Post-fire Soil Water Repellency: Persistence and Soil Moisture Thresholds

Lee H. MacDonald* and Edward L. Huffman

ABSTRACT

Fire-induced soil water repellency is a key control on post-fire runoff and erosion rates, but there are few data on the persistence of soil water repellency and the soil moisture threshold at which water repellent soils become hydrophilic. This study used repeated sampling to quantify changes in soil water repellency over time and identify soil moisture thresholds for the loss of soil water repellency. The study area was a wildfire in the northern Colorado Front Range that burned 43 km^2 of ponderosa and lodgepole pine forests in June 2000. Soil water repellency and soil moisture were measured periodically from June 2000 through June 2001 at 36 sites stratified by burn severity and nine unburned sites. Water repellency was assessed in the field at depths of 0 to 18 cm using the critical surface tension (CST) test. Soil water repellency was strongest in sites burned at high and moderate severity, decreased with increasing depth, and was spatially highly variable. The fire-induced soil water repellency progressively weakened and became statistically nondetectable by 1 yr after burning. The effect of time since burning on soil water repellency was increasingly significant with increasing burn severity and progressively less important with increasing soil depth. The soil moisture thresholds at which water repellent soils become hydrophilic apparently increase with increasing burn severity. The data suggest soil moisture thresholds of approximately 10% for unburned sites, 13% for sites burned at low severity, and no less than 26% for sites burned at moderate and high severity.

Fire-induced soil water repellency is often cited as a key factor controlling post-fire runoff and erosion rates (e.g., Morris and Moses, 1987; Imeson et al., 1992; Shakesby et al., 2000; Letey, 2001). The strength and persistence of fire-induced water repellency is of particular concern in the Colorado Front Range, as recent forest fires have been followed by severe flooding, erosion, and sedimentation (e.g., Moody and Martin, 2001; Graham, 2003). Millions of dollars are being spent on emergency treatments in burned areas to reduce post-fire increases in runoff and erosion and the associated threats to property, aquatic resources, and domestic water supplies (Robichaud et al., 2000). The assessment of post-fire erosion risks and design of rehabilitation treatments require an understanding of how soil water repellency changes over time and under different environmental conditions.

Studies in other areas have shown that several factors affect the strength and persistence of post-fire soil water repellency, including burn severity, vegetation type, soil texture, soil moisture, and time since burning (DeBano, 1981; de Jonge et al., 1999; DeBano, 2000a, 2000b; Doerr and Thomas, 2000). A study of soil water repellency after five different fires in the Colorado Front Range found that burn severity, percentage of sand, and soil moisture were the primary controlling variables (Huffman et al., 2001). Time since burning was not a significant control on soil water repellency because of the large variability in soil water repellency values between fires. The strongest soil water repellency was observed in prescribed fires 4 and 7 mo after burning, and significant water repellency was still present 22 mo after burning in the case of the Crosier Mountain fire (Huffman et al., 2001). Given the variability between fires, repeated measurements from one fire are needed to more accurately determine the persistence of fire-induced soil water repellency.

The generalized linear model developed in Huffman et al. (2001) showed that soil water repellency significantly decreased with increasing surface soil moisture. Other studies have suggested a soil moisture threshold or transition zone at which soils cease to be water repellent, as soils eventually wet up due to the strong hydraulic gradient and movement of water vapor (DeBano, 1981). Once wet, soils are no longer water repellent until they again dry out (Doerr and Thomas, 2000). For unburned soils, reported soil moisture thresholds range from 2 to 5% for a dune sand (Dekker et al., 2001) to 5 to 12% for naturally hydrophobic soils in Denmark (de Jonge et al., 1999), and 34 to 38% for clayey peat soils (Dekker and Ritsema, 1996).

For burned areas there are almost no data on the soil moisture threshold for the elimination of soil water repellency. Doerr and Thomas (2000) noted an absence of soil water repellency in a coarse-textured forest soil in Portugal once the soil moisture content exceeded 28%. A visual examination of the data from Huffman et al. (2001) suggests that the soil moisture threshold in the Colorado Front Range may range from about 12% in unburned areas to a minimum of 25% in severely burned areas, but a more rigorous analysis was hampered by the limited amount of soil water repellency data at high soil moisture contents.

