USDA
United States Department of Agriculture
Forest Service
Rocky Mountain Research Station
Research Note RMRS-RN-33
March 2008

New Procedure for Sampling Infiltration to Assess Post-fire Soil Water Repellency

P. R. Robichaud, S. A. Lewis, and L. E. Ashmun

Abstract—The Mini-disk Infiltrometer has been adapted for use as a field test of post-fire infiltration and soil water repellency. Although the Water Drop Penetration Time (WDPT) test is the common field test for soil water repellency, the Mini-disk Infiltrometer (MDI) test takes less time, is less subjective, and provides a relative infiltration rate. For each test, the porous base plate of the MDI is placed on the soil surface and the amount of water that passes into the soil in one minute is measured.

Thousands of paired WDPT and MDI tests were applied at burned sites throughout the western United States, and the data were significantly correlated ($r = -0.64$). A classification tree analysis was used to group the MDI test results into "degree of soil water repellency" categories (strong, weak, and none) that correspond to similar categories established for the WDPT test. Fire-induced soil water repellency has high spatial variability and requires a valid sampling method if the data are to be credible. The MDI test protocol and sampling method described in this Research Note were developed for post-fire assessment, and provide a practical evaluation of burned soil infiltration characteristics in a limited time.

Introduction

After forest fires, the potential for flooding and erosion dramatically increases, partially due to decreased infiltration across the burned landscape (Pierson and others 2001, Robichaud 2000). Combustion of the surface organic material (litter and duff) can create water repellent layers within the mineral soil. When organic material burns, some of the volatilized material with hydrophobic properties moves downward into the soil profile and condenses on cooler soil particles beneath the surface (DeBano 1981). The coated soil particles form a non-continuous water repellent layer that is generally parallel to and within 5 cm of the mineral soil surface (Clothier and others 2000, DeBano 2000). On naturally water repellent soils, fire may destroy existing surface soil water repellency and create a stronger water repellent layer beneath the surface. Water repellent soils have decreased infiltration and increased runoff and erosion as compared to non-water repellent soils (Benavides-Solorio and MacDonald 2001). The combustion of surface organic material reduces the absorption and water storage capacity ("sponge" effect) above the mineral soil, which also contributes to post-fire decreases in water infiltration rates.

Robichaud, P. R.; Lewis, S. A.; Ashmun, L. E. 2008. New procedure for sampling infiltration to assess post-fire soil water repellency. Res. Note. RMRS-RN-33. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 14 p.

Soil water repellency, whether naturally occurring or fire-induced, is not a stable phenomenon. When the soil is wet after snow melt, hydrologic behavior is normal; however, when the soil dries, water repellent conditions reoccur (Dekker and Ritsema 2000). Consequently, soil water repellency is generally strongest in the drier summer months. Over time, as the soil is intermittently exposed to moisture, fire-induced soil water repellency slowly declines (DeBano 1981, Letey 2001). The persistence of fire-induced soil water repellency depends on many physical and biological factors that affect the breakdown of the hydrophobic chemicals that coat the soil particles, and as a result, is highly site-specific (Doerr and others 2000). The time needed for fire-induced soil water repellency to dissipate has been reported to be less than 1 year after the Bobcat Fire in Colorado (Huffman and others 2001) and as long as 6 years after a severe wildfire in a lodgepole pine forest in Oregon (Dyrness 1976).

Estimating the reduced infiltration after a fire is essential for modeling post-fire hydrologic processes (Pierson and others 2001, Robichaud 2000). Because water repellent soils have a large impact on the soil infiltration characteristics, post-fire assessment of the extent and degree of fire-induced soil water repellency is used to estimate the reduction in infiltration (Robichaud and others 2000). This assessment is usually done within days after the wildfire is contained.

Of the two current field methods for assessing water repellent soil—the Molarity Ethanol Drop (MED) test

(King 1981) and the Water Drop Penetration Time (WDPT) test (DeBano 1981)—the WDPT is the most commonly used for post-fire assessment. In the WDPT test, water drops are placed on an exposed surface of the mineral soil and the time to infiltrate into the soil is observed (fig. 1). The time to infiltrate is often averaged over a number of drops and the mean is used to determine the degree of soil water repellency at the sample location and depth. The two extreme conditions of soil water repellency are easily evaluated—when soil is strongly water repellent water drops "bead up" and sit on the soil surface for the total observation time (300 seconds), and when soil has no water repellency water drops infiltrate within 5 seconds. However, in situations where water drops sit on the soil surface for a portion of the observation time and then slowly collapse and infiltrate the soil, more subjectivity is introduced. As water drops collapse on the soil surface, the observer must judge when infiltration has occurred. Given that water drops differ in size, may trap air within them, and tend to roll around soil particles and down slopes, determining the time to infiltration can be subjective and imprecise. In addition, some researchers feel that the time needed for a water drop to infiltrate measures the *stability* of soil water repellency rather than the *degree* of soil water repellency (Dekker and Ritsema 1994, Letey 2001).

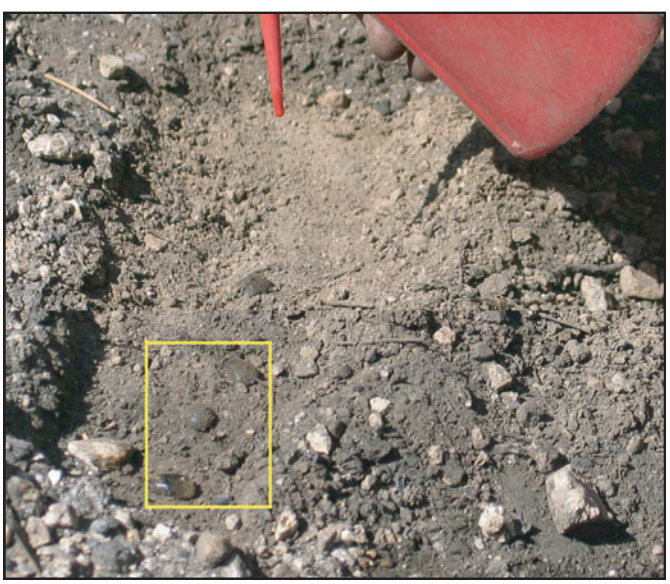

Figure 1—The water drop penetration time (WDPT) test performed at 1 cm below the surface of the soil. The water drops inside the rectangle are beaded up on the surface while drops outside of the rectangle have infiltrated the soil.

