Modeling Erosion on Steep Sagebrush Rangeland Before and After Prescribed Fire

Corey A. Moffet[1]
Frederick B. Pierson[2]
Kenneth E. Spaeth[3]

Abstract: Fire in sagebrush rangelands significantly alters canopy cover, ground cover, and soil properties that influence runoff and erosion processes. Runoff is generated more quickly and a larger volume of runoff is produced following prescribed fire. The result is increased risk of severe erosion and downstream flooding. The Water Erosion Prediction Project (WEPP), developed to model erosion on cropland, forest, and rangeland, is a tool that has the potential to model erosion and help managers address erosion and runoff risks following fire. WEPP views erosion as two processes: interrill and rill. Experimental results on a steep (35 to 50 percent slope) sagebrush site suggest that rill erosion is the dominant erosion process following fire and must be adequately understood so that models can provide reliable predictions. Evaluation of WEPP parameterization equations using data from steep burned sagebrush rangelands suggests that critical parameter estimation procedures within WEPP need improvement to include fire effects on infiltration and rill erosion processes. In particular, rill detachment estimates could be improved by modifying regression-estimated values of rill erodibility. In addition, the interactions of rill width and surface roughness on soil grain shear estimates may also need to be modified. In this paper we report the effects of prescribed fire on runoff and soil erosion and compare WEPP estimated erosion for several modeling options with measured erosion.

Introduction

Current trends in soil erosion modeling under various management scenarios consist of analyzing erosion in probabilistic terms to account for storm variability and provide accurate event-based erosion estimates (Elliott and others 2001). Under this paradigm, it is not sufficient if a model significantly underestimates large events or overestimates small events, but does well for long-term averages. The physically-based Water Erosion Prediction Project (WEPP) model (Flanagan and others 1995) is a model that has been used to provide event-level erosion estimates (Robichaud and others 2003).

Soto and Diaz-Fierros (1998) measured runoff and erosion from natural rainfall on burned and non-burned plots with similar vegetation, slopes, and soil textures on shrublands in northwest Spain over a 4-year period. Total runoff from the control was only 59 percent of that from the burned area during the 4 years of study. Measured erosion was significantly higher from the burned area than from the control during the first 2 years after fire.

Soto and Diaz-Fierros (1998) compared measured and WEPP estimated soil water content, runoff, and erosion on burned and non-burned sites. Their comparisons excluded events during May through September when the soil was dry and water repellent. They reported that WEPP did reasonably well at predicting runoff and erosion values, although they reported that on severely burned areas, erosion estimates were consistently underestimated. In one erosion measurement period (6 to 10 months post-burning), WEPP grossly underestimated erosion for control and prescribed burn plots that they attribute to the fact that the erosion all occurred during one large rainfall event (50.3 mm) when water repellency was severe. Soto and Diaz-Fierros (1998, p. 268) concluded, "the model shows a clear tendency to underestimate erosion following severe burns."

The objectives of this paper were to: (1) evaluate differences in runoff and erosion on a steep mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) community between burned and non-burned conditions; (2) test the capability of rangeland WEPP for estimating runoff and erosion for burned and non-burned conditions; and (3) suggest how improvements in rangeland WEPP might better represent fire impacts on rangelands.

WEPP

The WEPP model treats interrill and rill erosion as separate processes (Flanagen and others 1995). Interrill erosion is a function of soil interrill erodibility (K_i, adjusted for canopy and ground cover in the interrill area), effective rainfall intensity, interrill runoff rate, interrill sediment delivery ratio (computed as a function of random roughness), and runoff duration (Foster and others 1995; Foster 1982). Interrill erosion on undisturbed rangeland has been well studied and is typically low (Pierson and others 2001).

In WEPP, rill erosion is a function of rill detachment capacity, sediment load, transport capacity, rill width, runoff duration, and rill spacing. Rill detachment capacity is modeled

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as a function of excess soil shear stress (Foster and others 1995, Foster 1982):

$$D_{rc} = \begin{cases} K_r\,(\tau_{fe} - \tau_c); & \tau_{fe} > \tau_c \\ 0; & \tau_{fe} \le \tau_c \end{cases} \qquad [1]$$

where D_{rc} is the rill detachment capacity (kg m^{-2} s^{-1}), τ_{fe} is the soil shear stress due to rill flow at the end of the uniform slope (Pa), τ_c is the critical soil shear stress (Pa) that is required for detachment initiation, and K_r is the rill erodibility (s m^{-1}).

