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Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range

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Abstract

Fire-induced soil hydrophobicity is presumed to be a primary cause of the observed post-fire increases in runoff and erosion from forested watersheds in the Colorado Front Range, but the presence and persistence of hydrophobic conditions has not been rigorously evaluated. Hence the goals of this study were to: (1) assess natural and fire-induced soil hydrophobicity in the Colorado Front Range, and (2) determine the effect of burn severity, soil texture, vegetation type, soil moisture, and time since burning on soil hydrophobicity.

Five wild and prescribed fires ranging in age from 0 to 22 months were studied. Each fire had four study sites in ponderosa pine forests that had been burned at high, moderate, or low severity, and three sites were in unburned areas. Additional sites were established in lodgepole pine stands and an area with unusually coarse-textured soils. At each site the soil hydrophobicity was assessed in two pits using the water drop penetration time (WDPT) and the critical surface tension (CST). Measurements were made at the mineral soil surface and depths of 3, 6, 9, 12, 15, and 18 cm.

In sites burned at moderate or high severity the soils were often strongly hydrophobic at 0, 3, and 6 cm. Unburned sites or sites burned at low severity were typically hydrophobic only at the surface. Although soil hydrophobicity generally strengthened with increasing burn severity, statistically significant differences in soil hydrophobicity were difficult to detect because of the high variability within and between sites. Hydrophobicity also increased with increasing percent sand and was not present when soil moistures exceeded 12–25%. There were no significant differences in soil hydrophobicity between ponderosa and lodgepole pine stands, regardless of burn severity.

Repeat measurements on one fire suggest a weakening of fire-induced soil hydrophobicity after 3 months. Comparisons between fires suggest that fire-induced soil hydrophobicity persists for at least 22 months. Overall, CST values were more consistent and more highly correlated with the independent variables than the WDPT, and the CST is recommended for assessing soil hydrophobicity rather than the more commonly used WDPT. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS soil hydrophobicity; water repellency; burn severity; soil texture; Colorado Front Range; critical surface tension; ponderosa pine; lodgepole pine

INTRODUCTION

Soil hydrophobicity is a naturally occurring phenomenon (DeBano, 1981; Doerr *et al.*, 2000). This natural hydrophobicity usually is found at the mineral soil surface, and it is caused by the leaching of hydrophobic compounds, such as aliphatic hydrocarbons, from the litter and humus layers. Under unburned conditions the presence of hydrophobicity below the soil surface is commonly associated with fungal mycelia (Savage *et al.*, 1969).

The heat of a fire vaporizes hydrophobic compounds in the litter, humus, and soil organic matter (DeBano *et al.*, 1967). These compounds can escape into the atmosphere, or move into the soil atmosphere and condense

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on cooler soil particles at or below the soil surface (DeBano, 1981; Crockford *et al.*, 1991; Doerr *et al.*, 1996). The condensation of these compounds forms a hydrophobic coating on the soil particles (DeBano and Krammes, 1966; Savage, 1974).

In most forested areas the natural hydrophobicity is too weak and discontinuous to hinder infiltration and initiate infiltration-excess overland flow. Flow is mostly subsurface and the runoff and erosion rates are correspondingly low (DeBano, 1981). The formation of a strong hydrophobic layer after natural or prescribed fires can inhibit infiltration (Meeuwig, 1971; Scott and van Wyk, 1990). Once the ash and soil above the hydrophobic layer becomes saturated, any additional precipitation will become runoff. Hence the rate of runoff from forested areas can increase by more than an order of magnitude after burning, and this surface runoff, when combined with the loss of the protective litter layer, can cause even larger increases in surface erosion and catchment-scale sediment yields (e.g. Helvey, 1980; Scott and van Wyk, 1990).

Fire-induced soil hydrophobicity is believed to be the primary cause of the observed increases in runoff and erosion from forested watersheds after wildfires (DeBano and Krammes, 1966; DeBano, 1981; Wohlgemuth *et al.*, 1996). Fire is an important element in the ponderosa and lodgepole pine forests in Colorado's Front Range (Brown *et al.*, 1999), and increasing development means that an increase in runoff or erosion can threaten lives and property. The observed large increases in runoff and erosion after recent wildfires in Colorado have been ascribed to post-fire soil hydrophobicity (Colorado Water Conservation Board, 1997), but there has been no rigorous assessment of the extent and persistence of post-fire soil hydrophobicity in the fire-prone ponderosa and lodgepole pine forests of the Colorado Front Range.

A number of factors are believed to control the strength of soil hydrophobicity, and the most important of these are burn severity, vegetation type, soil texture, soil moisture, and time since burning. Burn severity is often cited as a primary control on the strength and extent of fire-induced soil hydrophobicity (DeBano and Krammes, 1966; DeBano, 1981), as high-severity fires vaporize more organic compounds and thereby generate a stronger and more continuous hydrophobic layer (Tiedemann *et al.*, 1979; DeBano, 1981).

Vegetation type also affects the formation and strength of a hydrophobic layer (DeBano, 1981; Imeson *et al.*, 1992; Doerr *et al.*, 1998; Scott, 2000). The amount of fuel affects burn severity, whereas the amount and types of hydrophobic compounds in plant materials control the potential strength of a hydrophobic layer. Most studies on fire-induced soil hydrophobicity in the USA have been done in chaparral (e.g. DeBano and Krammes, 1966), and a few studies have documented the formation of a water-repellent layer in *Pinus radiata* (radiata pine), *Pinus ponderosa* (ponderosa pine), *Pinus contorta* (lodgepole pine), and other forests dominated by the *Pinaceae* family (Meeuwig, 1971; Dyrness, 1976; Campbell *et al.*, 1977; Helvey, 1980; Doerr *et al.*, 1996).

Soil texture also affects the strength of the hydrophobic layer (DeBano, 1981). Since coarse-textured soils have a lower specific surface than fine-textured soils, a given amount of hydrophobic compounds will cause more hydrophobicity—both naturally and following burning—in coarse-textured soils (Meeuwig, 1971; DeBano, 1981).

Over time a hydrophobic soil will wet up due to the strong hydraulic gradient and movement of water vapour (DeBano, 1981). Once a hydrophobic soil begins to wet there is usually a soil moisture threshold at which these soils cease to be hydrophobic (Crockford *et al.*, 1991; Dekker and Ritsema, 1994; Doerr and Thomas, 2000). This soil moisture threshold ranges from 1·75% in dune sands (Dekker and Ritsema, 1994) to 28% in soils under eucalyptus (Doerr and Thomas, 2000). Upon drying, the hydrophobic conditions can be re-established (Shakesby *et al.*, 1993).

