water repellent (Dekker and Ritsema, 1994). The physical basis of water repellency testing is the approximation of the soil–water contact angle; water repellent soils are those with a soil–water contact angle greater than or equal to 90° (Letey *et al.*, 2000). The time that a drop of water will remain on the soil surface without infiltrating is indicative of the soil–water contact angle. The relationship between WDPT and contact angle is not linear, but rather an index of increasing water repellency. Some researchers suggest that the WDPT indicates the stability of soil water repellency at the test surface rather than the strength of water repellency (Dekker and Ritsema, 1994; Letey, 2001).

WDPT is extensively used due to its simplicity and ability to identify the presence of water repellent soils relatively quickly (Letey *et al.*, 2000). Problems with the WDPT include the subjectivity in the water drop size and determination of infiltration, the time required (3 to 5 min) to identify a strongly water repellent soil (Dekker and Ritsema, 1994), and the arbitrary category of water drop residence time used to classify the degree of water repellency.

The CST method measures the soil–water contact angle more precisely than the WDPT method by applying aqueous ethanol solutions of varying concentrations to the soil. Higher ethanol concentrations have a lower surface tension; thus, strongly repellent soils will only be infiltrated by a high-concentration ethanol solution (Letey *et al.*, 2000; Huffman *et al.*, 2001). This method, because of the number of solutions required, may be awkward to apply in the rugged postfire field environment.

A more recently devised method uses a portable MDI (Decagon Devices Inc., 1998). Two measurements are made using the MDI: the time between soil contact and the rise of the first air bubble in the infiltrometer tube measures the time to start of infiltration, and the amount of water that infiltrates into the soil in the first minute provides a relative infiltration rate. The relative infiltration rate (more specifically, the infiltration rate at a specific tension, in this case 5 mm) measured with the MDI is inversely related to the WDPT. As with the other tests, an index must be applied to use these measurements for classifying the degree of soil water repellency.

A project was initiated after the 2002 Hayman Fire in central Colorado aimed at evaluating the use of remote sensing techniques for rapidly and accurately determining burn severity and soil water repellency, parts of which are still in progress. Burn severity and water repellency field data were collected at 183 plots in varying burn severities immediately after the fire, and data collection methodologies were devised to meet multiple goals. The analysis of the burn-severity and water-repellency ground data is presented in this paper, as well as a comparison between ground truth burn severity and the remotely sensed Hayman Fire BAER burn severity map. The relationship between burn severity and water repellency found in this analysis will be applied in a separate effort to use remote sensing data to identify water repellent soils. The specific objectives of this study were to: (1) identify the most significant soil and vegetation characteristics for *in situ* classification of burn severity; (2) validate the BAER burn severity classifications of low, moderate and high as were assigned to sample plots of this study; (3) measure and compare *in situ* surface soil water repellency using two methods, the WDPT and MDI tests; (4) relate surface soil water repellency to burn severity classes.

METHODS

Study area

The study area was within the 55 000 ha Hayman Fire in the Pike and San Isabel National Forest in the Front Range of central Colorado (Figure 1). The long-term average annual precipitation is 400 mm at the

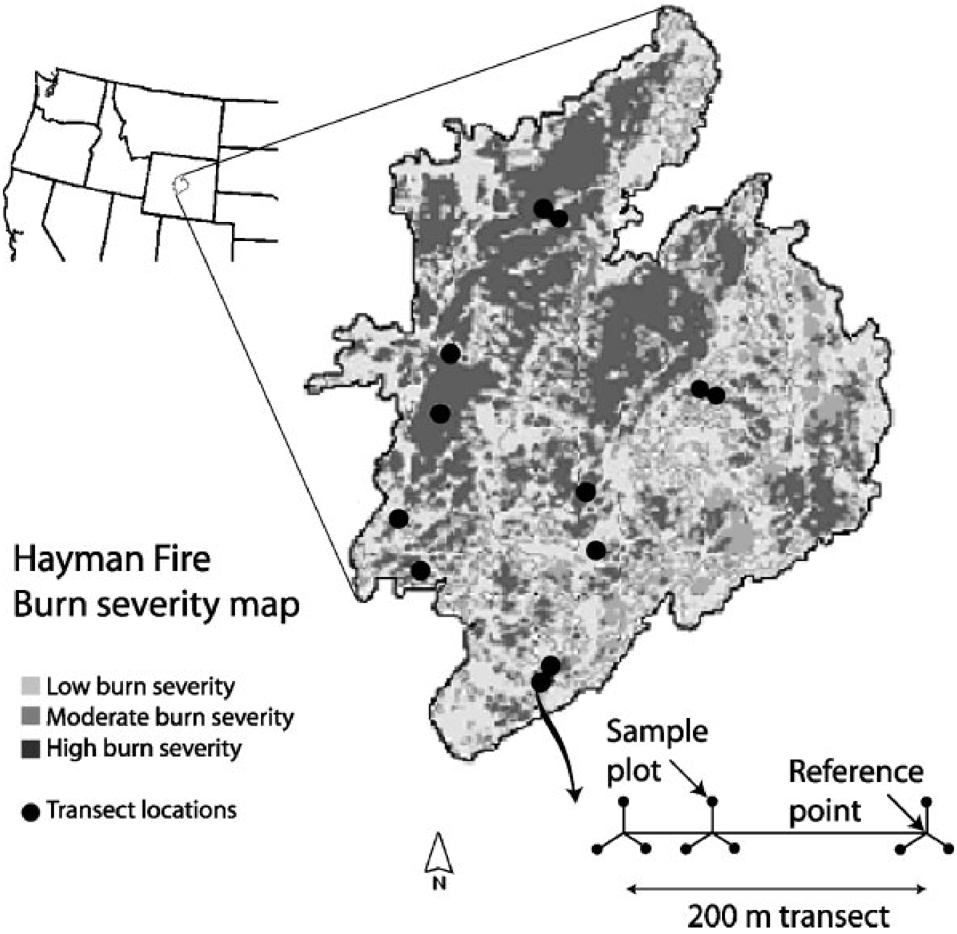

Figure 1. Sample plot locations within the Hayman Fire overlaid on the BAER burn severity map. Also shown is the sampling scheme, not to scale

Cheesman weather station, which is centrally located within the fire perimeter at an elevation of 2100 m (Colorado Climate Center, 2004). Elevations within the burned area extend to over 3000 m, and precipitation at higher elevations is likely to be greater than that measured at the weather station. The region is semi-arid, with a late-summer monsoon season characterized by short-duration, high-intensity storms.

