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Predicting post-fire sediment yields at the hillslope scale: Testing RUSLE and Disturbed WEPP

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High-severity wildfires can increase hillslope-scale sediment yields by several orders of magnitude. Accurate predictions of post-fire sediment yields are needed to guide management decisions and assess the potential impact of soil loss on site productivity and downstream aquatic resources. The Revised Universal Soil Loss Equation (RUSLE) and Disturbed WEPP are the most commonly used models to predict post-fire sediment yields at the hillslope scale, but neither model has been extensively tested against field data. The objectives of this paper are to: (1) compare predicted sediment yields from RUSLE and Disturbed WEPP against 252 plot years of data from nine fires in the Colorado Front Range; and (2) suggest how each model might be improved.

Predicted and measured sediment yields were poorly correlated for RUSLE (R^2=0.16) and only slightly better for Disturbed WEPP (R^2=0.25). Both models tended to over-predict sediment yields when the measured values were less than 1 Mg ha^{-1} yr^{-1}, and under-predict higher sediment yields. Model accuracy was not improved by increasing the soil erodibility (K) factor in RUSLE, and only slightly improved by

slowing the vegetative recovery sequence in Disturbed WEPP. Both models much more accurately predicted the mean sediment yields for hillslopes grouped by fire and severity (R^2=0.54 to 0.66) than for individual plots. The performance of RUSLE could be improved by incorporating an erosivity threshold and a non-linear relationship between rainfall erosivity and sediment yields. The performance of WEPP could be improved by reducing the effective hydraulic conductivity in sites that have recently burned at high severity. The results suggest that neither model can fully capture the complexity of the different controlling factors and the resultant plot-scale variability in sediment yields.

1. Introduction

Post-fire erosion is a major societal concern due to the potential effects on soil and water resources. High-severity wildfires are of particular concern because they completely consume the protective surface litter and they can induce soil water repellency at or below the soil surface [*Lowdermilk*, 1930; *Scott and van Wyk*, 1990; *DeBano*, 2000; *Huffman et al.*, 2001; *Certini*, 2005]. These changes can reduce the infiltration rate by an order of magnitude, and the resultant shift in runoff processes from subsurface stormflow to Horton overland flow can increase peak flows and sediment yields by two or more orders of magnitude [*Inbar et al.*, 1998; *Prosser and Williams*, 1998; *Robichaud and Brown*, 1999; *Moody and Martin*, 2001; *Benavides-Solorio and MacDonald*, 2005; *Neary et al.*, 2005; *Shakesby and Doerr*, 2006].

The consumption of the organic layer and increase in erosion can decrease site productivity [*DeBano and Conrad*, 1976; *Robichaud and Brown*, 1999; *Thomas et al.*, 1999]. The increase in runoff can induce downstream flooding [*Helvey*, 1980; *Moody* *and Martin*, 2001; *Neary et al.*, 2005], and the delivery of ash and sediment to downstream reaches can severely degrade water quality, aquatic habitat, and reservoir storage capacity [*Brown*, *1972*; *Ewing*, *1996*; *Greswell*, *1999*; *Moody and Martin*, 2001; *Kerchner et al.*, 2003; *Legleiter et al.*, 2003; *Libohova*, 2004].

Accurate predictions of post-fire sediment yields are needed to estimate the potential impacts of wild and prescribed fires on site productivity and downstream aquatic resources, estimate the potential benefits of post-fire rehabilitation treatments, and compare the effects of prescribed burning or forest thinning relative to wildfires. The procedures for predicting post-fire erosion include: empirical models, such as the Revised Universal Soil Loss Equation (RUSLE) [*Renard et al.*, 1997]; physically-based models, such as the Water Erosion Prediction Project (WEPP) [*Elliot*, 2004]; empirical models developed from previous wildfires [*Benavides-Solorio and MacDonald*, 2005; *Pietraszek*, 2006]; spatially-distributed models, such as KINEROS [*Woolhiser et al.*, 1990], SHESED [*Wicks and Bathurst*, 1996], and GeoWEPP [*Renschler*, 2003]; and professional judgment [*Robichaud et al.*, 2000]. The problem is that these methods typically yield widely different values [*Robichaud et al.*, 2000], and there have been almost no studies validating these models for burned areas.

Over the past six years an extensive dataset has been collected on post-fire site characteristics, rainfall rates, erosion processes, and sediment yields in the Colorado Front Range. The key data used in this study are the annual, hillslope-scale sediment yields measured from six wild and three prescribed fires from 2000 to 2004 [*Benavides-Solorio and MacDonald*, 2005; *Pietraszek*, 2006] (Figure 1; Table 1). These measurements were made on 83 plots burned at different severities in both older and recent fires, and many of the plots were monitored from immediately after burning for up to five years. This effort has yielded 281 plot-years of data (Table 1).

The sediment yield data and data from associated studies [*Huffman et al.*, 2001; *Benavides-Solorio and MacDonald*, 2001, 2002; *MacDonald and Huffman*, 2004; *Libohova*, 2004; *Benavides-Solorio and MacDonald*, 2005; *MacDonald et al.*, 2005; *Kunze and Stednick*, 2006; *Pietraszek*, 2006; *Wagenbrenner et al.*, 2006] were initially collected to determine the effects of various site factors on post-fire sediment yields, but they also provide a unique opportunity to evaluate the two models most commonly used to predict post-fire sediment yields. These are: (1) RUSLE [*Renard et al.*, 1997], and (2) Disturbed WEPP [*Elliot*, 2004], which is a web-based interface to the WEPP model [*Flanagan and Nearing*, 1995]. The specific objectives of this study were to: (1) test the accuracy of RUSLE and Disturbed WEPP to predict post-fire sediment yields; and (2) use the results to suggest how each model might be improved to increase prediction accuracy. The results—when combined with the other process-based studies—highlight areas where additional research is needed to improve our understanding of post-fire erosion processes and model performance. The results also can help resource managers quantify and incorporate model uncertainty into their management decisions.

2. RUSLE and Disturbed WEPP

2.1. RUSLE

RUSLE is an updated version of the Universal Soil Loss Equation (USLE) [*Wischmeier and Smith*, 1978]. USLE and RUSLE are widely-used, empirical, deterministic models that were developed largely from agricultural plot data in the central and eastern U.S. The models are designed to predict the average annual soil loss from rainsplash, sheetwash, and rill erosion at the hillslope scale using equation 1:

$$A=R * K * L * S * C * P \quad (1)$$

where A is the average annual unit-area soil loss (Mg ha^{-1} yr^{-1}), R is the rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1}), K is the soil erodibility factor (Mg ha^{-1} MJ^{-1} mm^{-1} ha h), L is the slope length factor [$(m\ m^{-1})^x$], S is the slope steepness factor, C is the cover-management factor, and P is the support practice factor [*Renard et al.*, 1997]. RUSLE does not explicitly model infiltration, overland flow, particle detachment, or sediment transport, but empirically represents these processes through these six factors. RUSLE is a lumped model at the hillslope scale, although algorithms are available to calculate the combined LS factor for complex hillslope shapes. The slope length used to calculate L is defined as the horizontal distance from the initiation of overland flow to the point of deposition, so RUSLE is best characterized as predicting soil loss rather than sediment yield [*Renard et al.*, 1997]. However, the predicted soil losses using RUSLE are equivalent to our measured sediment yields because there typically is little or no evidence of deposition upslope of the sediment fences used to measure sediment yields [*Pietraszek*, 2006].

2.2. Disturbed WEPP

Disturbed WEPP is an internet-based interface to the physically-based WEPP model that was developed for use on crop, range, and forested lands [*Flanagan and*

Nearing, 1995; *Elliot*, 2004]. WEPP uses a stochastically-generated daily climate to drive deterministic, physically-based models of infiltration, evapotranspiration, plant growth, plant decomposition, and the detachment, transport, and deposition of soil particles at the hillslope and small watershed scales [*Flanagan and Nearing*, 1995].

Disturbed WEPP was developed to predict average annual runoff and sediment yields for undisturbed forests and areas subjected to burning or forest harvest [http://forest.moscowfsl.wsu.edu/fswepp/; *Elliot*, 2004]. It basically provides a simplified interface between the WEPP program and users. Disturbed WEPP is spatially distributed only in the sense that hillslopes can be divided into upper and lower segments that can differ with respect to topography, surface cover, treatments, and soils.

The stochastically-generated daily weather data are derived from mean monthly climate statistics from one of the 2600 weather stations in the WEPP database. The monthly statistics include: the number of wet days; the probability of consecutive wet or dry days; and the mean, standard deviation, and skew coefficient of the amount of precipitation on days with precipitation [http://forest.moscowfsl.wsu.edu/fswepp/docs/rockclimdoc.html]. The amount of precipitation is combined with a storm duration to obtain a peak rainfall intensity and time to peak intensity for each storm.

Infiltration is modeled with the Green-Ampt equation as modified by *Chu* [1978] for unsteady rainfall. Overland flow occurs when the rainfall rate exceeds the infiltration rate and depression storage capacity. WEPP calculates the interrill detachment rate as a function of the interrill soil erodibility (K_i), rainfall intensity, interrill runoff rate, and slope. The sediment delivered to rills by interrill erosion is either transported or deposited depending on rill geometry and the carrying capacity of the rill flow. Rill detachment occurs when the shear stress within the rill exceeds the critical shear stress. The amount of rill detachment per unit excess shear stress is a function of the soil rill erodibility (K_r). Sediment yields from rainfall and snowmelt are continuously simulated for each day of the year over a user-defined, multi-year simulation period. The daily values are summed and divided by the length of the simulation period to obtain the mean annual sediment yield for a given scenario [*Elliot*, 2004].

Approximately 400 variables are needed to parameterize a typical run of WEPP Version 95.7 [*Flanagan and Nearing*, 1995]. Forest managers found the WEPP interface difficult to operate, the input data difficult to assemble, and the results difficult to interpret, so WEPP remained relatively unused [*Elliot*, 2004]. Disturbed WEPP was developed because it requires only seven user-defined inputs: identification of a climate station, slope length, slope steepness, soil texture, percent rock fragments in the soil, percent surface cover, and the specification of one of eight land use and land cover types ("treatments") [*Elliot*, 2004]. The Disturbed WEPP interface uses these inputs to generate all of the other input parameters needed to run the WEPP model [http://forest.moscowfsl.wsu.edu/fswepp/docs/distweppdoc.html].

The eight treatments in Disturbed WEPP are high severity burn, low severity burn, short grass, tall grass, shrub, 5-year old forest, 20-year old forest, and skid trails. Moderate severity burn is not a separate treatment because field data suggest that burned areas can be adequately characterized by using just two classes—high severity and low severity [*Robichaud*, 2000; *Pierson et al.*, 2001]. For burned areas, Disturbed WEPP assumes that the sequence of recovery follows the sequence of treatments listed in Table

2. A change in treatment automatically alters key variables such as the effective hydraulic conductivity (K_e) and K_r [*Elliot*, 2004].