The persistence of a post-fire hydrophobic layer will depend on the strength and extent of hydrophobic chemicals after burning and the many physical and biological factors that can aid in breakdown (DeBano, 1981). Soil hydrophobicity usually returns to pre-burn conditions in no more than 6 years (Dyrness, 1976; DeBano, 1981), and several studies have documented a much more rapid recovery (e.g. DeByle, 1973; Reeder and Jurgensen, 1979).

The goal of this study was to characterize natural and post-fire soil hydrophobicity in ponderosa and lodgepole pine forests in the central and northern Colorado Front Range. The specific objectives were to:

(1) measure the strength of soil hydrophobicity at different soil depths in both burned and unburned ponderosa and lodgepole pine forests; (2) relate the observed hydrophobicity to burn severity, vegetation type, soil texture, soil moisture, and time since burning; and (3) develop a model to predict those areas that are most likely to be strongly hydrophobic after a forest fire.

STUDY AREAS

Five wild and prescribed fires in the northern and central Colorado Front Range were selected for study (Table I; Figure 1). The time since burning ranged from 0 to 22 months. All five fires contained sites burned at high, moderate, and low severities as well as unburned areas. Ponderosa pine was the dominant vegetation type, although the Bobcat and Lower Flowers fires also burned areas dominated by lodgepole pine. The Bobcat and Hi Meadows wildfires were tested immediately after burning, and the sites in the Bobcat wildfire were retested 3 months after burning. Hydrophobicity was tested 4 months, 7 months, and 22 months after burning in the Dadd Bennett, Lower Flowers, and Crosier Mountain prescribed fires respectively. All fieldwork was conducted from May to September 2000. Each fire was tested in a 1–2 week period, depending on the number of sites.

Soil textures ranged from sand to loam, with the majority of soils classified as sandy loams (Table I). Soil types ranged from Typic Argicryolls to Ustic Haplocryalfs (E. Kelly, Colorado State University, personal communication, 2001).

METHODS

Site selection

Within each fire the sample sites were stratified by burn severity, vegetation type, and soil texture. A set of approximately 15 sites was established for each fire, each vegetation type, and each soil texture. For each set of 15 sites, four sites each were in areas burned at high, moderate, and low severity, and three sites were in unburned areas.

Table I. Fires selected for study, date of each fire, time since burning when hydrophobicity was tested, vegetation types within each fire, the type of fire, mean soil texture of the top 12 cm, and the number of sites tested for each fire. Percent sand, silt, and clay were calculated for the fine fraction (<2 mm). Standard deviations are in parentheses

Name of fire	Date of fire	Time since burning when tested (months)	Vegetation type(s)	Prescribed or wildfire	>2 mm (%)	Sand (%)	Silt (%)	Clay (%)	No. of sites
Bobcat	June 2000	0	Ponderosa and lodgepole pine	Wildfire	10·8 (7·7)	64·3 (9·9)	28·8 (8·0)	6·9 (3·5)	45
	June 2000	3							45
Hi Meadows	June 2000	0	Ponderosa pine	Wildfire	43·0 (5·5)	66·2 (4·2)	25·9 (4·0)	7·9 (1·4)	14
Dadd Bennett	February 2000	4	Ponderosa pine	Prescribed fire	20·5 (7·4)	69·6 (3·7)	22·5 (3·8)	7·9 (1·9)	15
Lower Flowers	November 1999	7	Ponderosa and lodgepole pine	Prescribed fire	21·2 (6·9)	72·8 (5·8)	21·6 (4·8)	5·6 (1·3)	30
Crosier Mountain	August 1998	22	Ponderosa pine	Prescribed fire	21·8 (10·2)	65·4 (3·2)	27·3 (2·9)	7·3 (1·2)	12

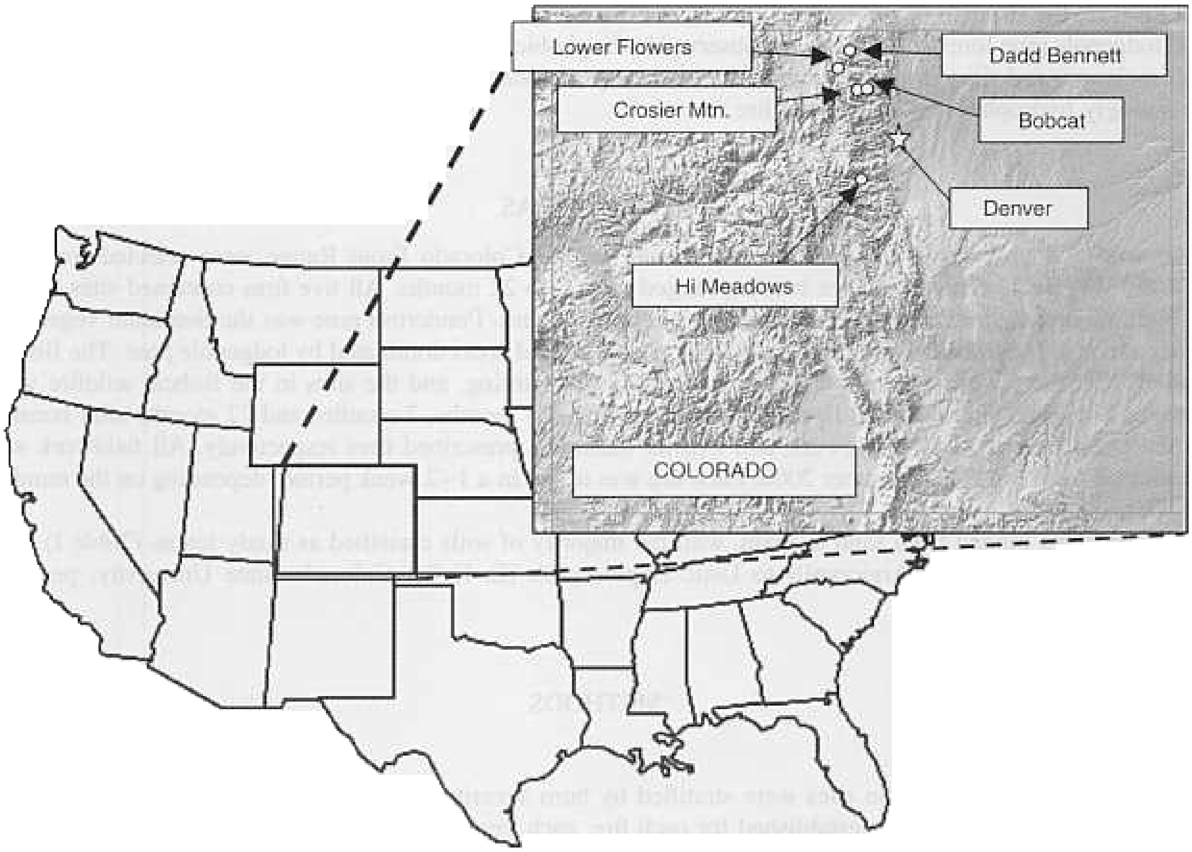

Figure 1. Location of the fires used in this study

Ponderosa pine sites were tested in all five fires, and complete sets of 15 sites were also established in lodgepole pine in the Bobcat and Lower Flowers fires (Table I). Large differences in soil texture were only present in the Bobcat fire, and an additional 15 sites were sampled in a ponderosa pine forest with unusually coarse soil textures. Sites in the same vegetation and burn severity class were always separated by at least 50 m. There were a total of 161 sites.