The values for K_r and τ_c are WEPP input parameters. In rangeland WEPP, these parameters are determined based on soil properties and do not vary with management, but τ_{fe} is a function of ground cover and soil surface characteristics, slope, and rill flow characteristics:

$$\tau_{fe} = \gamma\, R_h \sin(\tan^{-1}(S)) \left(\frac{f_s}{f_t}\right) \qquad [2]$$

where γ is the specific weight of water (N m^{-3}), R_h is the hydraulic radius of the rill flow (m), S is the slope of the energy gradient (assumed equal to the soil surface slope, fraction m/m), f_s is the Darcy-Weisbach roughness coefficient due to soil grains (assumed to be 1.11), and f_t is the total Darcy-Weisbach roughness coefficient due to soil grains, ground cover (litter, rock, plant bases, and cryptogams), and random roughness. The Darcy-Weisbach roughness coefficient used in rangeland WEPP is empirically estimated from ground cover and random roughness parameters.

The rill hydraulic radius (R_h) is the ratio of flow cross-sectional area ($A = wd$) to wetted perimeter ($P = 2d + w$), both are functions of width (w) and depth (d). In WEPP, rills are assumed of rectangular shape with width a function of rill discharge rate (q, m^3 s^{-1}):

$$w = 1.13q^{0.303}. \qquad [3]$$

Given the rill discharge rate, slope, width, and Darcy-Weisbach roughness coefficient, depth is computed by WEPP.

For a given storm, infiltration and therefore runoff volume are affected by the effective hydraulic conductivity (K_e) and the matric potential gradient across the wetting front, but not f_t. Peak discharge, q_{peak} (and therefore q), and runoff duration, t_{RO}, however, are sensitive to f_t. As f_t increases, q_{peak} decreases and t_{RO} increases.

For a given discharge rate the excess soil grain shear stress computed by WEPP is a function of only one factor affected by management—the Darcy-Weisbach roughness coefficient. In the current version of WEPP any effect of management on estimated rill erosion must be expressed through differences in runoff and Darcy-Weisbach roughness coefficients among the management scenarios.

Material and Methods

The study area is located in the Reynolds Creek Experimental Watershed in southwest Idaho near the divide between Reynolds Creek and Dobson Creek watersheds (43° 6' 30" N; 116° 46' 50" W). The elevation of the research site is about 1,750 m and mean annual precipitation is approximately 549 mm.

The vegetation was a typical mountain big sagebrush community with subdominant shrubs of rabbitbrush (*Chrysothamnus viscidiflorus*), antelope bitterbrush (*Purshia tridentata*), and widely scattered juniper (*Juniperus occidentalis*), and dominant grasses were bluebunch wheatgrass (*Pseudoroegneria spicata*) and Idaho fescue (*Festuca idahoensis*). The soils are mapped Kanlee-Ola-Quicksilver association, 3 to 50 percent slopes. All plots in the study are on the deeper Kanlee and Ola series. The slopes of the study area are 35 to 50 percent with an east facing aspect on granite bedrock hillslopes. Soil textures are coarse sandy loam in the surface 30 cm and loam or coarse sandy loam in the subsoil that extends beyond 100-cm depth. Rock fragment (>2 mm diameter) content in the surface layer is about 5 to 15 percent and ranges between 5 and 50 percent in the subsoil. Soil water content during all phases of this research was low (approximately 0.03 kg kg^{-1}).

Sixteen rectangular plots (6.5 m long by 5 m wide) were selected within a narrow elevation band near the top of the hillslope prior to prescribed fire. Eight plots each were assigned to the non-burned and burned treatments. Plots in the non-burned treatment were characterized (canopy and ground cover, slope, and random roughness) and rainfall simulations were performed in August and early September. The prescribed fire was ignited in late September and a head fire burned the study area. The burned plots were characterized and simulated rainfall was applied in October.

Rainfall was applied on two plots each day with a Colorado State University (CSU) type rainfall simulator (Holland 1969) at a rate of 61 mm hr^{-1} for 1 hr; however, observed application rates differed from the design due to mechanical difficulties and wind. The observed range was 45.3 to 76.1 mm. Several samples of rainfall that fell directly in the runoff collection trough were collected during the first several minutes of each simulation. Timed samples (500 ml to 1,000 ml) were collected approximately every minute. The mass of sediment and volume of water collected in each sample was determined in the laboratory. The mean trough catch that would have been collected during the sample time was subtracted from each sample volume.