3. Methods

3.1. Study Sites and Field Data Collection

The field data were collected from six wild and three prescribed fires that burned between July 1994 and August 2002 in the central and northern Colorado Front Range (Table 1; Figure 1). The dominant vegetation prior to burning was ponderosa pine (*Pinus ponderosa*) at lower elevations and lodgepole pine (*P. contorta*) at higher elevations (Table 1). The bedrock is predominantly granite, schist, or gneiss. Soils are usually less than 1 m deep and range from sandy loams to gravelly coarse sands. Soils at the Hayman and Schoonover fires are classified as Typic Ustorthents [*Moore*, 1992], and the soils at the other fires are Typic Argicryolls and Ustic Haplocryalfs [*E. Kelly*, *Colorado State Univ.*, *pers. comm.*, 2001].

The estimated mean annual precipitation ranges from 360 mm at lower elevations to about 500 mm at higher elevations [*Miller et al.*, 1973; *Gary*, 1975]. Winter precipitation falls as primarily as snow, and summer rainfall is dominated by localized, high intensity thunderstorms [*Gary*, 1975]. Precipitation in the spring and fall occurs primarily as a result of low intensity frontal storms that often shift between rain and snow. The precipitation that falls during the summer, defined here as 1 June to 31 October, accounts for 90% of the annual erosivity [*Renard et al.*, 1997] and at least 90% of the annual sediment yield from burned hillslopes [*Benavides-Solorio and MacDonald*, 2005]. Hence year 1 is always the first summer after burning, year 2 is the second summer, etc.

Data from unburned plots adjacent to the Hayman wildfire (Figure 1) indicate that rainfall intensities of 45-65 mm h^{-1} generally do not generate any surface runoff or sediment yields [*Libohova*, 2004; *Brown et al.*, 2005]. In contrast, storms with as little as 5 mm of rainfall and rainfall intensities of only 8-10 mm h^{-1} can generate overland flow and measurable amounts of sediment from high severity plots for up to three years after burning [*Pietraszek*, 2006; *Wagenbrenner et al.*, 2006]. The relative lack of surface erosion in unburned areas and from snowmelt in burned areas means that the sediment produced in the summer after burning can be treated as an annual value [*Benavides-Solorio and MacDonald*, 2005; *Pietraszek*, 2006]. At the scale of the study plots the only sediment generation processes are rainsplash, sheetwash, and rill erosion.

One or more sediment fences [*Robichaud and Brown*, 2002; http://www.fs.fed.us/institute/middle_east/platte_pics/silt_fence.htm] were used to measure sediment yields from 83 unbounded hillslope plots or zero-order catchments (Figure 2). The burn severity of each plot was qualitatively characterized as high, moderate, or low using the criteria developed by *Wells et al.* [1979] and applied by the *USDA Forest Service* [1995]. The forest canopy and surface litter were completely consumed in the 62 plots classified as high severity; three-quarters of the plots were in high severity areas (Table 1) because these areas have much higher runoff and sediment yields and are therefore of greatest concern [*Morris and Moses*, 1987; *Benavides-Solorio and MacDonald*, 2005].

The input data for RUSLE and Disturbed WEPP were derived from field measurements. In each plot the surface soils (0-5 or 0-3 cm) were sampled to determine the particle-size distribution by a combination of sieving and the hydrometer technique [*Gee and Bauder*, 1986]. Percent organic matter was determined by weight loss on ignition [*Cambardella et al.*, 2001] or treatment with hydrogen peroxide [*Nelson and Sommers*, 1996]. Surface cover within each plot was measured at 100 points along multiple transects with a density of 0.01-1.4 measurements per m^2 at the beginning and end of each growing season [*Parker*, 1951]. The contributing areas were defined by local topography and measured using a GPS with a horizontal accuracy of 2-5 m, a total station, or directly with cloth tapes. The amount and intensity of summer rainfall was measured to the nearest 0.2-1.0 mm using 1-4 tipping-bucket rain gages that we installed near our study plots within each fire (Table 1). Two-thirds of the plots were less than 500 m from the nearest rain gage and the maximum distance was 1600 m. Rainfall records were considered incomplete if more than one week of data was missing. Periods with incomplete data were filled with records from the nearest gage up to a maximum distance of 10 km; sediment yield data were omitted if there were no rainfall data from within 10 km.

Following precipitation events, the mass of sediment trapped by each fence was removed by hand and measured to the nearest ¼ kg. Samples were taken to determine the water content and convert the field-measured wet mass to a dry mass. Sediment yields were normalized by dividing the dry mass by the contributing area.

The primary dataset for model validation consisted of 183, 44, and 25 plot-years of sediment yield values from hillslopes burned at high, moderate, and low severity, respectively (Table 1). We excluded 29 of the 281 plot-years of data listed in Table 1 because of incomplete rainfall data or the sediment fences overtopped, but the exclusion of these data had little effect on the magnitude or distribution of the remaining data. The mean slope length of the plots used in this study was 71 m, and the range was from 20 m to 200 m. The mean hillslope gradient was 32%, and the range was from 12% to 82%. The mean contributing area was approximately 1600 m^2, and the range was from 70 m^2 to 11,200 m^2.

3.2. Model Inputs

3.2.1. RUSLE

The values for the R factor in RUSLE were calculated for each rain gage in each year by summing the erosivity [*Brown and Foster*, 1987] from 1 June to 31 October for each storm with at least 5 mm of rainfall. The use of these calculated R values meant that the predicted sediment yields were based on the observed rainfall rather than the average annual R factor. The K factor for the plots in the Hayman and Schoonover fires were obtained from a soil survey [*Moore*, 1992]. Soil survey data were not available for the other seven fires except for the small Hewlett Gulch fire, and the K values for each plot in these seven fires were determined from the measured soil textures and organic matter contents following *Stewart et al.* [1975].

Soil water repellency has been postulated as a major cause of the post-fire increases in runoff and erosion [*DeBano*, 1981; *Letey*, 2001], but water repellency is not explicitly included in RUSLE [*González-Bonorino and Osterkamp*, 2004]. *Miller et al.* [2003] suggested that the effect of post-fire soil water repellency could be incorporated into RUSLE by adding 0.016 Mg ha^{-1} MJ^{-1} mm^{-1} ha h to the K factor. This increase is equivalent to decreasing the soil permeability class from rapid to very slow [*Renard et al.*, 1997]. We therefore evaluated two versions of RUSLE, and the first version ("RUSLE") used the K values obtained from the soil surveys and soil texture data. The modified version ("$RUSLE_m$") increased the K values in the plots that had burned at high severity by 0.016 Mg ha^{-1} MJ^{-1} mm^{-1} ha h for the first and second summers after burning, or 60-80%.

The L and S factors were calculated from the field data for each plot following *Renard et al.* [1997]. The slope length used to calculate L was the horizontal distance from the sediment fence to the ridgetop, as our field data show that rilling often began within 10 m of a topographic divide. We assumed a high ratio of rill to inter-rill erosion when calculating L because 60-80% of the post-fire sediment yield in the Colorado Front Range is due to rill and channel incision [*Moody and Martin*, 2001; *Pietraszek*, 2006].

The cover-management factor (C) in RUSLE is one of the most important variables because values can range over nearly three orders of magnitude and percent cover is a dominant control on post-fire sediment yields [*Benavides-Solorio and MacDonald*, 2005; *Pietraszek*, 2006]. In RUSLE the C factor is calculated by:

$$C = PLU * CC * SC * SR * SM \quad (2)$$

where PLU is the prior land use subfactor, CC is the canopy cover subfactor, SC is the surface cover subfactor, SR in the surface roughness subfactor, and SM is the soil moisture subfactor [*Renard et al.*, 1997].

PLU is calculated from a soil reconsolidation factor, the mass of roots, and the mass of buried residue [*Renard et al.*, 1997]. Soil reconsolidation refers to the decrease in erosion with time following tilling, and we used a reconsolidation factor of 0.45 as recommended for forest soils [*Dissmeyer and Foster*, 1981]. The mass of roots was obtained by taking the rootmass value associated with the field-measured percent live vegetation and assuming the weeds vegetation class in the RUSLE 2.0 disturbed land database [*Foster*, 2004]; the mass of buried residue was assumed to be zero.

The CC subfactor was calculated from percent canopy cover and fall height [*Renard et al.*, 1997]. The percent canopy cover was assumed to equal the mean percent of live vegetation as measured by the spring and fall surface cover surveys. The canopy fall height was taken from the comparable weeds vegetation database in RUSLE 2.0 and the resulting mean fall height was 7 cm. We used this value since the mean fall height measured 1, 3, and 5 years after a high severity burn ranged from 5.5 cm to 12.2 cm with no obvious trend over time.

SC is one of the most important components of C, and it was calculated by:

$$SC = \exp\left[-b * S_p * \left(\frac{0.24}{R_u}\right)^{0.08}\right] \tag{3}$$

where b is a unitless coefficient that indicates the effectiveness of surface cover in reducing erosion, S_p is the percent surface cover, and R_u (inches) is the roughness of an untilled surface [*Renard et al.*, 1997]. A b value of 0.05 is recommended where rilling is the dominant soil erosion process [*Renard et al.*, 1997], and this value was used for all plots. S_p was assumed to equal the mean of the spring and fall cover values from each plot for each year. R_u data were not available, but the R_u value for pinion-juniper inter-spaces and rangeland soils with clipped vegetation and bare surfaces is 1.52 cm [*Renard et al.*, 1997]. This value was used for the high severity plots in the first two years after burning because these plots had so little surface cover and surface roughness. A R_u of 2.54 cm was used in subsequent years and for the plots that had burned at moderate and low severity [*Renard et al.*, 1997]. The SR subfactor was calculated using the same R_u values [*Renard et al.*, 1997].

The SM subfactor ranges from 0.0 when soils are very dry to 1.0 when soils are relatively wet [*Renard et al.*, 1997]. Since the SM subfactor has only been used in the wheat and range region of the northwestern U.S. [*Renard et al.*, 1997] and has not been calibrated for burned forest soils [*González-Bornino and Osterkamp*, 2004], a value of 1.0 was used. The P factor was set to 1.0 because no conservation treatments had been applied.