The objectives of this study were to determine: (i) the persistence of post-fire soil water repellency by repeated measurements within a single fire; (ii) if there is a soil moisture threshold for the loss of post-fire soil water repellency; and (iii) if the soil moisture threshold varies with fire severity. These results are needed to design post-fire rehabilitation treatments, identify the necessary design life for those treatments, and indicate when post-fire flooding and erosion risks may be substantially reduced.

L.H. MacDonald, Dep. of Forest, Rangeland, and Watershed Stewardship, Colorado State Univ., Fort Collins, CO 80523-1472; and E.L. Huffman, Allegheny National Forest, 222 Liberty St., Warren, PA, 16365. Received 22 Sept. 2003. *Corresponding author (leemac@cnr.colostate.edu).

Published in Soil Sci. Soc. Am. J. 68:1729–1734 (2004).

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: CST, critical surface tension.

MATERIALS AND METHODS

All measurements were made in or immediately adjacent to areas burned by the Bobcat fire in June 2000. This fire burned nearly 43 km^2 of predominantly ponderosa and lodgepole pine forests (*Pinus ponderosa* and *P. contorta*, respectively) approximately 25 km southwest of Fort Collins, CO. Dominant soil subgroups are Lithic Haplustepts, Lithic Haplustalfs, Typic Haplustepts, and Typic Haplustolls, with parent materials of slope alluvium and colluvium over residuum derived from gneiss, schist, and micaceous granite (USDA Forest Service, 2000).

Water repellency was assessed in the field using the CST test (Letey, 1969) and followed the procedure described in Huffman et al. (2001). A total of 45 sites were identified in June and July 2000. There were 12 sites each in areas burned at high, moderate, and low severity, and nine sites in adjacent unburned areas. Burn severity was classified from the condition of surface litter, ash, and soil following standard criteria (USDA Forest Service, 1995; Huffman et al., 2001).

At each site two pits 30 cm apart were sampled under the drip line of the tree canopy. Any litter, duff, or ash was swept aside, and soil water repellency was assessed at the mineral soil surface and depths of 3, 6, 9, 12, 15, and 18 cm. At each depth the CST was determined by applying at least five drops of deionized water mixed with increasing concentrations of pure ethanol. If all of the drops were not absorbed into the soil within 5 s, progressively higher ethanol concentrations were tested. The CST is the surface tension associated with the lowest concentration of ethanol that was readily absorbed by the soil, and this is a quantitative index of the strength of soil water repellency (Letey, 1969). We prepared solutions with 0, 1, 3, 5, 9, 14, 19, 24, 34, 48, and 60% concentrations of ethanol by volume, but never needed a solution with more than 34% ethanol. The CST values from the two pits were averaged to yield one value for each site. The CST values are reported in N m^{-1} $\times$ 10^3 (dynes cm^{-1}).

At each pit one sample was taken from 0 to 3 cm (surface) and another from 9 to 12 cm (subsurface). These samples were used to determine gravimetric soil moisture (Gardner, 1986), and the values from each pit were averaged to yield a value for each site for each sampling time. The dried samples from June and July 2000 were used to determine the surface and subsurface particle-size distributions for each site (Huffman et al., 2001).

Critical surface tension and soil moisture measurements were first made in June and July 2000 and repeated at each site 3 and 12 mo after burning (Fall 2000 and Summer 2001, respectively). For the repeated sampling new pits were dug immediately adjacent to the pits used previously. Critical surface tension and soil moisture measurements also were made in April and May 2001 at six sites burned at high severity and five sites burned at moderate severity. The combination of spring rains and snowmelt caused the soils to be much wetter at this time than the three other sampling periods.

Plots of CST values by time since burning and burn severity class use median CST values because the median is less sensitive to extreme values, and less affected by the upper limit on CST values of 72.7 N m^{-1} $\times$ 10^3 (the surface tension of pure water at 20°C). The mean CST values were used for the statistical comparisons between sampling dates by depth and burn severity class, and the comparisons between burn severity classes by depth and sampling date. These comparisons used the Ryan, Einot, Gabriel, Welsch (REGWQ) test (Gabriel, 1978) and controlled for maximum experiment-wise error at $\alpha = 0.05$. Since all of the data were from the same sites on the Bobcat fire, more sensitive pairwise *t* tests were used to test for differences in the mean CST values between sampling dates by depth and burn severity class. Pairwise comparisons between burn severity classes by depth and sampling date were not appropriate because the burn severity classes represented different sites.