Burn severity was determined qualitatively at each site following the USDA Forest Service (1995) criteria. High-severity sites were identified by the complete combustion of organic matter, leaving only black or white ash. In moderate-severity sites most of the organic matter was consumed; ash and scorching was found on the mineral soil surface. At low-severity sites most of the organic matter was not consumed, but the litter surface was at least charred. In these sites the duff layer below the unconsolidated litter was still intact and there were no visible effects of the fire at the mineral soil surface.

At each site two pits were located approximately 30 cm apart. Pits were located under the drip line of the canopy where the soil hydrophobicity was stronger (Huffman, 2001). When the Bobcat fire was retested new pits were dug at each site.

Hydrophobicity assessment

At each pit the litter, duff, and ash were carefully swept aside. Soil hydrophobicity was assessed at the mineral soil surface and at depths of 3, 6, 9, 12, 15, and 18 cm. Soil hydrophobicity was tested in the field by measuring the water drop penetration time (WDPT) and the critical surface tension (CST). These two measures are the most widely used tests for assessing soil hydrophobicity (Wallis and Horne, 1992). The WDPT is the time needed for a drop of de-ionized water to be absorbed into the soil (Letey, 1969). In this study the WDPT was replicated ten times at each depth in each pit. Observations were continued for a maximum of 360 s, and the median time was used as the WDPT for that depth. The median WDPT was averaged between pits to generate a mean site WDPT for each depth.

The CST, also known as the 90° surface tension, was determined by placing drops of varying concentrations of de-ionized water and pure ethanol on the soil surface (Letey, 1969). Surface tension decreases with increasing ethanol concentrations, and the 13 solutions used in this study were 0, 1, 3, 5, 9, 14, 19, 24, 34, 48, 60, 72, and 80% ethanol. Beginning with pure water, at least five drops were applied at each depth. If the drops were not absorbed within 5 s, drops with successively greater concentrations of ethanol were applied until all the drops were absorbed within 5 s (Watson and Letey, 1970). The CST of the last solution used was averaged between pits to generate a mean site CST for each depth. Lower CST values indicate stronger soil hydrophobicity (Watson and Letey, 1970). Surface tensions were corrected for the effect of air temperature at the time of sampling (Weast, 1983).

Soil moisture and particle-size analysis

At each pit one soil sample was taken from 0–3 cm ('surface') and another from 9–12 cm ('10 cm'). Each sample was weighed, dried, and weighed again to determine percent moisture (Gardner, 1986).

The two samples from each pit were combined after drying; approximately 50 g of the combined sample was used to determine the particle-size distribution by the hydrometer method (Gee and Bauder, 1986). The fraction greater than 2 mm was determined by sieving the sample used for the particle-size analysis (Gee and Bauder, 1986). Data from the two pits were averaged to obtain mean values for each site. Soil textures were classified according to the USDA classification scheme (Soil Survey Division Staff, 1993).

Data analysis

The soil hydrophobicity within fires was compared by depth and burn severity. The soil hydrophobicity was compared between fires by depth and burn severity. The soil hydrophobicity between vegetation types was compared by depth and burn severity for both the Bobcat and Lower Flowers fires. Each of these comparisons was analyzed by the Ryan, Einot, Gabriel, Welsch (REGWQ) test (Gabriel, 1978) to control for maximum experiment-wise error at $\alpha = 0{\cdot}05$. Pairwise t-tests were used to compare hydrophobicity by depth and burn severity for the sites on the Bobcat fire that were retested after 3 months.

The effect of soil texture and soil moisture on hydrophobicity was analyzed by testing the dependence of WDPT and CST on percent sand, percent clay, percent mass >2 mm, and percent soil moisture for each burn severity and depth. Plots of soil moisture content against WDPT and CST for each burn severity and depth were used to determine whether there was a sudden reduction in soil hydrophobicity with increasing percent soil moisture.

The significant predictors of WDPT and CST at each depth were identified using Mallows' C_p selection method (Ott, 1993). Burn severity was assigned values of 1 (unburned) through 4 (high severity). Similarly, ponderosa and lodgepole pine were assigned the categorical values of 1 and 2 respectively. WDPT and CST values were transformed to natural logarithms to control decreasing variance with depth and improve the normality of their distributions. General linear models (GLMs) were then constructed from the significant predictors identified using Mallows' C_p. In contrast to the regression procedure used for predictor selection, GLMs can use both discrete and continuous variables (Ott, 1993).

RESULTS

The CST and WDPT values were strongly correlated ($r = -0{\cdot}652$ to $-0{\cdot}999$) at all depths (Table II). The strongest correlations were at 12–18 cm because there was less hydrophobicity and hence less variability at these depths (Figure 2). In general, there was considerable variation in soil hydrophobicity between pits, between similar sites within a fire, and between comparable sites from different fires (Table III, Figure 3). In some cases the soils in one pit exhibited little or no hydrophobicity at 0, 3, and 6 cm, whereas the soils in the adjacent pit were strongly hydrophobic at these depths. The CST values had a mean coefficient of variation (CV) between pits of 4%, and the mean CV between sites stratified by fire, burn severity and depth was 9%. Individual CVs ranged from 0 to 53%. Because the CST values had much lower CVs than the WDPT and the CST values were more strongly related to the independent variables, only the CST values are reported here.