3.2.2. Disturbed WEPP

In Disturbed WEPP the stochastic daily weather is based on data from a user-selected weather station. The Cheesman weather station was used to represent the climate at the Hayman and Schoonover fires, and the Estes Park 1N station was used to represent the other fires (Figure 1). For June to October we substituted the measured monthly rainfall and number of wet days as recorded at each rain gage for the historic means at each of the two climate stations. Hence each predicted sediment yield was a mean value based on 50 years of simulated climate generated from the observed monthly rainfall and number of wet days. For the newly burned areas we set the precipitation from January to the month prior to burning to zero so that Disturbed WEPP would not over-predict sediment yields by simulating burned conditions prior to the time of burning.

Hillslopes in Disturbed WEPP are divided into upper and lower segments. Since a ridge crest typically formed the upper boundary of each study plot, the slope gradient for the top of the upper segment was set to 0% and the measured slope was used for the remainder of the hillslope. The upper segment was assumed to represent 15% of the total plot length, as this was the approximate proportion of the ridgetop sections relative to the total plot length.

Twenty-four parameters are required to describe the soil properties in the WEPP model [*Alberts et al.*, 1995]. In Disturbed WEPP the user specifies one of four soil textures (loam, clay loam, silt loam, and sandy loam), one of eight treatments, and the percent of rock fragments (>2mm). The Disturbed WEPP interface assigns a unique set of hydrologic, pedologic, and biologic values to each soil and treatment combination. The soil texture and percent of rock fragments were specified for each plot in accordance with the measured values.

Disturbed WEPP requires the user to input percent surface cover and uses this value to simulate plant growth and residue decomposition. Since the surface cover calculated by Disturbed WEPP generally was lower than our measured input values, we adjusted our input values until the calculated surface cover matched our measured values [*Elliot*, 2004].

Since Disturbed WEPP does not include a treatment for areas burned at moderate severity, the measured sediment yields from the 14 plots burned at moderate severity were compared to the values predicted using the high and low severity treatments, respectively. The low severity treatment provided a better match to the observed values, so the sediment yields for the plots burned at moderate severity were predicted using the low severity treatment.

We tested two versions of Disturbed WEPP because the surface cover and sediment yield data indicated a slower recovery for the plots burned at high severity than assumed in Disturbed WEPP (Table 2). The first version ("Disturbed WEPP") used the recommended sequence of treatments, and the modified version ("Disturbed $WEPP_m$") delayed the recovery of the plots burned at high severity by one year (Table 2).

3.3. Statistical Analysis

A series of statistics was calculated to assess the accuracy of each model, as no single statistic can fully characterize the match between predicted and observed values [*Willmott*, 1981]. The statistics used here include: (1) the slope (*b*) and intercept (*a*) of the least-squares linear regression fit to the plot of predicted versus observed sediment yields; (2) the square of the correlation (R^2) between the predicted and observed values; (3) the Nash-Sutcliffe model efficiency (R^2_{eff}) [*Nash and Sutcliffe*, 1970]; (4) the root mean square error (RMSE) [*Willmott*, 1981]; and (5) the proportion of predicted values that falls within the 95% confidence intervals (CI) developed from replicated erosion plots at agricultural sites [*Nearing*, 1998, 2000; *Nearing et al.*, 1999], as these CI have been used in previous WEPP validation studies [e.g., *Laflen et al.*, 2004]. These validation statistics also were calculated for each year since burning to assess model performance over time. The wide range of measured and predicted values meant that the data were plotted on a log-log scale, and a value of 0.001 Mg ha^{-1} yr^{-1} was assigned to the plots that generated no measurable sediment.

The Nash-Sutcliffe model efficiency is particularly useful because it facilitates comparison of our results with other RUSLE and WEPP validation studies [e.g., *Tiwari et al.*, 2000; *Yu et al.*, 2000; *Spaeth et al.*, 2003], and R^2_{eff} values can range from $-\infty$ to 1.0. Unlike R^2, a negative R^2_{eff} indicates that the mean observed value is a better predictor than the model, a value of 0.0 indicates that the mean observed value is as accurate a predictor as the model, and a R^2_{eff} of 1.0 indicates a perfect match between the predicted and observed values [*Nash and Sutcliffe*, 1970].

The mean of the observed and predicted sediment yields from groups of hillslopes were compared to determine the effect of plot-scale variability on model accuracy. The plots that burned at high severity were grouped by fire, whereas the plots that burned at moderate and low severity were grouped by severity because of the small number of such plots in each fire (Table 1).

4. Results

4.1. RUSLE and $RUSLE_m$

4.1.1. Erosivity and Cover Values

Summer rainfall and erosivity values at our field sites were generally lower than the long-term mean, but the values were highly variable between fires and between years. The overall mean erosivity of 286 MJ mm ha^{-1} h^{-1} was 21-24% below the long-term means [*Foster*, 2004]. The lowest summer erosivity was 6 MJ mm ha^{-1} h^{-1} at the Dadd Bennett fire in 2002, and the highest value was 1210 MJ mm ha^{-1} h^{-1} at the Green Ridge site at the Bobcat fire in 2003. Rainfall intensity varied considerably, but less than 2% of the 1706 rainfall events recorded through 2003 had maximum 30-minute intensity (I_{30}) values greater than 25 mm h^{-1} and only 5 of the rainfall events had I_{30} values greater than 40 mm h^{-1}, which is approximately a 2-5 year storm for the Colorado Front Range [*Pietraszek*, 2006].

In the first year after burning, the mean surface cover was 14% for the plots that had burned at high severity, 41% for the plots that had burned at moderate severity, and 70% for the plots that had burned at low severity (Figure 3a). The amount of surface cover increased rapidly over time due to vegetative regrowth and litterfall in the plots burned at moderate and low severity. On average, the surface cover reached 70% within four years for the plots burned at high severity and within two years for the plots burned at moderate severity (Figure 3a).

Since many of the subfactors in the C factor are inversely related to the amount of vegetative regrowth and surface cover, the calculated values of the C factor increased with burn severity and decreased non-linearly with time since burning (Figure 3b). In the first year after burning, the mean C factor was 0.20 for the plots that had burned at high severity, which significantly higher ($p<0.001$) than the mean C factor values of 0.05 and 0.01 for the plots that had burned at moderate and low severity, respectively. By the third year after burning the mean C factor for high severity plots had declined to 0.03. By the fourth year after burning the mean C factor was less than 0.006 for each burn severity class, and the maximum value for a single plot was 0.02.

4.1.2. RUSLE Model Performance

The correlations between the predicted and observed sediment yields for individual plots were very low, as the R^2 was 0.16 for RUSLE and 0.14 for $RUSLE_m$ (Table 3). The R^2_{eff} for RUSLE was 0.06, indicating that the model was only a slightly better predictor of post-fire sediment yields than the mean (Table 3). The R^2_{eff} for $RUSLE_m$ was worse at -0.26 (Table 3). Both RULSE and $RUSLE_m$ tended to substantially over-predict sediment yields when the observed values were less than 1 Mg ha^{-1} yr^{-1}, and under-predict sediment yields when the observed values were greater than 1 Mg ha^{-1} yr^{-1} (Figure 4). This meant that the slope of the regression line for the RUSLE model was only 0.24 instead of the desired value of 1.0 (Table 3; Figure 4). From a practical point of view, the errors at the low end are not as important as the absolute errors at the high end, and for sediment yields greater than 1 Mg ha^{-1} yr^{-1} the RMSE was 10.3 Mg ha^{-1} yr^{-1} for RUSLE and 11.9 Mg ha^{-1} yr^{-1} for $RUSLE_m$. Only 38% of the predicted values from either model were within the 95% CI (Figure 4).

When stratified by time since burning, the best performance was in the fourth year after burning, but the R^2_{eff} values never exceeded 0.17 (Table 4). When stratified by burn severity, the R^2_{eff} values were less than zero for both the high and the moderate severity plots for both RUSLE and $RUSLE_m$.

Increasing the K factor for high severity plots for the first two years after burning increased the predicted sediment yields and the slope of the regression line, but did not improve overall model performance relative to RUSLE (Table 3). Most importantly, the R^2_{eff} values for the first and second years after burning were lower for $RUSLE_m$ than for RUSLE (Table 4).

Model predictions were much better for groups of plots than for individual plots (Table 3; Figure 5). For RUSLE and $RUSLE_m$, the respective R^2_{eff} values increased to 0.52 and 0.31 (Table 3). The slopes of the regression lines increased and the intercepts decreased (Table 3; Figure 5). The percentage of values within the 95% CI increased to 56% for RUSLE and 59% for $RUSLE_m$ (Figure 5). The mean values for sites burned at low and moderate severity plotted very close to the 1:1 line for both RUSLE models (Figure 5). When the grouped data were stratified by time since burning, the R^2_{eff} values were positive for years 2-4 but negative for the first year after burning and for years 5-10 (Table 4). Overall, RUSLE performed better than $RUSLE_m$ for both the individual and the grouped hillslopes.

4.2. Disturbed WEPP and Disturbed $WEPP_m$

4.2.1. Rainfall

The long-term mean summer precipitation is 200 mm for Estes Park and 225 mm for Cheesman. From 2000 to 2003 the summer precipitation at each of these two stations was similar to or below the long-term mean, while the precipitation in summer 2004 was 106% above average at Estes Park and 20% above average at Cheesman. The measured summer precipitation values at Estes Park and Cheesman generally were comparable to the values measured at the corresponding field sites. Since the climate stations and fires are in similar climatic zones and had similar summer rainfall values, the climate statistics from Estes Park and Cheesman can be applied to our study sites.

4.2.2. Disturbed WEPP Model Performance

The two Disturbed WEPP models more accurately predicted the sediment yields from individual plots than either of the RUSLE models, but the performance of both versions of Disturbed WEPP was still only slightly better than the mean. For Disturbed WEPP the R^2_{eff} was 0.19, and for Disturbed $WEPP_m$ the R^2_{eff} was 0.23 (Table 3). As with RUSLE, both models tended to over-predict the smaller sediment yields and under-predict the larger sediment yields (Figure 6). The RMSE for sediment yields greater than 1 Mg ha^{-1} yr^{-1} were 9.4 Mg ha^{-1} yr^{-1} for Disturbed WEPP and 8.9 Mg ha^{-1} yr^{-1} for Disturbed $WEPP_m$, or slightly less than for RUSLE. This pattern of prediction errors meant that the regression lines had high intercepts and low slopes (Table 3). Approximately one-half of the predicted values from the Disturbed WEPP models fell within the 95% CI as compared to just 38% for the RUSLE models (Figure 6).

A one year delay in the recovery sequence for the high severity plots slightly improved model performance (Table 3). The R^2_{eff} values over time show that almost all of this improvement was associated with the substantially better performance of Disturbed $WEPP_m$ in the third year after burning. The slower recovery sequence had little or no effect on model performance in the first two years after burning and years 4-10 (Table 4).

