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Modeling soil erosion on steep sagebrush rangeland before and after prescribed fire

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Abstract

Fire in sagebrush rangelands significantly alters canopy cover, ground cover, and soil properties which influence runoff and erosion processes. Runoff can be generated more quickly and in larger volume following fire resulting in increased risk of severe erosion and downstream flooding. The Water Erosion Prediction Project (WEPP) model was developed to predict erosion on cropland, forest, and rangeland. WEPP is a tool that has potential to model the effect of fire on hillslope hydrological processes and help managers address erosion and runoff risks following fire. Experimental results on a steep (35 to 50% slope) sagebrush site suggest that rill erosion is the dominant erosion process following fire and the WEPP parameterization equations related to the rill erosion process need improvements. Rill detachment estimates could be improved by modifying regression-estimated values of rill erodibility. Also, the interactions of rill width and surface roughness on soil shear stress estimates may also need to be modified. In this paper we report the effects of prescribed fire on runoff, soil erosion, and rill hydraulics and compare WEPP estimated erosion for several modeling options with measured erosion.
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Keywords: WEPP; Rill erosion; Darcy–Weisbach roughness; Shear stress; Rill erodibility; Rill width

1. Introduction

The effects of fire on the risk of runoff and erosion can be significant in steep sagebrush rangelands until ground and canopy cover recover. The consequence of fire on runoff and erosion will depend on the weather pattern during the recovery period. Current trends in soil erosion modeling under various management scenarios (including fire) consist of analyzing erosion in probabilistic terms to account for storm variability which requires accurate event-based erosion estimates (Elliot et al., 2001; O'Dea and Guertin, 2003). Under this probabilistic 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 (Nearing et al., 1989; Flanagan et al., 1995) provides event-based erosion estimates and is used to estimate exceedance probabilities for erosion following fire (Robichaud et al., 2005).

Soto and Díaz-Fierros (1998) measured runoff and erosion from natural rainfall on burned and non-burned plots with similar vegetation, slopes and soil textures on gorse (*Ulex europaeus*) shrublands in northwest Spain over a 4-year period. Total runoff from the burned plots was 69% greater than from non-burned plots during the 4-year study. Measured erosion was significantly higher from the burned area than from the control during the first 2 years after fire. In a rainfall simulation experiment, Johansen et al. (2001) reported that erosion and runoff increased due to wildfire on loamy, 5% slope rangelands in New Mexico. Erosion increased by a factor of 25 while runoff

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increased by a factor of 2. In Arizona, on a gravelly loam soil (1 to 3% slope) O'Dea and Guertin (2003) reported smaller fire effects on erosion (increased by a factor of 1.4) with similar effects on runoff.

Soto and Díaz-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. They attributed this to one large rainfall event (50.3 mm) when water repellency was severe. Soto and Díaz-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 model improvement in rangeland WEPP to better represent fire effects on rangelands.

2. Theory

The WEPP model treats interrill and rill erosion as separate processes (Nearing et al., 1989). Under the rangeland option in WEPP, interrill erosion is computed as a function of soil interrill erodibility (K_i adjusted for canopy and ground cover in the interrill area), effective rainfall intensity, interrill runoff rate, and runoff duration (Foster, 1982; Foster et al., 1995). Interrill erosion on undisturbed rangeland has been well studied and is typically low (Hester et al., 1997; Pierson et al., 2001, 2002b; Moffet et al., 2005).

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 as a function of excess soil shear stress (Foster, 1982; Nearing et al., 1989; Foster et al., 1995):

$$D_{rc} = \begin{cases} K_r(\tau_f - \tau_c) : \tau_f > \tau_c \\ 0 : \tau_f \leq \tau_c \end{cases} \tag{1}$$

where D_{rc} is the rill detachment capacity (kg m^{-2} s^{-1}), τ_f is the soil shear stress due to rill flow (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 rill detachment rate (D_r, kg m^{-2} s^{-1}) is equal to rill detachment capacity for clear water flow, but as sediment load (G, kg m^{-1} s^{-1}) approaches the sediment transport capacity (T_c, kg m^{-1} s^{-1}), D_r approaches 0:

$$D_r = D_{rc}\left(1 - \frac{G}{T_c}\right) \tag{2}$$

where

$$T_c = k_t \tau_f^{3/2} \tag{3}$$

The adjusted transport coefficient (k_t, m$^{0.5}$ s^2 kg$^{-0.5}$) is computed as a function of soil particle characteristics and soil shear stress using a modification of the Yalin (1963) equation as described by Foster (1982). Further adjustment, is made to k_t for sandy soils by the adjustment factor, k_{adj} (Foster et al., 1995). On soils with surface sand content less than or equal to 50% $k_{adj}=1$ and above 50% k_{adj} decreases with increasing sand content.

The cumulative rill detachment (kg) from a hillslope segment with net soil loss is

$$E_r = D_r w l t_{RO}\left(\frac{w_h}{w_r}\right) \tag{4}$$

where w is the rill width (m), l is the segment length (m). t_{RO} is the effective runoff duration (s), w_h is the hillslope width (m), and w_r is the rill spacing (width between rill centers, m). Each overland flow element (OFE), a section of hillslope with similar soil and management, is divided into 100 slope segments.

The values for K_r and τ_c are WEPP input parameters. In rangeland WEPP these parameters are determined from soil properties and are only adjusted for freezing and thawing effects. Rill soil shear stress, τ_f, is a function of ground cover and soil surface characteristics, slope, and rill flow characteristics:

$$\tau_f = \gamma R_h \sin\left(\tan^{-1}(S)\right)\left(\frac{f_s}{f_t}\right) \tag{5}$$

where γ is the specific weight of water (9807 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^{-1}). 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, rill area ground cover (litter, rock, plant bases, and cryptogams), and random roughness. In rangeland WEPP, f_t is empirically estimated from ground cover and random roughness parameters, but under uniform flow conditions the definition is

$$f_t = \frac{8gR_hS}{V^2} \tag{6}$$

where g is the acceleration due to gravity (9.807 m s^{-2}) and V is the mean flow velocity (m s^{-1}).

The rill hydraulic radius (R_h) is computed assuming a rectangular cross-section as functions of width (w) and depth (d). In WEPP, width is a function of rill discharge (q, m^3 s^{-1}) (Gilley et al., 1990):

$$w = aq^b \tag{7}$$

where $a=1.13$ and $b=0.303$. Given the rill discharge, slope, width, and Darcy–Weisbach roughness coefficient, depth is computed by WEPP as

$$d = \frac{\left(\frac{q}{C\sqrt{S}}\right)^{2/3}(w+2d)^{1/3}}{w} \tag{8}$$

where C is the Chezy discharge coefficient ($C = \sqrt{8g/f_t}$).