A plot of CST values versus depth for all sites shows strong hydrophobicity at shallow depths in sites burned at high and moderate severity (Figure 2a and b). There was some evidence of hydrophobicity at the mineral soil surface in the sites burned at low severity, and only very weak hydrophobicity at the surface of the unburned sites. From 9–18 cm only a few sites exhibited much hydrophobicity. Two pits in an unburned

Table II. Correlations between CST and WDPT from the soil surface (0 cm) to a depth of 18 cm. All correlation (r are significant at $p < 0{\cdot}0001$

Depth (cm)	0	3	6	9	12	15	18
	-0·685	−0·730	−0·684	−0·652	−0·771	−0·9997	-0·893

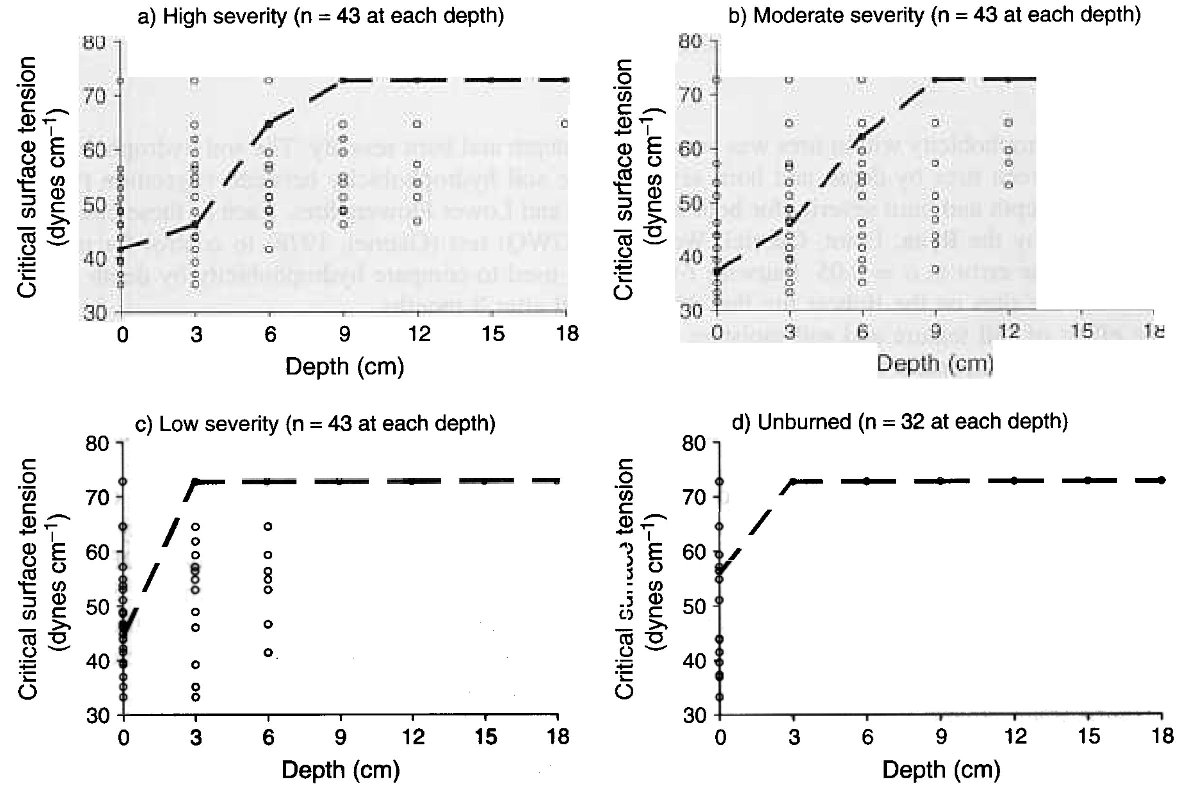

Figure 2. CSTs for (a) high severity, (b) moderate severity, (c) low severity, and (d) unburned sites. Each circle represents the average value at a site. Because so many values are overlapping, the median value for all sites is plotted as a dashed line. A decrease in CST indicates stronger hydrophobicity

Table III. Mean CST values for each fire and fire severity class at the mineral soil surface and depths of 3 and 6 cm. The horizontal comparisons are between fire severity classes within each fire and these are designated by the letters a, b, and c. The vertical comparisons are between fires within each fire severity class and these are designated by the letters x, y, and z. Values with the same letter are not significantly different at $p \leq 0{\cdot}05$. Standard deviations are shown in parentheses

Fire/(months since burning)		High severity	Moderate severity	Low severity	Unburned
Mineral soil surface					
Bobcat	0	41·7 (6·1) b x	38·9 (2·6) b x,y	47·8 (10·9) b x	59·2 (13·9) a x
	3	47·3 (10·4) b x	46·7 (11·4) b x	52·9 (11·9) a,b x	62·4 (13·2) a x
Hi Meadows	0	46·2 (1·9) b x	39·2 (1·9) b x,y	54·7 (12·2) a,b x	64·6 (11·6) a x
Dadd Bennett	4	39·8 (5·8) a x	33·2 (0) a y	37·2 (3·0) a x	49·8 (19·9) a x
Lower Flowers	7	38·8 (4·5) a x	35·2 (2·9) a y	40·0 (7·1) a x	47·4 (17·1) a x
Crosier Mountain	22	45·4 (5·9) a,b x	35·7 (2·1) b x,y	43·0 (3·5) a,b x	52·4 (9·6) a x
3 cm below the soil surface					
Bobcat	0	51·5 (11·5) a x,y	50·8 (11·3) a x	61·6 (9·8) a x	63·2 (14·7) a x
	3	55·8 (14·4) a x,y	52·9 (15·2) a x	67·6 (11·3) a x	65·7 (13·4) a x
Hi Meadows	0	46·9 (12·7) b y	54·7 (3·9) b x	72·75 (0) a x	72·75 (0) a x
Dadd Bennett	4	40·5 (4·6) c y	39·0 (5·4) c x	60·3 (5·0) b x	70·0 (4·7) a x
Lower Flowers	7	44·5 (4·3) b y	47·0 (11·8) b x	57·0 (14·5) a,b x	63·4 (15·3) a x
Crosier Mountain	22	67·3 (9·5) a x	52·4 (19·8) a x	72·75 (0) a x	72·75 (0) a x
6 cm below the soil surface					
Bobcat	0	63·1 (9·8) a x,y,z	64·3 (9·6) a x	67·9 (7·5) a x	68·6 (9·7) a x
	3	69·9 (6·8) a x,y	65·0 (13·1) a x	70·6 (5·5) a x	72·75 (0) a x
Hi Meadows	0	60·0 (8·6) a x,y,z	72·75 (0) a x	68·7 (4·7) a x	72·75 (0) a x
Dadd Bennett	4	54·1 (8·4) b z	48·9 (12·5) b x	70·7 (4·1) a x	72·75 (0) a x
Lower Flowers	7	55·4 (8·3) a y,z	51·4 (8·3) a x	62·1 (13·1) a x	66·5 (15·4) a x
Crosier Mountain	22	72·75 (0) a x	61·0 (20·4) a x	72·75 (0) a x	72·75 (0) a x

site and one pit in a site burned at low severity had strong hydrophobic conditions at all depths (Figure 2c and d), and this is probably due to abundant fungal mycelia from symbiotic mycorrhizae. As most of the observed soil hydrophobicity was at 0, 3 and 6 cm, the data analysis will focus on these depths.

There were no significant differences in CST values between ponderosa and lodgepole pine for any depth or burn severity class in either the Bobcat or the Lower Flowers fires. Because there also were no significant correlations between the CST values and vegetation type, the data from the two vegetation types were pooled.