As with RUSLE, the two versions of Disturbed WEPP much more accurately predicted the mean sediment yields for groups of hillslopes than for individual hillslopes (Figure 7). The R^2_{eff} values more than doubled to 0.53 for Disturbed WEPP and 0.65 for Disturbed $WEPP_m$ (Table 3). The slope of the regression line increased to 0.50 for Disturbed WEPP and 0.68 for Disturbed $WEPP_m$, and both intercepts decreased by about 50% (Table 3). The percentage of data points within the 95% CI increased to 56% for

Disturbed WEPP and 63% for Disturbed $WEPP_m$. Like RUSLE, the data points for the groups of plots that burned at low and moderate severity were very close to the 1:1 line (Figure 7). The improvement in model performance for the grouped plots was slightly smaller for Disturbed WEPP than Disturbed $WEPP_m$.

5. Discussion

5.1. Comparisons Against other Validation Studies

The R^2_{eff} values show that three of the four models (RUSLE, Disturbed WEPP, and $WEPP_m$) predicted the post-fire sediment yields from individual hillslopes better than the mean, but the highest R^2_{eff} was only 0.23. The predictions for the grouped hillslopes were much better (Table 3), but the quantitative results need to be compared to other validation studies because there are no accepted accuracy standards for sediment prediction models [*Nearing et al.*, 1999]. The most comprehensive validation of RUSLE and WEPP used 1600 plot-years of data from 190 plots at 20 agricultural research sites in the eastern and central U.S. [*Tiwari et al.*, 2000]. For RUSLE the overall R^2_{eff} for annual sediment yields was 0.60, and this increased to 0.72 for the mean annual sediment yields (Table 5). WEPP had a lower R^2_{eff} (0.40) for annual sediment yields, but a very similar R^2_{eff} (0.71) for the mean annual sediment yields (Table 5). The high R^2 and R^2_{eff} values may be somewhat misleading, as the equations and parameters in RUSLE and WEPP were based in part on the data from these plots [*Risse et al.*, 1995; *Zhang et al.*, 1995a, b; *Tiwari et al.*, 2000]. The improved performance for mean annual sediment yields helps confirm that RUSLE and WEPP are better at predicting values for average conditions than individual years.

A more rigorous test of these models is to evaluate their performance for environments and land uses that differ from where the models were developed. Negative R^2_{eff} values were obtained when RUSLE was used to predict erosion from successive rainfall simulations on 132 plots at 22 rangeland sites in the western U.S. [*Spaeth et al.*, 2003] (Table 5). In northwestern Australia, WEPP accurately predicted monthly sediment yields from agricultural plots only after the infiltration and soil erodibility parameters were calibrated to local conditions [*Yu et al.*, 2000] (Table 5).

Only two other studies have attempted to validate RUSLE and WEPP in forested or burned areas. In the first study, Disturbed WEPP explained 64% of the observed variability in sediment yields from harvested and burned sites in the western and southeastern U.S. [*Elliot*, 2004] and 90% of the predicted sediment yields fell within the 95% CI suggested by Nearing and colleagues [*Laflen et al.*, 2004]. In northwestern Spain the WEPP model was tested against four years of data from an unburned scrubland plot, two plots burned by a prescribed fire, and one plot burned by a high intensity wildfire [*Soto and Díaz-Fierros*, 1998]. Climate files were created from the on-site rainfall data, and the measured plant growth and residue decomposition in each plot were used to optimize the biomass and litter accumulation parameters [*Soto and Díaz-Fierros*, 1998]. We used their measured and predicted sediment yields to calculate the overall R^2_{eff} for each plot, and these values were 0.92 for the unburned plot, 0.61 for the plots burned by a prescribed fire, and only 0.03 for the plot burned by a wildfire (Table 5). As in the Colorado Front Range, the WEPP model under-predicted the sediment yields from the plot burned by a high intensity wildfire by 2-10 times.

Taken together, these results show that the RUSLE and WEPP models tend to be less accurate as they are taken to other geographic areas or applied to non-agricultural lands [*Toy et al.*, 1999], and they highlight the inherent difficulty in predicting plot or hillslope-scale sediment yields. The comparisons of our results against the values in Table 5 show that RUSLE and Disturbed WEPP were much less successful in predicting post-fire sediment yields from individual hillslopes in the Colorado Front Range than for agricultural plots in the U.S. Prediction accuracy for our groups of burned hillslopes was much stronger and comparable to the prediction accuracy for the mean annual sediment yields from agricultural plots in the eastern and central U.S. (Tables 4, 5).

5.2. Sources of Error

Prediction errors can be due to model error, errors in the input data, and errors in the data used for validation (i.e., sediment yields) [*Nearing et al.*, 1999]. Both RUSLE and WEPP are primarily deterministic, and model errors occur when the empirical or physically-based equations do not adequately represent key processes, or when a site-averaged value does not capture the smaller-scale variations in plot conditions and key processes such as infiltration [*Beven*, 2000]. It usually is very difficult to separate model errors from measurement errors, but the intensive field studies conducted in conjunction with our sediment yield measurements allow us to assess the accuracy of several key field measurements. Most of the remaining error can then be assigned to model errors.

5.3. Measurement Errors

The uncertainties in rainfall, surface cover, and sediment yields are the most important potential sources of measurement errors [*Pietraszek*, 2006]. Comparable tipping-bucket rain gages were used at each site, and the rainfall data were carefully reviewed and edited. While measurement errors from rain gages cannot be completely eliminated [*Sevruk*, 1986], the summer rainfall data should be relatively accurate and comparable. The biggest concern is whether the rain gages accurately represent the true rainfall at each individual plot, as nearly all of the sediment is generated from localized summer convective storms that can exhibit considerable spatial variability.

The highest density of rain gages was at the Hayman fire, and this fire accounted for 22% of the 252 plot-years of data. In 2003 and 2004 we measured rainfall at four gages that were less than 2 km apart, and in 2003 the coefficient of variation (CV) for the total summer rainfall for these four gages was only 10% or 15 mm. In the much wetter summer of 2004 the CV was 14% or 40 mm. There was slightly more spatial variability in the total summer erosivity, as the CV was 17% in 2003 and 20% in 2004.

The spatial variations in rainfall will have a greater effect on the predicted sediment yields in RUSLE than Disturbed WEPP because the rainfall erosivity values were more variable than total rainfall, and in RUSLE the predicted sediment yield is a linear function of erosivity (Eq. 1). Simulations using Disturbed WEPP show that for a typical hillslope a ±15 mm change in the 2003 summer rainfall at the Hayman fire would alter the predicted sediment yield by no more than 3%, while a ±40 mm change in summer 2004 rainfall would alter the predicted sediment yield by less than 5%. In 2003 and 2004 the RMSE for Disturbed WEPP at the Hayman fire was 9.9 Mg ha^{-1} yr^{-1}, and this was slightly higher than the mean measured sediment yield. This high RMSE means that the uncertainty in the rainfall data has minimal effect on the overall performance of Disturbed WEPP.

The accuracy of our surface cover data was assessed by repeating measurements with the same observer, testing different sampling schemes with the same observer, and comparing the data from different observers. Transect orientation and spacing had little influence on measurement accuracy, as the values for the different sampling schemes differed by only 2-3% from the overall mean. Observer variability was higher, as 27 pairwise comparisons between observers showed an absolute mean difference of 8% (s.d.=5%). The potential bias due to observer error is minimized because one observer collected most of the data in 2000 and 2001, and a second observer collected most of the data in 2002-2004.

A ±3% error in the amount of surface cover could cause the RUSLE SC subfactor to change by up to 15%, and this would cause a corresponding change in the C factor and predicted sediment yields. For Disturbed WEPP, a ±3% change in surface cover on a typical hillslope at the Hayman fire would alter the predicted sediment yields by ±11%. While any error in measuring surface cover will alter the predicted sediment yields, the potential effect of these errors is still small relative to the RMSE for RUSLE and Disturbed WEPP (Table 3).

Several lines of evidence indicate that the errors in our measured sediment yields are relatively small. First, most of the plots with a high potential for sediment production had two or more sediment fences in series (Figure 2), and the first fence typically trapped at least 90% of the total sediment, even for the largest rainstorms. The smallest storms had lower trap efficiencies because they only mobilized the finer particles [*Pietraszek*, 2006], but the sediment yields from these storms represented only a small fraction of the annual totals. Second, all of the sites have coarse-textured soils with less than 5% clay [*Pietraszek*, 2006], and the preponderance of coarse particles helps maximize trap efficiency [*Munson*, 1989]. Other studies have documented trap efficiencies of over 90% for sandy soils [*Munson*, 1989] and silt loam soils [*Robichaud et al.*, 2001]. Finally, any under-measurement of sediment yields would tend to degrade rather than improve model performance, as the low magnitude values have little influence on the R^2_{eff} or RMSE and the sediment yields greater than 1 Mg ha^{-1} yr^{-1} are already under-predicted (Figures 4, 6). These results indicate that most of the prediction errors are due to model errors rather than measurement errors.

5.4. Model Errors in RUSLE and Potential Improvements

Many studies have examined the different sources of error in USLE and RUSLE and suggested possible improvements. These include changes in model structure [*Tran et al.*, 2002; *Sonneveld and Nearing*, 2003], changes in specific parameters [*Kinnell and Risse*, 1998; *Kinnell*, 2005], and ways to extend RUSLE to new geographic areas [*McIsaac*, 1990; *Liu et al.*, 2000; *Cohen et al.*, 2005; *Hammad et al.*, 2005]. The use of RUSLE in undisturbed forests is troublesome because overland flow is so uncommon [*Dunne and Leopold*, 1978], but the predominance of overland flow after high severity burns [*Shakesby and Doerr*, 2006] means that RUSLE should be much more applicable. The primary effects of burning are to alter the soil and surface cover, and in RUSLE these changes have to be encompassed through changes in the K and C factors. Sections 5.4.1 and 5.4.2 discuss whether the K and C factors can account for the documented effects of fires on soils, vegetation, and litter. Section 5.4.3 discusses whether the relationship between rainfall erosivity and sediment yields should be linear as assumed in RUSLE.

5.4.1. K factor

The K factor is determined from the soil texture, percent organic matter, permeability class, and soil structure class [*Renard et al.*, 1997]. Post-fire soil water repellency and the resultant decline in infiltration is often considered the primary cause of the increase in runoff after burning [e.g., *DeBano*, 2000; *Shakesby and Doerr*, 2006], but soil water repellency is not explicitly considered in RUSLE. Hence this section focuses on whether the K factor can incorporate the effects of fire-induced changes in permeability, soil organic matter, and soil structure.