The dominant tree species are ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*). Above 2600 m, the vegetation shifts to a sub-alpine forest, dominated by lodgepole pine (*Pinus contorta* var. *latifolia*), limber pine (*Pinus flexilis*), aspen (*Populus tremuloides*), subalpine fir (*Abies lasiocarpa*), and Englemann spruce (*Picea engelmannii*) (Romme *et al*., 2003a). Understory shrub and forb species include mountain-mahogany (*Cercocarpus montanus*), juniper (*Juniperus* spp.), wax currant (*Ribes cereum*), wild rose (*Rosa* spp.), kinnikinnik (*Arctostaphylos uva-ursi*), yucca (*Yucca glauca*), geranium (*Geranium caespitosum*), and asters (*Aster* spp.). At the forest–grassland edge, grass species may also include black grama (*Bouteloua eriopoda*), needlegrasses (*Hesperostipa* and *Achnatherum* spp.), and western wheatgrass (*Pascopyrum smithii*) (Romme *et al*., 2003b; USDA Forest Service, 2004). The region is underlain by the granitic Pikes Peak batholith, with frequent rocky outcroppings (USDA Forest Service, 2002). The two main soil types are the Sphinx and Legault series; both are coarse textured and often excessively drained (Robichaud *et al*., 2003). Soil textures include sandy loams, gravelly sandy loams, and clay loams (Cipra *et al*., 2003).

Sampling scheme

The Hayman Fire started in early June and burned through early July 2002. Field measurements began as soon as access to the fire was allowed, and continued through mid-August 2002. Some 31% of the 55 000 ha was classified by the BAER burn severity map as low severity, 20% as moderate severity, 32% as high severity, and 17% was unburned (USDA Forest Service, 2002). Approximately 60 sample plots were selected in each of the three burn severity classes as delineated by the BAER burn severity map. East–west transects were established in visually homogeneous burn sites at least 20 m from roads. The transects were intended to be 200 m in length (Figure 1), with central reference plots at 0 m (west endpoint), 50 m, and 200 m (east endpoint). At each reference point three 20 m radials were established at 0°, 120° and 240°. The sample plots were 4 m in diameter at the end of each of these radials.

The actual transect lengths were between 50 and 400 m, depending on topography and the uniformity of burn severity. The shorter transects only had reference points at each end, whereas the longer transects had reference points at the endpoints as well as at 50 m from the west endpoint, and at 250 m from the west endpoint in the case of the 400 m transect. In the low burn severity class there were three 50 m transects with six plots each and five 200 m transects with nine plots each, for a total of 63 plots along eight transects. In the moderate burn severity class there were six 200 m transects and one 50 m transect for a total of 60 sample plots along seven transects. In the high burn severity class there were five 200 m transects and one 400 m transect for a total of 60 sample plots along six transects. The spatial and directional layout of the transects and sample plots was designed to encompass the spatial variability of the field measurements by sampling at short and long distances between sample plots (35 to 435 m apart), as well as sampling in different directions so that variation from slope position would be captured. Slopes at the sample plots ranged from 10 to 30%.

Burn severity assessment

At each plot the burn severity was assessed by measuring 24 variables indicative of soil and vegetation conditions and the local topography (Jain, 2002, unpublished study plan). The percentage of ground cover and depth of new litter (postfire needle cast) was estimated first, since this was the uppermost layer. The most minor cover fractions, which were often grasses, forbs, shrubs, woody debris, stumps or rocks, were estimated next. A value of 1% was recorded if there was a trace of the material within the plot. The more common types of cover (which were exposed mineral soil, ash, litter and rock) were then estimated, along with the depths of litter and humus when present. The largest cover component was estimated last and the percentage of cover was forced to sum to 100%. The percentage burned and degree of char (low, moderate or high) of each cover component was estimated following Ryan and Noste (1983; Ryan, 2002).

The number of new tree seedlings with a diameter at breast height (DBH) less than 25 mm and saplings (DBH 25 to 120 mm) were tallied. Live and dead trees (DBH greater than 120 mm) were counted, measured, and the percentage char of the tree bases and canopies estimated. An undisturbed soil sample was taken at the exposed mineral soil surface extending from 0 to 25 mm at a random location within each sample plot for OM content analysis.

A digital photograph was taken at each plot for future reference. Ground truth burn severity classes were independently assigned for each plot based on the ground characteristics, without consideration of the BAER burn severity classification. Care was taken to minimize the subjectivity between samplers through individual training and team calibration on plots.

Water repellency tests

The WDPT test was conducted at 11 evenly spaced points along a 0·5 m transect in each 4 m plot. The surface ash and litter cover were swept aside to expose the mineral soil. At each plot, a water drop was placed on the soil surface and the time to complete infiltration was measured. The soil was considered water repellent if the water drop remained on the soil surface for longer than 5 s (DeBano, 2000b; Letey *et al.*, 2000). The degree of soil water repellency was assessed by measuring the persistence of the drop on the surface for up to

300 s. Surface water repellency was divided into three classes by the median time for water drop infiltration per plot: weak (0–60 s), moderate (61–180 s), and strong (181–300 s) (Dekker and Ritsema, 1994).

MDI tests were performed on a parallel line within 0·2 m of the WDPT test transects at four evenly spaced locations. The MDI maintains a constant tension head of 5 mm and has a porous disk 31 mm in diameter. In order to minimize loss of water from the exposed side surface of the porous disk, care was taken not to let soil or ash touch the disk sides. The time to the start of infiltration was noted ($\mathrm{MDI}_{\mathrm{time}}$), as well as the volume of water that infiltrated the soil within 1 min ($\mathrm{MDI}_{\mathrm{rate}}$). Although the WDPT and MDI are generally used at different soil depths, the goal of this study was to detect water repellent soils using a non-penetrating remote sensing instrument. Thus, both WDPT and MDI water repellency measurements were only conducted at the soil surface.