The effect of soil moisture was analyzed by plotting surface soil moisture content against the CST values from 0 and 3 cm for the unburned sites and each of the three burn severity classes. The CST data from 0 and 3 cm were used because these depths exhibited the strongest water repellency and were more accurately characterized by the 0- to 3-cm samples used to determine soil moisture. Visual examination of these scatter plots was used to determine the highest soil moisture content associated with evidence of soil water repellency (i.e., CST values $<$65 N m^{-1} $\times$ 10^3). The highest moisture content with evidence of soil water repellency was assumed to represent the soil moisture threshold for that burn severity class.

RESULTS

Soil Texture and Water Contents

At the soil surface particles $>$2 mm accounted for nearly 11% of the mass. On average, the fine fraction consisted of 64% sand, 29% silt, and 7% clay. Thirty-five of the 45 sites were classified as a sandy loam, five sites as a loamy sand, four sites as a loam, and one site as a sand.

The mean surface soil water content for the samples taken immediately after burning was 6.2%. At three months after burning the mean soil water content was slightly greater at 7.7%, and at 12 mo the mean soil water content was 5.0%. There was considerable variability among sites, as the coefficient of variation for each sampling period was approximately 100%. There were no significant differences in soil water contents between these three sampling times for either the surface or subsurface samples. In Spring 2001 the mean water content for the surface samples was 12.6% and the coefficient of variation was 62%.

Soil Water Repellency by Burn Severity, Depth, and Time since Burning

Immediately after burning, the median CST values at 0, 3, and 6 cm were lower for all three burn severity classes than the corresponding CST values for the unburned sites (Fig. 1a; Table 1). Soil water repellency was strongest in the areas burned at high and moderate severity, and generally weakened with increasing depth. The median values for the unburned sites indicate that only the soil surface was consistently water repellent.

Comparisons among the mean CST values showed that the soil surface in all three burn severity classes was significantly more water repellent immediately after burning than the surface of the unburned sites (Table 1). The high variability in CST values between sites meant that there were no significant differences in soil water repellency at the soil surface between the burn severity classes. At both 3 and 6 cm there were no significant differences in the CST values between burn severity classes or between burned and unburned sites. Since there was little evidence of natural or fire-induced water repellency at depths of 9 to 18 cm (Fig. 1a), subsequent analyses focus only on the data from 0, 3, and 6 cm.

At three months after burning both the mean and median CST values were higher than immediately after burning for nearly all depths and burn severities, suggesting a weakening of the post-fire soil water repellency (Fig. 1a,b; Table 1). The soil surface in sites burned at high and moderate severity was significantly more water repellent than soil surface in the unburned sites, but there were no other significant differences between burn severity classes at any depth (Table 1).

At 12 mo after burning the median CST values suggest continuing water repellency at the soil surface in the areas that burned at high and moderate severity (Fig. 1c). However, the mean CST values in Table 1 indicate some water repellency at the soil surface for all three burn severity classes, and at 3 cm for areas burned at moderate severity. The difference between the mean and median values can be attributed to the greater effect of occasional low CST values on the mean relative to the median. At 6 cm, the mean CST values for each burn severity class are close to the value for hydrophilic conditions, but the high standard deviation for sites burned at moderate severity indicates that some sites were still strongly water repellent (Table 1). At 12 mo after burning the comparison of mean CST values yielded no significant differences between burned and unburned sites or among the burn severity classes.

The mean CST values show a progressive weakening of soil water repellency with increasing depth at each sampling time for each burn severity class and the unburned sites (Table 1). Mean soil water repellency decreases with time since burning at each depth for each burn severity class and the unburned sites. However, the high spatial variability meant that the only statistically significant decreases in soil water repellency with time since burning was at the soil surface in the areas burned at high and moderate severity, respectively (Table 1). For the high severity sites, there was significantly less soil water repellency at the soil surface in Summer 2001 than in either Summer or Fall 2000. Similarly, in sites burned at moderate severity there was significantly less water repellency in Summer 2001 than immediately after burning, while the mean CST value from Fall 2000 was intermediate (Table 1).

The more sensitive pairwise comparisons yielded more statistically significant declines in soil water repellency with increasing time since burning (Table 2). In sites burned at high severity, the soil water repellency at 0 and 3 cm was significantly weaker (higher CST values) at 12 mo after burning than at zero and three months after burning. The soil water repellency at 6 cm was significantly weaker at three months than immediately after burning. Sites burned at moderate severity showed a significant weakening of soil water repellency at the soil surface within the first three months after burning, but there were no other significant differences. In the sites burned at low severity, the soil water repellency at 12 mo after burning was significantly weaker at 0, 3, and 6 cm than immediately after burning (Table 2). At three months after burning, the soil water repellency values were intermediate, indicating a progressive weakening of soil water repellency over time.