The Mini-disk Infiltrometer

The Mini-disk Infiltrometer (MDI) (Decagon Devices, Inc., Pullman, WA) is a hand-held field instrument for rapidly assessing soil infiltration capacity (fig. 2). When the infiltrometer is placed on a wettable soil surface, the suction from the soil side of the porous disk is able to break the water surface tension across the disk and water passes from the infiltrometer into the soil. As water passes through the porous disk into the soil, bubbles rise in the main chamber and in the bubble chamber. When the MDI is placed on strongly water repellent soil, there is not enough suction to break the water surface tension across the porous disk and no water infiltrates the soil. The suction on the infiltrometer side of the disk is controlled by the "suction control tube" (0.5 to 7 cm) at the top of the infiltrometer. During field testing, we determined that 1 cm is the optimal suction setting for post-fire soil infiltration and water repellency field tests.

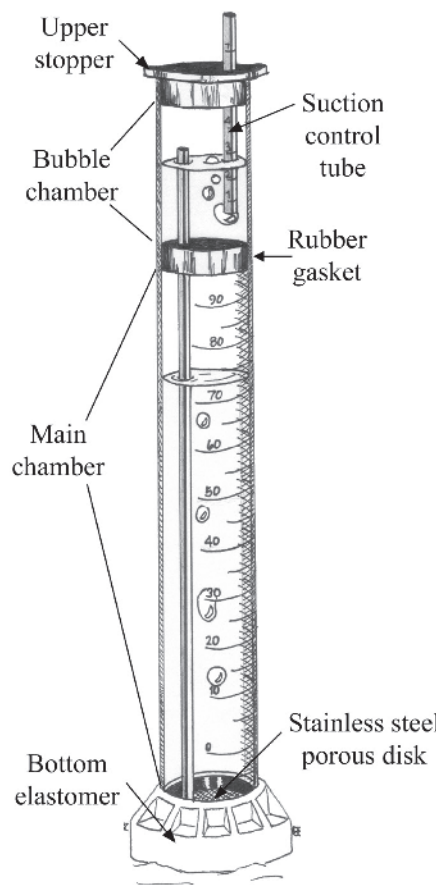

Figure 2—Diagram of the Mini-disk Infiltrometer (from Decagon Devices, Inc., Pullman, WA) with parts labeled.

The 1 cm setting provides enough suction to keep the MDI from dripping when held off the soil, but still allows the MDI to differentiate soils with strong, weak, and no water repellency.

The MDI test measures the volume of water (mL) that passes from the infiltrometer into the soil in 1 minute. The 1-minute interval was arbitrarily chosen and has proven to be long enough to detect water repellent soil conditions, yet fast enough to be a useful assessment procedure for post-fire assessment teams. The MDI test provides a relative infiltration rate, which can be used to classify soil water repellency as well as to compare the infiltration capacities of tested sites.

Comparing the Mini-disk Infiltrometer Test to the Water Drop Penetration Time Test

For several years, we made paired WDPT and MDI test measurements to evaluate the use of the MDI. Paired measurements (n = 2069) from eight wildfires in four states (CA, CO, ID, and MT) were analyzed using the non-parametric Spearman rank correlation analysis (SAS Institute Inc. 1999a). The tests were performed at recently burned sites that varied in soil burn severity. The mean of eight WDPT and of three MDI measurements from each sample location were correlated. The correlation of MDI to WDPT ($r = –0.64$) was significant ($p < 0.0001$) for all data (table 1).

An in-depth study of the MDI was implemented at the James Creek site following the 2003 Hot Creek Fire (Boise National Forest) in Idaho. Soil water repellency characterization was done adjacent to research plots that were established to study post-wildfire infiltration, erosion, and recovery. Twenty-nine high burn severity plot sites were tested in August 2004 using the MDI and WDPT tests at six depths (0, 1, 2, 3, 4, and 5 cm). The James Creek study provided data used to correlate the WDPT and MDI tests (table 1) and to derive MDI test values that could be used to classify "degree of soil water repellency" that correspond to the established WDPT test classifications.

The correlations between the WDPT and MDI tests were highest where soil water repellency existed (table 2). The Spearman correlation coefficients were

Table 1—Spearman correlation coefficients (r) for soil water repellency measurements made using the WDPT and MDI tests. All values are significant with p < 0.0001.

Fire name	Year	Sample size (n)	WDPT—MDI Correlation coefficient (r)
Hayman	2002	182	–0.68
Black Mountain	2003	170	–0.67
Cooney Ridge	2003	383	–0.59
Roberts	2003	410	–0.57
Simi	2003	358	–0.66
Old	2003	289	–0.60
Wedge	2003	103	–0.40
James Creek	2003[a]	174	–0.83
All data		2069	–0.64

[a]James Creek measurements were taken in 2004, 1 yr after the fire.

Table 2—Spearman correlation coefficients (r) for the WDPT–MDI tests done at 29 James Creek burned plots (n = 174) and sorted by depth. Values in bold type are significant at the p < 0.05 level.

	WDPT–MDI Correlation coefficient (r)
All data	**–0.83**
by depth	
0 cm	–0.24
1 cm	**–0.68**
2 cm	**–0.79**
3 cm	**–0.74**
4 cm	**–0.78**
5 cm	**–0.70**

significant at the $p < 0.05$ level for all depths below the surface and for all depths combined ($r = -0.83$). However, the surface measurements generally indicated non-water repellent soil (typical of recently burned soil) and the Spearman correlation coefficient for the surface measurements (–0.24) was not significant (table 2).

Data from post-fire WDPT field tests are most commonly used to classify soil into water repellency classes. The classes are arbitrarily assigned and vary between countries and agencies. In the United States, most post-fire researchers categorize WDPT results using the four water repellency classes developed by DeBano (1981); however, Burned Area Emergency Response (BAER) teams use a different classification system (fig. 3). To facilitate classification of soil water repellency using MDI data, class breakpoints in MDI values were determined using classification tree analysis of the James Creek data. This analysis did not find a break point in the MDI test values that would indicate moderate soil water repellency. Thus, two classes—strong (0 to <3 mL min^{-1}) and weak (3 to <8 mL min^{-1})—of soil water repellency were identified. MDI test values of 8 mL min^{-1} or more indicate no water repellency. A similar set of MDI values were determined by the BAER soil science team on the 2006 Derby Fire in the Bitterroot National Forest of Montana. The post-fire MDI field measurements ranged from 1 to 2 mL min^{-1} on the strongly water repellent soils and 7 to 11 mL min^{-1} on the soils with no water repellency (Sirucek and others 2006).

