New Erodibility Parameterization for Applying WEPP on Rangelands Using ERMiT

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Highlights

- A practical parameterization approach to estimate erodibility was developed for WEPP applications on rangelands.
- Soil texture had a greater effect on rill erodibility than vegetation cover.
- Vegetation cover had a greater effect on interrill erodibility than soil texture.
- A new set of erodibility input parameters was defined for ERMiT applications on rangelands.

Abstract. *The USDA Water Erosion Prediction Project (WEPP) is a process-based soil erosion prediction model. WEPP uses three soil erodibility parameters: rill erodibility (K_r), interrill erodibility (K_i), and critical hydraulic shear stress (τ_c). In this study, a new parameterization approach for estimating erodibility was developed for WEPP applications on rangelands. Data from overland flow experiments on disturbed and undisturbed rangelands were used to develop empirical equations to predict rill erodibility variation as a function of vegetation cover and soil texture. Data from rainfall simulation experiments were analyzed by piecewise regression to develop empirical equations for predicting the variability of interrill erodibility before and after disturbance and across a wide range of soil textures as a function of vegetation cover and soil texture. Critical shear values corresponding to the developed rill and interrill erodibility parameters were proposed. Our results show that the new erodibility approach predicts erosion at the plot scale with a satisfactory range of error (PBIAS =35.6 and Nash-Sutcliffe efficiency = 0.49). The new approach was used to provide soil erodibility values for the Erosion Risk Management Tool (ERMiT), which uses WEPP as the runoff and erosion calculation engine.*

Keywords. *ERMiT, Erosion, Interrill, Rangeland management, Rill, Shrub, Soil burn severity, WEPP.*

The USDA Water Erosion Prediction Project (WEPP) computer model (Flanagan and Nearing, 1995) is a process-based soil erosion prediction technology developed by the USDA-ARS for application to hillslopes and small watersheds. Erodibility parameter estimation equations in the original WEPP model were developed from multiple rainfall and runoff simulation experiment datasets collected by the USDA-ARS and USDA-NRCS. These simulation data were collected as part of the WEPP Cropland and Rangeland Field Experiments (Johnson and Blackburn, 1989; Simanton et al., 1991; Laflen et al., 1991), as well as by the Interagency Rangeland Water Erosion Team (IRWET) and National Range Study Team (NRST) (Franks et al., 1998; Pierson et al., 2002). The studies represent a wide scope of soil textures and rangeland vegetation community types throughout the western U.S. The respective dataset includes plot-scale data for a natural treatment (undisturbed) and bare treatment (standing vegetation was removed to the ground by clipping, and vegetation ground cover was removed by hand) (Johnson and Blackburn, 1989). The original WEPP erodibility parameter estimation equations were developed from a portion of these data as baseline equations. The baseline equations were then adjusted by adding more parameters. This approach resulted in many equations with several input parameters needed to estimate erodibility values. Some of these parameters are not readily available for model users, such as random roughness, organic matter, soil field capacity, and root biomass in the top 10 cm (Flanagan and Livingston, 1995).

The Erosion Risk Management Tool (ERMiT) is a web-based application that uses WEPP technology to predict erosion in probabilistic terms on burned and recovering forest, range, and chaparral lands, with and without the application of mitigation treatments (Robichaud et al., 2007). The current version of ERMiT uses parameters for rangelands derived from limited experimental data. Knowledge of rangeland hydrologic and erosion processes has greatly improved

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since ERMiT was first released in 2006 (Williams et al., 2016a), and more data are now available to improve rangeland erodibility parameterization across a wide variation of surface conditions, soils, and vegetation (Pierson et al., 2007, 2008, 2009, 2010; Williams et al., 2016b, 2020). Applications of WEPP in ERMiT have been analyzed and validated in forest lands (Robichaud et al., 2016). However, model performance for rangelands has not been validated against measured hillslope erosion rates or sediment yields.

The goal of this study is to develop a new broadly applicable parameterization approach to estimate erodibility on undisturbed and disturbed rangelands for WEPP using readily measurable vegetation cover and soil texture data. Specific objectives of this study are to: (1) develop empirical equations that predict the rill erodibility (K_r) parameter for undisturbed and disturbed rangeland, (2) develop empirical equations that predict the interrill erodibility (K_i) for undisturbed and disturbed rangeland, and (3) use the new equations to define a set of erodibility input parameters for ERMiT applications on rangelands.

WEPP Model Algorithms

The WEPP erosion algorithms are described in detail by Flanagan and Nearing (1995). We have summarized the equations from Flanagan and Nearing (1995) that were needed to determine soil erodibility from field research data.

Rill Erosion

The WEPP rill detachment capacity equation for clear water is:

$$D_c = K_r\left(\tau_s - \tau_c\right) \quad (1)$$

where
D_c = detachment capacity of a rill (kg s^{-1} m^{-2})
K_r = rill erodibility (s m^{-1})
τ_s = hydraulic shear stress from rill flow (N m^{-2})
τ_c = critical shear stress of the soil (N m^{-2}).

Hydraulic shear stress is calculated using the following equation:

$$\tau_s = \left(\frac{f_s}{f_t}\right)\gamma R_h \sin\left[\tan^{-1}\left(S\right)\right] \quad (2)$$

where
f_s = hydraulic friction factor due to the soil grains
f_t = total Darcy-Weisbach friction factor
γ = specific weight of water (kg m^{-2} s^{-2})
R_h = hydraulic radius (m)
S = mean plot slope (m m^{-1}).

The ratio of soil grain friction to total friction is calculated as follows (Flanagan and Nearing, 1995):

$$\frac{f_s}{f_t} = 1.11 \div \left[1.11 + 42.76\left(1 - e^{77.3rr}\right) + 1.85 rock + 113.73 litter^3 + 0.5\left(125.91 bascry^{0.8}\right)\right] \quad (3)$$

where
rr = surface random roughness (m)
$rock$ = rock cover (m^2 m^{-2})
$litter$ = litter cover (m^2 m^{-2})
$bascry$ = basal plant and cryptogam cover (m^2 m^{-2}).

Interrill Erosion

Interrill erosion rate is estimated by (Flanagan and Nearing, 1995):

$$D_i = K_{iadj} I q S_r F_n\left(\frac{R_S}{w}\right) \quad (4)$$

where
D_i = interrill detachment rate (kg s^{-1} m^{-2})
K_{iadj} = adjusted interrill erodibility of the soil, having incorporated a number of vegetation factors
I = rainfall intensity (m s^{-1})
q = runoff rate (m s^{-1})
S_r = sediment delivery ratio
F_n = adjustment factor to account for sprinkler irrigation nozzle impact energy variation
R_S = spacing of the rills (m)
w = rill width (m).

The sprinkler irrigation nozzle factor (F_n) is assigned a value of 1.0 for all WEPP simulations that exclude sprinkler irrigation. If the rill width is set equal to the rill spacing, and the rill width type is set as permanent in the input files, then broad sheet flow conditions will be assumed for flow shear stress and transport computations. If the initial rill width is set to zero and the rill width type is set to permanent, then WEPP will set the rill width to the rill spacing, functionally forcing the model to assume broad sheet flow (Flanagan and Livingston, 1995), which simplifies the equation to:

$$D_i = K_{iadj}\ S_r\ Iq \quad (5)$$

The most relevant factors are canopy cover, ground cover, slope, and live and dead root biomass:

$$K_{iadj} = K_i C_{Can} C_{GC} C_S C_{lr} C_{dr} \quad (6)$$

where
K_i = interrill erodibility of the soil (kg s m^{-4})
C_{Can} = canopy adjustment factor
C_{GC} = ground cover adjustment factor
C_S = slope adjustment factor
C_{lr} = adjustment factors for live roots
C_{dr} = adjustment factors for dead roots.