Permeability is considered when calculating the K factor by assigning a soil to one of six permeability classes [*Renard et al.*, 1997]. Several studies in the Colorado Front Range have shown that high severity burns reduce the infiltration rate to only 8-10 mm h^{-1} [*Moody and Martin*, 2001; *Kunze and Stednick*, 2006; *Wagenbrenner et al.*, 2006]. This infiltration rate falls into the slow-moderate permeability class (4-18 mm h^{-1}) in RUSLE. If the soils are assumed to be in the highest permeability class (rapid, or ≥108 mm h^{-1}) prior to burning, the reduction in permeability will increase the K factor by 0.0095 Mg ha^{-1} MJ^{-1} mm^{-1} ha h. This change would increase our K factors and predicted sediment yields by 40-50%. The problem is that high-severity burns increase sediment yields by several orders of magnitude [e.g., *Moody and Martin*, 2001; *Coelho et al.*, 2004; *Benavides-Solorio and MacDonald*, 2005; *Shakesby and Doerr*, 2006], so the maximum change in permeability can account for only a small fraction of the observed change in sediment yields. The suggestion to increase the K factor by 0.016 Mg ha^{-1} MJ^{-1} mm^{-1} ha h for sites burned at high severity [*Miller et al.*, 2003] is equivalent to a change from rapid to very slow permeability, but the resultant 60-80% increase in our K values and predicted sediment yields is again much smaller than the sediment yield increases observed after high severity burns.

High severity burns also consume the soil organic matter that binds soil aggregates, and this greatly reduces the structural stability of the soil and increases the soil erodibility [*Giovannini and Lucchesi*, 1983; *Neary et al.*, 1999; *DeBano et al.*, 2005; *Moody et al.*, 2005]. The nomograph or equation used to calculate K uses four soil structure classes, and for a given soil a very fine granular structure has the lowest K factor, a coarse granular structure has an intermediate K factor, and a soil with a blocky or platy structure has the highest K factor [*Renard et al.*, 1997]. Burning results in a more friable, less cohesive, and more erodible soil [*Scott et al.*, 1998; *Badía and Martí*, 2003; *DeBano et al.*, 2005; *Moody et al.*, 2005; *Shakesby and Doerr*, 2006], but the quantitative effect of the structure classes on the K factor presume the opposite relationship [*Wischmeier and Mannering*, 1969]. The net result is that a fire-induced decrease in aggregate stability decreases the K factor when it really should increase the K factor. This discrepancy was recently noted for unburned soils by *Foster* [2004].

The K factor is relatively sensitive to percent organic matter and decreases as organic matter increases [*Renard et al.*, 1997]. Our field measurements indicate that a high severity fire reduces the soil organic matter in the top 3 cm from about 2.2% to 1.9%, and this only increases our K factors by 1-2%.

As presently formulated, the maximum increase in the K factor after burning is limited because the effects of the decreases in permeability and percent organic matter are countered by the change in structural class. Even if the relationship between structural class and erodibility was reversed to be consistent with our understanding of post-fire erosion processes, the maximum increase in K for our study sites would still be about 0.023 Mg ha^{-1} MJ^{-1} mm^{-1} ha h or 100%.

The effect of burning on the K factor also can be loosely estimated by comparing the values for unburned soils against values back-calculated from our field plots. The original K values in RUSLE were determined by dividing the soil loss by the rainfall erosivity for a standard plot (22 m long, 1.8 m wide, 9% slope, no surface cover, and ploughed up and down) [*Renard et al.*, 1997]. While most of our plots are larger and steeper than a standard plot, the severely burned plots are similar in terms of having less than 15% surface cover. The mean back-calculated K factor for these plots is 0.05 Mg ha^{-1} MJ^{-1} mm^{-1} ha h, and this is 2.5 times the K values obtained from the soil survey [*Moore*, 1992] and twice the K values estimated using *Stewart et al.* [1975].

These results indicate that the algorithm for calculating K values are not consistent with our current understanding of erosion processes. A revision of the relationship between soil structure and erodibility would increase the K factors after burning and better match the K values that we back-calculated from our field data. Even if this relationship were reversed, the maximum increase in K is only 100%, and this increase is only a small fraction of the 2-3 order of magnitude increase in sediment yields induced by high severity burns [e.g., *Morris and Moses*, 1987; *Inbar et al.*, 1998; *Prosser* *and Williams*, 1998; *Robichaud and Brown*, 1999; *Libohova*, 2004; *Shakesby and Doerr*, 2006].

5.4.2. C factor

The C factor is the ratio of the soil loss from a plot with some surface cover to the soil loss from an identical plot with bare soil [*Renard et al.*, 1997]. In forest and shrub lands in the western U.S., sediment yields are highest when there is less than about 35% surface cover and very low when surface cover exceeds about 60-65% [e.g., *Packer*, 1951; *Brock and DeBano*, 1982; *Johansen et al.*, 2001]. Recent studies have shown a strong nonlinear relationship between percent bare soil and post-fire sediment yields [*Pannkuk and Robichaud*, 2003; *Benavides-Solorio and MacDonald*, 2005; *Wagenbrenner et al.*, 2006; *Pietraszek*, 2006]. Conceptually, a high-severity burn should greatly increase the C factor because of the loss of canopy cover, loss of surface cover, and reduction in surface roughness. The problem is that most studies of post-fire sediment yields have not incorporated detailed measurements of soil consolidation over time, soil root mass over time, drop fall height from the canopy to the soil surface, and surface roughness. In the absence of such data, it is not possible to assess how burning affects each of these subfactors or the validity of the relationships used to calculate the C factor [*González-Bonorino and Osterkamp*, 2004], particularly since the subfactors were derived primarily from agricultural plots and secondarily from rangeland plots [*Weltz et al.*, 1987; *Renard et al.*, 1997].

As with the K factor, there is an inconsistency between the known effects of burning on the different subfactors and the current formulation of the C factor. In particular, the SM (soil moisture) subfactor increases with increasing soil moisture. This relationship is generally valid for unburned sites, as higher soil moisture values reduce the hydraulic gradient, decrease infiltration, and thereby increase runoff and surface erosion [*DeBano*, 2000; *Hillel*, 2004]. However, high and moderate severity burns often induce a water repellent layer at or near the soil surface in vegetation types such as chaparral and coniferous forests [*DeBano*, 2000; *Huffman et al.*, 2001]. This soil water repellency generally weakens as soil moisture increases, so drier soils typically have lower infiltration rates than the same soil under wetter conditions [*DeBano*, 2000; *Huffman et al.*, 2001]. This tendency is opposite to the present formulation of the SM subfactor.

Any effort to revise the SM subfactor will be hindered by the complexity of soil water repellency in burned areas, and this includes the dependence of soil water repellency on burn severity, soil moisture, and time since burning, as well as the extreme spatial variability in soil water repellency [*Doerr and Thomas*, 2000; *Ferreira et al.*, 2000; *Leighton-Boyce et al.*, 2003; *Huffman et al.,* 2001; *MacDonald and Huffman*, 2004; *Woods et al., 2007*]. While additional studies are needed to predict soil water repellency and infiltration rates in burned areas, the current formulation of the C factor is problematic in that burning increases four of the five subfactors while decreasing the SM subfactor. One also could argue that the effects of soil moisture should be incorporated into the K factor rather than the C factor, since this is primarily a soils issue.

Our working hypothesis prior to conducting this study was that the C factor should be close to 1.0 in areas that recently burned at high severity, as the mean surface cover for these areas was only 14%. Our best efforts to calculate the C factor yielded a mean value of 0.20 for areas that recently burned at high severity, and a maximum value of 0.33. This mean value is nearly identical to the 0.21 value calculated for high severity burns in ponderosa pine at the Cerro Grande fire in northcentral New Mexico [*Miller et al.*, 2003]. We conclude that the post-fire increases in the K and C factors are too small given the under-prediction of sediment yields for the plots that generated more than 1 Mg ha^{-1} yr^{-1} (Figure 4).

5.4.3. R factor

The final issue with the use of RUSLE to predict post-fire sediment yields are the assumptions that: (1) sediment yields begin as soon as the rainfall erosivity exceeds zero and, (2) sediment yields increase linearly with rainfall erosivity. The pattern of errors in Figures 4 and 5 suggests that these assumptions are a primary cause of the over-prediction of low values and under-prediction of high values, and resulting low R^2_{eff} values. Most process-based rainfall-runoff models require a certain amount of precipitation before any overland flow is generated, and our field data indicate that 5-20 MJ mm ha^{-1} h^{-1} is the minimum storm erosivity needed to generate sediment from plots that recently burned at high severity [*Benavides-Solorio and MacDonald*, 2005; *Pietraszek*, 2006; *Wagenbrenner et al.*, 2006]. A substantially higher storm erosivity is necessary to generate sediment from less severely burned plots or burned plots that have partially revegetated. The tendency for RUSLE to over-predict low sediment yields could be easily improved by incorporating an erosivity threshold that must be exceeded before any sediment is generated.

The assumed linearity between rainfall erosivity and sediment yields also is inconsistent with field observations. Both our data and other studies indicate that sediment yields increase linearly as annual erosivity approaches 150-300 MJ mm ha^{-1} h^{-1}, but beyond this point doubling the erosivity increases sediment yields by a factor of three of more [*Tran et al.*, 2002; *Benavides-Solorio and MacDonald*, 2005]. It is difficult to determine the general form of the relationship between rainfall erosivity and sediment yields because the more extreme storms are infrequent and combining data from different sites can be problematic due to the high variability in sediment yields from apparently similar plots. The relationship between rainfall erosivity and sediment yields also is complicated by the fact that RUSLE is a conceptual model, so it uses rainfall erosivity as a surrogate for both raindrop energy and other processes, such as the velocity and depth of overland flow. Rainfall simulations may be the best means to characterize the upper end of the relationship between rainfall erosivity and sediment yields for different site conditions, but for burned areas these simulations need to be conducted on larger plots because of the predominance of rill erosion [*Moody and Martin*, 2001; *Benavides-Solorio and MacDonald*, 2005; *Robichaud*, 2005; *Pietraszek*, 2006]. The incorporation of a rainfall erosivity threshold and a nonlinear relationship between rainfall erosivity and sediment yields would be the simplest and most powerful way to improve the ability of RUSLE to predict post-fire sediment yields.