OM determination

The soil samples taken from the 183 sample plots were dried at 105 °C for 24 h to remove moisture. The dried samples were placed in a muffle furnace at 375 °C for 16 h to incinerate all soil OM. Upon cooling to room temperature, the percentage soil OM was calculated by mass (Smith and Atkinson, 1975).

Statistical analysis

Data were tested for normality using the UNIVARIATE procedure in SAS (SAS Institute Inc., 1990). Since all samples were non-normal, nonparametric statistical tests were used for subsequent analyses. Correlations among the 24 burn severity and water repellency variables were assessed using the nonparametric Spearman test on ranked data (SAS Institute Inc., 1999a). Correlations were regarded significant at $p < 0·05$.

Owing to the large number of burn severity variables measured in the field and the correlations between many of the variables, a factor analysis (FA) was performed on the data (SAS Institute Inc., 1999b). Highly correlated combinations of the variables were partitioned into principal factors and rotated onto orthogonal axes to maximize the variance. Variables on orthogonal axes were not correlated, wherease those on the same axes with opposite signs were inversely correlated. Variables with low coefficient values within each factor were left off the plots for clarity. Based on the initial correlation matrix from the Spearman test (Table I) and Kaiser's measure of sampling adequacy (MSA; SAS Institute Inc., 1999b), eight of the original variables were discarded due to low MSAs (less than 0·5). FA was applied to the remaining 16 variables (Table II), and six principal factors were retained for subsequent analysis.

A classification tree analysis was performed to determine the relationships between burn severity variables and their influence on burn severity classes using R software (rpart) (R Development Core Team, 2003).

Table I. Correlation matrix between burn severity variables. Only significant ($p < 0·05$) correlation coefficients r are shown. Correlations significant at $p < 0·0001$ are in bold. Non-significant correlations are denoted by 'ns' for easier reading

Variable	Litter cover	Litter depth	Ash cover	New litter cover	New litter depth	Rock cover	Soil OM	Small woody debris	Live trees	Dead trees	WDPT	MDI rate	MDI time
Exposed mineral soil	**−0·77**	**−0·51**	**−0·33**	−0·28	−0·23	0·23	ns	**−0·43**	**−0·47**	−0·23	**−0·29**	ns	ns
Litter cover		**0·62**	**−0·30**	**0·41**	**0·32**	−0·23	ns	**0·36**	**0·35**	−0·28	ns	ns	ns
Litter depth			ns	0·24	**0·40**	−0·21	ns	0·27	ns	**−0·29**	0·18	ns	ns
Ash cover				ns	ns	ns	ns	ns	ns	ns	**0·38**	**−0·39**	**0·36**
New litter cover					**0·71**	ns	ns	**0·29**	ns	ns	ns	−0·15	ns
New litter depth						ns	ns	0·16	ns	−0·18	ns	ns	ns
Rock cover							ns	ns	−0·23	ns	ns	ns	ns
Soil OM								ns	ns	ns	ns	ns	0·21
Small woody debris									0·16	ns	ns	ns	ns
Live trees										ns	0·25	ns	ns
Dead trees											ns	ns	ns

Table II. Results of factor analysis applied to 16 burn severity variables measured on the Hayman Fire. Absolute eigenvalues greater than 0·40 are in bold and values below 0·20 are denoted with 'ns' for easier reading

	Factor 1, soil water repellency	Factor 2, burn severity	Factor 3, new litter
MDI_{time}	**0·89**	ns	ns
WDPT	**0·78**	0·24	ns
Ash cover	**0·62**	ns	−0·27
MDI_{rate}	**−0·92**	ns	ns
Litter cover	ns	**0·80**	0·27
Live trees	ns	**0·62**	ns
Litter depth	ns	**0·59**	0·28
Rock cover	ns	**−0·47**	ns
Exposed mineral soil	ns	**−0·87**	ns
New litter depth	ns	ns	**0·86**
New litter cover	ns	0·22	**0·84**
Grass	ns	ns	ns
Soil OM	0·21	ns	−0·39
Dead trees	ns	−0·26	ns
New trees	ns	ns	ns
Small woody debris	ns	0·38	ns

Classification tree methods are also known as recursive partitioning regressions and operate by partitioning variables into increasingly homogeneous response variable classes (burn severity in this study). The weight of each predictor variable in the classification of burn severity class is calculated, and each predictor variable is used in order of significance to divide the data (Moisen and Frescino, 2002). All data at a terminal node are assigned the same class of burn severity. The classification tree was first built using the 16 variables determined as significant from the FA. Variables that did not improve the division of the response variable, i.e. burn severity, into classes were eliminated until only the two variables of litter cover and exposed mineral soil remained.

The burn severity classifications as determined by classification tree analysis were compared with the burn severity classes established by ground truth observations. The burn severity classes assigned by the BAER map were also compared with the ground truth classifications. Classification accuracy was calculated by dividing the number of correctly classified sample plots by the total number of sample plots in each ground truth burn severity class.

A median one-way analysis using the NPAR1WAY procedure in SAS (SAS Institute Inc., 1999b) was conducted to determine whether the medians of the water repellency variables were significantly different between burn severity classes. Box-and-whisker plots were made to illustrate the variability of the water repellency variables in each burn severity class.

RESULTS

Significant burn severity variables

Exposed mineral soil was significantly correlated with 10 other variables ($p < 0{\cdot}05$) (Table I). The amount of exposed mineral soil was inversely correlated ($p < 0{\cdot}0001$) with litter cover ($r = -0{\cdot}77$), litter depth (−0·51), ash cover (−0·33), small woody debris (−0·43), live trees (−0·47) and WDPT (−0·29) (Table I). Exposed mineral soil was mostly correlated with variables that are indicative of burn severity. Positive correlations indicate higher burn severity, whereas negative correlations indicate a low burn severity. Litter cover was positively correlated with litter depth ($r = 0{\cdot}62$), new litter cover (0·41), new litter depth (0·32), small woody debris (0·36), and live trees (0·35), and negatively correlated with ash cover (−0·30), rock cover (−0·23), and dead trees (−0·28) (Table I). Soil water repellency was most highly correlated with ash cover. Both WDPT ($r = 0{\cdot}38$) and MDI_{time} (0·36) were positively correlated with ash cover, whereas MDI_{rate} (−0·39) was negatively correlated. Ash cover on the plots increased as burn severity increased, and water repellency generally increased as burn severity increased. The only variable significantly correlated with soil OM was MDI_{time} ($r = 0{\cdot}21$), indicating that water repellency tends to increase with increasing soil OM.