Vegetation cover, ground cover, slope, and surface random roughness were sampled in each large plot prior to the rainfall simulations with 100 evenly-spaced point samples recorded along six horizontal transects (0.5, 1.5, 2.5, 3.5, 4.5, and 5.5 m from the upslope end of a plot). At each point the relative elevation of the ground surface (measured to the nearest mm), the ground cover class and the canopy cover class (if present) were recorded. Vegetation and litter mass were determined by harvesting all standing plant material by functional group and collecting litter from 30 small (1 m^2) plots nearby. The vegetation and litter samples were oven-dried and weighed.

Three parameterization schemes were used to explore the WEPP rill erosion estimation capabilities. The first scheme

(Option A) used readily available data; infiltration and erosion parameters were computed by WEPP from soil and cover data. The next scheme (Option B) used optimized effective hydraulic conductivity (K_e) values to match total runoff on a plot by plot basis. Option C used the (K_e) values from Option B, and optimized rill erodibility (K_r) values and 0.0001 for critical shear (τ_c).

In all scenarios, the soil data were those available in the 1995 WEPP soils database. Initial saturation was always adjusted to 25 percent and K_e and K_r were adjusted as described above. The management data were written to run WEPP for rangelands in event mode using measured canopy cover, ground cover (litter, plant base, cryptogam, and rock), and random roughness to parameterize the initial condition section for each plot. Precipitation data were based on the measured simulated rainfall on each plot. Pattern parameters were assumed to be the same on all plots (duration of 1 hr, peak intensity of 1.01 times the mean intensity, and time to peak intensity at 20 percent of the simulation duration).

One-way analysis of variance was used to test the significance of treatment effects on response variables. Since only two treatment levels were studied, a significant F-test indicated that the means were different. Welch's *t*-test was used within each treatment to compare WEPP estimated responses with measured responses.

Table 1. Comparison of site and simulation characteristics between burned and non-burned treatments. Means for a characteristic followed by the same letter are not significantly different.

Characteristic	Units	Burned	Non-burned
Precipitation	mm	59.1 a	61.4 a
Slope	%	41.6 a	40.8 a
Random roughness	mm	10.8 b	21.1 a
Ground Cover[a]			
Litter below canopy	%	0.1 b	49.6 a
Rock below canopy	%	0.0 a	0.1 a
Basal cover below canopy	%	0.0 b	1.3 a
Litter outside canopy	%	23.3 a	24.7 a
Rock outside canopy	%	1.0 a	0.3 b
Basal cover outside canopy	%	0.0 b	0.6 a
Canopy cover	%	0.2 b	57.0 a
Litter total	%	23.4 b	74.3 a
Rock total	%	1.0 a	0.5 b
Basal cover total	%	0.0 b	1.9 a
Bare ground total	%	75.6 a	24.3 b
Ground litter	kg ha^{-1}	808[b]	9517
Vegetation	kg ha^{-1}	–[c]	12125

[a] The sum of litter, rock, and basal cover below canopy and outside canopy and total bare ground is equal to 100.

[b] Burned treatment litter samples were collected in the spring and early summer following the fire.

[c] Burned treatments vegetation samples were not collected.

Results and Discussion

Plot and Simulation Characteristics

Total precipitation applied and plot slope were similar for burned and non-burned treatments (table 1). On burned plots, almost no standing material remained except occasional bitterbrush shrub skeletons (sagebrush was consumed to within 5 cm of the soil surface). Average canopy cover of the shrub skeletons was 0.2 percent.

The burn treatment significantly reduced total litter, plant basal cover, and canopy cover (table 1). Litter cover outside the plant canopy (ashy unconsumed litter and wood) was not different between the burned and non-burned treatments even though the fire reduced total litter cover. This was because the total area outside the canopy significantly increased following the fire. Random roughness was significantly less in burned than in non-burned treatment plots (table 1). This was most likely due to much of the root crowns and litter under shrubs being consumed during the fire. The burned treatment plots had greater rock cover compared to the non-burned treatment plots (table 1). However, a 0.5 percent increase in rock cover in burned plots probably had little or no effect on hillslope hydrologic or erosion responses.