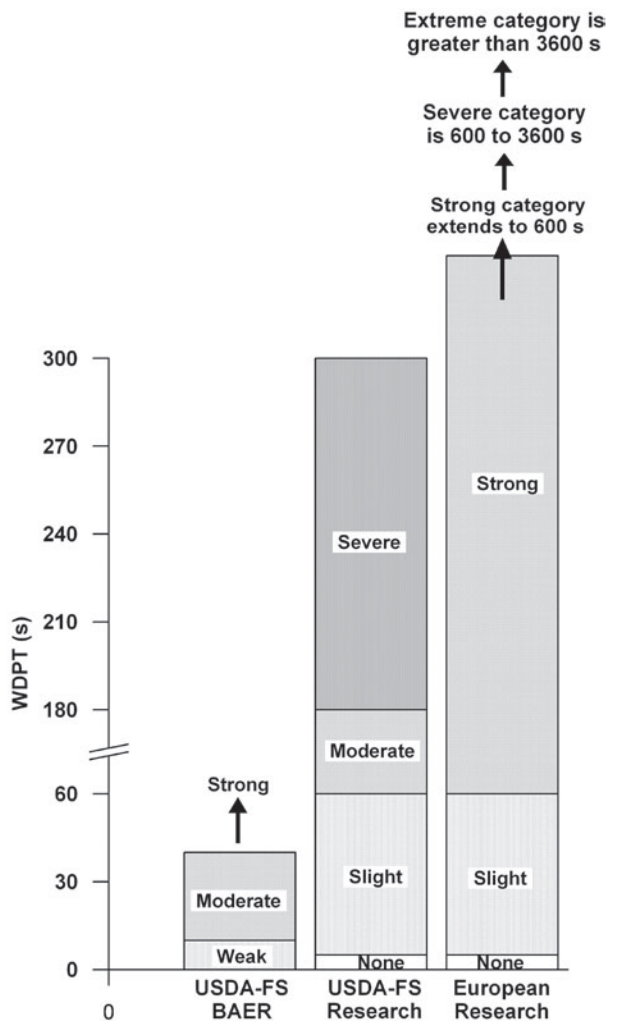

Figure 3—Soil water repellency classifications based on water drop penetration time (WDPT) as used by USDA-FS BAER (USDA Forest Service 1995), USDA-FS researchers (DeBano 1983), and European researchers (Doerr and others 2006).

The relative infiltration rates measured by the MDI test provide more information than the WDPT about the infiltration capacity of low and non-water repellent soils. For example, 51 test locations within the James Creek data set were classified "non-water repellent" by both the WDPT and MDI test values. The range of values was 0 to 4 seconds for the WDPT test and 8 to 25 mL min^{-1} for the MDI test. Thus, some non-water repellent locations had three times greater infiltration rates than others. This difference in infiltration capacity cannot be detected using the WDPT test. Relative infiltration rates may be useful for predicting the watershed response to future rain events.

In our research, fire-induced soil water repellency has most often been detected at 1 to 3 cm below the surface. In burned areas, surface measurements (immediately below the ash layer where soil and ash mix) often indicate non-water repellent soil, making sub-surface testing necessary to determine the existence and extent of a fire-induced water repellent soil layer. The data from James Creek is typical of forested areas burned at high severity—no detectable soil water repellency at the surface with a strongly water repellent soil layer at 1 to 2 cm below the surface (fig. 4).

In general, if fire-induced water repellency is prevalent at 1 to 3 cm below surface and there is little or no cover on the soil, the risk for post-fire erosion is high. During a rain event, the thin, wettable soil layer on the surface quickly becomes saturated. The water, which is hindered by the sub-surface water repellent soil layer, can not infiltrate deeper into the soil and becomes excess overland flow that easily entrains and carries the saturated soil downslope (Doerr and others 2006).

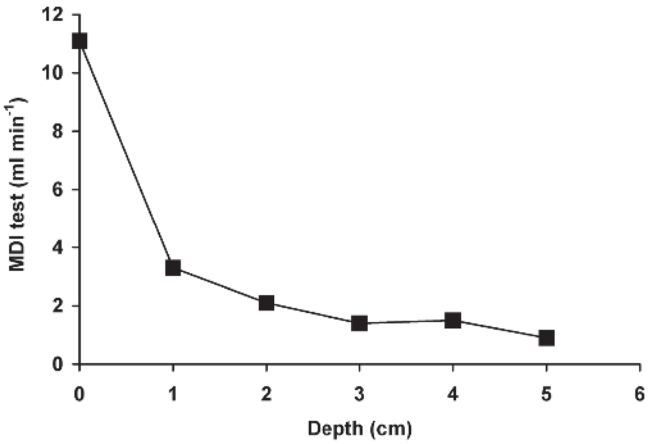

Figure 4—Mean Mini-disk Infiltrometer (MDI) test values at the surface and at five depths (1 to 5 cm) below the surface for burned sites.

The MDI Test for Fire-induced Soil Water Repellency and Infiltration___

Field Test Materials (fig. 5)

- Mini-disk Infiltrometer
- 1 L (or larger) water bottle to refill the infiltrometer as needed
- small trowel
- stopwatch
- small ruler to measure soil depth (or a ruled trowel blade)
- recording sheets (appendix A)
- plastic wash bottle to rinse the porous disk after each test

Test Steps

1. Use the trowel to cut to the soil depth being tested and lift off the overlying ash, surface organic material, and mineral soil to expose the soil at 1 or 3 cm depth.
2. Fill the infiltrometer (fig. 2)
    a. Remove the upper stopper and fill the bubble (upper) chamber. Once it is full, replace the upper stopper and slide the suction control tube all the way down so that it rests on the rubber gasket between the two chambers.
    b. Invert the infiltrometer, remove the bottom elastomer with the porous disk, and fill the main (lower) chamber. Replace the bottom elastomer, ensuring the porous disk is firmly in place.
3. Turn the infiltrometer upright and adjust the suction to 1 cm by aligning the surface of the water in the bubble chamber with the 1 cm mark on the adjustable suction tube.
4. Hold the top of the infiltrometer so that the water surface in the main chamber is at eye level and record the start volume (mL).
5. Place the infiltrometer porous disk flat against the soil with the infiltrometer held perpendicular to the surface. Start the timer when the infiltrometer disk and soil come into contact. (On steep slopes [50 to 60 percent or more], you may observe water from inside the tube seeping from the side of the infiltration disk and running downslope along the soil surface and not infiltrating. If this happens, use the trowel to cut a level "shelf" as close as possible to the depth being tested within the mineral soil. Set the infiltrometer perpendicular to the cut surface rather than the hillslope.)
6. Continue to hold the infiltrometer against the soil surface so that the entire infiltration disk is in contact with the soil for an uninterrupted minute. The infiltrometer needs to be held against the soil, but it does not need to be pushed into the soil with any force.
7. At the end of 1 minute, remove the infiltrometer from the soil and hold the top of the tube so that the water is at eye level. Record the end volume.