The units for all adjustment factors are decimal fractions between 0 and 1. The adjustment factors are predicted by the following equations (Flanagan and Nearing, 1995):

$$C_{Can} = 1 - 2.941\frac{cancov}{h}\left[1 - e^{-0.34h}\right] \quad (7)$$

where $cancov$ is the canopy cover (fraction), and h is the canopy height (m).

$$C_{GC} = e^{-2.5 inrcov} \quad (8)$$

where $inrcov$ is the interrill cover (0 to 1).

$$C_S = 1.05 - 0.85e^{-4\sin\Omega} \quad (9)$$

where Ω is the interrill slope angle (rad).

$$C_{lr} = e^{-0.56 l_r} \text{ and } C_{dr} = e^{-0.56 d_r} \quad (10)$$

where l_r is the live root biomass (kg m^{-2}), and d_r is the dead root biomass (kg m^{-2}).

The interrill slope angle is set to be the plot slope angle for broad sheet flow where rill width is equal to rill spacing or when plot slope is larger than interrill slope. Typical values for l_r for rangeland plant communities are one-third the aboveground live biomass, and typical values for d_r are 0.1 and 0.2 for sod grass and bunch grass plant communities, respectively (Elliot and Hall, 2010). In cropland modeling, an additional adjustment factor addresses surface sealing following tillage.

ERMiT Application of WEPP Model

In the ERMiT model, the vegetation effects on soil erodibility are minimized with minimal plant growth, senescence, and residue decomposition (Robichaud at al., 2007). The inputs to the ERMiT application are intended to describe canopy and surface residue as part of the K_r and K_i soil properties. This will not affect parameterizing K_r, but it reduces K_{iadj} to consider the slope factor only as all other factors are incorporated in K_i for ERMiT. Thus, equation 5 can be simplified to consider only the slope factor:

$$D_i = K_i \, S_r \, I \, q C_S \quad (11)$$

Materials and Methods

Rill Erodibility Measurement

The data used to develop the equation to estimate K_r values were obtained from rangeland field overland flow experiments by the USDA-ARS Northwest Watershed Research Center in Boise, Idaho (table 1). The experiments were conducted on sites with diverse landscapes, where most exhibit some degree of wildfire or prescribed fire. In these experiments, overland flow was applied on each plot for a range of flow rates over near-saturated surface soil conditions. Each flow release rate (experimental run) was applied for 12 min using a flow regulator. In the early experiments (before 2006), the applied flow release rates were 3, 7, 12, 15, 21, and 24 L min^{-1}, while they were 15, 30, and 45 L min^{-1} in the later experiments, with the exception of the Breaks site in 2004 for which the flow release rates were 3, 7, 12, 15, 21, 24, and 48 L min^{-1}. Soil texture, vegetation foliar cover, vegetation ground cover (litter, basal plant, and cryptogam), rock cover, ground surface slope, flow depth, flow width, flow velocity, runoff, and sediment delivery rates were measured for each experimental run.

The experimental runs resulted in two runoff categories: concentrated flow runs, and sheet flow runs. For the current study, concentrated flow runs in the dataset were separated from sheet flow runs by comparing the hydraulic radius to the flow depth for the respective flow path (Al-Hamdan et al., 2013). Only experimental runs with concentrated flow were used to determine rill erodibility. The overland flow discharge for each experimental run in the dataset was calculated as the average of the flow release rate and the outflow rate measured as runoff at the respective plot outlet.

Previous studies showed that critical shear stress approaches zero or is negative when deriving sediment

Table 1. Location, land management treatments, dominant plant community, soil series and texture, and slope for each rangeland site used to develop the rill erodibility regression equation. More detailed site descriptions can be found in site-specific references at the bottom of the table.

Site	State	Treatment	Plant Community	Soil Type	Sand %	Silt %	Clay %	Slope %
Breaks[a]	Idaho	Burned[b], untreated	Sagebrush steppe	Kanlee-Ola course sandy loam	73	24	3	35 to 57
Castlehead[c]	Idaho	Burned[b], cut (short-term impact[d]), untreated	Western juniper, sagebrush steppe	Mulshoe-Squawcreek-Gaib stony loam	46 to 64	33 to 49	3 to 6	13 to 24
Denio[e]	Nevada	Burned[b], untreated	Sagebrush steppe	Ola boulder sandy loam	69 to 84	10 to 24	7	26 to 66
Marking Corral[f]	Nevada	Burned[b], cut (short-term impact[g]), untreated	Single-leaf pinyon, Utah juniper, sagebrush steppe	Segura-Upatad-Cropper gravelly loam	66	30	4	6 to 21
Onaqui[f]	Utah	Burned[b], tree mastication, cut (short-term impact[g]), untreated	Utah juniper, sagebrush steppe	Borvant gravely loam	56	37	7	9 to 26
Steens[h]	Oregon	Cut (long-term impact[i]), uncut	Western juniper, sagebrush steppe	Pernty gravelly cobbly silt loam	45 to 46	38 to 39	15 to 17	16 to 22
Upper Sheep[j]	Idaho	Burned[b], untreated	Sagebrush steppe	Harmel silt or Harmel silt loam	30 to 56	31 to 52	14 to 18	12 to 39

[a] Pierson et al. (2009) and Moffet et al. (2007).
[b] Experiments conducted 0, 1, 2, and 3 years post-fire at Denio; 0, 1, and 2 years post-fire at Breaks; 1 and 2 years post-fire at Marking Corral and Onaqui; and 1 year post-fire at Castlehead and Upper Sheep.
[c] Pierson et al. (2013) and Williams. et al. (2014).
[d] Experiments conducted immediately after cutting.
[e] Pierson et al. (2008).
[f] Pierson et al. (2010, 2015).
[g] Experiments conducted one year after cutting.
[h] Pierson et al. (2007).
[i] Experiments conducted ten years after cutting.
[j] Flerchinger and Cooley (2000) and Williams et al. (2016b).

detachment data from concentrated overland flow experiments on rangelands (e.g., Moffet et al., 2007; Wagenbrenner et al., 2010; Al-Hamdan et al., 2012). In these experiments, the concentrated flow paths are considered instantaneous initiated rills. Starting from the first collected sediment sample, the erosion is considered from rill detachment. Therefore, for these experiments, equation 1 can be approximated as:

$$D_c = K_r\left(\tau_s\right) \tag{12}$$

The measured detachment capacity for each experimental run was calculated using the approximation solution of the following equation developed by Al-Hamdan et al. (2012):

$$D_c = \frac{D_r}{\left(1-0.5\left(\frac{q_s}{T_c}\right)\right)} = \frac{\frac{q_s}{wl}}{\left(1-0.5\left(\frac{q_s}{T_c}\right)\right)} \tag{13}$$

where

D_r = calculated detachment rate (kg s^{-1} m^{-2})

q_s = minimum measured sediment transport rate (kg s^{-1}) at the plot outlet collected by runoff samples

w = measured rill width (m)

l = length of the plot (4 m)

T_c = rill transport capacity (kg s^{-1}).

T_c was estimated using a derivation from Yalin's bed load transport theory (Yalin, 1963) as modified for the WEPP model (Finkner et al., 1989):

$$T_c = wB\tau_s^{1.5} \tag{14}$$

where w is the rill width (m), and B is the transport coefficient (s^2 m$^{0.5}$ kg$^{-0.5}$).

Transport coefficient values were obtained from Elliot et al. (1989), who presented estimates for values of B for 36 different soil sites. Each site in table 1 was assigned a B value from the Elliot et al. (1989) data set that was most comparable to its soils (similar in soil texture fractions).

Equations 2, 3, 12, 13, and 14 were applied using rill hydraulic and sediment delivery observations to estimate the rill erodibility from each set of flow rates. Regression relationships were then developed between the mean rill erodibility properties for each plot and the plot soil texture, ground cover, and vegetation properties. To be consistent across all the experiment years, only overland flow experimental runs with a high flow release rate (larger than 15 L min^{-1}) were used to calculate measured K_r using equation 12. The data used to develop the K_r estimation equation have vegetation foliar cover ranges from almost zero to 100%, silt value ranges from 10% to 52%, and clay value ranges from 3% to 18%.