Mass of litter and vegetation were reduced by fire (table 1). Litter accumulation, including dung, and wood accounted for nearly 45 percent of the total mass of above ground organic matter. Litter in non-burned treatment plots was not uniformly distributed on the ground, but rather occurred as a thick almost continuous layer under canopies and patchy thin accumulations outside canopies. The litter mass in burned treatment plots was 8 percent of that in non-burned plots, but total litter cover on the burned treatment was 31 percent of that on the non-burned treatment. The effect of fire on litter cover reduction was less than its effect on litter mass/volume reduction.

Measured Large Plot Runoff and Erosion

Fire significantly increased total runoff volume from burned plots (16.6 mm) compared to non-burned plots (3.1 mm, fig. 1). All burned plots yielded runoff, whereas three of the eight non-burned plots yielded no runoff. This is consistent with findings from Soto and Diaz-Fierros (1998) who found that wet-season runoff doubled in the first year after fire.

Areas burned by fire generated runoff more quickly than non-burned areas. The mean time to initiation of runoff for burned and non-burned plots was 3.3 min and 7.1 min, respectively (excluding the three non-burned plots with no runoff). Peak runoff rates from burned treatment plots were about three times higher than the non-burned treatment plots (all non-burned plots) and about two times greater than the five non-burned treatment plots with measurable runoff (fig. 1). Regardless of treatment, runoff rates peaked 10 to 20 minutes into the simulated rainfall event and diminished with time thereafter (fig. 1). The decrease in runoff rate with time during the simulation, for both burned and non-burned treatment plots, indicates that the soil in both treatments may have had significant water repellent soil properties. Pierson and others (2001) found significant water repellency in both burned and non-burned plots for similar sites during late summer and early

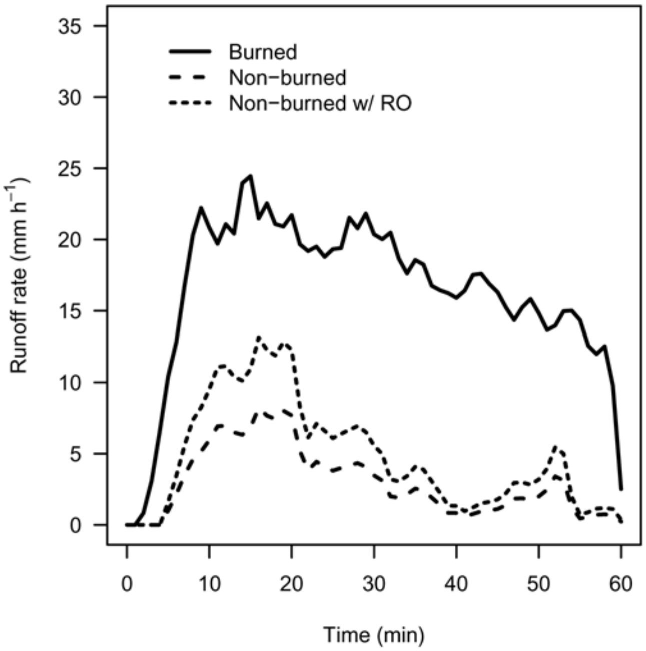

Figure 1. Mean hydrographs for 60-minute simulated rainfalls on burned and non-burned plots (n = 8). Three non-burned plots yielded no runoff and the mean hydrograph for the five plots that did generate runoff is also shown (dotted line).