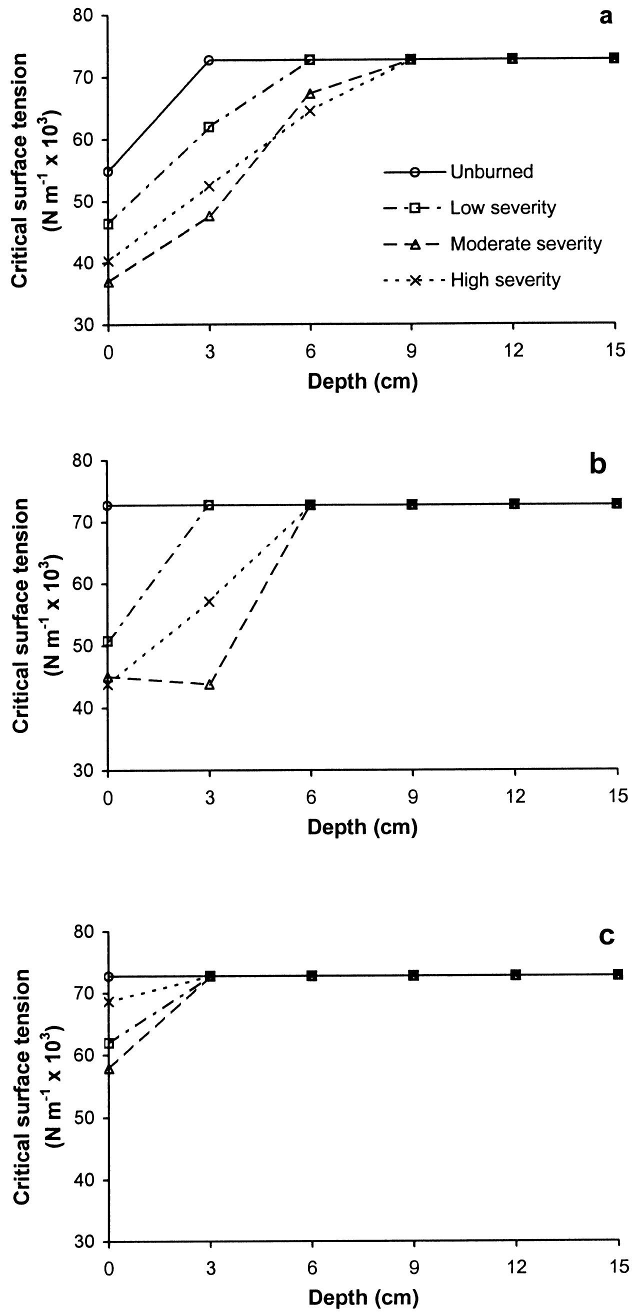

Fig. 1. Median critical surface tension (CST) values for unburned sites and sites burned at high, moderate, and low severity: (a) immediately after burning, (b) three months after burning, and (c) 12 mo after burning. Each symbol represents the median of 12 site values for each burn severity class and nine site values for unburned sites.

Soil Moisture Thresholds

Scatterplots of the CST data from 0 and 3 cm generally show an absence of soil water repellency beyond a certain soil moisture threshold. The apparent threshold is approximately 10% for unburned sites (Fig. 2d), 13% for low severity sites (Fig. 2c), and 28% for moderate severity sites (Fig. 2b). Some sites burned at high sever-

Table 1. Mean critical surface tension (CST) values in N m^{-1} × 10^3 (dynes cm^{-1}) for each time since burning and burn severity class at the mineral soil surface and depths of 3 and 6 cm.