Interrill Erodibility Measurement

The data used for developing the interrill erodibility parameter estimation equations included rainfall simulation experiment data collected for WEPP (Johnson and Blackburn, 1989; Simanton et al., 1991; Laflen et al., 1991), IR-WET, and NRST (Franks et al., 1998; Pierson et al., 2002) studies. In these studies, a rotating-boom rainfall simulator (Swanson, 1965) was used to apply rainfall to each plot for 30 min at 60 mm h^{-1} intensity on pre-wet soil conditions. Approximately 24 h prior to this application, each plot was pre-wet with rainfall at a rate of 60 mm h^{-1} over a 1 h duration using the rotating-boom simulator on antecedent soil moisture conditions. The experimental data include a natural treatment (undisturbed) and a bare treatment (standing vegetation was removed to the ground by clipping, and ground cover was removed by hand) (Johnson and Blackburn, 1989). Plots were 10.7 m long and 3.05 m wide. The amounts of vegetation foliar cover and vegetation ground cover and the dominant plant life form were determined for all plots prior to rainfall simulation using point-frequency frame measures. The vegetation community for each plot was classified based on the dominant plant life form. The combined data sets cover a wide scope of soil textures and vegetation types (table 2). Soil texture, ground surface slope, runoff, and sediment delivery rates were measured for each plot using methods described by Johnson and Blackburn (1989), Simanton et al. (1991), and Laflen et al. (1991). For the current study, the erodibility parameter (K_i, kg s m^{-4}) was calculated for each plot by applying equation 4 and the respective measured runoff, sediment delivery, and rainfall intensity from the rainfall simulation experiments.

The interrill detachment rate (D_i) in equation 11 was calculated as the sediment delivery rate divided by the plot area with the assumption that the sediment detachment in these experimental runs is dominated by rain splash and thin sheet flow, while the major role of concentrated flow paths is transporting the splash- and sheet-detached sediments (Al-Hamdan et al., 2017). The data used to develop the estimation equation have vegetation ground cover and foliar cover ranges from 1% to 84% and from 0% to 92%, respectively.

Critical Shear Stress for Rill Erosion

The minimum values of critical shear stress for each soil texture were determined by running the WEPP model for each interrill experimental run at different τ_c values, starting with zero and incrementing by 0.05 N m^{-2}. The smallest critical shear stress that resulted in zero rill detachment rate represents the τ_c value necessary to meet the assumption made for calculating the interrill detachment rate (D_i) in equation 4 for that run (i.e., erosion in WEPP-IRWET experimental runs is dominated by rain splash and thin sheet flow).

Data Used for Model Evaluation

The data used to evaluate the new erodibility equations in the model were obtained from independent rainfall simulation experiments (table 3) (Pierson et al., 2007, 2009, 2010, 2013; Moffet et al., 2007; Williams et al., 2014). These experiments used a Colorado State University type rainfall simulator (Holland, 1969) consisting of multiple stationary sprinklers elevated 3.05 m above the ground surface. Data were obtained for multiple sites, including historical sagebrush sites that have been encroached by conifers and/or burned by prescribed fire or wildfire. Plot length in this group varied from 6 to 7 m, and width varied from 2 to 5 m. The rainfall intensity and duration varied among sites. In most cases, plots were pre-wetted by applying rainfall

Table 2. Characteristics and locations of the experimental sites used to develop the interrill erodibility parameterization equations.

Site	Soil Texture	City	State	No. of Plots	Treatments	Slope
A187[a]	Sandy clay loam	Tombstone	Arizona	4	Natural, bare	0.1
A287[a]	Sandy loam	Tombstone	Arizona	1	Natural	0.04
C187[a]	Silty clay	Sonora	Texas	3	Natural, bare	0.083
Coyote87[b]	Silt loam	Coyote Butte	Idaho	4	Natural, bare	0.101
D187[a]	Sandy loam	Chickasha	Oklahoma	3	Natural, bare	0.05
D287[a]	Sandy loam	Chickasha	Oklahoma	4	Natural, bare	0.05
E287[a]	Loam	Freedom	Oklahoma	3	Natural, bare	0.06
F187[a]	Loam	Sidney	Montana	4	Natural, bare	0.103
G187[a]	Silty clay	Degater	Colorado	2	Bare	0.1
H187[a]	Clay	Cottonwood	South Dakota	1	Bare	0.09
H287[a]	Clay	Cottonwood	South Dakota	4	Natural, bare	0.118
I187[a]	Loam	Los Alamos	New Mexico	4	Natural, bare	0.068
J187[a]	Sandy loam	Cuba	New Mexico	4	Natural, bare	0.07
K187[a]	Loam	Susanville	California	2	Natural	0.11
Nancy87[b]	Silt loam	Reynolds	Idaho	4	Natural, bare	0.059
Summit87[b]	Sandy loam	Summit	Idaho	4	Natural, bare	0.09
D188[c]	Sandy loam	Chickasha	Oklahoma	4	Natural, bare	0.05
D288[c]	Sandy loam	Chickasha	Oklahoma	4	Natural, bare	0.048
E288[c]	Loam	Freedom	Oklahoma	4	Natural, bare	0.06
E588[c]	Loam	Woodward	Oklahoma	3	Natural, bare	0.06
H188[c]	Clay	Cottonwood	South Dakota	2	Natural	0.08
H288[c]	Clay	Cottonwood	South Dakota	1	Natural	0.12
K188[c]	Loam	Susanville	California	3	Natural, bare	0.117
B190[d]	Clay loam	Wahoo	Nebraska	2	Natural	0.1
B290[d]	Clay loam	Wahoo	Nebraska	5	Natural	0.11
C190[d]	Clay loam	Amarillo	Texas	5	Natural	0.03
C290[d]	Loam	Amarillo	Texas	3	Natural	0.02
E191[d]	Silty clay	Eureka	Kansas	6	Natural	0.05
E291[d]	Silty clay	Eureka	Kansas	2	Natural	0.05
E391[d]	Silty clay	Eureka	Kansas	5	Natural	0.03
F191[d]	Sandy clay loam	Akron	Colorado	5	Natural	0.074
F291[d]	Sandy loam	Akron	Colorado	6	Natural	0.08
F391[d]	Sandy clay loam	Akron	Colorado	5	Natural	0.066
G191[d]	Sandy loam	Newcastle	Wyoming	6	Natural	0.06
G291[d]	Sandy loam	Newcastle	Wyoming	5	Natural	0.084
G391[d]	Sandy loam	Newcastle	Wyoming	5	Natural	0.074
H192[d]	Sandy loam	Killdeer	North Dakota	4	Natural	0.123
H292[d]	Sandy loam	Killdeer	North Dakota	6	Natural	0.113
H392[d]	Sandy loam	Killdeer	North Dakota	6	Natural	0.01
I192[d]	Clay loam	Buffalo	Idaho	6	Natural	0.011
I292[d]	Clay loam	Buffalo	Idaho	4	Natural	0.068
J192[d]	Silt loam	Blackfoot	Idaho	6	Natural	0.077
J292[d]	Silt loam	Blackfoot	Idaho	5	Natural	0.08
K192[d]	Loam	Prescott	Arizona	6	Natural	0.052
K292[d]	Loam	Prescott	Arizona	6	Natural	0.05

[a] Simanton et al. (1991).
[b] Johnson and Blackburn (1989).
[c] Laflen et al. (1991).
[d] Franks et al. (1998).

Table 3. Experimental sites used to evaluate the erodibility parameterization scheme.

Site	State	Soil Texture	No. of Plots	Treatment/Disturbance	Slope	Mean Applied Rainfall (mm h^{-1})	Length (m)	Width (m)
Breaks	Idaho	Sandy loam	28	Natural, prescribed fire	0.43	65 for 1 h	6 to 7	5
Castlehead	Idaho	Stony loam	18	Tree encroachment, wildfire	0.17	113 for 45 min	6 to 7	2
Marking Corral	Nevada	Gravelly loam	22	Tree encroachment, prescribed fire	0.10	106 for 45 min	6 to 7	2
Onaqui	Utah	Gravelly loam	29	Tree encroachment, prescribed fire	0.16	109 for 45 min	6 to 7	2
Steens	Oregon	Gravelly silt loam	10	Tree encroachment, ten years after tree cutting	0.19	54 for 1 h	6 to 7	5

simulation for a specific period of time under dry antecedent soil moisture conditions.