Figure 5—Using the Mini-disk Infiltrometer in the field.

8. Record the amount of water that has infiltrated the soil during the 1-minute test.
9. Rinse the porous disk to remove any soil particles that cling to the disk.
10. Refill the infiltrometer as needed.
11. Repeat steps 4 through 10 for each test.

Sampling a Burned Area

Post-fire assessments of soil water repellency and reduced infiltration are needed within days after fire containment. This short time frame for sampling necessitates a sampling scheme that 1) focuses on areas where soil water repellency and reduced infiltration are most likely; 2) provides a logical method for extrapolation of sample results to burned areas that are not sampled; and 3) attaches a level of confidence to the measurements.

Fire-induced soil water repellency has high spatial variability and may vary at the 10-cm scale (Lewis and others 2006). MDI test measurements usually reflect this high spatial variability, and if the sample size is small, the results have low statistical power and may not accurately reflect the average soil water repellency of the area. The classification of the burned area based on variables related to soil water repellency that have spatial structure (in other words, are not random) can increase statistical power and at the same time reduce sample size (Klironomos and others 1999). Regardless of the sampling method used, it is recommended that a minimum of three MDI tests be done in close proximity (immediately adjacent to, but not on top of or beneath, a previous test) at each sample location to compensate for measurement variability.

The sampling method described in appendix B is applied to a burned area that has similar soil (e.g., granitic or volcanic) and pre-fire vegetation (e.g., forest or grass). If the post-fire assessment includes more than one general soil or vegetation type, a separate evaluation of infiltration and soil water repellency should be done in each area. To determine where to sample, the burned area is divided using two characteristics—burn severity and slope aspect. Slope aspect has been highly correlated to burn severity, and soil burn severity is the factor most highly correlated to post-fire soil water repellency (Lewis and others 2006). Areas burned at high severity often have strongly water repellent soils, while areas burned at low severity have weak or no fire-induced soil water repellency. Moderately burned areas are typically a mosaic of high and low soil burn severity areas and generally have soils with a mix of both strong and weak water repellency. Hillslopes with north aspects tend to be wetter and more densely vegetated, while slopes with south aspects are generally dryer and have less fuel. Fire reacts to these differences in slope, soil moisture, and vegetation, often spreading more quickly on a slope with a south aspect, but sometimes with less fire residence time and, therefore, less soil heating. Although the hillslopes in an area may all be designated as high or moderate burn severity, the soil water repellency may vary by slope aspect. In addition, because fire spread and duration also vary from the base to the top of a hillslope, soil water repellency may vary by hillslope position. For this reason, samples from both the upper and lower portion of the hillslope are needed.

With any sampling scheme, the goal is to estimate the true variability and mean of a specific trait within the whole population by measuring that trait in a subset of the population. If too few samples are measured, the results will have a low confidence level (a measure of the certainty that the sample data represents the entire population). However, there is always a trade off between confidence level and time and resources spent on the sampling process.

Adequacy of sample size is often evaluated in terms of *statistical power*—the probability that the true mean of the data is within a pre-determined precision (SAS Institute Inc. 1999b). When determining post-fire infiltration and soil water repellency using the MDI, statistical power is dependent on the inherent variability of the data and the selected *precision*—the pre-determined limit that the measured mean can vary from the true mean MDI test value. The *real* statistical power of any data set can only be calculated after-the-fact, when the true variability (standard deviation) can be calculated. However, we derived the inputs needed for a power analysis, including the standard deviation, from the portion of our existing post-fire MDI test data that could be classified by slope and aspect ($n > 1000$). We used these inputs to calculate a range of sample sizes with corresponding confidence levels. We then estimated sample sizes corresponding to 70, 80, 90, and 95 percent confidence levels and applied them to the sampling method presented in appendix B. Like most statistical analyses, the more measurements taken, the higher the confidence level assigned to the conclusions.

The short time available for post-fire assessment often restricts the number of samples that can be obtained and results may have less-than-desired confidence levels. Also, the results obtained from a relatively small sample within a category will, by necessity, be applied to other burned areas of the same category. Although these minimal sampling guidelines may not be adequate for science research purposes, they do provide practical guidance for making the most of the limited time available for post-fire assessment.

Management Implications

Soil water repellency and infiltration assessments are needed for post-fire emergency stabilization and rehabilitation planning. The Mini-disk Infiltrometer has been adapted for use as a field test of fire-induced soil water repellency. The MDI test is an effective technique to quickly assess the existence and degree of water repellent soil as well as the relative infiltration capacity. In addition to the development of a MDI test protocol, the MDI test values have been correlated to the current soil water repellency classifications based on the WDPT test. Thus, MDI results can be used for reporting the degree and extent of soil water repellency in customary terms.

The sampling method described in appendix B uses burn severity and slope aspect to classify the burned area into hillslopes that are likely to have similar soil water repellency and infiltration characteristics. This classification provides a way to systematically sample the burned area and have reasonable confidence that soil water repellency and infiltration assessments can be applied to non-sampled areas with similar characteristics. The sampling method provided in appendix B may challenge the time and resources available to many BAER teams; however, it does describe the minimum evaluation needed for various levels of statistical power and assessment confidence.

The Authors

Peter R. Robichaud is a Research Engineer and Sarah A. Lewis and Louise E. Ashmun are Civil Engineers with the Air, Water and Aquatic Environments Science Program of the Rocky Mountain Research Station located at the Forestry Sciences Laboratory in Moscow, Idaho.

References

Benavides-Solorio, J.D.; MacDonald, L.H. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrological Processes. 15(15): 2931-2952.

Clothier, B.E.; Vogeler, I.; Magesan, G.N. 2000. The breakdown of water repellency and solute transport through a hydrophobic soil. Journal of Hydrology. 231-232: 255-264.

DeBano, L.F. 1981. Water repellent soils: a state of art. Gen. Tech. Rpt. PSW-46. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 21 p.