5.5. Model Errors in Disturbed WEPP and Potential Improvements

An analysis of model errors is much more difficult for Disturbed WEPP because it has so many interacting parameters and controlling equations. Previous studies have shown that WEPP under-predicts annual runoff from forested areas [*Covert et al.*, 2005] and underestimates high rill detachment values [*Elliot et al.*, 1991; *Zhang et al.*, 2005], but these studies did not indicate how these errors would affect the predicted sediment yields. WEPP also incorrectly predicts storm patterns and the resulting errors in predicted sediment yields can range up to 47% [*Zhang and Garbrecht*, 2003]. A comparison of predicted post-fire sediment yields across the western U.S. showed that WEPP generated unrealistically high values in wetter areas [*Miller and MacDonald*, 2005]. An explicit evaluation of each of the individual parameters and equations is needed to determine which components are causing the low R^2_{eff} values for the individual hillslopes, and this would require an extensive, coordinated research effort. Section 5.5.1 discusses the effective hydraulic conductivity and rill erodibility, as these are two of the most sensitive parameters in Disturbed WEPP, and section 5.5.2 discusses the validity of the assumed vegetative recovery sequence.

5.5.1. Effective Hydraulic Conductivity and Rill Erodibility

Previous studies have shown that predicted sediment yields in Disturbed WEPP are very sensitive to the effective hydraulic conductivity (K_e) and rill erodibility (K_r) [*Nearing et al.*, 1990; *Tiscareno-Lopez et al.*, 1993]. These are the two main parameters that are altered to simulate burned conditions [http://forest.moscowfsl.wsu.edu/fswepp/docs/distweppdoc.html].

For agricultural and rangeland areas, K_e and K_r are empirically estimated from soil properties [*Alberts et al.*, 1995]. The K_e and K_r values for burned forests are based on field measurements from several fires in the western U.S. [*Robichaud*, 2000, 2005]. In

Disturbed WEPP the baseline K_e value for a sandy loam soil burned at high severity is 16 mm h^{-1}, and this is about twice the observed threshold of 8-10 mm h^{-1} for generating overland flow and sediment from severely burned sites in the Colorado Front Range [*Moody and Martin*, 2001; *Kunze and Stednick*, 2006; *Pietraszek*, 2006]. This baseline K_e is then reduced according to the soil rock content and percent surface cover, but we could not manually reduce the K_e values in Disturbed WEPP to determine how this would affect our predicted sediment yields. Simulations using the WEPP model showed that a 50% reduction in K_e increased the predicted sediment yields from recently burned hillslopes by 2-2.5 times. Reducing the baseline K_e in Disturbed WEPP would greatly improve predictions for hillslopes that produced more than 1 Mg ha^{-1} yr^{-1}, as the mean measured sediment yield was about double the predicted mean. A separate study on the Hayman fire is attempting to measure rill erodibility and how K_r values change over time [*P. R. Robichaud*, *USDA Forest Service*, *pers. comm.*, 2005], but more studies are needed to better predict K_e and K_r values after burning for different soil types and post-fire conditions.

There also may be a limit on the extent to which Disturbed WEPP can adequately represent post-fire conditions, as the interface was explicitly designed to minimize the number of user inputs. It is not clear whether the limited number of user inputs is sufficient to accurately estimate K_e, K_r, and the other parameter values needed to represent the full range of post-fire conditions. At least in the short term, the performance of Disturbed WEPP is probably constrained more by the lack of data for model calibration than the limitation on the number of user inputs. The lack of calibration data also will constrain the ability of the full WEPP model to accurately predict post-fire sediment yields despite its much greater flexibility in terms of user inputs.

5.5.2. Rate of Recovery

Disturbed WEPP accounts for the decline in post-fire sediment yields over time by specifying a sequence of treatments (i.e., vegetation types) for sites burned at high and low severity, respectively (Table 2). The different treatments trigger changes in K_e, K_r, and other parameters in the underlying WEPP model. The assumed recovery sequence for burned areas is based on fires in the northern Rocky Mountains [*P. Robichaud*, *USDA Forest Service*, *pers. comm.*, 2005], but the rate at which sediment yields return to pre-fire conditions varies with climate, vegetation type, site conditions, and the amount and timing of precipitation.

In eastern Oregon, for example, sediment yields dropped by one or two orders of magnitude from the first to the second year after burning due to rapid vegetative regrowth [*Robichaud and Brown*, 1999]. In the Colorado Front Range, sediment yields from high severity burns are just as high or higher in the second summer after burning because severely-burned sites still average less than 40% surface cover and the second summer is often wetter than the summer of burning [*Benavides-Solorio and MacDonald*, 2005; *Pietraszek*, 2006]. Our work and other studies show that 3-4 years are needed for post-fire sediment yields from high severity burns to decline to near-background levels [*Morris and Moses*, 1987; *Moody and Martin*, 2001; *Pietraszek*, 2006; *Wagenbrenner et al.*, 2006]. Plots with coarse-textured soils have noticeably slower rates of vegetative recovery and a correspondingly slower decline in post-fire sediment yields [*Benavides-*

Solorio and MacDonald, 2005; *Pietraszek*, 2006], and this can be attributed to the lower water holding capacity.

The burned areas used to develop and calibrate Disturbed WEPP typically have a more mesic climate than the mid-elevation forests in the Colorado Front Range [*P. Robichaud*, *USDA Forest Service*, *pers. comm.*, 2005], and these conditions facilitate a more rapid vegetative recovery. Our results show that a one year delay in the assumed recovery sequence improves the overall performance of Disturbed WEPP (Table 3), and nearly all of this improvement occurred in the third year after burning (Table 4). To more accurately model post-fire conditions, Disturbed WEPP should be modified to allow for different recovery sequences, and these could be input by the user, or programmed into Disturbed WEPP as a function of the user-selected climate station, soil type, and percent rock content.

5.6. Accuracy of Individual Hillslope Predictions versus Grouped Hillslopes

Both RUSLE and Disturbed WEPP were much more successful in predicting mean sediment yields from groups of hillslopes than predicting sediment yields from individual hillslopes. The measured sediment yields from groups of plots were highly variable, as the mean CV was 93% for sediment yields from the high severity sites in each fire for each year after burning. Other studies have shown a similar degree of variability in sediment yields from replicated plots [e.g., *Wendt et al.*, 1986; *Boix-Fayos, et al.*, 2007]. The underlying causes of this high variability include: within-plot variability in rainfall, infiltration, and soil properties; and between-plot variations in micro-topography and the spatial distribution of soil properties, rills, and surface cover

[*Wendt et al.*, 1986; *Reid et al.*, 1999; *Boix-Fayos et al.*, 2007]. Neither model can be expected to represent all of these factors, as RUSLE is a lumped model at the hillslope scale and Disturbed WEPP can only divide a hillslope into two uniform planes. Hence replicated plots generally will have nearly identical parameterizations and little variation in predicted sediment yields [*Nearing*, 1998].

Our results show that for each group of hillslopes, the predicted variability in sediment yields was typically only about half of the observed variability. Averaging sediment yields across groups of hillslopes reduces both the relative and absolute variability, and this reduction in variability should increase prediction accuracy. If the observed variability in sediment yields from replicated plots is considered random [*Nearing*, 1998], a stochastic component may be needed to model the potential range in post-fire sediment yields, and the predicted sediment yields should be represented by a probability distribution instead of a single value [i.e., *Robichaud*, 2005].

The lower accuracy of the Disturbed WEPP predictions for individual hillslopes also can be attributed to the fact that we were comparing the sediment yields for individual years against the predicted mean value using 50 years of simulated climate. The simulated climate is based on the monthly rainfall and number of wet days, but the 50-year average includes both wet and dry years and cannot necessarily be expected to perfectly match the sediment yield measured from a particular site for a given year. The difference in sediment yields between a single year and a 50-year average is another reason why a probabilistic approach is needed for predicting sediment yields.

The use of more spatially-explicit models also cannot be expected to improve prediction accuracy in the present study, as most topographic and soil survey data will still not have the necessary spatial resolution given the typical size of our hillslope plots. For practical reasons, users generally will not be able to measure and represent all of the controlling factors for each hillslope on a spatially explicit basis. Similarly, one cannot expect to incorporate all of the small-scale variations into management-oriented, deterministic, and user-friendly models such as RUSLE and Disturbed WEPP. In most applications model accuracy will be limited by both the availability and the resolution of the necessary input data. The implication is that model users may need to adjust their expectations of model performance, and explicitly recognize that most models will better predict sediment yields for average conditions than for individual sites.

6. Conclusions

Post-fire sediment yields predicted by RUSLE and Disturbed WEPP were compared to 252 plot-years of data collected from 83 burned hillslopes from six wild and three prescribed fires in the Colorado Front Range. The correlations between the predicted and observed sediment yields for individual hillslopes were quite low for both RUSLE (R^2=0.16) and Disturbed WEPP (R^2=0.25). Both models tended to substantially over-predict sediment yields that were less than 1 Mg ha^{-1} yr^{-1}, and under-predict sediment yields that were larger than 1 Mg ha^{-1} yr^{-1}. Increasing the soil erodibility factor to account for post-fire soil water repellency did not improve the performance of the RUSLE model. The performance of Disturbed WEPP was slightly improved by imposing a one-year delay in the assumed sequence of vegetative recovery. Both models were able to much more accurately predict mean annual sediment yields when the hillslopes were grouped by fire or burn severity (R^2 = 0.54 to 0.66).

There are two sets of inherent limitations to using RUSLE for predicting post-fire sediment yields in forested areas. Most importantly, the linear structure of RUSLE is inconsistent with the observed rainfall erosivity threshold for initiating post-fire erosion, and with the nonlinear increase in sediment yields with increasing erosivity. Second, burning at high severity greatly alters soils and surface cover, but the resulting increases in the K and C factors are too small to account for observed increases in sediment yields. Disturbed WEPP under-predicts high-magnitude sediment yields for recently burned high severity sites in the Colorado Front Range because the assumed effective hydraulic conductivity is too high and the vegetation recovery is too rapid.

Both RUSLE and Disturbed WEPP are limited in their ability to predict post-fire sediment yields from individual hillslopes because we cannot realistically measure and represent all of the temporal and spatial variability in the factors and processes that control post-fire sediment yields. Both models can more accurately predict mean post-fire sediment yields for groups of hillslopes. Model users should be aware of the inherent limitations to model performance and consider the absolute magnitude of the prediction errors when making management decisions.

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Table 1. List of the fires, years monitored, primary vegetation type, mean elevation of the study plots, number of rain gages, and number of hillslope plots by burn severity. Year 1 is defined as the year of burning and an asterisk indicates a prescribed fire.