Soil hydrophobicity by fire and burn severity

The patterns of hydrophobicity in the Bobcat fire immediately after burning (Figure 3a) are similar to the CST values for all fires when stratified by burn severity (Figure 2). For this fire, the soil hydrophobicity immediately after burning generally decreased with decreasing burn severity and increasing depth (Figure 3a). The moderate- and high-severity sites at the soil surface had the lowest CST values (strongest hydrophobicity). The soil surface in the burned areas was significantly more hydrophobic than the soil surface in the unburned areas, but the surface hydrophobicity in the burned sites did not vary significantly among the three burn severity classes (Table III). The CST values at 3 cm were lower in the sites burned at high and moderate severity than unburned and low-severity sites, but the differences were not significant with respect to burn severity class or between burned and unburned sites. Similarly, there was some evidence for stronger hydrophobicity at 6 cm in sites burned at high and moderate severity than in unburned and low-severity sites (Figure 3a), but the differences were not significant (Table III).

A comparison of Figure 3a and b suggests that the soil hydrophobicity in the Bobcat fire was slightly weaker 3 months after burning than immediately after the fire. In particular, the CST values at 6 cm for the sites burned at moderate and high severity showed less evidence of hydrophobicity. The sites burned at low severity also had higher CST values (weaker hydrophobicity) at the soil surface and at a depth of 3 cm

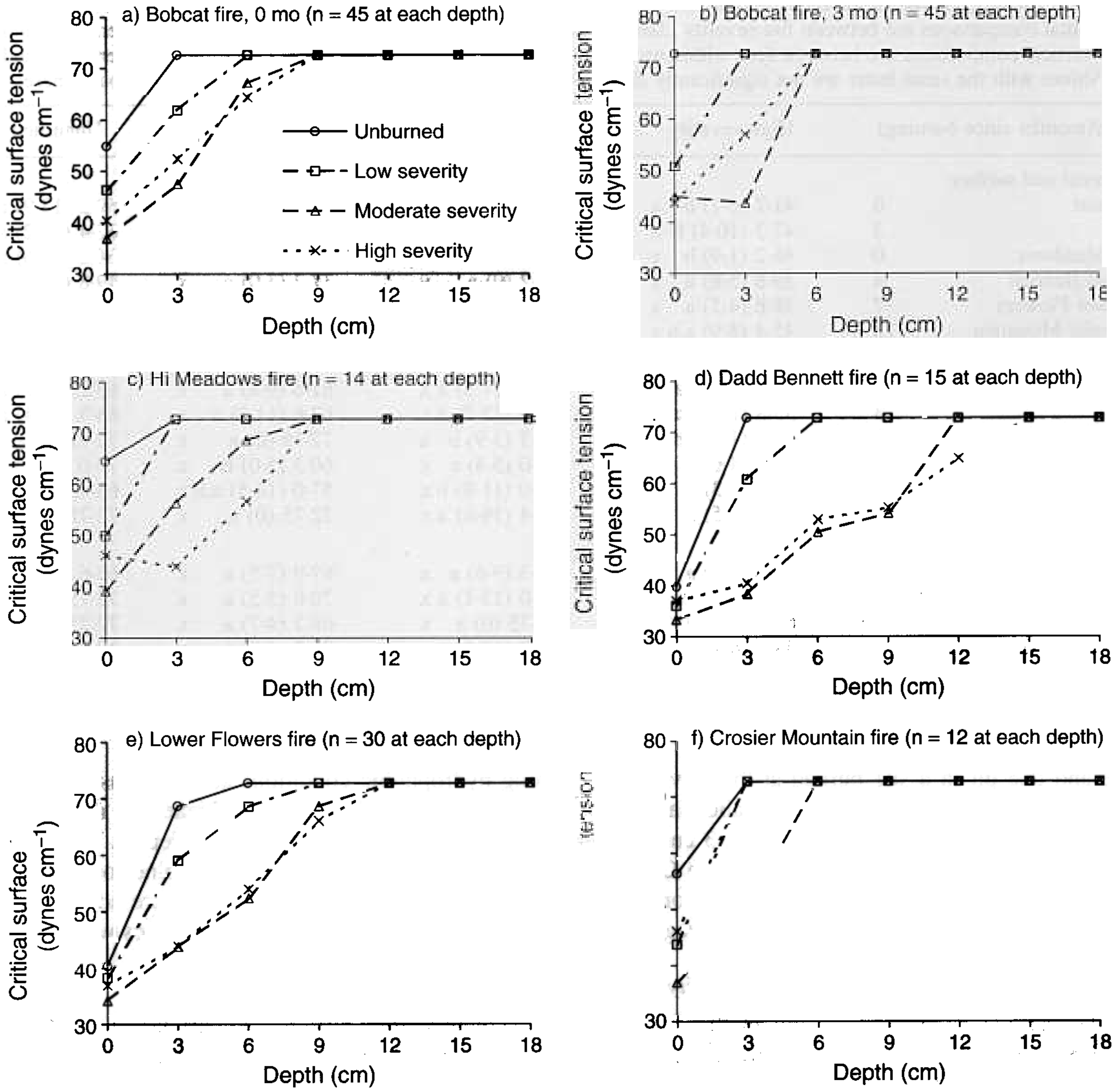

Figure 3. CST for high severity, moderate severity, low severity, and unburned sites in the (a) Bobcat fire shortly after burning, (b) Bobcat fire 3 months after burning, (c) Hi Meadows fire, (d) Dadd Bennett fire, (e) Lower Flowers fire, and (f) Crosier Mountain fire. Each symbol represents the median value at a given depth. The legend in (a) applies to all figures

than 3 months earlier. The unburned sites also had weaker hydrophobicity at the soil surface. However, the multiple comparisons test indicated that there were no significant differences in CST values between the two sampling dates for any depth or burn severity (Table III). The comparisons by depth and burn severity for this sampling time showed that, as in the case of the Bobcat fire immediately after burning, the only significant difference was that the sites burned at high and moderate severity were significantly more hydrophobic at the soil surface than the unburned sites (Table III).

The Hi Meadows wildfire also burned in June 2000, and the overall trends in hydrophobicity were similar to the Bobcat fire (Figure 3c). The strongest hydrophobicity was at 0 and 3 cm in the sites burned at high and moderate severity, and there was little evidence of hydrophobicity at or below 9 cm. Unburned sites were weakly hydrophobic only at the soil surface. The sites burned at high and moderate severity had significantly stronger hydrophobicity at the soil surface and at 3 cm than the unburned sites (Table III). The soils at 3 cm in the moderate- and high-severity sites were significantly more hydrophobic than the soils at 3 cm in the low severity sites (Table III). Sites burned at low severity had intermediate or low levels of hydrophobicity and were not statistically different from the unburned sites.

