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Effects of Topographic Features on Postfire Exposed Mineral Soil in Small Watersheds

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Exposed mineral soil is an immediate result of forest fires with direct relevance on surface runoff and soil erosion. The goal of this study was to determine which topographic features influence the distribution of exposed mineral soil following wildfire in forested watersheds. In a field investigation 2 months after a simulated wildfire, ground cover was measured and a number of topographic variables, including slope, aspect, distance to streams, solar radiation, elevation, curvature, and profile curvature, were used to determine their relationships to postfire exposed mineral soil. The spatial distribution of fire effects along hill slopes was assessed using geographic information system (GIS), and a regressional relationship was derived to estimate postfire exposed mineral soil from key topographic variables, namely, aspect, solar radiation, and profile curvature. Solar radiation, aspect, and profile curvature were significantly correlated with the amount of soil exposed after the fire; however, aspect and profile curvature were the leading variables in the predictive regression model. Convex-shaped profile curvatures on south-facing slopes had higher values of exposed mineral soil than concave surfaces on north-facing slopes. These results can help land managers with decisions on prioritizing areas in need of pre- or postfire treatment.

Keywords: simulated fires, burn severity, topography, spatial distribution, forest

Past wildfire suppression in the United States resulted in an accumulation of extensive biomass in forested ecosystems, which increased the risk of severe wildfires (Westerling et al. 2006, NWCG 2009). More intense forest fires represent an increasing threat to both human and natural resources. Burn severity is heterogeneous and within the same ecosystem we can find areas that burn at low, medium, or high intensities. However, large fires can often contain greater homogenous patches of high severity (Keane et al. 2008), which can generate larger areas of soil disturbances. Intense wildfires not only consume or char the vegetation but also affect the properties of soils, including the soil structure, porosity, and hydraulic conductivity (Neary et al. 1999). Studies showed that when soil structure degrades, the macropores larger than 0.6 mm in diameter decrease and so does the soil infiltration capacity, leading to an increase in runoff (Neary et al. 1999, Robichaud and Miller 1999). The degradation of the soil structure is also related to the decrease in silt- and clay-size particles following fires (Moody and Martin 2009).

The presence of ash on the soil surface has a high impact on soil infiltration capacity (Moody and Martin 2001, Cerdà and Robichaud 2009, Moody and Martin 2009, Cannon et al. 2010). At first, ash can temporarily increase the infiltration capacity. However, the redistribution of ash by wind and rain can clog pores at the soil surface, which creates a repellent layer that decreases infiltration capacity (Cerdà and Robichaud 2009, Moody and Martin 2009). Water repellency is also affected by soil properties, fire behavior and severity, and temperature during fire (DeBano 1981). For example, combustion of litter and organic matter vaporizes the organic compounds and transports them downward through the soil where they condense and render the soil water repellent (DeBano 2000).

A major environmental problem related to forest fires is the increase in surface runoff and water erosion during rain and snowmelt events as a result of increased detachment of exposed mineral soil months after vegetation is burned. As the amount of mineral soil exposed increases, the risk of excessive sedimentation also increases. Postfire soil recovery is influenced not only by rainfall events

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immediately after fire but also by prolonged droughts. Unprotected soil, combined with high-intensity precipitation, can cause detachment and erosion of soil (Mayor et al. 2007, Myronidis et al. 2010). In the postfire environment, exposed mineral soil is usually the most important fire-related factor that can be measured in addressing soil erosion (Hudak et al. 2007).

There are several models that predict runoff and erosion from burned areas, such as the Soil Conservation Service Curve Number (CN), Revised Universal Soil Loss Equation (RUSLE), Water Erosion Prediction Project (WEPP), and Erosion Risk Management Tool (ERMiT) (Renard et al. 1997, Elliot 2004, Robichaud et al. 2007, Elliot et al. 2010). Most of these models require topography as an input. Topography has been used to characterize forest soils (Griffiths et al. 2009), for autocorrelation of wildfire distribution (Chou et al. 1990), and to analyze the reoccurrence of forest fires (Vázquez and Moreno 2001). Topography is also considered an important factor controlling spatial patterns of soil properties as well as water distribution and vegetation production (Petersen and Stringham 2008).