The FA yielded six principal factors that accounted for 66% of the total variance in the data. Factor 1 (F1), soil water repellency, accounts for 20% of the variance; Factor 2 (F2), burn severity, accounts for 16% of the variance; and Factor 3 (F3), new litter, accounts for 9% of the variance. Each of these factors is heavily weighted by at least two variables that are highly correlated and essential for determining burn severity (Table II; Figures 2 and 3). Soil water repellency (F1) is weighted by WDPT, both MDI_{time} and MDI_{rate}, ash cover and soil OM. Burn severity (F2) is weighted both positively and negatively. Variables with positive weights within burn severity (F2) include litter cover, litter depth, live trees, and small woody debris and are the most significant indicators of low burn severity (Table II, Figure 2). Burn severity (F2) is negatively weighted by exposed mineral soil, rock cover, and dead trees, which are indicators of high burn severity. New litter (F3) is weighted by new litter cover and new litter depth, which are indicators of moderate burn severity (Table II, Figure 3).

The F1 versus F2 plot illustrates soil water repellency versus burn severity (Figure 2). WDPT and MDI_{time} are on the opposite end of the y-axis from MDI_{rate}, since they are highly and inversely correlated. Ash cover and soil OM are also on this axis because they are significantly correlated with soil water repellency. Exposed mineral soil and litter cover are on opposite ends of the x-axis; the variables with positive values (litter depth, small woody debris, live trees) tend toward low burn severity, and the variables with negative values (rock cover, dead trees) tend toward high burn severity (Figure 2).

Statistical evaluation of the burn severity classes

The classification tree analysis shows that litter cover and exposed mineral soil best separate the three classes of burn severity (Figure 4). Litter cover was a more significant partitioning factor than exposed mineral soil; thus, the litter cover classification tree was used first to assign plots low (69% or more litter cover) or high (less than 5% litter cover) burn severity classes (Figure 4). The exposed mineral soil classification-tree was then used to assign plots low (less than 9% exposed mineral soil) or high (greater than or equal to 54% exposed mineral soil) burn severity (Figure 4). Forty-eight plots were classified as low burn severity and

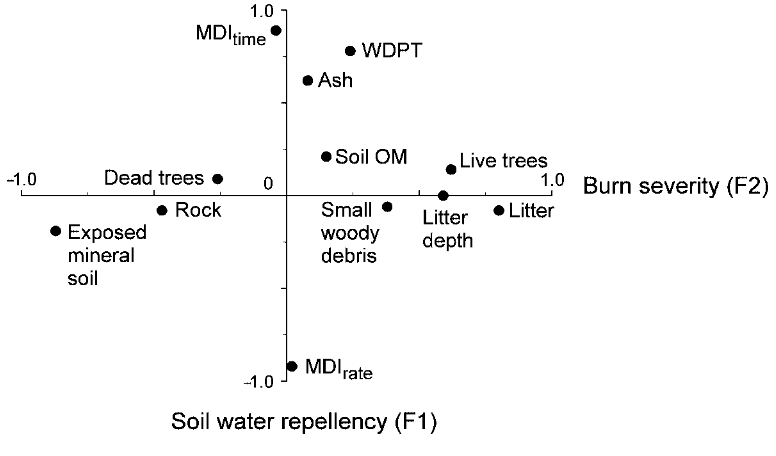

Figure 2. The factor analysis results showing the rotated axes: soil water repellency (F1, y-axis) versus burn severity (F2, x-axis). High values on the y-axis indicate strong water repellency. High positive values on the x-axis indicate low burn severity, and high negative x-axis values indicate high burn severity. The water repellency variables are more strongly correlated with exposed mineral soil than litter cover

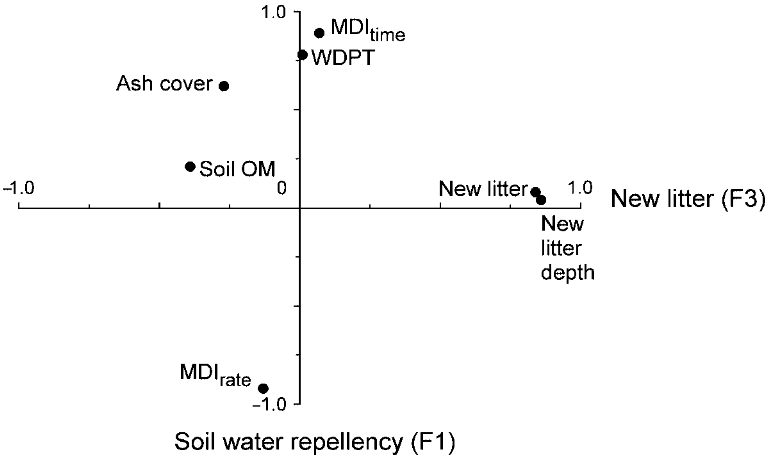

Figure 3. The FA results showing the rotated axes: soil water repellency (F1, *y*-axis) versus the third axis (F3, *x*-axis), new litter. There is no evident relationship between soil water repellency and new litter, as these variables are tightly grouped on their respective axes

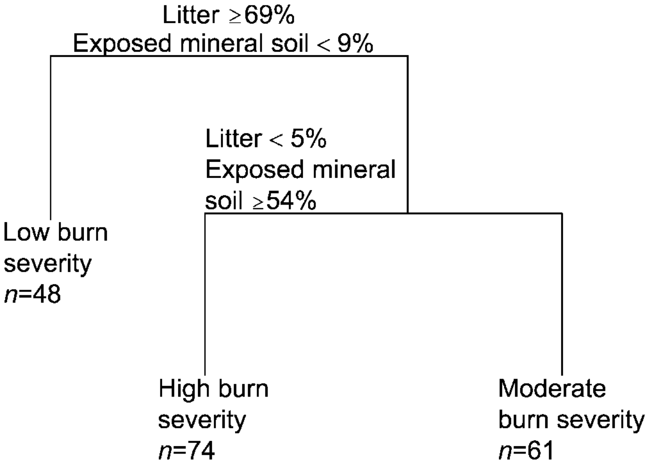

Figure 4. The results of the classification tree analysis. Plots were sorted first into low and high burn severity by the litter cover and exposed mineral soil criteria; remaining plots fit the moderate burn severity criteria

74 plots as high burn severity. The remaining 61 plots were classified as moderate burn severity by both classification trees. The classification tree results were compared with the ground truthed plots: of the 62 ground truthed low severity plots, 34 (55%) were classified as low burn severity using the classification tree analysis; of the 74 ground truthed moderate-severity plots, 36 (49%) were classified as moderate severity by the classification-tree analysis; and of the 47 ground truthed high severity plots, 33 (70%) were classified as high severity using the classification tree analysis (Table III).