The hydrophobicity at 3 cm in severely burned sites appeared to be substantially stronger in the Hi Meadows fire than the Bobcat fire (Figure 3a–c). However, the high variability between sites meant that none of the differences in hydrophobicity between the Bobcat and Hi Meadows fires was statistically significant (Table III).

In the Dadd Bennett prescribed fire the soil was hydrophobic to a greater depth in sites burned at high and moderate severity than in any of the other four fires. There was evidence of soil hydrophobicity from the soil surface to a depth of 12 cm in the sites burned at high severity, and to a depth of 9 cm in the sites burned at moderate severity (Figure 3d). The strength of the observed hydrophobicity was very similar between the high- and moderate-severity sites.

Both the unburned sites and the sites burned at low severity were strongly hydrophobic at the soil surface, and there were no significant differences in the CST values at the soil surface with burn severity (Table III). However, the sites burned at moderate and high severity were significantly more hydrophobic at 3 cm than the sites burned at low severity, and the sites burned at low severity were significantly more hydrophobic at 3 cm than the unburned sites. At 6 cm the sites burned at high and moderate severity were significantly more hydrophobic than the low-severity and unburned sites (Table III).

The soils in the high- and moderate-severity sites in the Dadd Bennett fire were more hydrophobic than the corresponding sites in the Bobcat and Hi Meadows fires, but these differences were generally not significant (Table III). However, comparisons with the Bobcat fire 3 months after burning showed that the moderate-severity sites in the Dadd Bennett prescribed fire were more strongly hydrophobic at the soil surface, and the high-severity sites had significantly stronger hydrophobicity at 6 cm.

The values and overall patterns of soil hydrophobicity in the Lower Flowers prescribed fire were similar to the Dadd Bennett fire, even though soil hydrophobicity was tested 7 months after burning as opposed to 4 months in the case of the Dadd Bennett fire (Table I). The surface soils in the Lower Flowers fire were hydrophobic at all sites, and there were no significant differences between the CST values with burn severity (Table III). At 3 cm the sites burned at high and moderate severity were significantly more hydrophobic than the unburned sites, whereas the sites burned at low severity had intermediate CST values. At 6 cm there were no significant differences in hydrophobicity with burn severity, even though the CST values in high- and moderate-severity sites were lower than in the low-severity and unburned sites (Table III).

The CST values from the Lower Flowers fire suggest slightly weaker hydrophobicity in sites burned at high and moderate severity relative to the Dadd Bennett fire, and stronger hydrophobicity than the Hi Meadows and Bobcat fires. Although most of these differences were not significant at $p < 0.05$, the moderate-severity sites in the Lower Flowers fire had significantly stronger surface hydrophobicity than the corresponding sites in the Bobcat fire 3 months after burning.

Hydrophobicity was measured in the Crosier Mountain prescribed fire 22 months after burning, and the CST values indicate relatively little hydrophobicity except at the soil surface in the burned sites (Figure 3f). The only significant difference was that the hydrophobicity at the soil surface in sites burned at moderate severity was significantly stronger than the unburned sites (Table III). The sites burned at moderate severity also had the strongest hydrophobicity at 3 and 6 cm, but the differences in hydrophobicity with burn severity were not statistically significant at either of these depths.

Comparisons between fires showed that the sites burned at high severity at Crosier Mountain were significantly less hydrophobic at 3 cm than the corresponding sites in the Hi Meadows, Dadd Bennett, and Lower Flowers fires (Table III). Similarly, the hydrophobicity at 6 cm in sites burned at high severity at Crosier Mountain was significantly weaker than in the Dadd Bennett and Lower Flowers prescribed fires.

Table IV. Correlations between each independent variable and measured CST values at depths of 0, 3 and 6 cm. The first number for a given correlation is the correlation coefficient r and the number in parentheses is the p value. Values in bold are significant at $p \leq 0.05$

Variable	CST		
	Depth = 0 cm	Depth = 3 cm	Depth = 6 cm
Fire severity	**−0·179 (0·0235)**	**−0·308 (<0·0001)**	**−0·161 (0·0418)**
Vegetation type	0·087 (0·27)	−0·025 (0·75)	−0·057 (0·47)
Time since burning	−0·130 (0·10)	0·108 (0·17)	−0·008 (0·92)
Surface soil moisture	**0·382 (<0·0001)**	**0·349 (<0·0001)**	**0·266 (0·0007)**
Percent >2 mm	0·116 (0·14)	0·016 (0·84)	−0·074 (0·35)
Percent sand	**−0·295 (0·0001)**	**−0·398 (<0·0001)**	**−0·418 (<0·0001)**
Percent clay	**0·175 (0·026)**	**0·300 (0·0001)**	**0·244 (0·0018)**

Effect of soil texture

Of the 161 soil samples, 152 had more than 50% sand and 145 had less than 10% clay. The soil samples from the Lower Flowers and Dadd Bennett fires had significantly more sand than the soil samples from the Bobcat and Crosier Mountain fires (Table I). The soils in Lower Flowers' also had significantly less clay than the soils from the other fires.

When all the data were pooled, there was a significant increase in soil hydrophobicity at 0, 3 and 6 cm with increasing percent sand ($p < 0.001$). Percent clay was negatively correlated with soil hydrophobicity at the same three depths (Table IV). For each depth the correlation between percent sand and the CST values was stronger than the correlation between percent clay and the CST values. The percent mass >2 mm was not significantly correlated with the CST values (Table IV).

When stratified by burn severity the relationship between percent sand and CST values was significant at $p < 0.05$ at the soil surface for low- and moderate-severity sites, and at 3 cm for unburned, low-severity, and moderate-severity sites. In each case the R^2 decreased with increasing burn severity.

Effect of soil moisture

An increase in soil moisture was generally associated with a decrease in hydrophobicity at 0, 3 and 6 cm (Table IV). The correlations between CST values at these three depths and surface soil moisture were all significant at $p < 0.001$. Surface soil moisture explained more of the variability in CST values at the soil surface than burn severity or any of the soil texture variables. However, the R^2 was low owing to the variability in CST values and the lack of a true linear relationship between surface soil moisture and CST values. Percent soil moisture at 10 cm was not significantly correlated with the CST values at 9, 12, 15, or 18 cm, and this is probably due to the absence of much hydrophobicity at these depths.