Brown et al. (1985) developed a model for duff consumption by fire that considered only preduff depth and duff water content at the time of fire as important in determining the remaining postfire duff, a surrogate for mineral soil exposure (Robichaud and Miller 1999). Miller et al. (2011) used this relationship along with the Landfire forest fuel characteristics database to estimate the duff reduction and subsequent soil erosion risk for western US forests. A limitation of their study was that the duff cover was estimated from satellite imagery, which typically does not reflect differences in duff cover associated with topography. Duff water content is often not known at the time of a wildfire; however, the distribution of water content on the landscape is largely a function of topography and aspect. For example, shoulders of hills dry out first, and concave areas at foothill retain soil water, providing a relatively higher water content later into the summer (Barling et al. 1994). Similarly, aspect plays a major role in the distribution of soil water with south-facing slopes being generally drier compared to north-facing slopes due to longer exposure to solar radiation. Forest managers need reliable estimates of runoff and erosion to make decisions about postfire mitigation activities.

The purpose of this paper was to determine if there is a relationship between the exposure of mineral soil after wildfire and topographic variables. If a relationship does exist, then a predictive equation can be developed to aid forest managers to target postfire erosion mitigation treatments.

It was assumed that the postfire exposed mineral soil in different watersheds differs due to changes in topography. Both slope length and steepness affect downslope mechanical movement of the soil (Toy et al. 2002), and slope shape controls soil depth and water content (Wendt et al. 1974). The exposed mineral soil on a hill slope after a fire may erode with increasing slope length and steepness (Craddock and Pearse 1938). Elevation and aspect play an important role in soil formation and vegetative pattern (Weisberg 2004). Throughout the year south-facing slopes receive more solar radiation, experience more intense evapotranspiration processes, and have overall less vegetation, compared to the north-facing slopes (Fekedulegn et al. 2003). In addition, the drier south-facing slopes have a higher fire occurrence probability (Yang et al. 2007) and, consequently, may be more prone to increased postfire mineral soil exposure and erosion.

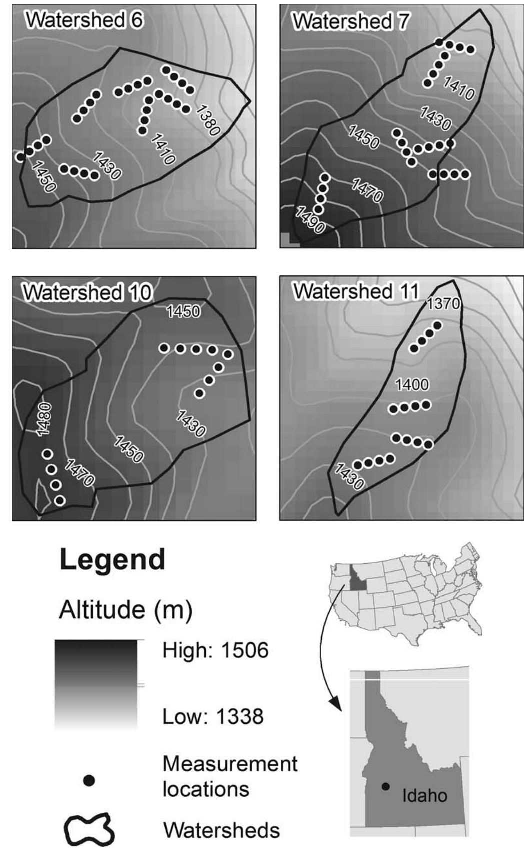

Figure 1. Study watersheds in the Boise Basin Experimental Forest and distribution of the measurement locations.