ERMiT Parametrization

ERMiT combines the probability of occurrence for three sources of variability (rain event and its associated runoff event occurrence probability, soil burn spatial arrangement occurrence probability, and soil parameter set occurrence probability) to produce sediment delivery predictions for every permutation of input of the three sources of variability. The exceedance probability (%) for each event sediment delivery prediction is computed as the sum of one plus the occurrence probabilities for all greater sediment yield predictions (Robichaud et al., 2007). Erodibility estimation equations developed in this study were used to determine the erodibility parameter values for ERMiT. ERMiT has four soil textural categories: silt loam, sandy loam, clay loam, and loam. Within each category, five erodibility classes reflect the range of erodibility values determined from field studies. The values approximate the mean value and values that are approximately 1 and 2 standard deviations above and below the mean. A probability for each of the values occurring is assigned to each erodibility value. The matrix of erodibility values and probabilities, combined with runoff event occurrence probabilities and soil burn spatial arrangement occurrence probabilities, is used in subsequent calculations to provide an erosion rate that would be exceeded for a given probability (e.g., there is an *xx* probability that the sediment delivery from this hillslope will exceed *yy* Mg ha^{-1}).

Erodibility parameter distributions were calculated for three categories representing three surface conditions: unburned, low-severity fire, and high-severity fire for each texture. We assumed that the distribution of rangeland ground cover would serve as a surrogate for the distribution of soil erodibility on a given site. The probability distribution of ground cover for the unburned treatment was based on the ground cover data of the natural plots of the WEPP IRWET data. The probability distributions of ground cover for low-severity fire and high-severity fire were assumed to be equal to 75% and 25% of the natural ground cover, respectively. These values are based on traditional definitions of fire severity, where high fire severity is when more than 75% of the pre-fire vegetation is removed by burning, and low fire severity is when less than 25% of the pre-fire vegetation is removed by burning (Miller et al., 2009).

Statistical Analysis

Statistical analyses were conducted using SAS version 9.4 (SAS, 2015). Multiple stepwise linear regression analysis was used to derive the relationship between rill and interrill erodibilities as dependent variables and ground and foliar cover attributes, slope, and soil texture as independent variables. Prior to this analysis, values of erodibility were log-transformed (base 10) to address deviation from normality as well as to improve homoscedasticity and linearity (Allison, 1999). Residual plots were used to examine the homoscedasticity and linearity assumptions. Piecewise (segmented) regression analysis was applied where two continuous relationships between the log-transformed interrill erodibility and the independent variables were fitted to improve the linear relationship (Ryan et al., 2002, 2005). The analysis technique PROC NLIN in SAS was used to find the breakpoint at which the relationship between interrill erodibility and vegetation ground cover changes (Ryan and Porth, 2007). A significance level of 0.05 was used for all statistical tests, including the criteria for including variables in the multiple regressions. Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and percent bias (PBIAS) (Gupta et al., 1999) were used to evaluate the applicability of the new erodibility equations in WEPP. NSE was calculated by:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(O_i - M_i\right)^2}{\sum_{i=1}^{n}\left(O_i - O_{avg}\right)^2} \tag{15}$$

and PBIAS was calculated by:

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}\left(O_i - M_i\right)}{\sum_{i=1}^{n}\left(O_i\right)} \times 100 \tag{16}$$

where

O = ith observation to be evaluated

M_i = value simulated by the model for the corresponding ith observation

O_{avg} = average of observed values

n = number of observations.

The NSE value can range from $-\infty$ to 1, where a negative value indicates that the mean value of the observations would have a better representation for the observed data than the model. Performance of sediment predictions for monthly values is considered "very good" when NSE > 0.75, "good" when 0.65 < NSE ≤ 0.75, "satisfactory" when 0.5 ≤ NSE < 0.65, and "unsatisfactory" when NSE < 0.5. Typically, less strict NSE values are acceptable for shorter time steps (e.g., daily or single event). With respect to PBIAS, performance of the sediment prediction for monthly values is considered "very good" when PBIAS < ±15, "good" when ±15 ≤ PBIAS < ±30, "satisfactory" when ±30 ≤ PBIAS < ±55, and "unsatisfactory" when PBIAS ≥ ±55 (Moriasi et al., 2007).

Sensitivity Analysis

Sensitivity analyses of the predictive equations were performed to determine the robustness of the resultant equations for use in the WEPP model. The parameters selected for the analysis were runoff, slope, vegetation ground cover, foliar cover, and soil texture. The ranges of the parameters were selected to cover the entire observation space in this study as well as extreme conditions. The ranges of values were: four soil textures (silt fractions from 0.18 to 0.68, clay fractions from 0.06 to 0.51, and sand fractions 0.1 to 0.8), vegetation ground cover fractions (V_G) (0 to 0.8), total ground cover fractions (0 to 0.9), foliar cover fractions (V_F) (0 to 0.9), slope gradient (0.05 to 0.5), and runoff (2 to 64 mm), all under the conditions of a uniform rainfall of 100 mm h^{-1} for one hour.

Results

Ranges of Erosivity, Erodibility, and Sediment Transport Parameters

The flow shear stress values in the rill experiments that were used to develop the rill erodibility estimation equation varied from 0.1 to 8.1 N m^{-2}. Detachment capacity varied from near zero to 0.0398 kg s^{-1} m^{-2} and was generally highest at burned sites. The transport capacity varied from 0.007 to 0.357 kg s^{-1}. The values of calculated rill erodibility varied from 0.001 × 10^{-4} to 47.8 × 10^{-4} s m^{-1}.

The values of measured sediment transport rate to transport capacity ratio (q_s/T_c) were low, with an average of 2.9%, which indicated that the erosion process in the experiments was not limited in general by transport capacity. Applying equation 13 with q_s/T_c equal to 0.029 showed that on average D_c = 1.015 × D_r. The calculated K_r values were not sensitive to changes in the transport coefficient (B) within the range in this study because the sediment deliveries were well below the sediment transport capacity. Values of B varied from 0.077 to 0.121, so in the worst-case scenario if 0.077 was selected instead of 0.121 in equation 14, the T_c value would decrease by the factor 77/121 = 0.64, and q_s/T_c would increase to 0.045. Applying equation 13 with this q_s/T_c shows that on average $D_c = 1.023 \times D_r$, or a change of less than 1% in D_c and its corresponding K_r.

The values of runoff rate in the rainfall simulation experiments that were used to develop the interrill erodibility estimation equation varied from 1.4×10^{-8} to 1.53×10^{-5} m s^{-1}. The rainfall intensity varied from 1.2×10^{-5} to 2×10^{-5} m s^{-1}. The interrill erodibility varied from 1.5×10^{4} to 3.0×10^{6} kg s m^{-4}. The interrill detachment rate varied from 1.7×10^{-8} to 3.8×10^{-4} kg s^{-1} m^{-2}.

Rill Erodibility Estimation Equation

A multiple regression equation between the logarithm of rill erodibility as a dependent variable and vegetation ground cover (litter cover and plant basal cover) (V_G), rock cover (Ro), clay (Cl), and silt (Si) amounts as independent variables resulted in the following equation:

$$\log(K_r) = -3.4481 - 1.3517 \times V_G - 5.1099 \times Cl + 3.3164 \times Si \quad (17)$$

$$(n = 166,\ \mathrm{R}^2 = 0.44)$$

where all independent variables are in decimal fractions. Although equation 17 has a small R^2 value, it shows that K_r is significantly dependent on vegetation cover and soil texture ($p < 0.05$). This equation was derived from data obtained from a wide range of undisturbed to disturbed (i.e., fire) rangeland sites.