Persistence of fire-induced soil hydrophobicity

There were no significant differences in hydrophobicity at the soil surface between the different fires for the sites burned at high severity, but there were significant differences in the CST values among the different fires at 3 and 6 cm (Table III). In high severity sites the soil hydrophobicity was significantly weaker at 3 cm in the 22-month-old Crosier Mountain prescribed fire than the corresponding sites in the Hi Meadows fire immediately after burning, the 4-month-old Dadd Bennett fire, or the 7-month-old Lower Flowers fire (Table III). Similarly, soil hydrophobicity was significantly weaker in high-severity sites at 6 cm in the Bobcat fire 3 months after burning and the 22-month-old Crosier Mountain fire than in the 4-month-old Dadd Bennett fire. Soil hydrophobicity at 6 cm in the sites burned at high severity in the Crosier Mountain fire was significantly weaker than in the 7-month-old Lower Flowers fire (Table III).

In sites burned at moderate severity the surface hydrophobicity was significantly weaker in the Bobcat fire 3 months after burning than in the 4-month-old Dadd Bennett and the 7-month-old Lower Flowers fires. Between-fire comparisons showed no other significant differences in hydrophobicity for sites burned at moderate severity. There were no significant differences in CST values between fires for the sites burned at low severity or the unburned sites.

For the Bobcat fire, the more sensitive pairwise comparisons showed significantly weaker surface hydrophobicity 3 months after burning in high- ($p = 0{\cdot}02$) and moderate-severity ($p = 0{\cdot}03$) sites. At a depth of 3 cm there were no significant differences in hydrophobicity between the two sets of measurements. At 6 cm, the hydrophobicity in sites burned at high severity was significantly weaker 3 months after burning than immediately after the fire ($p = 0{\cdot}02$).

There was no significant correlation between time since burning and CST (Table IV). This is probably due to the low CST values in high- and moderate-severity sites in the 4- and 7-month-old fires relative to the 3- and 22-month-old fires.

Predicting soil hydrophobicity

The significant variables for predicting CST values at 0, 3 and 6 cm were burn severity, percent sand, and percent soil moisture (Table V). These three variables explained 38% of the variability in CST values at the soil surface and 41% of the variability in CST values at 3 cm. At 6 cm the predictive model uses the soil moisture at 10 cm rather than surface soil moisture, and the overall model R^2 drops to 30%.

The general linear models indicate stronger soil hydrophobicity with increasing burn severity and increasing percent sand, and weaker soil hydrophobicity with increasing percent soil moisture. Burn severity was the most significant variable at the soil surface, but this declined in importance with increasing depth (Table V). Percent sand became progressively more important with increasing depth. Percent soil moisture was the least significant variable at all three depths (Table V).

DISCUSSION

Assessing soil hydrophobicity

The strong correlations between CST and WDPT in this study are consistent with previous work (Crockford *et al.*, 1991; Dekker and Ritsema, 1994; Harper and Gilkes, 1994; Scott, 2000). A recent study compared five different methods for measuring hydrophobicity: WDPT, CST, water repellency index, liquid–solid contact angle, and apparent advancing contact angle. All five measures were strongly correlated with one another and only the CST was recommended for future use (Scott, 2000). Crockford *et al.* (1991) concluded that the reproducibility of WDPT was poor, providing further evidence for using CST rather than the more common WDPT. We found that the CST had much lower variability and was faster to measure. For these reasons the CST is recommended for assessing soil hydrophobicity.

Table V. R^2, F, and p values for the overall model to predict the natural logarithm of CST values, and the statistics for each significant variable. The soil moisture at the surface was used for predicting ln CST at 0 and 3 cm, whereas the model for ln CST at 6 cm uses the soil moisture at 10 cm

	Depth = 0 cm			Depth = 3 cm			Depth = 6 cm		
	R^2	F	p	R^2	F	p	R^2	F	p
Overall model	0·38	18·87	<0·0001	0·41	21·46	<0·0001	0·30	13·36	<0·0001
Burn severity		16·71	<0·0001		17·68	<0·0001		9·12	<0·0001
Soil moisture		9·78	0·0021		7·57	0·0066		7·0	0·009
Percent sand		12·91	0·0004		22·81	<0·0001		20·61	<0·0001

Burn severity

The amount of soil heating in prescribed fires is often assumed to be less than in wildfires (Robichaud and Hungerford, 2000). However, in upper Michigan there was no difference in the fire-induced water repellency between wildfires and prescribed fires (Reeder and Jurgensen, 1979).

The data from our study showed stronger soil hydrophobicity in the Dadd Bennett and Lower Flowers prescribed fires than the two recent wildfires (Table III), even though the prescribed fires were tested 4 and 7 months after burning. Stronger hydrophobicity after prescribed fires could be due to higher fuel loads, a slower rate of spread (Pyne *et al.*, 1996), and the tendency for prescribed fires to stay on the ground rather than become crown fires (Pyne *et al.*, 1996). Data on pre-burn fuel loadings are not available for the Bobcat or Hi Meadows wildfires, but the rate of spread was much slower for the Dadd Bennett and Lower Flowers prescribed fires than the Bobcat and Hi Meadows wildfires.

A difference in the natural hydrophobicity prior to burning might also affect the degree of soil hydrophobicity after burning. In this study there were no significant differences in soil hydrophobicity between fires for unburned and low-severity sites (Table III). This suggests that the different fires are comparable, and the between-fire differences in soil hydrophobicity in high- and moderate-severity sites are not due to differences in hydrophobicity prior to burning.

Vegetation

There were no significant differences in the CST values between ponderosa and lodgepole pine sites when stratified by burn severity and depth. This implies that these two species have similar types and amounts of hydrophobic compounds in their litter. Different species in the *Pinaceae* family have been shown to have a similar extractive content in their litter (Shafizadeh *et al.*, 1977). Although the amount of litter will vary with site conditions and forest age, the similarity in extractive compounds suggests a similar heat content and chemical composition, and hence a similar propensity for pre- and post-fire soil hydrophobicity.

Both ponderosa and lodgepole pine have large ranges in North America, suggesting that there may be large differences in site productivity, decomposition rates, and fuel loadings. Since the depth of fire-induced soil hydrophobicity is believed to be a function of soil heating (DeBano, 1981), the amount of fuel will affect the depth and strength of the hydrophobic layer. Lodgepole pine sites in Oregon that burned at high or moderate severity had a strongly hydrophobic layer from 5 to 15 cm below the soil surface, whereas in unburned sites the soils were moderately hydrophobic from the soil surface to a depth of 5 cm (Dyrness, 1976). The greater depth of hydrophobicity in lodgepole pine sites in Oregon may stem from the higher productivity of lodgepole pine forests in Oregon than Colorado. Differences in productivity should be considered when comparing or extrapolating the results of our study to other areas.

Soil texture

Like many previous studies (DeBano *et al.*, 1970; Campbell *et al.*, 1977; DeBano, 1981; Crockford *et al.*, 1991), we found stronger fire-induced and natural soil hydrophobicity in coarser-textured soils. The stronger hydrophobicity in the Dadd Bennett and Lower Flowers fires may be partly due to the significantly higher percent sand in these two fires relative to the Bobcat and Crosier Mountain fires. Pre-burn data on soil moisture and fuel loadings are needed to more clearly identify the effect of soil texture on fire-induced soil hydrophobicity.