Rather than relate fire behavior and subsequent burn severity to postfire erosion, this study investigated correlations between exposed mineral soil after a fire and topographic variables. Other variables, such as soil water content and duff thickness, are important in predicting exposed mineral soil. However, they were not included in this study as they have been widely documented in literature (Robichaud et al. 2000, Miller et al. 2011). Results from this study may provide information to fire managers for identifying and targeting areas to focus postfire rehabilitation if resources are not available to measure ground cover by on-the-ground survey or remote sensing, and a Digital Elevation Model (DEM) map is the only data available.

Materials and Methods

Site Description

The study site was located in the Boise Basin Experimental Forest managed by the USDA Forest Service, Rocky Mountain Research Station (Figure 1). The elevation at the study site is 1,381–1,485 m, with a dominant north-northeast aspect. Slopes range between 4 and 67%.

Information on the soil properties was obtained using the land-type data from the Boise National Forest GIS library and the Soil Hydrologic Reconnaissance for the Boise Ranger District (Wendt et al. 1974). Eighty-six percent of the study area is comprised of strongly dissected mountain slope land, moderately deep and deep skeletal, loamy and sandy soils. The dominant soil family within the study area is a typic cryumbrept, loamy skeletal mixed. The soil profile varies in-depth from 50 to 150 cm, depending on slope

Table 1. Prefire tree stand properties within the four study watersheds.

	Trees (ha^{-1})	Basal area ($m^2\ ha^{-1}$)	Top height (m)	Quadratic mean diameter (cm)
Minimum	0	0	0	0
Average	57	42	27	44
Maximum	650	148	48	90

Table 2. Characteristics of the four study watersheds and prefire ground cover measurements.

Watershed	Area (ha)	Elevation (m)	Average slope (%)	Prefire ground cover data (% mineral soil exposed)
6	2.1	1,357	40	2
7	1.9	1,363	46	0
10	1.2	1,424	37	10
11	1.2	1,363	34	1

position and aspect, to the well-fractured, granite bedrock. A partially decomposed organic layer (0–10 cm) covers the gravelly sandy loam to gravelly sandy clay loam surface horizon (25–60 cm) that has a weak to fine granular structure. The soils are medium to slightly acidic, 20–55% gravel, and up to 20% rock. The subsoil horizons (from 60–130 cm in depth) have weak granular or single grain to massive structure and gravelly sandy loam to gravelly loam textures (USDA 1999) and are medium to slightly acidic 20–60% gravel and up to 60% rock.

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) are the dominant tree species. None of the four watersheds had been disturbed in the past 50 years by fire, thinning, or harvesting prior to the simulated wildfire in 2008 (Elliot and Glaza 2008). The stands were of uniform age, suggesting the forest had previously been clearcut. There were on average 57 trees ha^{-1} of 27 m average height and 44 cm quadratic mean diameter (Table 1). The understory vegetation consisted primarily of shrubs and regeneration with Douglas-fir. Within the study areas, the average winter and summer temperatures are $-4°$ and 19° C, respectively, with most of the 635 mm of annual precipitation occurring between October and June (USDA Forest Service 2014). From field observations, there was negligible precipitation during June through September in the year of 2008, and minimum regeneration occurred at this time of the year. The very low regeneration, as observed, primarily appeared along the streams.

Prefire Conditions

Four watersheds received a simulated wildfire treatment on June 16 and 17, 2008, and prior-burning ground cover data had been recorded (Table 2). Only Watershed 10 had an elevated prefire exposed mineral soil component (10%), all other watershed's exposed mineral soil were negligible: 2, 0, and 1% for Watersheds 6, 7, and 1, respectively. The simulated fire was designed to mimic a moderate intensity surface fire. A strip ignition pattern was used to ignite each watershed. On average the flame lengths ranged from 1 to 1.5 m. On June 16, the dry temperature during the fire increased between 21° C at 11 am to 27° C at 5 pm. Similarly, the relative humidity decreased from 40 to 20%, and wind speed increased from 0.13 m s^{-1} in the morning to 1.03 m s^{-1} in the afternoon. Weather observations from the June 17 fire followed a similar pattern.