Fire	Date burned	Years monitored post-burning	Primary vegetation type	Mean elevation (m)	Number of rain gages	Number of plots by burn severity		
						High	Moderate	Low
Big Elk	Aug 02	2-3	Lodgepole pine	2670	1	3	2	1
Hayman	Jun 02	1-3	Ponderosa pine	2280	4	23	1	0
Schoonover	May 02	1-3	Ponderosa pine	2210	1	6	0	0
Hewlett Gulch	Apr 02	1-3	Ponderosa pine	1920	1	3	0	0
Bobcat	Jun 00	1-5	Ponderosa pine	2160	3	13	2	1
Dadd Bennett*	Jan 00	1-4	Ponderosa pine	2340	2	1	3	2
Lower Flowers*	Nov 99	1-4	Ponderosa pine	2650	1	4	4	2
Crozier Mountain*	Sep 98	2-5	Lodgepole pine	2300	1	4	1	0
Hourglass	Jul 94	7-10	Lodgepole pine	2720	1	5	1	1
				Totals	15	62	14	7

Table 2. Sequence of vegetation recovery for sites burned at high and low severity as assumed in Disturbed WEPP and the modified version (Disturbed WEPP$_m$) tested in this study. Year 1 is the year of burning.

	High severity		Low severity
Year(s)	Disturbed WEPP	Disturbed WEPP$_m$	
1	High severity fire	High severity fire	Low severity fire
2	Low severity fire	High severity fire	Short grass
3	Short grass	Low severity fire	Tall grass
4	Tall grass	Short grass	Shrub
5	Shrub	Tall grass	5-year old forest
6	5-year old forest	Shrub	5-year old forest
7 to 15	5-year old forest	5-year old forest	5-year old forest
>15	20-year old forest	20-year old forest	20-year old forest

Table 3. Validation statistics for the standard and modified versions of RUSLE and Disturbed WEPP for individual and grouped hillslopes.

	Individual hillslopes				Grouped hillslopes			
	RUSLE	$RUSLE_m$	Disturbed WEPP	Disturbed $WEPP_m$	RUSLE	$RUSLE_m$	Disturbed WEPP	Disturbed $WEPP_m$
R^2	0.16	0.14	0.25	0.27	0.56	0.54	0.59	0.66
R^2_{eff}	0.06	-0.26	0.19	0.23	0.52	0.31	0.53	0.65
RMSE (Mg ha^{-1} yr^{-1})	6.46	7.48	5.99	5.84	3.56	4.25	3.50	3.03
b (slope)	0.24	0.38	0.24	0.35	0.54	0.90	0.50	0.68
a (intercept) (Mg ha^{-1} yr^{-1})	1.40	2.08	1.38	1.72	0.57	0.72	0.81	0.83

Table 4. R^2_{eff} values for different times since burning for the standard and modified versions of RUSLE and Disturbed WEPP for individual and grouped hillslopes.

	Individual hillslopes				Grouped hillslopes			
Years since burning	RUSLE	$RUSLE_m$	Disturbed WEPP	Disturbed $WEPP_m$	RUSLE	$RUSLE_m$	Disturbed WEPP	Disturbed $WEPP_m$
1	-2.84	-10.09	-0.39	-0.39	-0.19	-5.86	-1.03	-1.03
2	0.04	0.00	0.10	0.10	0.36	0.46	0.43	0.64
3	-0.02	-0.02	0.06	0.19	0.22	0.22	0.37	0.52
4	0.17	0.17	-0.03	-0.01	0.13	0.13	-0.35	-0.28
5-10	-9.72	-9.72	-9.59	-9.59	-60.4	-60.4	-7.72	-24.1

Table 5. Summary of the results from different RUSLE and WEPP validation studies.

Study	Land use	Location	Model	Measurement time scale	R^2	R^2_{eff}
Tiwaria et al. (2000)	Agriculture	Eastern and central U.S.	RUSLE	Annual	0.62	0.60
"	Agriculture	Eastern and central U.S.	RUSLE	Mean annual	0.75	0.72
"	Agriculture	Eastern and central U.S.	WEPP	Annual	0.43	0.40
"	Agriculture	Eastern and central U.S.	WEPP	Mean annual	0.72	0.71
Spaeth et al. (2003)[1]	Rangeland	Western U.S.	RUSLE	Minutes	nd	-2.18 to -0.33
Yu et al. (2000)	Agriculture (bare)	Queensland, Australia	WEPP	Monthly	0.63	-0.47
"	Agriculture (mulched)	Queensland, Australia	WEPP	Monthly	0.63	0.45
"	Agriculture (conventional pineapple)	Queensland, Australia	WEPP	Monthly	0.69	-0.05
"	Agriculture (bare)	Queensland, Australia	WEPP[2]	Monthly	0.94	0.91
"	Agriculture (mulched)	Queensland, Australia	WEPP[2]	Monthly	0.76	-1192
"	Agriculture (conventional pineapple)	Queensland, Australia	WEPP[2]	Monthly	0.62	0.28
Elliot (2004)	Forest harvest and fires	Western and southeastern U.S.	Disturbed WEPP	Varies	0.64	nd
Soto and Díaz-Fierros	Scrubland (unburned)	Northwest Spain	WEPP[4]	Varies	0.92	0.92
(1998)[3]	Scrubland (prescribed fire)	Northwest Spain	WEPP[4]	Varies	0.67	0.61
"	Scrubland (wildfire)	Northwest Spain	WEPP[4]	Varies	0.59	0.03

nd=no data

[1]Data from Spaeth et al. (2003) are based on rainfall simulations; all other studies are from unbound or bound plots

[2]Calibrated infiltration and erodibility parameters

[3]Statistics were calculated from data in Soto and Diaz-Fierros (1998)

[4]Vegetation growth and decomposition were calibrated to match measured values

Figure Captions

Figure 1. Location of the nine fires where sediment yields were measured and the two weather stations used in Disturbed WEPP (names in italics).

Figure 2. A typical set of sediment fences used to measure hillslope-scale sediment yields from a convergent hillslope. Photo taken one month after the Hayman fire.

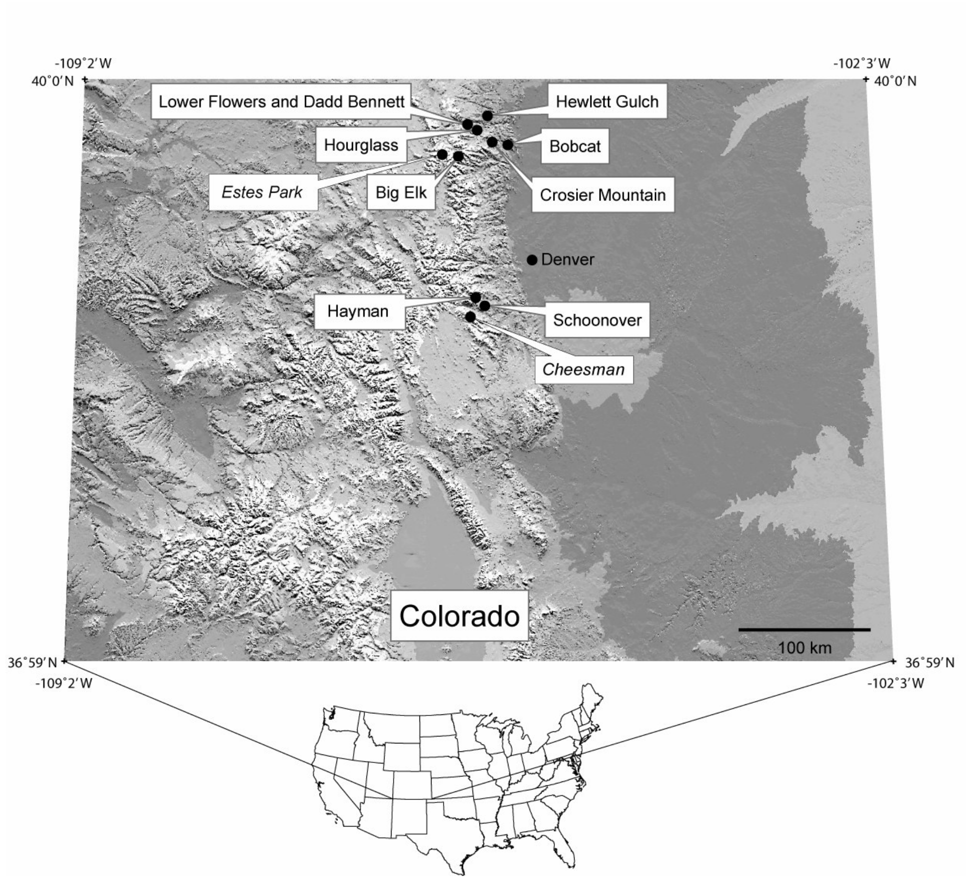
Figure 3. A) Percent surface cover versus time since burning for each plot. B) Calculated values of the RUSLE C factor versus time since burning for each plot.

Figure 4. A) Predicted sediment yields for each plot using RUSLE versus the observed values. B) Predicted sediment yields for each plot using $RUSLE_m$ versus the observed values. The solid line is the 1:1 line and the dashed lines are the 95% confidence intervals defined for replicated agricultural plots [*Nearing*, 1998, 2000; *Nearing et al.*, 1999].

Figure 5. A) Mean of the predicted sediment yields using RUSLE for each group of plots versus the mean of the observed values. B) Mean of the predicted sediment yields using $RUSLE_m$ for each group of plots versus the mean of the observed values. The solid line is the 1:1 line and the dashed lines are the 95% confidence intervals defined for replicated agricultural plots [*Nearing*, 1998, 2000; *Nearing et al.*, 1999].

Figure 6. A) Predicted sediment yields using Disturbed WEPP for each plot versus the observed values. B) Predicted sediment yields using Disturbed $WEPP_m$ for each plot versus the observed values. The solid line is the 1:1 line and the dashed lines are the 95% confidence intervals defined for replicated agricultural plots [*Nearing*, 1998, 2000; *Nearing et al.*, 1999].

Figure 7. A) Mean of the predicted sediment yields using Disturbed WEPP for each group of plots versus the mean of the observed values. B) Mean of the predicted sediment yields using Disturbed $WEPP_m$ for each group of plots versus the mean of the observed values. The solid line is the 1:1 line and the dashed lines are the 95% confidence intervals defined for replicated agricultural plots [*Nearing*, 1998, 2000; *Nearing et al.*, 1999].