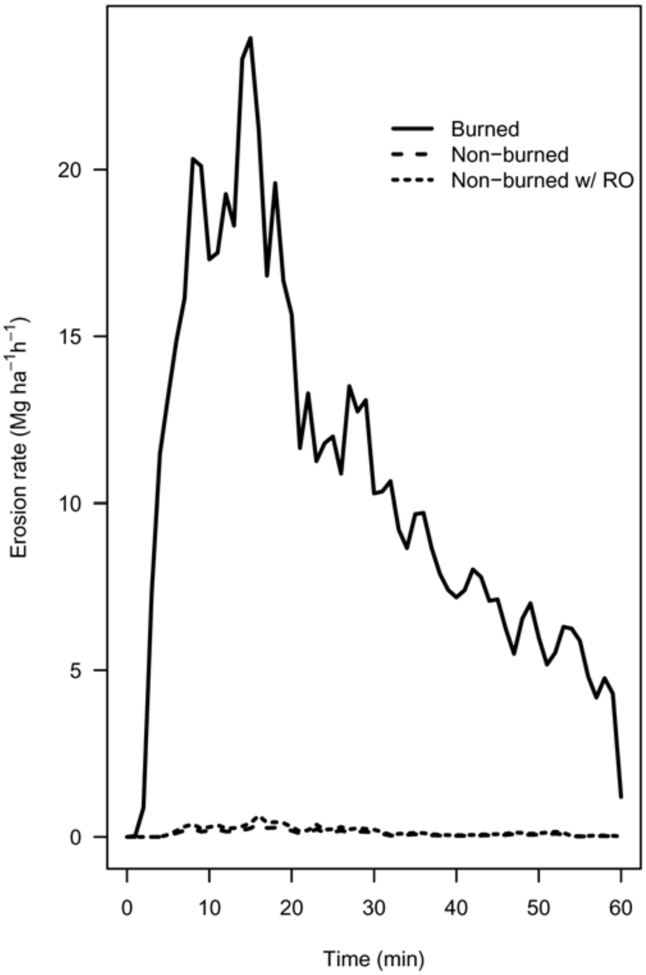

Figure 2. Mean sediment yield for 60-minute simulated rainfalls on burned and non-burned plots (n = 8). Three non-burned plots yielded no runoff or sediment and the mean sediment yield response for the five plots that did generate runoff is also shown (dotted line).

fall when the soils were dry. Soto and Diaz-Fierros (1998) reported that runoff to precipitation ratios for natural rainfall on control and burned plots were significantly greater during periods of high water repellency.

The effect of burning on total soil erosion was also significant ($\alpha = 0.05$, fig. 2). Sediment yield for burned plots was significantly greater (10.7 Mg ha^{-1}) than non-burned plots (0.1 Mg ha^{-1}). Erosion rates in both burned and non-burned treatments were greatest during the first 7 to 20 minutes of the simulated rainfall event and steadily decreased thereafter (fig. 2). Soto and Diaz-Fierros (1998) reported that erosion was higher in burned compared to control plots the first 2 years post fire. In one erosion measurement period, when almost all erosion occurred from one 50.3 mm storm on dry water repellent soils, erosion was 6.6 times greater from burned plots than from control plots (Soto and Diaz-Fierros 1998).

WEPP Estimated Runoff and Erosion

Using WEPP estimated infiltration and erosion parameters (Option A), model predicted runoff was significantly greater than measure runoff regardless of treatment (fig. 3). Predicted runoff was nearly 10 times greater than measured runoff in the non-burned treatment and nearly double in the burned. Burning caused a large increase in measured runoff while model predicted runoff was similar between treatments (fig. 3). This indicates a lack of model sensitivity to burning.

Model predicted erosion was significantly less than measured in burned treatments and significantly greater than measured in non-burned treatments. Predicted erosion was 24 percent less than measured in the burned treatment, but 2.6 times greater in the non-burned. However, model estimates of erosion showed some degree of sensitivity to burning (fig. 4). Interpretation of this sensitivity is complicated by errors in runoff prediction. Because runoff drives the rill erosion process, treatment induced trends in predicted erosion cannot be effectively evaluated.

To correct errors in model predicted runoff (Option B) we used optimized effective hydraulic conductivity (K_e) for each plot which ranged from 6.7 to 32.3 mm h^{-1} for burned and 26.3 to 77.9 for non-burned. These values are two to four times greater than WEPP estimated K_e values used in Option A (table 2). Using optimized K_e values, runoff matched measured runoff within 0.2 mm on all plots (fig. 3).

Using optimized K_e and WEPP estimated erosion parameters (Option B), predicted erosion was 13 percent of measured erosion for the burned treatment and statistically similar for the non-burned treatment (fig. 4). WEPP adequately estimated low erosion for the non-burned condition and showed an increase in erosion due to fire. However, the predicted increase was only 1.3 Mg ha^{-1} compared to a 10.6 Mg ha^{-1} measured