The prefire measurements were conducted in 19 plots within the four watersheds. The plots were placed on a grid with plots placed 62 m apart and covered the entire watershed. All surface components were surveyed, including litter, humus, rock, exposed mineral soil, tree density, grass, forbs, mosses, and shrub cover. The estimates were ocular and were conducted on a 13.5 m^2 plots. Litter depth was measured using a ruler at the four cardinal directions of each plot. Litter and humus had a 90 and 91% cover, respectively, with a mean depth of 23 mm for both. They were the most abundant surface components followed by grass and live low shrubs at 23% each. On average, there were two trees per plot with a maximum of three and a standard deviation of one. The low shrubs and medium shrubs had a mean cover of 1 and 8%, respectively, with 50 and 55% of maximum cover. Figure 2 is an example of the site conditions before and after the simulated fire.

Field Measurements

Ground-cover measurements were conducted after the fire during Sept. 15–18, 2008. Twenty sites were established within the four small watersheds prior to the prescribe fire and marked by iron stakes at 60-m spacing as displayed in Figure 1 From each of these 20 sites a 40-m transect was selected in a random direction following the Cressie method (1993). Ground cover variability was quantified every 10 m along the transect (resulting in 80 total measurement locations) using a 1-m^2 frame. The frame was equipped with a grid, which allowed the recording of the ground cover for 100 equally distributed points beneath the frame. The cover material for each of 100 points beneath the frame was recorded as mineral soil, ash, rock, woody material (unburned fuel), organic matter (unburned vegetation), or charcoal. Overall the ground cover at each of the 80 measurement locations was represented as percentage for the 100 points.

GIS-Derived Variables

The GIS analysis was conducted using a 10-m resolution DEM (USDA 2009) in ArcGIS 9.2 (ESRI 2007). Each pixel from the DEM represents a 10 × 10 m area. Because each pixel's properties are averaged over the 10 × 10 m area, it was assumed that any variability within this area is negligible. At this resolution, variables like elevation, aspect, slope, etc. might change substantially on high elevation mountainous area or on fragmented landscapes, but on this site, there is an average difference in elevation of only about 60 m between the lowest and the highest measurement locations. Therefore, the derived variables from the 10 × 10 m DEM should be fairly representative for the 1-m^2 grid sampling. A higher resolution DEM may have given a more precise estimate of slope steepness at a given point, but studies have shown that DEM resolution less than 10 m does not necessarily increase the accuracy for describing hill slope characteristics, at least in terms of derived morphological parameters such as slope and aspect, or erosion prediction (Zhou and Liu 2004, Zhang et al. 2009).

The 80 field measurement locations were added to the DEM map. The study examined the topographic variables for each measurement location as related to exposed mineral soil after fire: elevation, slope, aspect, distance to streams, solar radiation, plan curvature, and profile curvature.

A solar radiation map was generated in ArcGIS 9.2 (ESRI 2007) from the DEM with the Spatial Analyst tool, where each pixel is assigned an insolation value (WH m^{-2}). The tool provides options of creating solar radiation maps for different time intervals. In this study, a whole year, 3 summer months, and the month of August were selected as time intervals.

Figure 2. Example of prefire (left) and postfire (right) site conditions in Watershed 11.

The global radiation was calculated as a sum of direct radiation and diffuse radiation that were obtained by overlaying the viewshed, sunmap, and skymap layers, which are created automatically when computing the global radiation (ESRI 2007). Spearman correlation coefficients were obtained to determine which form of solar radiation best correlated with the exposed mineral soil.