Validation of the BAER burn severity map

The BAER burn severity map was 69% accurate when compared with the ground truth burn severity classes (Table IV). The highest accuracy was in the high burn severity class (91%), followed by the low (73%) and moderate burn severity classes (53%). Twenty-two plots were overclassified by the BAER map (e.g. low severity based on ground truthing and moderate severity according to the burn severity map) and 34 plots

Table III. Classification matrix comparing observed ground truth burn severity to the burn severity determined by classification tree analysis. Agreement shows the percentage of plots where burn severity was classified the same by both methods

Ground-truth burn severity	Burn severity as classified by tree analysis			Agreement (%)
	Low	Moderate	High	
Low (sample size $n = 62$)	34	15	13	55
Moderate ($n = 74$)	10	36	28	49
High ($n = 47$)	4	10	33	70
Total ($n = 183$)				56

Table IV. Classification matrix comparing observed ground truth burn severity to the BAER burn severity map. The agreement between the BAER map and ground truth burn severity classifications is nearly 70% overall, with no plots over- or under-classified by more than one class

Ground-truth burn severity	Burn severity as classified by the BAER burn severity map			Agreement (%)
	Low	Moderate	High	
Low (sample size $n = 62$)	45	17	0	73
Moderate ($n = 74$)	18	39	17	53
High ($n = 47$)	0	4	43	91
Total ($n = 183$)				69

were underclassified by the BAER map (e.g. high severity on the ground and moderate severity according to the burn severity map).

Comparison of WDPT and MDI tests

The correlations among WDPT, MDI_{time}, and MDI_{rate} were significant for all data grouped together (regardless of burn severity class), as well as at each individual burn severity class ($p < 0{\cdot}0001$, Table V). WDPT versus either MDI_{time} or MDI_{rate} was slightly lower ($r \approx |0{\cdot}5|$ to $|0{\cdot}7|$), whereas MDI_{time} versus MDI_{rate} was higher ($r \approx |0{\cdot}85|$ to $|0{\cdot}9|$) The correlations for the high burn severity sites were weaker than for the grouped data, whereas correlations for the low and moderate severity sites were generally equivalent to those for the grouped data.

Surface soil water repellency and burn severity

Surface soil water repellency generally increased as burn severity increased. The median WDPT times increased from 43 s for low burn severity to 80 s for high burn severity (Figure 5), but the increase was not significantly different between the three burn severity classes (Table VI). Median MDI_{time} values at low, moderate and high burn severity were 2 s, 8 s, and 12 s respectively (Figure 5). The medians were significantly different between low and moderate burn severity and low and high burn severity (Table VI). Median MDI_{rate} values decreased from 4 to 2 ml min^{-1} between low and moderate (and high) burn severity (Figure 5), and the MDI_{rate} value for the high burn severity class was not significantly different than either the low or moderate burn severity class (Table VI).

Table V. Spearman correlations between WDPT and MDI tests by burn severity class. MDI_{time} is the time to start of infiltration and MDI_{rate} is the volume of water that infiltrates in the first minute. All correlations are significant at $p < 0.0001$

Variable	WDPT (s)	MDI_{time} (s)
All data (sample size $n = 183$)		
MDI_{time} (s)	0·59	
MDI_{rate} (ml min^{-1})	−0·64	−0·87
Low burn severity ($n = 62$)		
MDI_{time} (s)	0·58	
MDI_{rate} (ml min^{-1})	−0·60	−0·84
Moderate burn severity ($n = 73$)		
MDI_{time} (s)	0·59	
MDI_{rate} (ml min^{-1})	−0·69	−0·85
High burn severity ($n = 47$)		
MDI_{time} (s)	0·48	
MDI_{rate} (ml min^{-1})	−0·54	−0·91

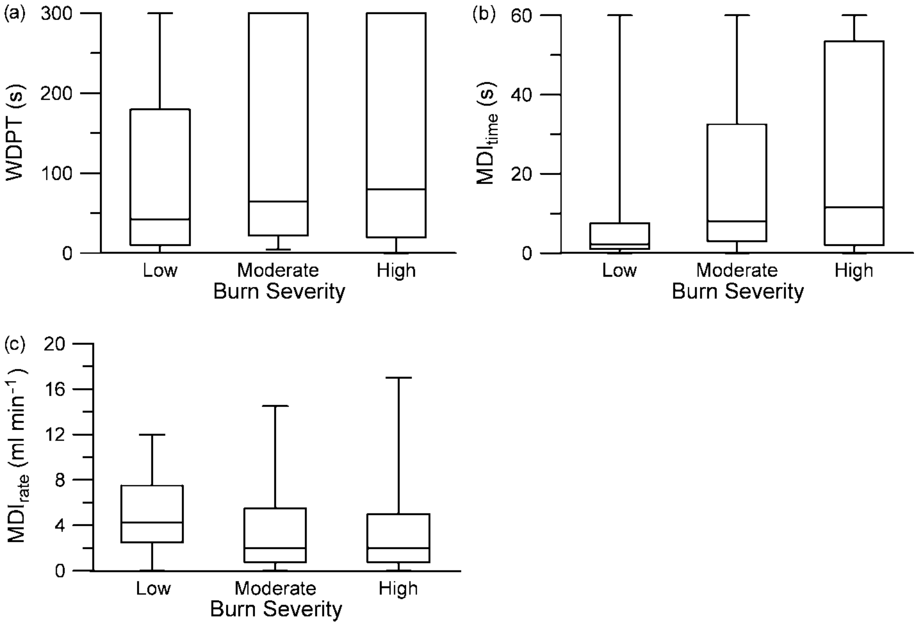

Figure 5. Box-and-whisker plots of water repellency measurements by burn severity class for three tests: (a) WDPT, (b) MDI_{time}, and (c) MDI_{rate}. Based on ground truth burn severity classes, the number of plots n in each class was $n = 62$ for low, $n = 74$ for moderate, and $n = 47$ for high