Time since burning	High severity	Moderate severity	Low severity	Unburned
mo				
		Mineral soil surface		
0	41.7 (6.1) b Y†	38.9 (2.6) b Y	47.8 (10.9) b X	59.2 (13.9) a X
3	47.3 (10.4) b Y	46.7 (11.4) b X, Y	52.9 (11.9) a,b X	62.4 (13.2) a X
12	62.6 (13.0) a X	54.8 (12.6) a X	57.8 (13.0) a X	65.2 (9.6) a X
		3 cm below the soil surface		
0	51.5 (11.5) a X	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	52.9 (15.2) a X	67.6 (11.3) a X	65.7 (13.4) a X
12	64.5 (9.0) a X	59.3 (13.9) a X	68.3 (8.2) a X	68.6 (9.7) a X
		6 cm below the soil surface		
0	63.1 (9.8) a X	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	65.0 (13.1) a X	70.6 (5.5) a X	72.7 (0) a X
12	71.4 (4.7) a X	68.0 (11.6) a X	72.7 (0) a X	72.7 (0) a X

† The horizontal comparisons are between burn severity classes for each time since burning, and these are designated by the letters a, b, and c. The vertical comparisons are between times since burning for each burn severity class, and these are designated by the letters X, Y, and Z. Values with the same letter are not significantly different at $p \leq 0.05$. Standard deviations are shown in parentheses.

ity were strongly water repellent at soil moisture contents of up to 26% (Fig. 2a), but the lack of CST data at higher soil moisture contents precludes the identification of a soil moisture threshold for sites burned at high severity. A comparison of Fig. 2a through 2d shows that the soil moisture threshold for the change from hydrophobic to hydrophilic conditions increases with increasing burn severity.

DISCUSSION

Persistence of Fire-Induced Soil Water Repellency

Previous comparisons of CST values from fires of different ages suggested that time since burning was not a significant control on soil water repellency (Huffman et al., 2001). However, successive CST measurements from the Bobcat fire show a significant decline in fire-induced soil water repellency over time. The apparent discrepancy between our earlier study and this work can be attributed to the additional variability associated with comparing data from fires with varying ages, soils, and site conditions. Repeated sampling of sites from a single fire provides a much more sensitive assessment of the persistence of fire-induced soil water repellency.

In the case of the Bobcat fire, time since burning was an increasingly important control on CST values with increasing burn severity, and was progressively less important with increasing depth. These trends have not been clearly documented in the literature, but they are not surprising. The decreasing effect of time since burning with decreasing burn severity is probably because areas burned at higher severities initially were more water repellent. Given the high spatial variability in soil water repellency in this and other studies (e.g., Robichaud, 2000; Dekker et al., 2001), changes over time are difficult to detect when sites are only weakly water repellent at the beginning of a study, and easier to detect when sites are initially more strongly water repellent and can exhibit larger changes over time. Similarly, time since burning tended to be less important with increasing depth because the initial soil water repellency decreased with increasing depth (Fig. 1; Table 1).

Table 2. Results of pairwise comparisons between the sampling times at 0, 3, and 12 mo after burning by burn severity class and depth.

Severity	Depth	CST differences ($p \leq 0.05$)†
	cm	
High	0	0 mo. = 3 mo. < 12 mo.
	3	0 mo. = 3 mo. < 12 mo.
	6	0 mo. < 3 mo. = 12 mo.
Moderate	0	0 mo. < 3 mo. = 12 mo.
	3	0 mo. = 3 mo. = 12 mo.
	6	0 mo. = 3 mo. = 12 mo.
Low	0	0 mo. < 12 mo.
	3	0 mo. < 12 mo.
	6	0 mo. < 12 mo.

†Critical surface tension.

The limited literature suggests considerable variability with respect to the persistence of post-fire soil water repellency. The persistence of 1 yr or less for most sites in the Bobcat fire is similar to the results of studies in Montana (DeByle, 1973) and Michigan (Reeder and Jurgensen, 1979), but much shorter than the 6-yr recovery period for severely burned lodgepole pine forests in Oregon (Dyrness, 1976). Data from our other sites in the northern Colorado Front Range suggest that the decline in soil water repellency following the Bobcat fire was relatively rapid. At the nearby Crosier Mountain fire, soil water repellency was still relatively strong at the soil surface 22 mo after burning (Huffman et al., 2001). Limited sampling in Summer 2002 indicated some soil water repellency more than 2 yr after the Lower Flowers and Dadd Bennett prescribed fires, and confirmed the absence of soil water repellency for most sites in the Bobcat Fire (S. Cochran, Colorado State University, personal communication, 2002).