The equation addresses fire impact on rill erodibility indirectly, where high-severity fire results in substantial removal of vegetation cover. In addition, the equation addresses the impact of tree removal management practice on rill erodibility indirectly, where understory vegetation cover increases after tree removal. However, equation 17 shows that soil texture has a greater effect on rill erodibility than the basal plant cover term. For instance, reduction from 100% to 0% vegetation cover would increase rill erodibility for a given soil texture (silt loam) by about 25 times. Silt loam (65% silt, 15% clay) would have about 90 times the rill erodibility of clay loam soils (34% silt, 33% clay) with the same vegetation cover.

Interrill Erodibility Estimation Equation

In general, interrill erodibility was negatively correlated with ground cover and canopy cover. The regression analysis to develop equations that describe the relationship between K_i as the dependent variable and ground cover, foliar cover, slope, and soil texture as independent variables resulted in the following equation:

$$\log_{10} K_i = 5.7836 - 0.841 \times V_G - 0.77 \times V_F - 0.9178 \times Ro \quad (18)$$

$$(n = 181,\ \mathrm{R}^2 = 0.51)$$

where

V_G = area fraction of vegetation ground cover

V_F = area fraction of foliar cover

Ro = area fraction of ground rock cover (m^2 m^{-2}).

The residual of the regression analysis of equation 18 (fig. 1a) shows that even though log transformation improved the homoscedasticity and linearity, these assumptions were not totally satisfied because the equation still overestimated low erodibility values at high ground cover. To address this problem, piecewise regression analysis was applied to develop two continuous linear relationships that intersect at a breakpoint. The piecewise regression analysis showed that the best two-piece regression occurs when the vegetation ground cover of 0.315 is the breakpoint:

$$\log_{10} K_i = \begin{cases} 6.1982 - 3.2458 \times V_G - 0.671 \times V_F - 0.7843 \times Ro & \text{if } V_G \le 0.315 \\ 5.246 - 0.223 \times V_G - 0.671 \times V_F - 0.7843 \times Ro & \text{if } V_G > 0.315 \end{cases} \quad (19)$$

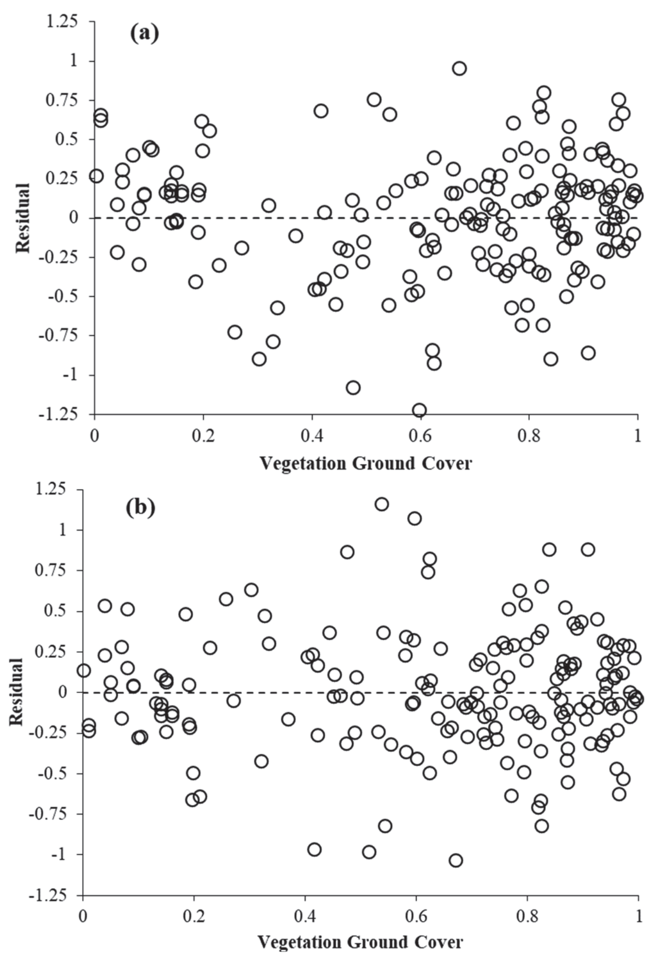

Figure 1. Vegetation ground cover versus regression analysis residual associated with (a) equation 18 and (b) equation 19.

The coefficient of determination in the piecewise regression analysis was greater ($R^2 = 0.57$) than in the analysis resulting in equation 18. Homoscedasticity was also improved by applying the piecewise regression approach as the model ability to predict K_i (i.e., range of residual values) at low and high vegetation ground cover becomes more similar (fig. 1b). Unlike the rill erodibility equation, vegetation cover terms have the greatest effect on the interrill erodibility equation.

Plant life forms (grass, forbs, shrubs) and growth habit (sodgrass, bunchgrass) exhibit significant effects on factors that determine surface hydrology (Spaeth et al., 1996; Pierson et al., 2002; Elliot, 2004; Hernandez et al., 2017). Therefore, it is likely that physically based models such as ERMiT require separate equations for the different dominant life forms. Applying the general linear regression analysis, where plant life form is the categorical variable, along with the piecewise approach, resulted in the following equations, where Sa is the soil sand fraction:

Bunch grass:

$$\log_{10} K_i = \begin{cases} 5.5287 - 2.1358 \times V_G \\ -0.6652 \times V_F + 1.0532 \times Cl & \text{if } V_G \le 0.451 \\ +0.5042 \times Sa - 1.8674 \times Ro \\ \\ 4.5859 - 0.0454 \times V_G \\ -0.6652 \times V_F + 1.0532 \times Cl & \text{if } V_G > 0.451 \\ +0.5042 \times Sa - 1.8674 \times Ro \end{cases} \quad (20)$$

Sod grass:

$$\log_{10} K_i = \begin{cases} 5.3988 - 2.1358 \times V_G \\ -0.6652 \times V_F + 1.0532 \times Cl & \text{if } V_G \le 0.451 \\ +0.5042 \times Sa - 1.8674 \times Ro \\ \\ 4.456 - 0.0454 \times V_G \\ -0.6652 \times V_F + 1.0532 \times Cl & \text{if } V_G > 0.451 \\ +0.5042 \times Sa - 1.8674 \times Ro \end{cases} \quad (21)$$

Shrub:

$$\log_{10} K_i = \begin{cases} 5.9846 - 2.1358 \times V_G \\ -0.6652 \times V_F + 1.0532 \times Cl & \text{if } V_G \le 0.451 \\ +0.5042 \times Sa - 1.8674 \times Ro \\ \\ 5.0418 - 0.0454 \times V_G \\ -0.6652 \times V_F + 1.0532 \times Cl & \text{if } V_G > 0.451 \\ +0.5042 \times Sa - 1.8674 \times Ro \end{cases} \quad (22)$$

Forbs:

$$\log_{10} K_i = \begin{cases} 5.774 - 2.1358 \times V_G \\ -0.6652 \times V_F + 1.0532 \times Cl & \text{if } V_G \le 0.451 \\ +0.5042 \times Sa - 1.8674 \times Ro \\ \\ 4.831 - 0.0454 \times V_G \\ -0.6652 \times V_F + 1.0532 \times Cl & \text{if } V_G > 0.451 \\ +0.5042 \times Sa - 1.8674 \times Ro \end{cases} \quad (23)$$

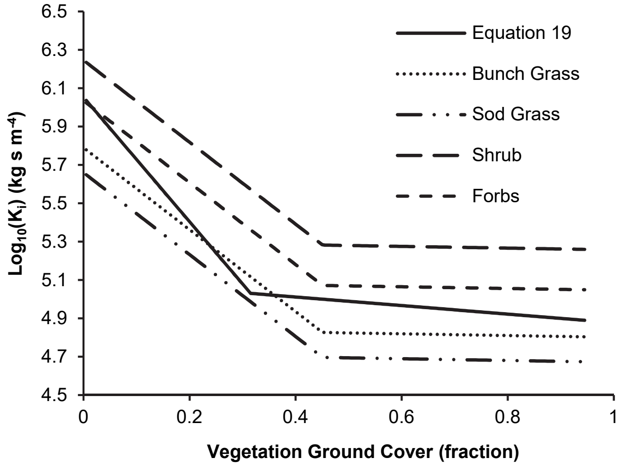

Figure 2. Values of $\log_{10}(K_i)$ using equations 19, 20 (bunch grass), 21 (sod grass), 22 (shrub), and 23 (forbs) versus vegetation ground cover when rock cover is 0.1 and foliar cover is 0.1.