Soil moisture

Soil moisture is assigned a linear relationship with the natural logarithm of CST in the general linear models, but a plot of the data by burn severity indicates that there may be a soil moisture threshold rather than a linear relationship (Huffman, 2001). Any change in soil moisture below this threshold will not necessarily alter the strength of soil hydrophobicity (Doerr and Thomas, 2000).

To more accurately determine the effect of soil moisture on soil hydrophobicity more tests should be done when soil moisture levels are in the range 15–30%. This would help determine whether there is a threshold where hydrophobic soils become easily wettable. Alternatively, one could dry soil samples in the laboratory and compare the potential water repellency of dried soils with the actual water repellency as measured in the field under varying soil moisture conditions (Dekker and Ritsema, 1994). Dekker *et al.* (1998) concluded that the most reliable estimate of soil hydrophobicity was from undried samples collected during dry periods.

The effect of soil moisture on soil hydrophobicity means that runoff from spring snowmelt should be less affected by soil hydrophobicity than runoff from summer rainstorms. The slow rate of snowmelt should wet the soil above the soil moisture threshold and allow meltwater to infiltrate readily. High-intensity summer convective storms are more likely to occur when the soil surface is dry and the hydrophobic layer is more likely to limit infiltration. This means that mid- and late-summer precipitation events are of greatest concern for increasing runoff from burned watersheds in Colorado.

Persistence of fire-induced soil hydrophobicity

The time since burning was not a significant predictor of fire-induced soil hydrophobicity, because the differences in hydrophobicity between fires of similar ages were almost as great as the differences between fires of different ages. Hydrophobicity was stronger in the Dadd Bennett and Lower Flowers prescribed fires than in the two younger fires and the much older Crosier Mountain fire.

The short-term nature of this study means that we cannot reliably determine the persistence of fire-induced soil hydrophobicity in the pine forests of the Colorado Front Range. However, the data suggest a weakening of fire-induced soil hydrophobicity in the Bobcat fire after 3 months, and still weaker hydrophobicity in the Crosier Mountain fire 22 months after burning. The high-severity sites in the Crosier Mountain fire had the highest (i.e. least hydrophobic) CST values at 3 and 6 cm, and the CST values in these sites were not significantly different than unburned sites. Limited testing showed no evidence of fire-induced soil hydrophobicity at any depth for the Buffalo Creek fire 4 years after burning, or for the 1994 Hourglass fire 5 years after burning (Huffman, 2001).

In contrast, fire-induced soil hydrophobicity persisted for 6 years in lodgepole pine stands in the upper Cascades of Oregon (Dyrness, 1976), and about 4 years in ponderosa pine stands in Arizona (Campbell *et al.*, 1977). In upper Michigan over 50% of the burned sites that were initially classified as water repellent were no longer water repellent within 1 year after burning (Reeder and Jurgensen, 1979). In conifer forests in Montana the post-fire water repellency also disappeared within 1 year (DeByle, 1973).

This variability means that the persistence of post-fire hydrophobicity cannot be readily extrapolated between regions (Doerr *et al.*, 2000). The persistence of fire-induced soil hydrophobicity should be determined by repeated testing on individual fires in different regions while controlling for variables such as soil moisture, burn severity, and soil texture.

Scale implications

In hydrophobic soils the water flow is generally limited to preferential flow paths or finger flow (Dekker and Ritsema, 1994). Even if large areas within a fire are hydrophobic, infiltration can occur at some locations through finger flow (Imeson *et al.*, 1992), root channels, rodent burrows (Ferreira *et al.*, 2000), or other preferential flow paths. Since infiltration rates in most forest soils are relatively high, a few preferential flow paths or scattered areas with weak hydrophobicity can significantly reduce runoff at the hillslope scale.

Preliminary testing for soil hydrophobicity indicated that fire-induced soil hydrophobicity was stronger under the drip line than in intercanopy areas (Huffman, 2001). Stands with high tree densities will have less intercanopy area and hence a potentially greater continuity of areas with hydrophobic soils, whereas less dense stands should have more areas where runoff can infiltrate.

In addition to stand density, the proportion of area burned at high and moderate severity will also affect post-fire increases in runoff. The Bobcat and Hi Meadows wildfires had a higher proportion of area burned at high or moderate severity than the three prescribed fires. This means that the proportion of the area that is hydrophobic in a prescribed fire may be lower than for a wildfire, and there would be more non-hydrophobic areas for overland flow to infiltrate (Tiedemann *et al.*, 1979). Runoff and erosion from prescribed fires might, therefore, be much less than for wildfires, even though a prescribed fire could have similar or even stronger fire-induced soil hydrophobicity in sites burned at high or moderate severity.

CONCLUSIONS

CST was less variable than the WDPT when stratified by fire, burn severity and depth. CST was also better correlated with the variables measured in this study than the WDPT. Since CST is also quicker and easier to measure, the CST should be used for assessing soil hydrophobicity in the field.

In sites burned at high and moderate severity the soils were generally hydrophobic from the soil surface to a depth of 6 cm. In low-severity and unburned sites the soils were generally hydrophobic only at the soil surface, and this surface hydrophobicity was generally weaker than in sites burned at high and moderate severity. Soil hydrophobicity was often stronger and deeper in the prescribed fires than the wildfires, but the effect of hydrophobicity on runoff is likely to be less in prescribed fires because they are usually smaller and have less area burned at high and moderate severity. Three of the 161 sites tested in this study had strong natural hydrophobicity to a depth of 18 cm, and this was associated with fungal mycelia.

Burn severity and percent sand are the most significant predictors of fire-induced soil hydrophobicity in ponderosa and lodgepole forests in the central and northern Colorado Front Range. Together with soil moisture, these factors explained approximately 40% of the variability in soil hydrophobicity at the soil surface and a depth of 3 cm. The time since burning was not a significant predictor of soil hydrophobicity, and this is probably due to the variability of fire-induced soil hydrophobicity between fires. There was some evidence that hydrophobic soils become hydrophilic when soil moisture levels exceed 12 to 25%. Fire-induced and natural soil hydrophobicity were not significantly different between lodgepole and ponderosa pine stands.

Repeated measurements suggest that fire-induced soil hydrophobicity weakens within 3 months after burning. Hydrophobicity measurements 22 months after burning showed little evidence of fire-induced soil hydrophobicity at 3 and 6 cm in sites burned at high and moderate severity. However, the soil surface was significantly more hydrophobic in sites burned 22 months earlier at moderate severity than in unburned sites.

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