The persistence of post-fire soil water repellency depends on the strength and extent of hydrophobic chemicals after burning, and the many physical and biological factors that affect the breakdown of these chemicals (DeBano, 1981; Doerr and Moody, 2004). The variation in these factors means that the persistence of fire-induced soil hydrophobicity is highly site-specific (Doerr et al., 2000), and the high spatial variability in the breakdown of soil water repellency may partially explain the high variability in our CST values at 3 and 12 mo after burning. In the case of the Bobcat fire, the rapid breakdown

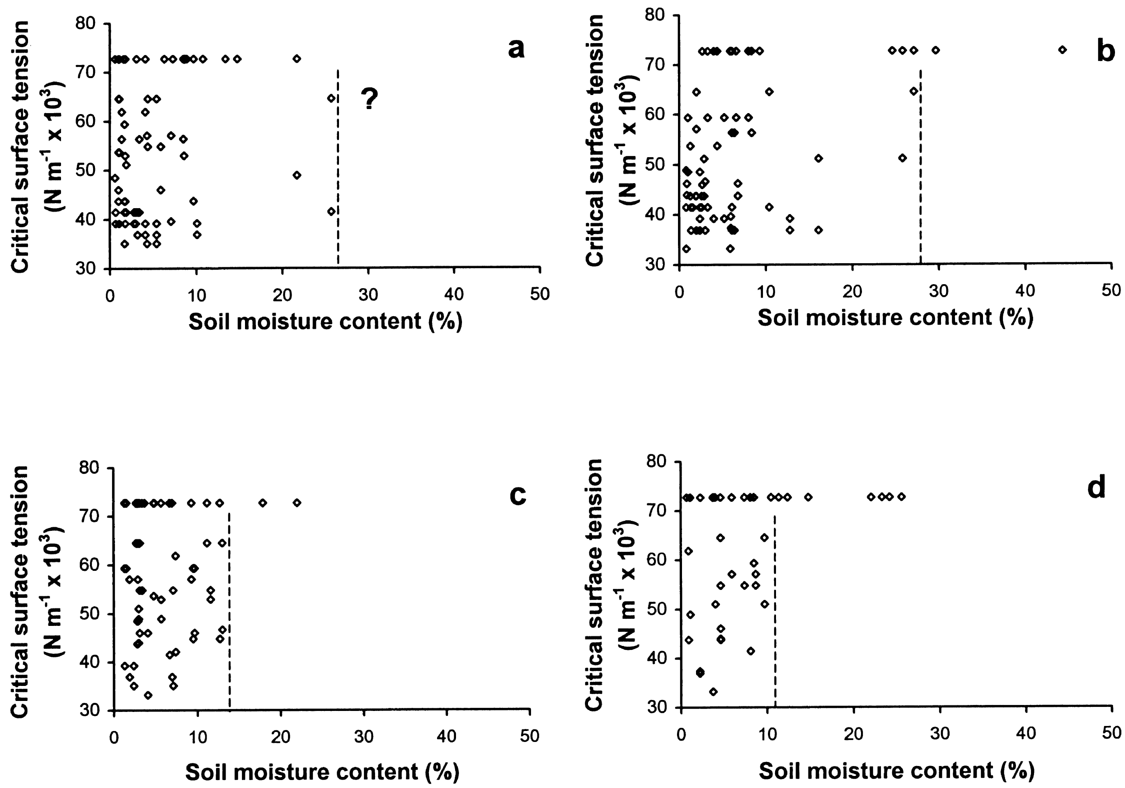

Fig. 2. Critical surface tension (CST) values at the soil surface and 3 cm versus surface soil moisture content for: (a) sites burned at high severity (n = 84); (b) sites burned at moderate severity (n = 82); (c) sites burned at low severity (n = 74); and (d) unburned sites (n = 54). Vertical dashed lines in (b) through (d) indicate the proposed soil moisture thresholds for the change from water repellent to hydrophilic. The question mark in (a) indicates that the soil moisture threshold for areas burned at high severity is at least 26% but is uncertain because of the lack of CST data at higher soil moisture values.

of soil water repellency may be due to both the lower fuel loadings and less soil heating due to the very rapid spread of this wildfire relative to nearby prescribed fires. The implication is that the results from the Bobcat fire may not be directly applied to other fires, either wild or prescribed, in the Colorado Front Range.

The high spatial variability indicates that extensive sampling is needed to adequately characterize post-fire soil water repellency. The high spatial variability also implies that infiltration and runoff generation will be very patchy (Doerr and Moody, 2004).

Effect of Soil Moisture on Post-Fire Soil Water Repellency

The soil moisture threshold for the change from hydrophobic to hydrophilic conditions is increasingly well documented for unburned soils. Reported values for this threshold range from 2 to 5% for a dune sand (Dekker et al., 2001) to as much as 38% for clayey peat soils (Dekker and Ritsema, 1996).