Figure 2 shows an example of values obtained from equations 20 through 23 as a function of vegetation ground cover. Dividing the data into four groups based on the dominant vegetation community by applying the general linear model improved the coefficient of determinant (adjusted $R^2 = 0.63$). Using equation 19 for simplicity instead of equations 20 through 23 will not change prediction performance significantly, given the slight difference in R^2 values between the two methods. However, the variable coefficient values (sensitivity to variables) are different, and soil texture factors are added in the regression that have a significant correlation with erodibility. In addition, using different equations for different vegetation communities might be useful when comparing hydrologic and erosion responses for different undisturbed ecological sites. Even though equations 20 through 23 have small differences in their coefficients, these differences could still lead to a high percentages of difference between two sites with low erosion values because they are logarithmic relationships.

The breakpoint generated by the piecewise regression in equations 20 through 23 identifies a threshold at which there is a substantial change in the rate of erodibility increase with respect to bare soil area and therefore provides an objective means for detecting changes between natural and disturbance phases. The value of 0.451 corroborates with several studies which concluded that the erosion to runoff ratio (erodibility) increases substantially when bare ground exceeds 50% in rangelands (e.g., Al-Hamdan et al., 2013, 2017; Pierson et al., 2013) and 50% in forest environments (Pannkuk and Robichaud, 2003). This is supported by the extensive reviews of the literature on rangeland cover by Gifford (1985) and Weltz et al. (1998), which concluded that ground cover should be maintained above a critical threshold of 50% to 60% to adequately protect the soil surface.

CRITICAL SHEAR STRESS FOR RILL EROSION

The minimum values required for critical shear stress (τ_c) so that the model will not predict rill erosion rates that are larger than interrill erosion rates in the WEPP-ERMiT runs are presented in table 4. These values are not necessarily the

Table 4. Minimum value of critical shear stress (τ_c, N m^{-2}).

Clay	Clay Loam	Loam	Sandy Clay Loam	Sandy Loam	Silt Loam	Silt Clay
0.65	1.05	5.05	5.35	3.65	2.85	0.85

measured critical shear stress but rather a reference to be used for calibration corresponding to the erodibility equations developed in this study. The proposed critical shear values fall within the range of τ_c values recommended for WEPP application (0.3 to 7 N m^{-2}) (Alberts et al., 1995).

Erodibility Equation Evaluations

The new erodibility predictions were tested by running batch executable file of WEPPwin 2012.800. To test the performance of the new erodibility equations, the effective hydraulic conductivity (K_e) was optimized on total volume of runoff. By using optimized K_e values, average total runoff converged within less than a 0.01 mm of the average of the measured values for all plots. The erosion model performance was analyzed in two different parameterization schemes for erodibility. In the first parameterization scheme, interrill erodibility (K_i) was calculated using equation 22. The shrub equation was used to estimate K_i for this evaluation because the evaluation data set is mostly from shrublands or tree-encroached shrublands, while rill erodibility (K_r) was set to almost zero. In this parametrization scheme, the model simulates only interrill erosion while the major role of rills is assumed to be transporting detached sediments. In the second parameterization scheme, K_i is estimated in the same way as in the first scheme. However, K_r was calculated by equation 17, and critical shear stress (τ_c) values were assumed based on table 4. The difference between the results of the first scheme and the second scheme can be used to determine the simulated contributions of rill erosion and interrill erosion to total erosion. The results of the two parameterization schemes were compared to the results of using the erodibility equations suggested in the WEPP user guide for rangelands (Flanagan and Livingston, 1995).

The results when applying the first parameterization scheme show that the overall performance of WEPP using the estimated erodibility had a satisfactory PBIAS of 51.3 and NSE of 0.27 (fig. 3a). These results are a considerable improvement compared to the old rangeland erodibility equations of the WEPP user guide, which has an unsatisfactory PBIAS value of 61.8 (fig. 3c). Even though the use of the first parameterization scheme improved the prediction of the measured sediment yield at highly erodible plots, it underestimated sediment yield at these sites and predicted only about 40% of the measured sediment yield. Applying the second parameterization scheme improved the overall performance of the model, with a lower absolute value of PBIAS (35.6) and a higher NSE (0.49) (fig. 3b). When adding the rill erosion, the model predicted about 60% of the measured sediment yield at highly erodible plots. In addition, the simulated rill erosion contribution was about half of the simulated interrill erosion, which is consistent with most experimental observations where interrill erosion processes are dominant except for extremely disturbed sites (Pierson et al., 2009; Al-Hamdan et al., 2017).

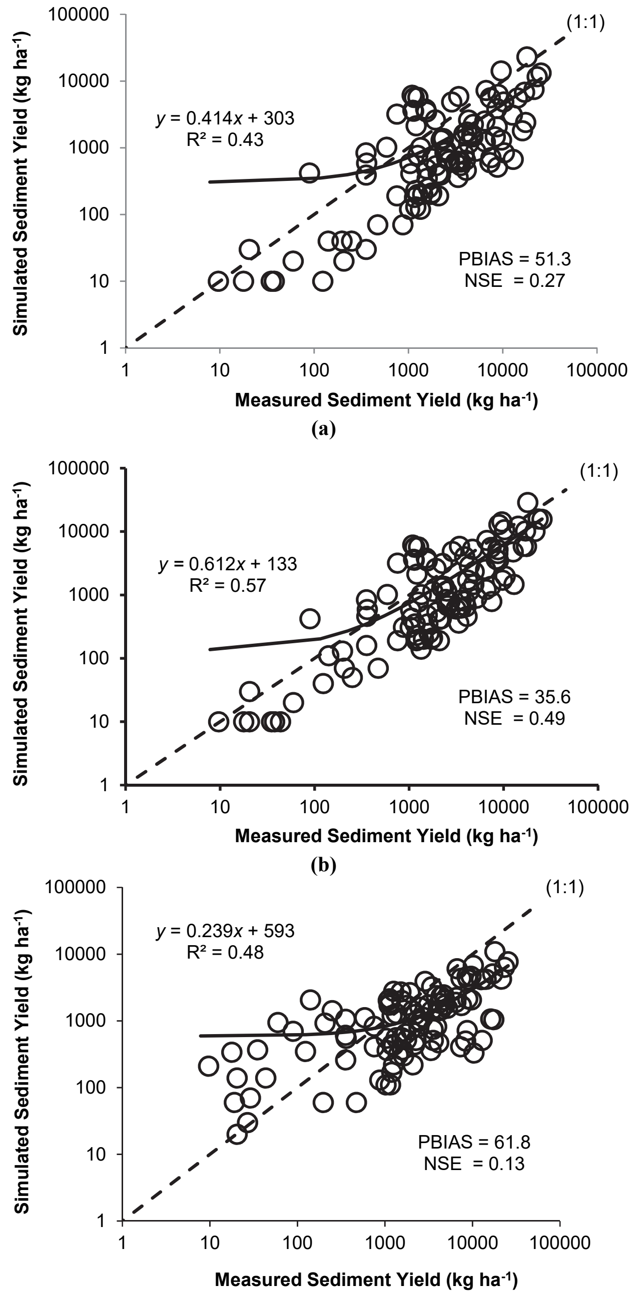

Figure 3. Measured sediment yield versus sediment yield estimated by WEPP when: (a) using equation 22 for estimating K_i and while assuming no rill detachment, (b) using equation 22 for estimating K_i and equation 17 for estimating K_r while obtaining τ_c from table 4, and (c) using equations from NSERL Report No. 10 (Flanagan and Nearing, 1995) and No. 11 (Flanagan and Livingston, 1995).