DeBano, L.F. 2000. Fire-induced water repellency: an erosional factor in wildland environments. In: Proceedings of Land stewardship in the 21st century: the contributions of watershed management. Tucson, AZ, 13-16 March 2000. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 307-310.

Decagon Devices Inc. (2005). Infiltrometer Product Guide, [Online]. Available: http://www.decagon.com/infiltrometer/ [17 January 2007].

Dekker, L.W.; Ritsema, C.J. 1994. How water moves in a water repellent sandy soil. 1. Potential and actual water repellency. Water Resources Research. 30: 2507-2517.

Dekker, L.W.; Ritsema, C.J. 2000. Wetting patterns and moisture variability in water repellent Dutch soils. Journal of Hydrology. 231-232: 148-164.

Doerr, S.H.; Shakesby, R.A.; Walsh, R.P.D. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Review. 51: 33-65.

Doerr, S.H.; Shakesby, R.A.; Blake, W.H.; Chafer, C.J.; Humphreys, G.S.; Walbrink, P.J. 2006. Effects of differing wildfire severities on soil wettability and implications for hydrological response. Journal of Hydrology. 319: 295-311.

Dyrness, C.T. 1976. Effect of wildfire on soil wettability in the high Cascades of Oregon. Res. Pap. PNW-202. Corvallis OR: U.S. Department of Agriculature, Forest Service, Pacific Northwest Research Station. 19 p.

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

King, P.M. 1981.Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. Australian Journal of Soil Research. 19: 275-285.

Klironomos, J.N.; Rillig, M.C.; Allen, M.F. 1999. Designing belowground field experiments with the help of semi-variance and power analyses. Applied Soil Ecology. 12: 227-238.

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

Lewis, S.A.; Wu, J.Q.; Robichaud, P.R. 2006. Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. Hydrological Processes. 20: 1-16.

Pierson, F.B.; Robichaud, P.R.; Spaeth, K.E. 2001. Spatial and temporal effects of wildfire on the hydrology of a steep rangeland watershed. Hydrological Processes. 15: 2905-2916.

Robichaud, P.R. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. Journal of Hydrology. 231-232: 220-229.

Robichaud, P.R.; Beyers, J.L.; Neary, D.G. 2000. Evaluating the effectiveness of postfire rehabilitation treatments. Gen. Tech. Rep. RMRS-GTR-63. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 85 p.

SAS Institute Inc. 1999a. SAS/STAT User's Guide, Volume 1, Version 8.2. Cary, NC: Statistical Analysis Systems (SAS) Institute Inc.

SAS Institute, Inc. 1999b. The Analysts Application, First Edition. Cary, NC: Statistical Analysis Systems (SAS) Institute Inc. 476 pp.

Sirucek, D.; Rolfes, T; Rone, G. 2006. Soil Resource—Derby Mountain Fire, U.S. In: Department of Agriculture, Forest Service, Derby Mountain Fire—burned area report. (Derby Mountain Fire BAER 2500-8). Unpublished report on file at: U.S. Department of Agriculture, Forest Service, Gallatin National Forest, Bozeman, MT. 27 p.

U.S. Department of Agriculture, Forest Service. 1995. Water-Repellent Soils - Article 23.31. In: Burned-Area Emergency Rehabilitation Handbook, Section FSH 2509.13 of the Forest Service Handbook. Washington D.C.

Appendix A—Data Recording Sheet

Site:		**Soil Burn Severity:**	High	Moderate
		Slope Aspect:	North	South
Date:	**Sampler:**	**Slope Position:**	Upper	Lower

For each test, record the MDI water level at the start, place the MDI on the soil for 1 min, and record the MDI water level at the end. Subtract the two readings to obtain "**water infiltrating (mL)**"

0 m Transect meter mark

	Trial 1			**Trial 2**			**Trial 3**		
Depth (cm)	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**
1									
3									

10 m Transect meter mark

	Trial 1			**Trial 2**			**Trial 3**		
Depth (cm)	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**
1									
3									

30 m Transect meter mark

	Trial 1			**Trial 2**			**Trial 3**		
Depth (cm)	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**
1									
3									

60 m Transect meter mark

	Trial 1			**Trial 2**			**Trial 3**		
Depth (cm)	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**
1									
3									

100 m Transect meter mark

	Trial 1			**Trial 2**			**Trial 3**		
Depth (cm)	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**	Start reading (mL)	End reading (mL)	**Water infiltrating (mL)**
1									
3									

Appendix B—Sampling Method for Post-fire Assessment of Soil Water Repellency

Classification of the Burned Area

The burned area is divided into areas of similar characteristics based on the factors that correlate strongly with post-fire soil water repellency—burn severity and slope aspect. MDI tests are done along transects located on selected hillslopes (upper and lower slope positions) of each class or category (fig. B1). The results from the sampled hillslopes will be extrapolated and applied to other burned hillslopes of the same class (in other words, with the same burn severity and aspect). However, if the burned area covers more than one general soil type (for example, course granitic and fine ash cap) or vegetation type (for example, conifer forest and chaparral), a separate post-fire assessment of soil water repellency should be completed in each soil and vegetation type.

Soil Burn Severity—The initial Burned Area Reflectance Classification (BARC) map provides the first post-fire burn severity designations (unburned, low, moderate, or high). Because ground verification of this map is often done simultaneously with soil water repellency testing, it is necessary to first check the soil burn severity classification of each slope chosen for soil water repellency testing (Note: in the descriptions below, the canopy information is included as "confirmation" of the degree of fire effects on the hillslope).

- *High soil burn severity* will have extensive exposed charred (orange, gray, or black) mineral soil and ash with very little litter or other organic cover. Tree canopies are mostly burned and/or black.
- *Moderate soil burn severity* is characterized by a mix of charred soil, ash, and some remaining vegetation cover. There will often be charred or scorched needles remaining in the trees or on the ground as a post-fire litter cover.
- *Low soil burn severity* has little charred soil or ash, and usually has a majority of remaining litter cover. Tree canopies are mostly unscorched and green.

Areas of high and moderate soil burn severity should be tested for water repellency, but it is not essential to test low soil burn severity and unburned areas when under the time constraints of post-fire emergency assessment. Moderately burned areas are typically a mosaic of highly and lightly burned areas. Efforts should be made to place the sampling transects through a representative area that captures the average burn severity of the hillslope.