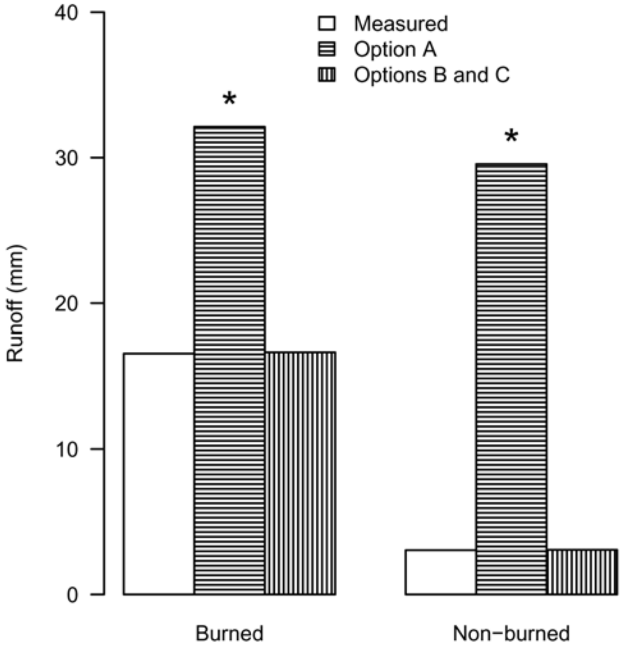

Figure 3. Mean measured and WEPP estimated total runoff for three parameterization options. WEPP estimated values within a treatment that are marked above the bar with an asterisk are significantly different (α = 0.05) from the mean measured value.

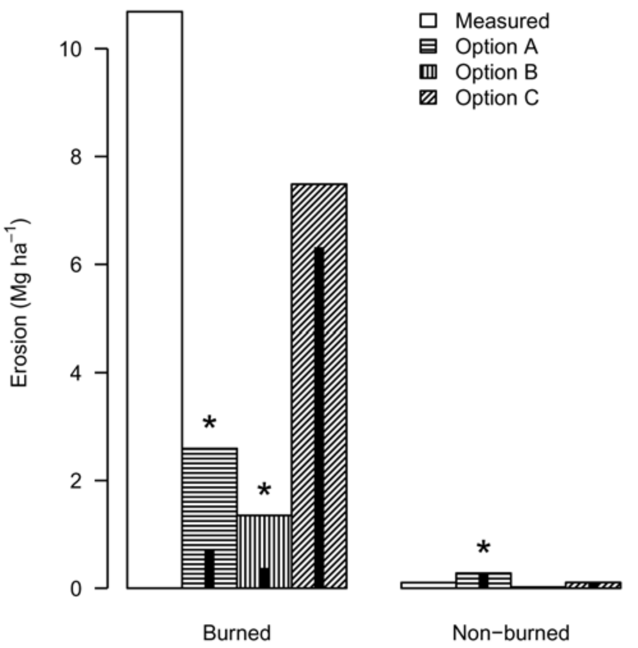

Figure 4. Mean measured and WEPP estimated erosion for three parameterization options. Solid vertical line in the center of each bar is the mean WEPP estimated rill erosion. WEPP estimated erosion values within a treatment that are marked above the bar with an asterisk are significantly different (α = 0.05) from the mean measured value.

Table 2. Mean WEPP estimated and optimized runoff and erosion parameters for burned and non-burned treatments.

Parameter	Units	Burned	Non-burned
WEPP estimated			
K_e	mm h^{-1}	8.97	11.31
K_r	s m^{-1} x 10^3	0.629	0.629
τ_c	Pa	0.939	0.939
$K_{i,adj}$ [a]	kg s m^{-4} x 10^{-6}	0.3470	0.0001
Optimized values			
K_e	mm h^{-1}	20.66	44.79
K_r	s m^{-1} x 10^3	67.290	1.132[b]
τ_c	Pa	0.0001	0.0001

[a] Adjusted interrill erodibility.
[b] Mean of the five non-burned plots with runoff.

increase. The increase in WEPP estimated erosion due to fire was predominately due to an increase in interrill erosion (fig. 4). Pierson and others (2003) found that for similar sites rill erosion dominated total sediment yield compared to interrill erosion. Therefore, it was assumed the majority of error in WEPP estimated erosion under Option B was due to error in estimated rill erodibility (K_r) and perhaps critical shear (τ_c) parameters.

Optimized K_r values were greater than WEPP estimated values regardless of treatment (table 2). When we optimized K_r values (Option C), WEPP estimated and measured erosion converged (within 0.02 Mg ha^{-1}) in only three of the eight burned plots. The K_r values for these plots ranged from 0.00373 to 0.02470 s m^{-1} compared to the model estimated value of 0.00063 s m^{-1}. The remaining five burned plots had such high measured erosion values that WEPP underpredicted erosion even using the highest allowable value for K_r (0.09999). On all eight non-burned plots (only five of which produced runoff), good agreement was achieved with optimized K_r values (fig. 4). Optimized K_r values for the non-burned plots ranged from 0.00037 to 0.00296 s m^{-1} compared with a model estimated value of 0.00063 s m^{-1} (table 2) that did not vary between burned and non-burned conditions.