This study hypothesized that the distance to streams may play a role in fire intensity, that is, soils closer to the stream have a higher water content, thus limiting soil exposure after fire. This assumption was used in the postfire erosion model developed by Robichaud et al. (2007), but it has not been assessed using field data. Based on the 10-m DEM, two distances to stream were computed: (1) the perpendicular distance from a measurement location to the stream and (2) the distance to stream in the direction perpendicular to topographic contour lines. The reason was that this method computes the runoff and flow path distance along the natural slope from the measurement location downslope to the stream.

Maps of curvature, plan curvature, and profile curvature were also generated. Curvature represents the derivative of elevation (ESRI 2007) as indicated on a cell-by-cell basis. The profile curvature is calculated in the direction of the maximum slope, while the plan curvature is calculated perpendicular to the direction of the maximum slope.

Developing a Regression Equation for Exposed Mineral Soil

The statistical analysis included a correlation and a multiple linear regression. The correlation analysis was helpful in revealing the direction and strength of the relationship between variables, while the regression analysis allowed for an estimate of how well the topographic variables explain the mineral soil exposed after the fire. All statistical analyses were conducted in SAS 9.1 at a significance level of $\alpha = 0.05$ (SAS 1999). To assess the normality of each variable, the Shapiro–Wilk normality test in SAS was used. The variable curvature was found to be normal distributed ($P = 0.286$) and solar radiation close to normality ($P = 0.049$). A normal distribution was assumed for solar radiation and transformations were applied on the others (natural logarithm, square root, and power) to derive normality. None of the transformations converted all the variables to a normal distribution. The lack of normality of the aspect was expected as the watersheds all had a predominantly northeast aspect to meet other objectives in a larger study (Elliot and Glaza 2008). However, due to landscape undulations within the watersheds, a range of aspect perspectives were found to range between 0° to 360°.

A correlation analysis was conducted among all 14 variables using the nonparametric Spearman correlation coefficient. Aspect was a variable of interest in this study, as more southerly facing slopes receive greater solar radiation, which generally leads to drier soils and duff that could promote more intense fires. At the time of the fire, drier soils and duff result in greater duff consumption exposing additional mineral soil. The aspect variable was transformed for the statistical analysis with the following relationship

$$\text{Transformed Aspect} = 180° - |\text{Observed Aspect} - 180°| \quad (1)$$

Using this equation, the true north value will be 0°, and the south aspect will have a maximum value of 180° with the east and west aspects at 90°.

To develop an equation to predict the exposed mineral soil from the topographic variables, the PROC REG procedure in SAS was used for multiple regression with stepwise selection. From all 14 variables, mineral soil exposed was chosen as the dependent variable, and the remaining 13 variables were considered independent variables. Stepwise model selection is a combination of both forward and backward selections subject to a preset significance level ($\alpha = 0.05$ in this study). In the forward selection, the independent variables will be added one at a time until R^2 reaches a maximum value. In the backward selection, the variables that do not significantly decrease R^2 will be removed successively. The residuals of the regression were found to be normally distributed but with unequal variances. To correct for the unequal variances, a weighted-least-squared (WLS) regression was applied to the best model selected through the stepwise regression. In the WLS, data points with large variances on the independent variable will be assigned small weights while larger weights will be assigned to data points with smaller variances. The parameter estimates will be similar as in the case of the stepwise regression, but the standard error should decrease.

Results

On average, the watersheds had 65% organic matter and woody material after the fire (Table 3), which indicates a low-severity fire. At 30 out of the 80 measurement locations, no exposed mineral soil was observed. Between 1 and 67% exposed mineral soil was recorded at the other 50 measurement locations.

Correlation Analysis

All forms of solar radiation were significantly correlated to exposed mineral soil at $\alpha = 0.05$, but for the subsequent analysis only annual solar radiation was used as it showed a slightly stronger correlation. Neither method for computing distance to stream was

Table 3. Postfire percentage cover measurements within the studied watersheds.