DISCUSSION

Significant burn severity variables

The FA and classification tree analysis indicated that six variables were the most important for a quick field determination of burn severity after the Hayman Fire. Extensive exposed mineral soil and dead trees are indicative of high burn severity. Postfire new litter cover, mainly needle cast, is an important indicator of moderate burn severity (Pannkuk and Robichaud, 2003). Needle cast occurs primarily in moderately burned

Table VI. Results from a nonparametric median one-way analysis to determine whether surface soil water repellency medians are different by burn severity class. Chi-square values are reported with p-values in parentheses; significant values are in bold ($p < 0.05$)

Burn severity classes	WDPT	$\mathrm{MDI}_{\mathrm{time}}$	$\mathrm{MDI}_{\mathrm{rate}}$
Low versus moderate	1·68 (0·19)	**12·68 (0·0004)**	**10·1 (0·0015)**
Moderate versus high	0·03 (0·85)	0·86 (0·35)	0·04 (0·84)
Low versus high	1·35 (0·25)	**13·8 (0·0002)**	3·24 (0·07)

areas because low severity burns produce little tree crown scorching and high severity burns completely consume tree crowns. More ash is present in moderate- and high-severity burns, and ash cover is correlated with soil water repellency. Litter cover and live, green trees typically indicate low burn severity. The three factors, soil water repellency (F1), burn severity (F2), and new litter (F3) together account for 66% of the variance in the data. Using the variables that are most widely opposite in an FA (e.g. exposed mineral soil and percentage litter cover; Figure 2) allows burn severity to be classified from a few characteristics.

Some individual variables were significantly related to burn severity, but were less useful for classification because they were closely correlated with other predictive variables (Table II). For example, it is not necessary to measure both litter cover and litter depth, or new litter cover and new litter depth. Other highly correlated pairs of variables included large woody debris and new trees (seedlings and saplings) and soil OM and litter depth.

Factors 4 (organic cover), 5 (trees), and 6 (non-organic cover) were statistically significant in terms of differentiating burn severity classes and each accounted for 6 to 8% of the variance in the data. These factors were weighted by variables that had little overlap with the essential variables in the principal factors, or they are not easily determined in the field. Consequently, these factors are not as useful for a quick field classification of burn severity.

Statistical evaluation of the burn severity classes

The classification tree analysis used litter cover and exposed mineral soil to separate plots statistically into burn severity classes with an overall agreement of 56% with the ground truth classes. More than 20 other variables were measured, but they did not provide additional refinement to the burn severity classification determined by the classification tree method. The largest sources of error were 13 low and 28 moderate severity plots classified as high severity plots using the classification tree. This overclassification of low and moderate burn severity sites occurred because all of these plots had a large percentage of exposed mineral soil, but were classified as low to moderate burn severity from ground truthing. Several low burn severity plots were nearly unburned and had little vegetation or litter cover, leaving large areas of exposed mineral soil. In the Colorado Front Range, the undisturbed semi-arid forest environment with its sparse understory vegetation does not support excessive litter and humus build-up on the forest floor, especially on the drier, south-facing slopes (Romme *et al.*, 2003a).

Validation of the BAER burn severity map

To estimate postfire hydrologic response and erosion potential adequately, the burn severity classifications used by BAER teams would ideally be based on fire-induced soil effects. In reality, little validation of the remotely classified burn severity map is accomplished due to time constraints. In this study, the BAER burn severity map was approximately 70% accurate when compared with the ground truthed burn severity of the sample plots. The accuracy was greatest for the high burn severity class due to the relative ease of mapping blackness spectrally, or the absence of greenness. For the same reason, the low burn severity class had fairly high accuracy because of the presence of green canopy over much of these areas. The moderate burn severity class was the most difficult to determine spectrally because of the mix of green, brown and black that was present. Not surprisingly, the BAER burn severity map was the least accurate for determining moderately burned areas. A possible source of discrepancy between BAER burn severity map and the ground truthed classifications may be inconsistencies between the individuals taking the field measurements. However, the digital photographs were used during the analysis to reconcile discrepancies and to improve the consistency and accuracy of burn severity ground truthing.

The foremost potential problem with the BAER maps is underclassification of areas that were burned at high severity. These areas will likely be excluded from postfire rehabilitation treatments and are at high risk for increased runoff and erosion. Underclassified moderately burned areas near valuable resources may also pose a risk, as water repellent soils often form on the soil surface in these areas. Areas that are overclassified by the BAER map may be treated unnecessarily, thus increasing treatment costs. Emergency rehabilitation treatments, such as aerial mulching and aerial hydromulching, cost thousands of dollars per hectare treated (General Accounting Office, 2003). In addition, treatments can adversely affect the watershed by introducing non-native species, which may replace or compete with natural revegetation, thus increasing recovery time (Beyers, 2004).

Comparison of WDPT and MDI tests

The WDPT has been the most widely used method for *in situ* testing of soil water repellency. The MDI test, as it has been adapted for testing soil water repellency, provides the time to start of infiltration and a relative infiltration rate, a more useful measurement for hydrologic analysis. The time to water drop absorption is the only measurement that the WDPT provides, and this can be subjective. For example, the water drop may be slowly absorbed, or it may be covered in fine dust, and these conditions make it hard to determine the time to absorption. The MDI technique is not as ambiguous, as the first air bubble indicates the time to the start of infiltration and the amount of water that has infiltrated is read directly from the instrument.

The time required for completing an MDI test is less than the WDPT method (especially for strongly water repellent soils), allowing water repellency to be sampled over a large area more rapidly. Both field tests use point measurements to make inferences for large burned areas, posing great challenges for field application due to the high spatial variability of fire-induced soil water repellency (Doerr and Moody, 2004; MacDonald and Huffman, 2004). In this study, the WDPT and MDI tests had an 80% agreement when classifying a strongly water repellent soil (181–300 s WDPT; 0–3 $\mathrm{ml\,min^{-1}}$ $\mathrm{MDI_{rate}}$). These results indicate that a strongly water repellent soil may be classified with the MDI in 1 min, compared with 3 to 5 min with the WDPT test.