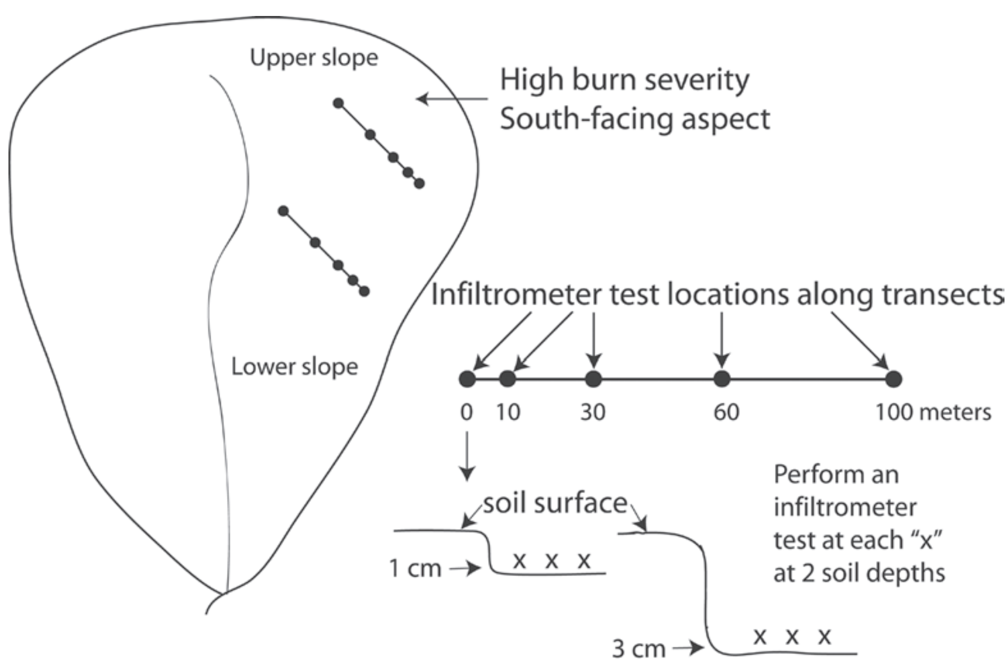

Figure B1—Diagram of the transect layout and Mini-disk Infiltrometer sampling points (note: diagram not to scale).

Slope Aspect—A simple dichotomous division of aspect into north (270 to 360 and 1 to 89 compass degrees) and south (90 to 269 compass degrees) is adequate for post-fire assessment of soil water repellency. Aspect is measured facing downhill in the direction water would run if poured on the slope. Both north and south aspects within areas burned at high and moderate severity need to be sampled.

Sampling Along Transects

After a forest fire, typical hillslopes of high and moderate soil burn severity with north and south aspects are selected for sampling. Two slope positions—upper slope and lower slope—are sampled. A 100-m transect is laid along the hillslope contour and MDI tests are performed at the 0, 10, 30, 60, and 100 meter marks (fig. B1). At each test location, three MDI tests are done at both 1 and 3 cm below the mineral soil surface. (Testing below the 3-cm depth may be necessary if unusually high soil heating is suspected, such as under slash piles, blowdown, or other large accumulations of materials.)

Determining the Number of Transects or Sample Size

Power analysis was performed to estimate the number of sample transects needed to confidently draw conclusions about post-fire soil water repellency and infiltration. A statistical power of 80 percent and a precision of 2 mL min^{-1} (±1 mL min^{-1}) were used as inputs in the power analysis. This means that the power analysis was completed with the assumption that "an 80 percent probability that the true mean is within ±1 mL min^{-1} of the sampled mean" would be adequate power for the post-fire assessment of soil water repellency.

The results of the power analysis provide a range of sample size prescriptions correlated to an *alpha*, which is a measure of the certainty that the sample data represents the value of the entire population (in our case, all the burned hillslopes of the class). The alpha represents the risk of being wrong, and its counterpart, *confidence level* ([1-α] ×100 percent) is the probability of being correct. Table B1 presents the prescribed sample sizes for confidence levels of approximately 70 percent ($\alpha = 0.3$), 80 percent ($\alpha = 0.2$), 90 percent ($\alpha = 0.1$), and 95 percent ($\alpha = 0.05$). The number of samples needed based on the power analysis is listed in the second column of table B1; however, the prescribed number of transects is rounded to the nearest multiple of 10, or a full transect amount of samples. At the 70 percent confidence level, the sample size (23) is rounded *down* to 20 to fit two full transects, which will have a confidence level that is slightly less than 70 percent. At 80, 90, and 95 percent confidence levels, the sample size is rounded *up* to fit the transect sampling method, which increases the confidence levels as compared to the values listed in the first column of table B1. As a check on this methodology, we used a stratified random sampling of our data to test the ability of 20 samples from a class to approximate the class mean from the full data set and calculated an average difference of 6 percent.

Selecting a confidence level is a balance between not wanting to incorrectly assess the soil water repellency or reduced infiltration (especially as results are likely to be applied to other similar, but not sampled hillslopes) and the time and expense of post-fire MDI testing. In most post-fire assessments, setting the confidence level will not be the criterion for sample size selection, rather time and availability of human resources will dictate the maximum amount of sampling that can occur. The time needed for MDI testing has been estimated for four sampling prescriptions (table B2). Based on our experience using the MDI, a person can complete the six tests (three tests at two depths) at a sampling point in

Table B1—Sample size prescriptions based on power analysis. The selected inputs for this analysis were a) 80 percent power and b) ± 1 mL min^{-1} precision. The other input, a standard deviation of 4 mL min^{-1}, was calculated from over 1000 postfire measurements (Note: 2 depths × 5 locations = 10 samples per transect).

Power analysis		Sampling prescription		
Confidence level (%) [α]	Samples per class	Transects per class	Samples per class	Approximate confidence level (%)
70 [α = 0.3]	23	2	20	<70
80 [α = 0.2]	34	4	40	>80
90 [α = 0.1]	53	6	60	>90
95 [α = 0.05]	73	8	80	>95

Table B2—The number of person-days, samples, and transects needed to estimate post-fire soil water repellency and reduced infiltration at four confidence levels—70, 80, 90, and 95 percent. The four classes are indicated as HS = High burn severity-South aspect; HN = High burn severity-North aspect; MS = Moderate burn severity-South aspect; MN = Moderate burn severity-North aspect.