	Watershed 6		Watershed 7		Watershed 10		Watershed 11	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Mineral soil	15	17	9	12	19	23	5	7
Ash	15	19	24	19	9	11	23	16
Rock	0	1	0	0	0	0	0	0
Woody material	7	8	8	8	9	11	7	6
Other organic matter	56	24	54	21	60	23	57	18
Charcoal	7	7	4	6	3	4	7	8

Table 4. Correlation between topographic and ground cover variables.

	Slp.	Asp.	Min.	Ash	Rock	WD	OM	Char.	DS	SR	Elev.	Curv.	PLC	PFC
Slp.	1	NS	NS	NS	NS	NS	NS	NS	−0.34**	−0.39***	NS	NS	−0.35**	NS
Asp.		1	0.30**	NS	NS	NS	NS	NS	−0.39***	0.80***	NS	NS	NS	NS
Min.			1	0.25*	NS	NS	NS	NS	NS	0.23*	NS	NS	NS	−0.24*
Ash				1	NS	NS	NS	0.61***	NS	−0.26*	NS	NS	NS	NS
Rock					1	NS	NS	NS	NS	NS	NS	NS	NS	NS
WD						1	0.47***	NS	0.36**	NS	0.29**	NS	NS	NS
OM							1	NS	0.28*	−0.22*	NS	NS	NS	NS
Char.								1	NS	NS	NS	NS	NS	−0.34**
DS									1	NS	0.50***	0.54***	0.58***	−0.22*
SR										1	NS	NS	NS	NS
Elev.											1	0.29**	0.25*	NS
Curv.												1	0.77***	−0.75***
PLC													1	−0.26*
PFC														1

The nonsignificant correlations are denoted by "NS" and * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
Slp., slope; Asp., aspect; Min., mineral soil; WD, woody debris; OM, organic matter; Char., charcoal; DS, distance to stream; SR, solar radiation; Elev., elevation; Curv., curvature; PLC, plan curvature; PFC, profile curvature.

significantly correlated with the exposed mineral soil; however, for the final analysis the distance to stream in the direction perpendicular to topographic contour lines was chosen.

The results from the Spearman correlation analysis are presented in Table 4. Twenty-six correlations were significant among all 14 variables. Four of the variables were significantly correlated with exposed mineral soil: solar radiation ($r_s = 0.23$), aspect ($r_s = 0.30$), profile curvature ($r_s = -0.24$), and ash ($r_s = 0.25$). Out of all the significant correlations, eight were at $P < 0.0001$: ash and charcoal, aspect and solar radiation, wood and organic matter, distance to stream and elevation, distance to stream and curvature, distance to stream and plan curvature, curvature and plan curvature, and curvature and profile curvature.

Among the variables, distance to the streams had the highest number of significant correlations, followed by solar radiation and profile curvature. The rock variable had no correlation with any other variable. The following correlations characterize the study area: slope increases closer to the streams and is steeper on concave surfaces in a plan profile; the surfaces become more convex in plan profile at higher elevations and the further they are from the streams; aspect is more southerly closer to the streams in the study watersheds.

Aspect was an important variable correlated with exposed mineral soil (Figure 3). The least amount of exposed mineral soil after the fire was in Watershed 11 (5%), which has mostly north- facing slopes, whereas the greatest amount of exposed mineral soil was in Watershed 6 (15%), which has mostly southeast- or east-facing slopes. Another observation was that the relatively long, narrow Watersheds 7 and 11 had less exposed mineral soil than the wider Watersheds 6 and 10.