In contrast, there are almost no data on the soil moisture threshold for burned areas, despite the common recognition that post-fire soil water repellency is eliminated after a soil wets up and reappears once the soil dries out. For example, Ferreira et al. (2000) observed much less water repellency and overland flow in the winter wet season from burned *Eucalyptus globulus* forests. The soil moisture thresholds suggested in Fig. 2 are consistent with the soil water repellency data at higher soil moisture contents from other fires in the Colorado Front Range (Huffman et al., 2001), and are consistent with the threshold of 28% for coarse-textured burned and unburned forest soils in Portugal (Doerr and Thomas, 2000).

The tendency for the soil moisture threshold to increase with increasing burn severity is consistent with the overall behavior of water repellent soils, but the precise physical mechanism is not clear. Stronger water repellency means an increasing contact angle, greater difficulty for water to flow as films or to fill smaller pores, and a resulting tendency for water to first fill the larger pores during the wetting phase (Bauters et al., 2000). As water repellency increases soil particles should have more and possibly thicker hydrophobic surfaces, and more pores will be resistant to filling. It follows that a more strongly water repellent soil will have to be wetter before water repellency is eliminated. We were not able to identify a soil moisture threshold for the sites burned at high severity, as none of these sites had more than 26% soil moisture. In contrast, six sites burned at moderate severity had at least 27% soil moisture, and these data allowed us to identify a soil moisture threshold of approximately 28% for sites burned at moderate severity.

Further testing of recently burned sites is needed to identify a threshold or transition zone for sites burned at high severity, confirm the soil moisture thresholds for sites burned at moderate and low severity, and evaluate the possible variation in these thresholds with both soil texture and the strength of soil water repellency under dry conditions. From a practical point of view, the identification of soil moisture thresholds for the loss of water repellency can lead to a more accurate assessment of post-fire flooding and erosion risks under different antecedent conditions.

CONCLUSIONS

Fire-induced soil water repellency was strongest at the soil surface in areas burned at high and moderate severity, and declined in strength with decreasing burn severity and increasing depth. There was an apparent weakening of this water repellency within three months. By 12 mo after burning there were no statistically significant differences in soil water repellency between burned and unburned areas for any depth or between burn severity classes. Time since burning was a significant control on the strength of soil water repellency at the soil surface for all three burn severity classes. Time since burning was progressively less important with increasing depth and decreasing burn severity. The breakdown of the fire-induced, water-repellent layer in the Bobcat fire appears to be faster than for some other wild and prescribed fires in the northern Colorado Front Range, and this may be partly due to a low fuel loading before burning and less soil heating due to the high speed of the Bobcat fire.

The soil water repellency observed in the study area is eliminated at higher soil moisture contents. The soil moisture threshold for the shift from hydrophobic to hydrophilic is approximately 10% for unburned sites, 13% for sites burned at low severity, and 28% for sites burned at moderate severity. The apparent increase in this threshold with increasing burn severity has not been documented previously, but is consistent with our understanding of how increased soil water repellency is likely to inhibit infiltration and soil wetting. Successive testing within individual fires is needed to confirm the rate at which soil water repellency declines after burning, and the variation in soil moisture thresholds with burn severity, soil texture, and the initial strength of soil water repellency.

ACKNOWLEDGMENTS

We are grateful to Carl Chambers of the Arapaho-Roosevelt National Forest for providing financial and logistical support for this project through Agreement No. 00-CS-11021000-038. We thank Phil Chapman, John Stednick, Greg Butters, Gene Kelly, Esmaeil Khazaei, David Chandler, and two anonymous reviewers for their respective contributions to this project and paper.

REFERENCES

Bauters, T.W.J., T.S. Steenhuis, D.A. DiCarlo, J.L. Nieber, L.W. Dekker, C.J. Ritsema, J.-Y. Parlange, and R. Haverkamp. 2000. Physics of water repellent soils. J. Hydrol. (Amsterdam) 231/232:195–206.

DeBano, L.F. 1981. Water repellent soils: A state-of-the-art. USDA Forest Service Gen. Tech. Rep. PSW-46. Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

DeBano, L.F. 2000a. Water repellency in soils: A historical overview. J. Hydrol. (Amsterdam) 231/232:4–32.

DeBano, L.F. 2000b. The role of fire and soil heating on water repellency in wildland environments. J. Hydrol. (Amsterdam) 231/232: 195–206.