	1 person-day	2 person-day	3 person-day	4 person-day
Number of samples – transects	80–8	160–16	240–24	320–32
Number of transects/class	2/HS, 2/HN, 2/MS, 2/MN	4/HS, 4/HN 4/MS, 4/MN	6/HS, 6/HN 6/MS, 6/MN	8/HS, 8/HN 8/MS, 8/MN
Number of hillslopes (sites)	4	8	12	16
Confidence level	70%	80%	90%	95%
Description	A	B	C	D

A. one person would spend one day:
 2 transects (upper/lower) at 4 sites (hillslopes) = 2 transects per class

B. one person would spend two days or two people would spend one day:
 2 transects (upper/lower) at 8 sites (hillslopes) = 4 transects per class

C. one, two, or three people sample to total 3 person-days:
 2 transects (upper/lower) at 12 sites (hillslopes) = 6 transects per class

D. one to four people sample to total 4 person-days:
 2 transects (upper/lower) at 16 sites (hillslopes) = 8 transects per class

under 15 minutes and, with five sampling points along a transect, the time needed for one transect is less than 1¼ hours. Given two transects per hillslope, it would likely take one person about 2½ hours to sample a hillslope site.

Interpreting Results

At each transect test location (0, 10, 30, 60, and 100 m), six individual MDI tests (three tests at each of two depths) are performed (fig. B1). The mean of the three individual MDI readings is the MDI value at that sample location and depth. The MDI value determines the degree of soil water repellency (Strong, Weak, or None) at each sample location, and for each hillslope, the proportion of MDI values (percent) that indicate Strong, Weak, and No soil water repellency are calculated. These percentages are used to describe the degree and extent of soil water repellency on the assessed hillslope.

Example

Table B3 presents a spreadsheet format and analysis for a soil water repellency sample data set that could have been collected in 1 day by a single person (this spreadsheet is available for downloading at http://forest.moscowfsl.wsu.edu/BAERTOOLS). Based on these sample data, a post-fire assessment team would assume that soil water repellency in the burned area is distributed as follows:

- Moderate soil burn severity, North aspect: Strong-35 percent; Weak-40 percent; None-5 percent
- Moderate soil burn severity, South aspect: Strong-75 percent; Weak-20 percent; None-5 percent
- High soil burn severity, North aspect: Strong-75 percent; Weak-15 percent; None-10 percent
- High soil burn severity, South aspect: Strong-90 percent; Weak-10 percent; None-0 percent

Because only two transects on a single hillslope in each sampling class were assessed (table B1), these results have a fairly low confidence level (slightly less than 70 percent). Additional sampling within a class would improve the statistical confidence level for that class. In this example, the BAER team may decide that additional sampling should be done on moderate soil burn severity hillslopes to increase confidence that the post-fire soil water repellency and infiltration differences between north and south aspect slopes is valid.

The soil water repellency data is specific to a class of soil burn severity and slope aspect (M/N; M/S; H/N; or H/S as described in table B2), and the assessment from the sampled slopes is applied to the unsampled slopes of the same soil burn severity and aspect. This can be useful in prioritizing areas for post-fire stabilization treatments. In the example (table B3), stabilization treatments may not be needed on moderate soil burn severity-north aspect slopes (only 35 percent Strong soil water repellency), especially if fallen needle cover (needle cast) may provide substantial natural protection from erosion. However, stabilization treatments may be necessary on the moderate soil burn severity-south aspect slopes (75 percent Strong soil water repellency) and the high soil burn severity slopes (75 and 90 percent Strong soil water repellency) in areas where downstream values are at risk from increased flooding and sedimentation.

Table B3. Example spreadsheet of MDI test data analysis. In the column headers, ID = site identification code; TM = transect mark (0, 10, 30, 60, or 100); ml = mL min^{-1}; and SBS = soil burn severity.

Site (ID/TM)	Soil Burn Severity	Slope Aspect	Slope Position	Depth (cm)	Test 1 Volume (ml)	Test 2 Volume (ml)	Test 3 Volume (ml)	Mean (ml)	Water Repellency Strong 0<3	Water Repellency Weak 3 to <8	Water Repellency None ≥8	Site SBS/aspect mean (ml)
M1/0	M	N	U	1	48.0	7.0	0.0	18.3			+	
M1/0	M	N	U	3	14.0	8.0	1.0	7.7		+		
M1/10	M	N	U	1	18.0	13.0	3.5	11.5			+	
M1/10	M	N	U	3	8.0	0.5	1.0	3.2		+		
M1/30	M	N	U	1	32.0	0.0	1.5	11.2			+	
M1/30	M	N	U	3	0.0	1.5	2.5	1.3	+			
M1/60	M	N	U	1	2.5	0.0	1.0	1.2	+			
M1/60	M	N	U	3	4.0	0.5	31.5	12.0			+	
M1/100	M	N	U	1	5.0	12.0	1.0	6.0		+		
M1/100	M	N	U	3	5.5	2.5	1.5	3.2		+		
M2/0	M	N	L	1	3.0	1.5	1.0	1.8	+			
M2/0	M	N	L	3	0.0	7.0	2.5	3.2		+		
M2/10	M	N	L	1	0.0	1.0	1.0	0.7	+			
M2/10	M	N	L	3	0.5	2.5	10.0	4.3		+		
M2/30	M	N	L	1	19.0	0.5	2.5	7.3		+		
M2/30	M	N	L	3	0.0	1.3	0.0	0.4	+			
M2/60	M	N	L	1	6.0	1.0	0.0	2.3	+			
M2/60	M	N	L	3	0.0	1.0	1.5	0.8	+			
M2/100	M	N	L	1	31.0	1.5	1.0	11.2			+	**M/N**
M2/100	M	N	L	3	13.0	6.0	0.5	6.5		+		**5.7**
					Number of samples in the water repellency group				**7**	**8**	**5**	
					Percentage of samples in the water repellency group				**35%**	**40%**	**25%**	
M3/0	M	S	U	1	42.5	8.0	0.0	16.8			+	
M3/0	M	S	U	3	6.0	2.5	3.0	3.8		+		
M3/10	M	S	U	1	16.0	0.0	7.0	7.7		+		
M3/10	M	S	U	3	7.0	0.0	1.0	2.7	+			
M3/30	M	S	U	1	5.0	0.0	0.5	1.8	+			
M3/30	M	S	U	3	6.0	2.0	0.0	2.7	+			
M3/60	M	S	U	1	3.0	0.0	0.0	1.0	+			
M3/60	M	S	U	3	0.0	0.0	4.0	1.3	+			
M3/100	M	S	U	1	0.5	0.0	0.0	0.2	+			
M3/100	M	S	U	3	0.0	2.0	0.0	0.7	+			
M4/0	M	S	L	1	9.0	0.5	0.0	3.2		+		
M4/0	M	S	L	3	10.0	1.0	7.0	6.0		+		
M4/10	M	S	L	1	0.0	0.0	0.0	0.0	+			
M4/10	M	S	L	3	0.0	5.0	0.0	1.7	+			
M4/30	M	S	L	1	0.5	1.0	4.0	1.8	+			
M4/30	M	S	L	3	0.0	0.5	0.0	0.2	+			
M4/60	M	S	L	1	2.0	0.0	0.0	0.7	+			
M4/60	M	S	L	3	0.0	0.0	4.0	1.3	+			
M4/100	M	S	L	1	0.0	0.0	0.0	0.0	+			**M/S**
M4/100	M	S	L	3	0.5	0.0	0.0	0.2	+			**2.7**
					Number of samples in the water repellency group				**15**	**4**	**1**	
					Percentage of samples in the water repellency group				**75%**	**20%**	**5%**	