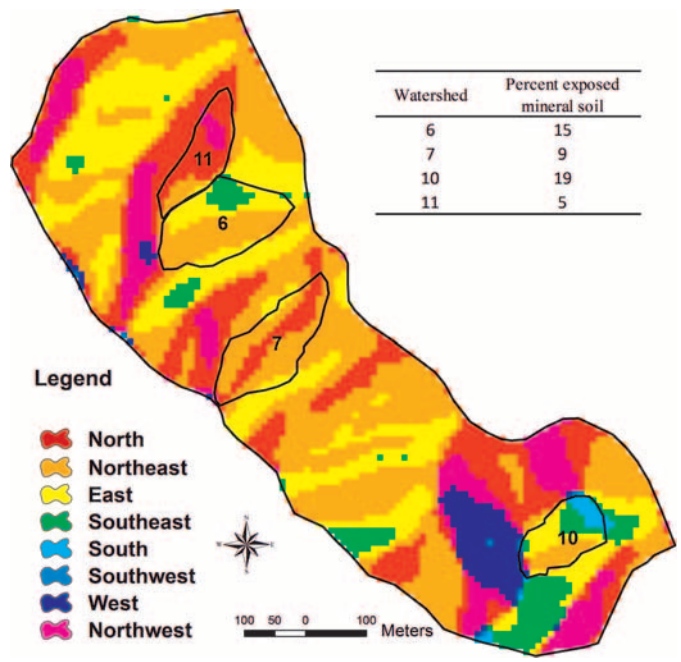

Figure 3. The aspect map and the percentage exposed mineral soil measured for Watersheds 6, 7, 10, and 11.

A Regression Equation for Postfire Exposed Mineral Soil

The correlation analysis showed that aspect, solar radiation, and profile curvature were the variables that significantly correlated with exposed mineral soil. The stepwise procedure in SAS yielded two independent variables as being significant in a multiple linear regression for predicting postfire exposed mineral soil: aspect and profile curvature.

Because aspect and solar radiation were correlated with each other ($r_s = 0.8$), only one of these two variables, the one that gave a better fit, was used in the stepwise procedure. With an adjusted $R^2 = 0.24$ and a root-mean-squared error (RMSE) of 14.2, the final regression equation for mineral soil is given by

$$\text{Exposed mineral soil} = 0.48 + 0.17 \times \text{aspect} - 2.60 \times \text{profile curvature} \quad (2)$$

The WLS regression yielded similar parameter estimates, but the RMSE decreased to 1.28. The final equation for predicting mineral soil exposed after a fire is

$$\text{Exposed mineral soil} = 1.28 + 0.16 \times \text{aspect} - 1.78 \times \text{profile curvature} \quad (3)$$

Discussion

There was a positive correlation between exposed mineral soil with both solar radiation and aspect; the amount of exposed mineral soil after a fire was greater for plots situated on south-facing slopes that receive more solar radiation. There was less exposed mineral soil after the fire for plots situated on north-facing slopes. This might be the influence of aspect on soil water content. Throughout the year, south-facing slopes receive more solar radiation and experience greater evapotranspiration than the north-facing slopes (Fekedulegn et al. 2003). In addition, these drier south-facing slopes have a higher fire occurrence probability (Yang et al. 2007), will exhibit drier soils and vegetation, and, consequently, will tend to burn at a higher intensity. This is especially true in watersheds that have not experienced recent wildfires or silvicultural treatments and have accumulated ground biomass, as in our study watersheds. In case of a wildfire, the south-facing slopes from such watersheds will have more areas that burn at a higher intensity with greater exposure of mineral soil than the north-facing slopes. With less vegetation, precipitation from a rainfall event will more likely detach soil particles that will either stay loose at the surface of the soil or will move downhill as sediment.