Prescribed fire increased K_r values by nearly two orders of magnitude (table 2). It seems reasonable that loss of surface soil organic matter by fire (Soto and Diaz-Fierros 1998) could result in increased rill erodibility. Fire consumes organic matter that binds soil particles together making them more difficult to detach (Pierson and others 2001). Currently, WEPP has no mechanism to incorporate this effect. This paper shows that appropriate adjustments to K_r could provide improved erosion predictions. However, adjustments in WEPP parameter estimation procedures for Darcy-Weisbach roughness coefficients, rill width, and rill depth may also aid in improving rill erosion predictions following fire. Future work will explore these options.

Summary

Runoff and erosion from high intensity storms on steep sagebrush rangeland were greatly increased immediately after prescribed burning. Runoff was generated more rapidly and in larger volume from burned areas compared to non-burned areas. Soil erosion increased 100 times following the prescribed fire. The rangeland WEPP model significantly underestimated soil erosion after fire. The model was unable to achieve agreement with measured erosion values even using optimized infiltration (K_e) and rill erosion parameters (K_r and τ_c). The WEPP model does not currently provide sufficient mechanisms to adequately model the impacts of fire on soil erosion. Improvements are needed in estimated adjustments to K_e and K_r to account for changes in surface cover and organic matter decreases following burning. In addition, adjustments to other factors such as the hydraulic radius and Darcy-Weisbach roughness coefficients need to also be considered.

Literature Cited

Elliot, W. J.; Robichaud, P. R.; Hall, D. E.; Cuhaciyan, C. O.; Pierson, F. B.; Wohlgemuth, P. M. 2001. A probabilistic approach to modeling erosion for spatially-varied conditions. American Society of Agricultural Engineers Annual Meeting, Sacramento, CA. July 2001. Paper No. 01-8006. 16 p.

Flanagan, D. C.; Ascough II, J. C.; Nicks, A. D.; Nearing, M. A.; Laflen, J. M. 1995. Chapter 1. Overview of the WEPP erosion prediction model. In: D. C. Flanagan and M. A. Nearing, editors. USDA-water erosion prediction project: Technical documentation. USDA-ARS National Soil Erosion Research Laboratory, NSERL Report No. 10, West Lafayette, IN.

Foster, G. R. 1982. Modeling the erosion process. In: C. T. Haan; Johnson, H. P.; Brakensiek, D. L. (Eds). Hydrologic modeling of small watersheds. ASAE Monograph No. 5, Saint Joseph, MI.

Foster, G. R.; Flanagan, D. C.; Nearing, M. A.; Lane, L. J.; Risse, L. M.; Finker, S. C. 1995. Chapter 11. Hillslope erosion component. In. D. C. Flanagan; Nearing, M. A., editors. USDA-water erosion prediction project: Technical documentation. USDA-ARS National Soil Erosion Research Laboratory, NSERL Report No. 10, West Lafayette, IN.

Holland, M. E. 1969. Colorado State University experimental rainfall-runoff facility, design and testing of rainfall system. Colorado State University experiment station, CER 69-70 MEH 21.

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.

Pierson, F. B.; Robichaud, P. R.; Spaeth, K. E.; Moffet, C. A. 2003. Impacts of fire on hydrology and erosion in steep mountain big sagebrush communities. p. 625-630. In: Renard, K. G.; McElroy, S. A.; Gburek, W. J.; Canfield, H. E; Scott, R. L., (eds.) First Interagency Conference on Research in the Watersheds, October 27-30, 2003. U.S. Department of Agriculture, Agricultural Research Service.

Robichaud, P. R.; Elliot, W. J.; Hall, D. E.; Pierson, F. B.; Moffet, C. A. 2004. Erosion risk management tool (ERMiT). Available at: http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/ermit/ermit.pl, United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Moscow, ID.

Soto, B.; Diaz-Fierros, F. 1998. Runoff and soil erosion from areas of burnt scrub: comparison of experimental results with those predicted by the WEPP model. Catena 31:257-270.

The Authors

[1] Rangeland Scientist, USDA-ARS, Dubois, ID. cmoffet@pw.ars.usda.gov

[2] Research Hydrologist, USDA-ARS, Northwest Watershed Research Center, Boise, ID.

[3] Rangeland Hydrologist, USDA-NRCS, Ft. Worth, TX.