Table B3 continued—Example spreadsheet of MDI test data analysis. In the column headers, ID = site identification code; TM = transect mark (0, 10, 30, 60, or 100); ml = mL min^{-1}; and SBS = soil burn severity.

Site	Soil Burn	Slope			Test 1	Test 2	Test 3		Water Repellency Strong	Water Repellency Weak	Water Repellency None	Site SBS/aspect
(ID/TM)	Severity	Aspect	Position	Depth (cm)	Volume (ml)	Volume (ml)	Volume (ml)	Mean (ml)	$0<3$	3 to 8	≥ 8	mean (ml)
H1/0	H	N	U	1	0.0	0.0	0.0	0.0	+			
H1/0	H	N	U	3	0.5	0.0	1.5	0.7	+			
H1/10	H	N	U	1	20.0	0.5	0.5	7.0		+		
H1/10	H	N	U	3	1.0	1.0	1.0	1.0	+			
H1/30	H	N	U	1	6.0	5.0	2.0	4.3		+		
H1/30	H	N	U	3	1.0	28.8	1.0	10.3			+	
H1/60	H	N	U	1	1.0	0.0	0.0	0.3	+			
H1/60	H	N	U	3	0.5	0.5	1.0	0.7	+			
H1/100	H	N	U	1	7.0	0.0	16.0	7.7		+		
H1/100	H	N	U	3	1.0	0.0	7.0	2.7	+			
H2/0	H	N	L	1	43.0	1.0	1.0	15.0			+	
H2/0	H	N	L	3	0.0	2.0	3.0	1.7	+			
H2/10	H	N	L	1	0.0	5.0	3.0	2.7	+			
H2/10	H	N	L	3	0.5	1.5	1.0	1.0	+			
H2/30	H	N	L	1	0.0	0.5	8.0	2.8	+			
H2/30	H	N	L	3	1.0	0.0	7.0	2.7	+			
H2/60	H	N	L	1	2.0	0.5	0.5	1.0	+			
H2/60	H	N	L	3	3.0	1.5	0.0	1.5	+			
H2/100	H	N	L	1	0.5	0.0	0.5	0.3	+			**H/N**
H2/100	H	N	L	3	1.0	3.0	0.0	1.3	+			**3.2**
								Number of samples in the water repellency group	**15**	**3**	**2**	
								Percentage of samples in the water repellency group	**75%**	**15%**	**10%**	
H3/0	H	S	U	1	1.0	0.0	0.0	0.3	+			
H3/0	H	S	U	3	1.0	2.0	0.0	1.0	+			
H3/10	H	S	U	1	9.0	10.0	0.0	6.3		+		
H3/10	H	S	U	3	0.5	4.0	2.0	2.2	+			
H3/30	H	S	U	1	0.0	7.0	2.0	3.0		+		
H3/30	H	S	U	3	1.0	0.0	0.0	0.3	+			
H3/60	H	S	U	1	2.0	0.0	0.0	0.7	+			
H3/60	H	S	U	3	0.0	0.0	3.0	1.0	+			
H3/100	H	S	U	1	3.5	0.0	0.0	1.2	+			
H3/100	H	S	U	3	0.0	0.5	0.0	0.2	+			
H4/0	H	S	L	1	0.0	4.0	0.0	1.3	+			
H4/0	H	S	L	3	1.0	3.0	0.0	1.3	+			
H4/10	H	S	L	1	2.0	0.0	0.5	0.8	+			
H4/10	H	S	L	3	1.0	0.0	0.0	0.3	+			
H4/30	H	S	L	1	6.0	0.0	0.0	2.0	+			
H4/30	H	S	L	3	0.5	0.0	0.0	0.2	+			
H4/60	H	S	L	1	4.0	0.0	0.0	1.3	+			
H4/60	H	S	L	3	0.0	0.0	2.0	0.7	+			
H4/100	H	S	L	1	0.5	0.0	0.0	0.2	+			**H/S**
H4/100	H	S	L	3	0.0	5.0	0.0	1.7	+			**1.3**
								Number of samples in the water repellency group	**18**	**2**	**0**	
								Percentage of samples in the water repellency group	**90%**	**10%**	**0%**	

You may order additional copies of this publication by sending your mailing information in label form through one of the following media. Please specify the publication title and number.

Publishing Services

Telephone	(970) 498-1392
FAX	(970) 498-1122
E-mail	rschneider@fs.fed.us
Web site	http://www.fs.fed.us/rmrs
Mailing Address	Publications Distribution Rocky Mountain Research Station 240 West Prospect Road Fort Collins, CO 80526

Federal Recycling Program Printed on Recycled Paper

RMRS
ROCKY MOUNTAIN RESEARCH STATION

The Rocky Mountain Research Station develops scientific information and technology to improve management, protection, and use of the forests and rangelands. Research is designed to meet the needs of National Forest managers, Federal and State agencies, public and private organizations, academic institutions, industry, and individuals.

Studies accelerate solutions to problems involving ecosystems, range, forests, water, recreation, fire, resource inventory, land reclamation, community sustainability, forest engineering technology, multiple use economics, wildlife and fish habitat, and forest insects and diseases. Studies are conducted cooperatively, and applications may be found worldwide.

Research Locations

Flagstaff, Arizona
Fort Collins, Colorado*
Boise, Idaho
Moscow, Idaho
Bozeman, Montana
Missoula, Montana
Reno, Nevada
Albuquerque, New Mexico
Rapid City, South Dakota
Logan, Utah
Ogden, Utah
Provo, Utah

*Station Headquarters, Natural Resources Research Center,
2150 Centre Avenue, Building A, Fort Collins, CO 80526