The negative correlation between mineral soil and profile curvature indicates that there was more exposed mineral soil where profile curvature was negative, on the shoulders of the hills, and less exposed mineral soil where the curvature was positive, near the bottoms of the slopes near the channels. Surface curvature influences the erosion pattern and erosion losses. On concave surfaces, soil removed at the top of the hill is deposited at the bottom of the hill. Depending on the size and length of the slope, little or no eroded soil may end up in the watercourse (Toy et al. 2002). This study did not measure erosion directly but exposed mineral soil, which might or might not be transformed into eroded material depending on the weather in the years following the fire (Robichaud et al. 2011). The negative correlation between profile curvature and mineral soil may be explained by the importance of profile curvature in the spatial distribution of soil water content. Studies have shown that concave surfaces can have higher soil water content than convex surfaces (Sulebak et al. 2000), which could be the case in this study. Barling et al. (1994) identified similar areas in their study where the positive curvature was particularly wet and described these areas as "topographic hollows." The topographic hollows rational may also explain why charcoal appeared to decrease on concave surfaces. Higher water content on convex slopes can also facilitate the development of more litter, which in case of a wildfire can protect the soil, resulting in less postfire mineral soil exposed.

There was more organic matter and woody debris further from the streams where the slopes are gentler and have a northern aspect, possibly because gentler topography facilitates the formation of deeper soils with more stable soil structure and, thus, better conditions for vegetative growth. The negative correlations between organic matter and solar radiation suggest that more organic matter was found on slopes that receive less solar radiation (i.e., north-facing slopes). These slopes experience less intense evapotranspiration and have higher soil water content, presenting conditions more favorable for vegetative cover development. It should be noted that the correlations between exposed mineral soil and other cover variables may differ from site to site. As shown in a previous study (Lewis et al. 2006) at the Hayman Fire, Colorado, mineral soil was strongly correlated with ash (-0.33, $P < 0.0001$), a correlation which opposes these findings. Studies show that ash can easily be redistributed by winds immediately after the fire (Cerdà and Robichaud 2009). Hence, a similar pattern of ash distribution on the hill slope among all the watersheds cannot be expected. Additionally, it was found in the study of Lewis et al. (2006) that exposed mineral soil was correlated with rock ($r_s = 0.23$) and woody debris ($r_s = -0.23$). The watersheds in this study had a low percentage of rock outcrop, explaining the weak correlations between the topographic variables and the rock cover. Furthermore, the woody debris were considered a broad category, whereas in the study of Lewis at al. (2006) it was further divided into small woody debris, live trees, and dead trees. It can be anticipated that some topographic variables may have similar influences and correlations with exposed mineral soil after a fire, but variables like rock or woody debris most often are related to prefire conditions and differ from site to site.

The results of this study should be useful to forest managers, as they can use simple GIS tools to identify areas with greater potential for postfire erosion for mitigation treatment. Currently, such targeting is based on satellite images that tend to show differences in vegetation and not ground cover (Lewis et al. 2006). For example, using only a topographic map, managers can locate convex-shaped slopes with south-facing aspects and map them as potentially sensitive areas. In watersheds at risk of wildfires, stand thinning or ground biomass reduction can be applied to these areas to decrease postfire risks. On the sensitive slopes, management practices such as mastication (Rummer 2010) may be more appropriate than prescribed fire to reduce fuel loads. Similarly, in the case of wildfires spread over large areas, intervention teams can first target the postfire treatments for erosion control to the sensitive areas increasing the efficiency of their intervention.

Conclusions

Aspect, solar radiation, and profile curvature were strongly correlated with exposed mineral soil following simulated wildfires in the four Boise Basin watersheds. Generally, more exposed mineral soil was found after a fire on convex, uphill, and south-facing slopes. The linear regression equation yielded useful information about variables that can influence fuel management and postfire mitigation in Pacific Northwest forests.

This study was a first attempt to quantify and analyze the mineral soil exposed after a fire in relationship to topography and aspect. The results provide forest managers with a predictive tool that allows them to better identify areas that may require postfire erosion mitigation. Future efforts can enhance its predictive value and should focus on determining if the relationships found in this study apply to larger wildfires or to fires that burn at higher intensities. Such information would be useful not only for helping fire managers identify and target areas to focus postfire rehabilitation but also for improving models of fire behavior predictions.

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