When the MDI is used on highly wettable surface layers (e.g. ash, very dry fine soils), some lateral infiltration may occur. This problem was avoided by ensuring that the base of the porous plate was the only surface in contact with the mineral soil. The infiltration rates may be naturally high until the surface layer is saturated and the wetting front reaches the water repellent soil layer below and/or until capillary forces decrease.

Surface soil water repellency and burn severity

The statistical results show that surface soil water repellency increased with increasing burn severity (Figure 5). Low burn severity plots had weak surface soil water repellency when tested with either the WDPT or MDI (Table VI). The litter and surface organics on most of these plots either did not burn or burned very lightly, and if a water repellent layer did form then it only formed weakly on the soil surface. Moderate and high severity plots did not have significantly different surface soil water repellency when tested with either the WDPT or MDI (Table VI). The median WDPT times for the moderate and high severity classes were 65 s and 80 s respectively, which were classified as moderately water repellent. Fifty-eight plots had strong surface soil water repellency (greater than 180 s), with nearly half of these (26) in the moderate burn severity plots. Only 15 of the 58 strong surface soil water repellency plots were in the high burn severity plots.

At first glance, these results may seem to counter the general conception that the greater the burn severity, the greater the water repellency. However, in this study, water repellency was only measured at the surface.

Owing to the condensation of volatilized organic compounds, fire-induced soil water repellency frequently occurs 5 to 50 mm below the surface in high burn severity areas (Clothier *et al.*, 2000; DeBano, 2000a). On the other hand, burning temperatures and fire residence times often allow volatilized organic compounds to condense on the soil surface in moderately burned sites. It is likely that a water repellent soil layer existed in the high burn severity plots, but went undetected below the surface.

CONCLUSIONS

Exposed mineral soil, litter cover, new litter cover, ash cover, and the number of live and dead trees were the variables most strongly related to burn severity. Of these six variables, the amount of litter cover and exposed mineral soil were the most useful field measurements for making a quick determination of burn severity. Based on classification tree analysis, the study plot burn severity designations from the BAER burn severity map were 70% accurate. Twenty-two plots had characteristics of moderate or high burn severity, but were underclassified by one class on the BAER map. Since high burn severity areas are at greater risk for increased postfire runoff and erosion, proper classificaton is needed for appropriate treatment application.

The WDPT and MDI tests indicated similar degrees of soil water repellency in each burn severity class, as well as overall ($r \approx |0{\cdot}6| - |0{\cdot}7|$). The MDI is faster, less subjective, and provides a relative initial infiltration rate in addition to the time to start of infiltration. Both the WDPT and MDI results indicated that surface soil water repellency increased with burn severity, but the differences are not significant between the moderate and high burn severity classes. The high burn severity sites often did not exhibit a strong surface water repellent layer; however, based on the process of fire-induced soil water repellency formation, it is likely that a water repellent layer may be present below the soil surface.

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REFERENCES

Beyers JL. 2004. Postfire seeding for erosion control: effectiveness and impacts on native plant communities. *Conservation Biology* **18**(4): 947–956.

Cipra JE, Kelly EF, MacDonald L, Norman J. 2003. Ecological effects of the Hayman Hire part 3: soil properties, erosion and implications for rehabilitation and aquatic ecosystems. In *Hayman Fire Case Study Analysis*, Graham RT (tech. ed.). GTR-RMRS-114. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO; 204–219.

Clothier BE, Vogeler I, Magesan GN. 2000. The breakdown of water repellency and solute transport through a hydrophobic soil. *Journal of Hydrology* **231–232**: 255–264.

Colorado Climate Center. 2004. http://climate.atmos.colostate.edu/dataaccess.shtml [25 February 2004].

DeBano LF. 1981. *Water repellent soils: a state of the art*. GTR-PSW-46. USDA Forest Service, Pacific Southwest Research Station, Berkeley, CA.

DeBano LF. 2000a. Water repellency in soils: a historical overview. *Journal of Hydrology* **231–232**: 4–32.

DeBano LF. 2000b. The role of fire and soil heating on water repellency in wildland environments: a review. *Journal of Hydrology* **231–232**: 195–206.

DeBano LF, Savage SM, Hamilton DA. 1976. The transfer of heat and hydrophobic substances during burning. *Soil Science Society of America Journal* **40**: 779–782.

Decagon Devices Inc. 1998. http://www.decagon.com/instruments/infilt.html [20 February 2004].

Dekker LW, Ritsema CJ. 1994. How water moves in a water repellent sandy soil 1. Potential and actual water repellency. *Water Resources Research* **30**: 2507–2517.

Doerr SH, Moody JA. 2004. Hydrological effects of soil water repellency: on spatial and temporal uncertainties. *Hydrological Processes* **18**: 829–832.

Doerr SH, Shakesby RA, Walsh RPD. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews* **51**: 33–65.

General Accounting Office. 2003. *Wildland fires: better information needed on effectiveness of emergency stabilization and rehabilitation treatments*. GAO-03-430. US General Accounting Office: Washington, DC.

Giovannini G, Lucchesi S. 1997. Modifications induced in soil physio-chemical parameters by experimental fires at different intensities. *Soil Science* **1627**: 479–486.

Huffman EL, MacDonald LH, Stednick JD. 2001. Strength and persistence of fire-induced soil water repellency under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes* **15**: 2877–2892.

Letey J. 2001. Causes and consequences of fire-induced soil water repellency. *Hydrological Processes* **15**: 2867–2875.

Letey J, Carillo MLK, Pang XP. 2000. Review: approaches to characterize the degree of water repellency. *Journal of Hydrology* **231–232**: 61–65.

MacDonald LH, Huffman EL. 2004. Post-fire soil water repellency: persistence and soil moisture thresholds. *Soil Science Society of America Journal* **68**: 1729–1734.

Mataix-Solera J, Doerr SH. 2004. Hydrophobicity and aggregate stability in calcareous topsoils from fire-affected pine forests in southeastern Spain. *Geoderma* **118**: 77–88.