The margin of error is considered reasonable, given that the dataset used for developing the parameterization equation and the dataset used for the evaluation were obtained using different rainfall simulators. There are a few possible sources of error driving the model bias. One source of error could be the error in the measured values of sediment yield and total runoff. The measured soil erodibility properties were highly variable. Another major source of error could be in measured runoff. Erosion is highly dependent on runoff (Pierson et al., 2010, 2013; Williams et al., 2014); thus,

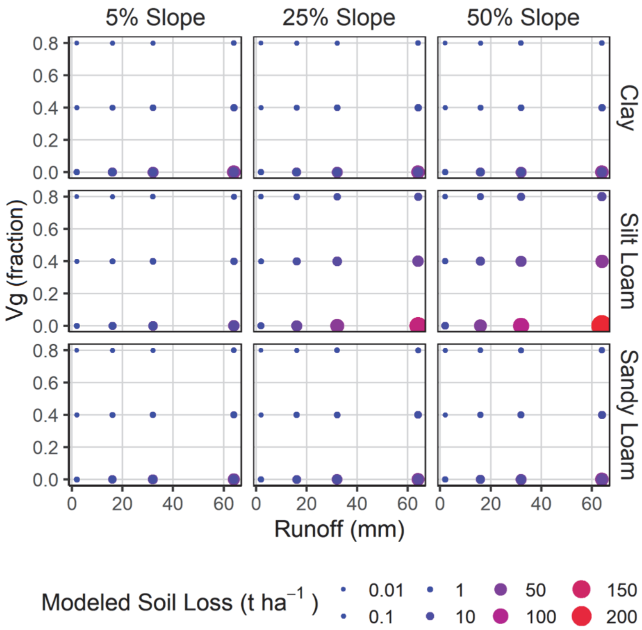

Figure 4. Values of WEPP-modeled soil loss (t ha^{-1}) when using equations 17 and 22 as a function of vegetation ground cover (V_G in fraction), runoff (mm) in an hour duration, soil texture, and slope, all under the conditions of uniform rainfall of 100 mm h^{-1} for one hour.

errors in runoff propagate to less accuracy in erosion prediction. Even though the model was optimized for total runoff, runoff starting time and the shape of the hydrograph (e.g., peak time, rising limb, and recession limb) were not necessarily matched with the experimental values. Given the uncertainty associated with measured data in the rainfall simulation and soil erosion experiments, the model still performed reasonably well. Assigning a fixed critical shear value (table 4) for all plots with similar soil texture could be another source of error. However, using these values improved the overall performance of the model by adding simulated rill erosion only from plots with high sediment yield values. These plots tended to be on burned sites with steep slopes and high silt where incising rills were active (Al-Hamdan et al., 2017). Finally, as for all complex process-based models, the uncertainty in many required input parameters and the complicated structural interactions in the model could be a major source of error.

The sensitivity analysis for WEPP responses using equations 17 and 22 (fig. 4) show that the values of modeled soil erosion varied from 0.01 to 230 t ha^{-1}. The extremely high responses, in hundreds of tons per hectare, only occurred when the soil has high silt content on steep slope gradients with low cover, and large runoff, which results in high rill erosion. Other relatively high responses also occurred with the other soil textures but only with extreme runoff and no cover, as expected. Overall, the responses are reasonable and within typical soil loss values.

ERMiT Parameterization

Erodibility equations 17, 20, and 22 were used to provide ERMiT with K_r and K_i values. Table 5 shows the vegetation, ground, and foliar cover values associated with each treatment based on the probability of having a specific value of ground cover: 10% (5th percentile), 20% (20th percentile), 40% (median), 20% (80th percentile), and 10% (95th percentile) of the probability distribution of ground cover based on the WEPP-IRWET data. To ensure that total ground cover does not exceed 100%, the rock cover values in table 5 were estimated by finding the distribution of rock cover for the bare plots with zero vegetation ground cover and then reducing the value of rock cover based on the percentage of vegetation ground cover of the corresponding percentile for each category. For instance, the 95th percentile of rock cover values in bare grass plots was 0.32. Because the 95th percentile of vegetation ground cover for unburned grass is 0.46, it was assumed that 0.46 of the rock was covered by vegetation (i.e., the 95th percentile of rock cover values for all grass plots was reduced by 0.46 and became 0.173). The values in table 5 were used to assign the independent variables for the erodibility equations.

Table 6 shows the K_r values developed for ERMiT using equation 17, and table 7 shows the K_i values developed for ERMiT using equations 20 and 22 for grass and shrub, respectively. The bunch grass equation was selected for the grass category because it is more common on rangelands. Initial values for critical shear can be obtained from table 4 and do not vary for a given rangeland soil texture.

Discussion

In the current WEPP model, equations 5 and 6 can be combined to give:

$$D_i = S_r\, i\, q\, K_i C_{Can}\, C_{GC}\, C_S\, C_{lr}\, C_{dr} \tag{24}$$

Within the WEPP technology, live roots are generally assumed to have a mass about 1/3 of the live biomass, dead roots are also related to the aboveground live biomass, and the aboveground live biomass is related to canopy cover, so these three factors can be lumped into a single vegetation factor for rangelands, where such detailed vegetation information is seldom available. For rangeland applications, this reduces equation 24 to:

Table 5. Ground and vegetation cover values associated with each treatment based on probability of having a specific value of ground cover: 10% (5th percentile), 20% (20th percentile), 40% (median), 20% (80th percentile), and 10% (95th percentile) of the probability distribution of ground cover based on the WEPP-IRWET data.

Vegetation Type	Soil Burn Severity	Vegetation Ground Cover Percentiles					Rock Cover Percentiles					Foliar Cover Percentiles				
		5th	20th	50th	80th	95th	5th	20th	50th	80th	95th	5th	20th	50th	80th	95th
Shrub	Unburned	0.261	0.564	0.687	0.862	0.933	0	0	0	0.001	0.002	0.135	0.270	0.442	0.667	0.736
	Low	0.196	0.423	0.515	0.646	0.670	0	0	0	0.002	0.008	0.101	0.202	0.332	0.500	0.552
	High	0.065	0.141	0.172	0.215	0.233	0	0	0	0.005	0.021	0.034	0.067	0.111	0.167	0.184
Grass	Unburned	0.016	0.033	0.164	0.263	0.460	0	0	0	0.004	0.173	0.106	0.240	0.477	0.733	0.834
	Low	0.012	0.025	0.123	0.197	0.345	0	0	0	0.004	0.210	0.080	0.180	0.357	0.55	0.626
	High	0.004	0.008	0.041	0.066	0.115	0	0	0	0.005	0.283	0.027	0.060	0.119	0.183	0.209

Table 6. Rill erodibility (**K_r**, s m^{-1} × 10^{-4}) for ERMiT applications developed using equation 17 where values for soils 1, 2, 3, 4, and 5 are the equation's response when using the 95th, 80th, 50th, 20th, and 5th percentile ground cover, respectively.

Vegetation Type	Soil Burn Severity	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5
		Clay Loam (34% silt, 33% clay)					Silt Loam (65% silt, 15% clay)				
Shrub	Unburned	0.054	0.067	0.116	0.170	0.436	4.785	5.978	10.280	15.094	38.696
	Low	0.112	0.132	0.198	0.264	0.535	9.889	11.686	17.55	23.408	47.426
	High	0.476	0.504	0.577	0.635	0.803	42.245	44.662	51.145	56.300	71.240
		Sandy Loam (25% silt, 10% clay)					Loam (40% silt, 20% clay)				
	Unburned	0.406	0.508	0.873	1.282	3.286	0.394	0.492	0.846	1.242	3.185
	Low	0.84	0.992	1.490	1.988	4.027	0.814	0.962	1.444	1.926	3.903
	High	3.587	3.792	4.343	4.780	6.049	3.477	3.676	4.209	4.634	5.863
		Clay Loam (34% silt, 33% clay)					Silt Loam (65% silt, 15% clay)				
Grass	Unburned	0.236	0.435	0.590	0.889	0.935	20.891	38.557	52.361	78.875	82.960
	Low	0.337	0.533	0.671	0.912	0.947	29.871	47.298	59.501	80.904	84.027
	High	0.689	0.803	0.866	0.960	0.972	61.066	71.176	76.835	85.122	86.203
		Sandy Loam (25% silt, 10% clay)					Loam (40% silt, 20% clay)				
	Unburned	1.774	3.274	4.446	6.697	7.044	1.719	3.173	4.309	6.491	6.828
	Low	2.536	4.016	5.052	6.869	7.134	2.458	3.893	4.897	6.659	6.916
	High	5.185	6.043	6.524	7.227	7.319	5.026	5.858	6.324	7.006	7.095

Table 7. Interrill erodibility (**K_i**, kg s m^{-4} × 10^{3}) for ERMiT applications developed using equations 20 and 22 where values for soils 1, 2, 3, 4, and 5 are the equations' response when using the 95th, 80th, 50th, 20th, and 5th percentile ground cover, respectively.