DeByle, N.V. 1973. Broadcast burning of logging residues and the water repellency of soils. Northwest Sci. 47:77–87.

de Jonge, L.W., O.H. Jacobsen, and P. Moldrup. 1999. Soil water repellency: Effects of water content, temperature, and particle-size. Soil Sci. Soc. Am. J. 63:437–442.

Dekker, L.W., and C.J. Ritsema. 1996. Variation in water content and wetting patterns in Dutch water repellent peaty clay and clayey peat soils. Catena 28:89–105.

Dekker, L.W., S.H. Doerr, K. Oostindie, A.K. Ziogas, and C.J. Ritsema. 2001. Water repellency and critical water content in a dune sand. Soil Sci. Soc. Am. J. 65:1667–1674.

Doerr, S.H., and J.A. Moody. 2004. Hydrological effects of soil water repellency: On spatial and temporal uncertainties. Hydrological Processes 18:829–832.

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 2000. Soil water repellency: Its causes, characteristics and hydro-geomorphological significance. Earth-Sci. Rev. 51:33–65.

Doerr, S.H., and A.D. Thomas. 2000. The role of soil moisture in controlling water repellency: New evidence from forest soils in Portugal. J. Hydrol. (Amsterdam) 231–232:134–147.

Dyrness, C.T. 1976. Effect of wildfire on soil wettability in the high Cascades of Oregon. USDA Forest Service Res. Pap. PNW-202, USDA Forest Service, Corvallis, OR.

Ferreira, A.J.D., C.O.A. Coelho, R.P.D. Walsh, R.A. Shakesby, A. Ceballos, and S.H. Doerr. 2000. Hydrological implications of soil water-repellency in *Eucalyptus globulus* forests, north-central Portugal. J. Hydrol. (Amsterdam) 231–232:165–177.

Gabriel, K.R. 1978. A simple method of multiple comparisons of means. J. Am. Stat. Assoc. 73:724–729.

Gardner, W.H. 1986. Water content. p. 493–544. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Mongr. No. 9. ASA and SSSA, Madison, WI.

Graham, R.T. (ed.). 2003. Hayman fire case study. USDA Forest Service Gen. Tech. Rep. RMRS-GTR-114. USDA Forest Service, Fort Collins, CO.

Huffman, E.L., L.H. MacDonald, and J.D. Stednick. 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. Hydrol. Proc. 15:2877–2892.

Imeson, A.C., J.M. Verstraten, E.J. van Mulligan, and J. Sevink. 1992. The effects of fires and water repellency on infiltration and runoff under Mediterranean type forest. Catena 19:345–361.

Letey, J. 1969. Measurement of contact angle, water drop penetration time, and critical surface tension. p. 43–47. *In* L.F. DeBano and J. Letey (ed.) Proceedings of a symposium on water repellent soils. Univ. of California, Riverside.

Letey, J. 2001. Causes and consequences of fire-induced soil water repellency. Hydrol. Proc. 15:2867–2875.

Moody, J.A., and D.A. Martin, 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surf. Processes Landforms 26:1049–1070.

Morris, S.E., and T.A. Moses. 1987. Forest fire and the natural soil erosion regime in the Colorado Front Range. Ann. Assoc. Am. Geog. 77:245–254.

Reeder, C.J., and M.F. Jurgensen. 1979. Fire-induced water repellency in forest soils of upper Michigan. Can. J. For. Res. 9:369–373.

Robichaud, P.R. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. J. Hydrol. (Amsterdam) 231–232:220–229.

Robichaud, P.R., J.L. Beyers, and D.G. Neary. 2000. Evaluating the effectiveness of postfire rehabilitation treatments. USDA Forest Service Gen. Tech. Rep. RMRS-GTR-63. USDA Forest Service, Fort Collins, CO.

Shakesby, R.A., S.H. Doerr, and R.P.D. Walsh. 2000. The erosional impact of soil hydrophobicity: Current problems and future research directions. J. Hydrol. (Amsterdam) 231–232:178–191.

USDA Forest Service. 1995. Burned-area emergency rehabilitation handbook. Chapter 20, Forest Service Handbook 2509.13-95-6. USDA, Washington, DC.

USDA Forest Service. 2000. Bobcat fire burn area emergency rehabilitation assessment. Arapaho and Roosevelt National Forests and Pawnee National Grassland. USDA, Fort Collins, CO.