Miller JD, Yool SR. 2002. Mapping post-fire canopy consumption in several overstory types using multi-temporal Landsat TM and ETM data. *Remote Sensing of Environment* **82**: 481–496.

Moisen GG, Frescino TS. 2002. Comparing five modeling techniques for predicting forest characteristics. *Ecological Modeling* **157**: 209–225.

Moody JA, Martin DA. 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms* **26**: 1049–1070.

Morris SE, Moses TA. 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. *Annals of the Association of American Geographers* **77**(2): 245–254.

Pannkuk CD, Robichaud PR. 2003. Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* **39**(12): 1333.

Parsons A, Orlemann A. 2002. Mapping post-wildfire burn severity using remote sensing and GIS. In *2002 ESRI International User Conference*, 8–12 July, San Diego, CA. USDA Forest Service, Remote Sensing Applications Center, Salt Lake City, UT.

Patterson MW, Yool SR. 1998. Mapping fire-induced vegetation mortality using Landsat Thematic Mapper data: a comparison of linear transformation techniques. *Remote Sensing of Environment* **65**: 132–142.

R Development Core Team. 2003. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org [10 March 2004].

Robichaud PR. 2000. Fire effects on infiltration rates after prescribed fire in northern Rocky Mountain forests, USA. *Journal of Hydrology* **231–232**: 220–229.

Robichaud PR, Brown RE. 2000. What happened after the smoke cleared: onsite erosion rates after a wildland fire in eastern Oregon. In *Proceedings of an American Water Resources Association Specialty Conference on Wildland Hydrology*, Olsen DS, Potyondy JP (eds), Bozeman, MT, 30 June–2 July, 1999; 419–426 (revised; original publication 1999).

Robichaud PR, Hungerford RD. 2000. Water repellency by laboratory burning of four northern Rocky Mountain forest soils. *Journal of Hydrology* **231–232**: 207–219.

Robichaud PR, Waldrop TA. 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. *Water Resources Bulletin* **30**(1): 27–34.

Robichaud PR, Beyers JL, Neary DG. 2000. *Evaluating the effectiveness of postfire rehabilitation treatments*. GTR-RMRS-63. USDA Forest Service, Rocky Mountain Research Station, Ft. Collins CO.

Robichaud P, MacDonald L, Freeouf J, Neary D, Martin D, Ashmun L. 2003. Postfire rehabilitation of the Hayman Fire. In *Hayman Fire Case Study Analysis*, Graham RT (tech. ed.). GTR-RMRS-114. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO; 293–313.

Romme WH, Veblen TT, Kaufmann MR, Sherriff R, Regan CM. 2003a. Ecological effects of the Hayman Fire part 1: historical (pre-1860) and current (1860 to 2002) fire regimes. In *Hayman Fire Case Study Analysis*, Graham RT (tech. ed.). USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 181–195.

Romme WH, Regan CM, Kaufmann MR, Huckaby L, Veblen TT. 2003b. Ecological effects of the Hayman Fire part 4: forest succession. In *Hayman Fire Case Study Analysis*, Graham RT (tech. ed.). USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 220–227.

RSAC. 2004. Burned Area Emergency Response (BAER) Imagery Support. http://www.fs.fed.us/eng/rsac/baer/ [15 March 2004].

Ryan KC. 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. *Silva Fennica* **36**(1): 13–39.

Ryan KC, Noste NV. 1983. Evaluating prescribed fires. In *Proceedings, Symposium and Workshop on Wilderness Fire*, Lotan JE, Kilgore BM, Fischer WC, Mutch RW (tech. coords). GTR-INT-182. USDA Forest Service, Intermountain Research Station, Ogden, UT; 230–238.

SAS Institute Inc. 1990. *SAS Procedures Guide*, Version 6, 3rd edition. Statistical Analysis Systems (SAS) Institute Inc.: Cary, NC.

SAS Insititute Inc. 1999a. *SAS/STAT User's Guide*, Volume 1, Version 8·2. Statistical Analysis Systems (SAS) Institute Inc.: Cary, NC.

SAS Institute Inc. 1999b. *SAS OnlineDoc*®, Version 8. Statistical Analysis Systems (SAS) Institute Inc., Cary, NC. SASOnlineDocV8\sasdoc\sashtml\onldoc.htm [26 March 2004].

Savage SM, Osborn J, Letey J, Heaton C. 1972. Substances contributing to fire-induced water repellency in soils. *Soil Science Society of America Proceedings* **36**: 674–678.

Shakesby RA, Doerr SH, Walsh RPD. 2000. The erosional impact of soil hydrophobicity: current problems and future research directions. *Journal of Hydrology* **231–232**: 178–191.

Smith RT, Atkinson K. 1975. *Techniques in Pedology: A Handbook for Environmental and Resource Studies*. Elek: London.

USDA Forest Service. 2002. Burned area report. http://wildfiresw.nwcg.gov/colorado/baer/hayman_fire_BAER_final.htm [10 April 2003].

USDA Forest Service. 2004. *Fire effects information system. Distribution and occurrence of* Pinus ponderosa *var.* scopulorum. http://www.fs.fed.us/database/feis/plants/tree/pinpons/distribution_and_occurrence.html [20 October 2004].

van Wagtendonk JW, Root RR, Key CH. 2004. Comparison of AVIRIS and Landsat ETM+ detection capabilities for burn severity. *Remote Sensing of Environment* **92**: 397–408.

Wang Z, Wu QJ, Ritsema CJ, Dekker LW, Feyen J. 2000. Effects of soil water repellency on infiltration rate and flow instability. *Journal of Hydrology* **231–232**: 265–276.

Watson CL, Letey J. 1970. Indices of characterizing soil water-repellency based upon contact angle–surface tension relationships. *Proceedings of the Soil Science Society of America* **34**: 841–844.

Wells CG, Campbell RE, DeBano LF, Lewis CE, Fredriksen RL, Franklin EC, Froelich RC, Dunn PH. 1979. *Effects of fire on soil: a state-of-knowledge review*. GTR-WO-7. USDA Forest Service, Washington, DC.

Wondzell SM, King JG. 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. *Forest Ecology and Management* **178**: 75–87.