Vegetation Type	Soil Burn Severity	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5
		Clay Loam (34% silt, 33% clay)					Silt Loam (65% silt, 15% clay)				
Shrub	Unburned	105	118	170	224	708	58	66	95	125	394
	Low	138	154	205	288	1029	77	86	114	161	572
	High	690	828	1143	1421	2170	383	460	635	790	1206
		Sandy Loam (25% silt, 10% clay)					Loam (40% silt, 20% clay)				
	Unburned	87	98	141	186	588	83	93	135	178	561
	Low	115	128	170	240	854	110	122	162	229	814
	High	573	687	949	1180	1801	546	655	904	1125	1717
		Clay Loam (34% silt, 33% clay)					Silt Loam (65% silt, 15% clay)				
Grass	Unburned	16	97	237	651	865	9	54	132	362	481
	Low	32	177	348	742.7	919	18	99	194	413	511
	High	135	591	751	967	1038	75	329	417	537	577
		Sandy Loam (25% silt, 10% clay)					Loam (40% silt, 20% clay)				
	Unburned	13.2	81	197	540.3	718	12.6	76.8	188	515	685
	Low	26.2	147	289	617	763	25.0	140	276	588	728
	High	111.9	491	623	803	862	107	468	594	765	822

$$D_i = S_r\, i\, q\, K_i\, C_V\, C_{GC}\, C_S \quad (25)$$

where C_V incorporates the effects of canopy and live and dead roots on interrill erosion. The combined factors of slope (C_S), vegetation, and ground cover in equation 24 can be lumped into a single term where:

$$K_{iadj} = C_S C_V C_{GC} K_i \quad (26)$$

Equation 26 is similar to equations 18 through 23 where K_{iadj} is a function of soil properties, canopy, and ground cover. Equation 26 is also similar to the splash-sheet erodibility equation in the RHEM model that includes slope, canopy, and ground cover terms (Al-Hamdan et al., 2017). The original WEPP documentation also included the sand content for predicting interrill erodibility, but also included soil organic matter and soil water content and field capacity (Flanagan and Livingston, 1995).

Equation 17, which predicts K_r, includes terms for ground cover and the clay and silt contents of the soil. It is similar to the K_ω term for concentrated flow in the RHEM model (Al-Hamdan et al., 2012) but much less complicated than the original WEPP model that included soil root concentration and bulk density, two terms that are not readily available.

Equations 18 through 23 can be used directly to calculate K_{iadj} for WEPP. However, the current WEPP version requires two steps to calculate K_{iadj}: the baseline K_i, and then equations 24 through 26 to adjust the values to K_{iadj}. To make equations 18 through 23 more useful for the applications of WEPP in rangelands, use of these equations is recommended to replace the current two-step K_i estimation. In ERMiT, the effects of vegetation (C_V and C_{GC}) are lumped into the K_i value, as was done in this study. WEPP users who would like to apply the interrill erodibility values presented herein would need to divide the K_i values by the factors presented in equation 24 (C_{Can}, C_{GC}, C_S, C_{lr}, and C_{dr}) to estimate an input value if they selected the cropland management. The K_r and τ_c values can be used in WEPP as presented in this study.

The proposed ERMiT erodibility values are within the suggested limit described for WEPP applications (Alberts et al., 1995). The proposed values have no general relationship with the old values (table 8). While the new K_i values are higher for shrub for all fire severities, they are sometimes smaller for grass. In some cases, the new K_i values are higher but are smaller with larger τ_c for a given soil texture, such as loam soil. These values indicate that interrill erosion is expected to be dominant in this soil texture, even for steep hillslopes.

Table 8. Values of K_i, K_r, and τ_c developed for ERMiT using the new parametrization equations compared to current values for the ERMiT parameters (shown in parentheses).

Parameter	Vegetation Type	Soil Burn Severity	Clay Loam	Silt Loam	Sandy Loam	Loam
K_i (kg s m^{-4} × 10^3)	Shrub	Unburned	105 to 708	58 to 394	87 to 588	74.3 to 561
		Low	138 to 1029 (13 to 170)	77 to 572 (16 to 230)	115 to 854 (75 to 930)	101 to 814 (3.4 to 93)
		High	690 to 2170 (39 to 170)	383 to 1206 (49 to 230)	573 to 1801 (230 to 930)	531 to 1720 (11 to 93)
	Grass	Unburned	16 to 865	9 to 481	13 to 540	13 to 515
		Low	32 to 919 (1.9 to 15)	18 to 511 (12 to 150)	26 to 763 (50 to 650)	25 to 588 (2.6 to 63)
		High	135 to 1038 (6.6 to 85)	75 to 577 (40 to 840)	112 to 862 (170 to 3600)	107 to 765 (11 to 350)
K_r (s m^{-1} × 10^{-4})	Shrub	Unburned	0.054 to 0.436	4.79 to 38.7	0.406 to 3.29	0.394 to 3.19
		Low	0.112 to 0.535 (0.38 to 6)	9.89 to 47.4 (0.33 to 7.8)	0.84 to 4.03 (0.09 to 7.2)	0.814 to 3.9 (0.51 to 4.6)
		High	0.476 to 0.803 (3 to 27)	42.2 to 71.2 (2.7 to 33)	3.59 to 6.05 (0.95 to 31)	3.48 to 5.86 (3.8 to 22)
	Grass	Unburned	0.236 to 0.935	20.9 to 83	1.77 to 7.04	1.72 to 6.83
		Low	0.337 to 0.947 (0.38 to 6)	29.9 to 84 (0.33 to 7.8)	2.54 to 7.13 (0.09 to 7.2)	2.46 to 6.92 (0.51 to 4.6)
		High	0.689 to 0.972 (3 to 27)	61.1 to 86.2 (2.7 to 33)	5.19 to 7.32 (0.95 to 31)	5.03 to 7.1 (3.8 to 22)
Minimum τ_c (N m^{-2})			1.05 (low 1.9, high 1.5)	2.85 (low 3.4, high 2.7)	3.65 (low 2.8, high 2.2)	5.05 (low 0.8, high 0.6)

Summary and Conclusions

New parameterization schemes for erodibility were developed for the application of WEPP on undisturbed and disturbed rangelands. Empirical equations were developed that estimate K_r and K_i in terms of readily available parameters for ground cover, vegetation cover, slope, and soil texture. The results showed that, in general, soil texture has a greater effect on rill erodibility than vegetation cover. On the other hand, vegetation cover terms have the greatest effect on interrill erodibility. In addition, minimum critical shear values corresponding to the developed erodibility were estimated. The new parameterization approach expands the applicability of WEPP to a wider range of landscapes and soil textures.

The new approach for estimating K_r and K_i for WEPP has several advantages. First, the approach addresses that erosion rates become substantially greater above a bare ground threshold. Second, the equations use readily available and commonly collected data for estimating erodibility values. Third, the equations are applicable for a wide range of ground cover and foliar cover. The new approach was used to provide parameters for the Erosion Risk Management Tool (ERMiT), which uses WEPP as the runoff and erosion calculation engine.

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