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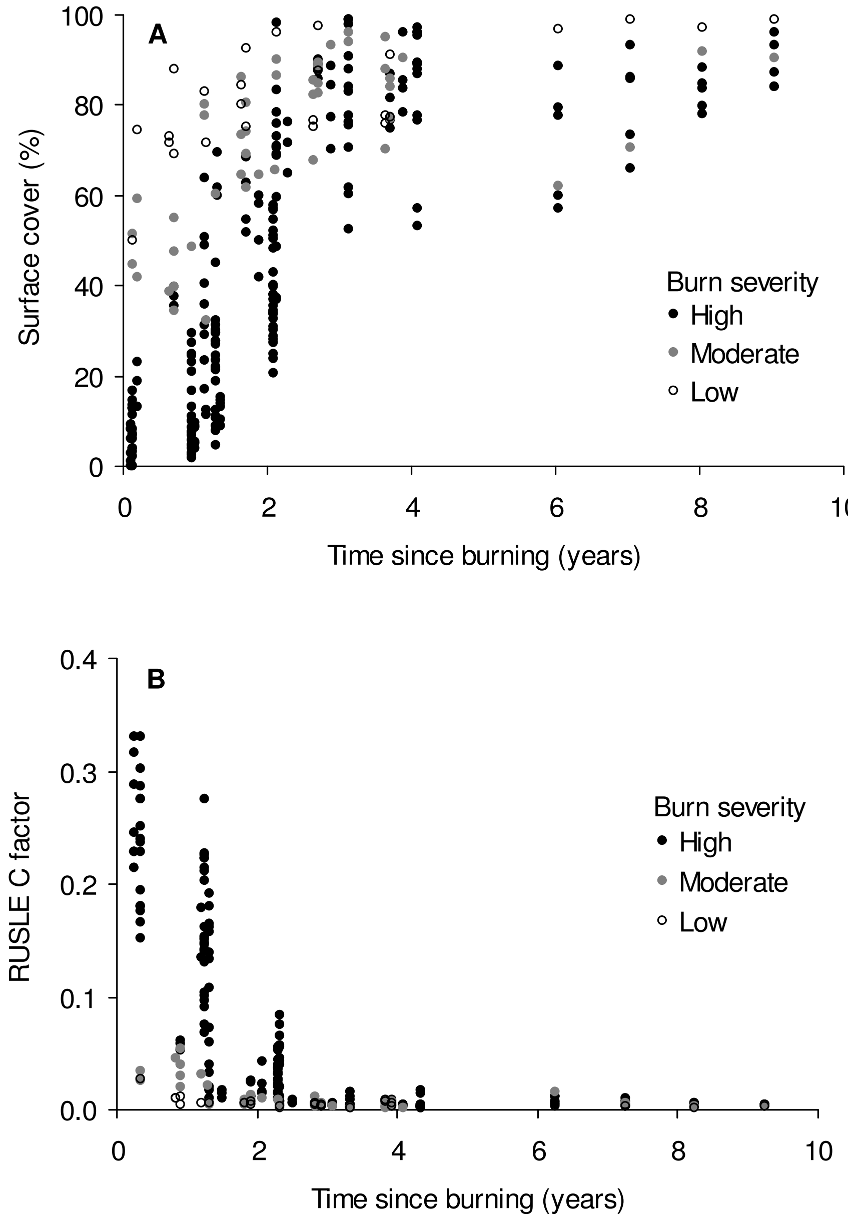

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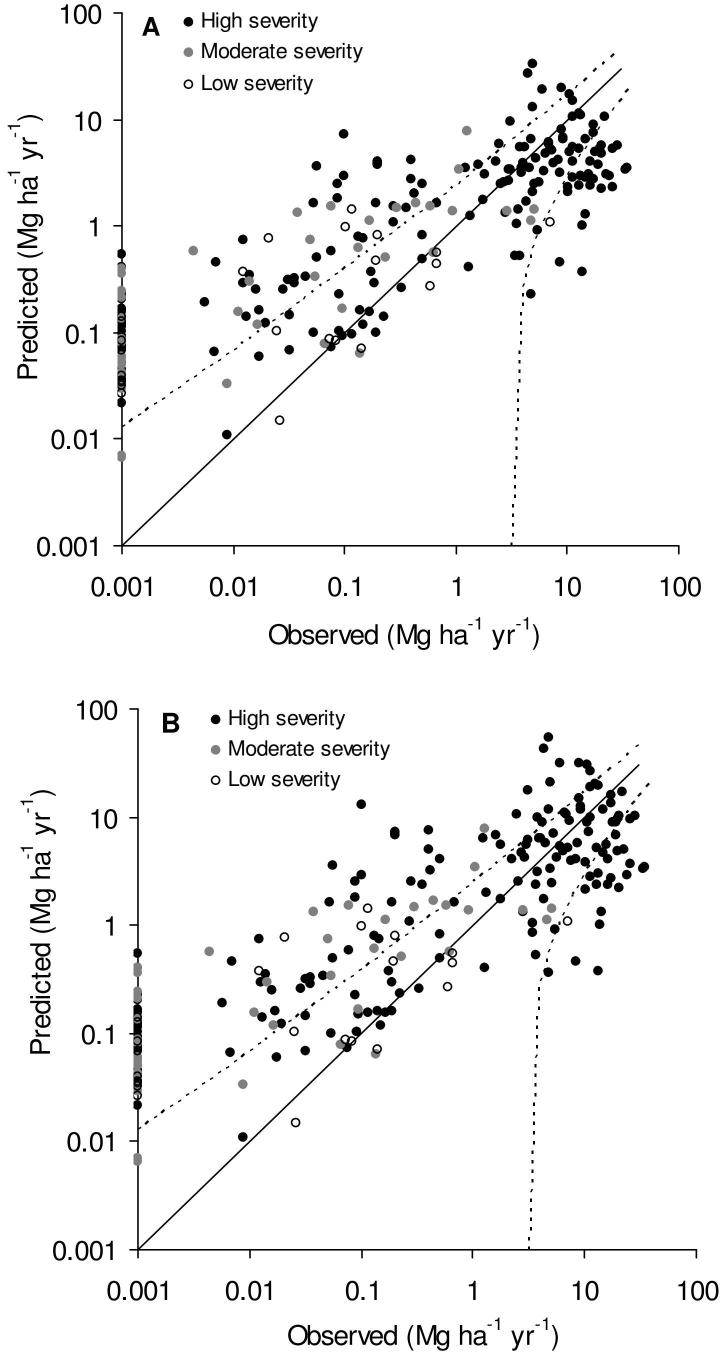

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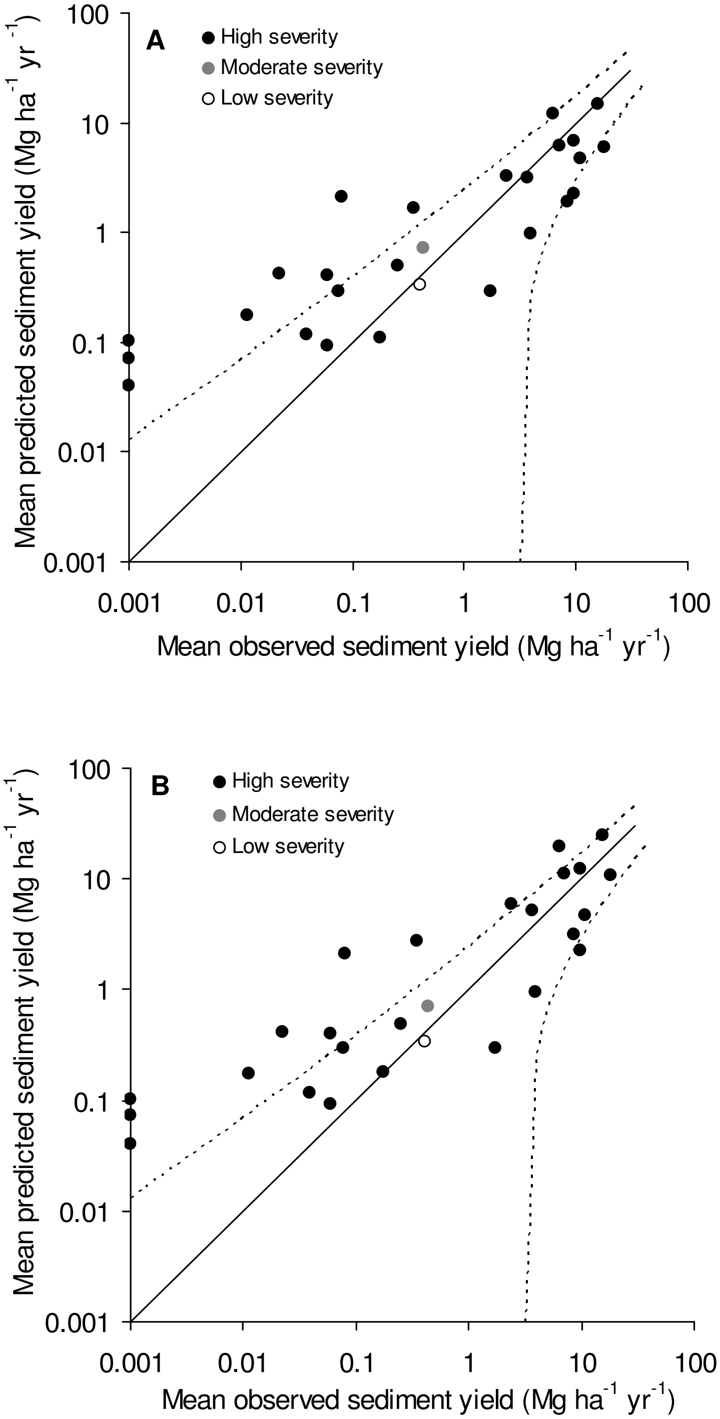

Figure 5. A) Mean of the predicted sediment yields using RUSLE for each group of plots versus the mean of the observed values. B) Mean of the predicted sediment yields using $RUSLE_m$ for each group of plots versus the mean of the observed values. The solid line

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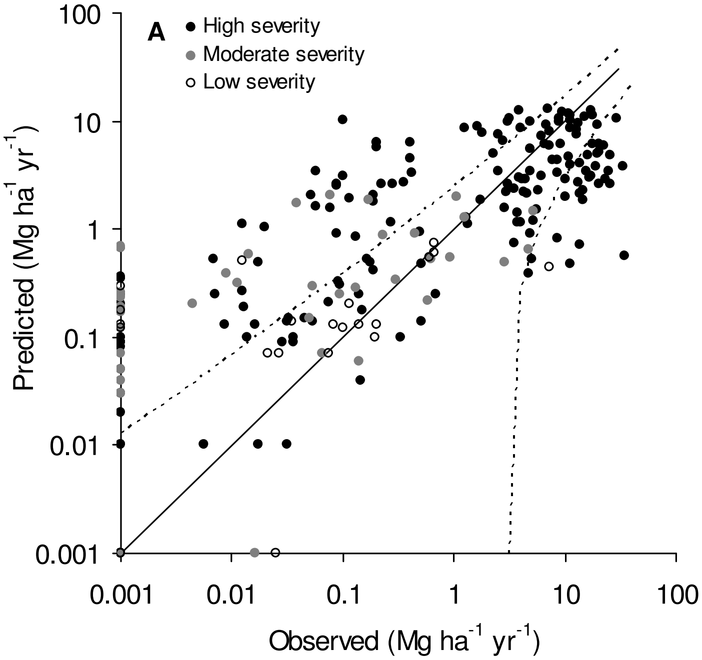

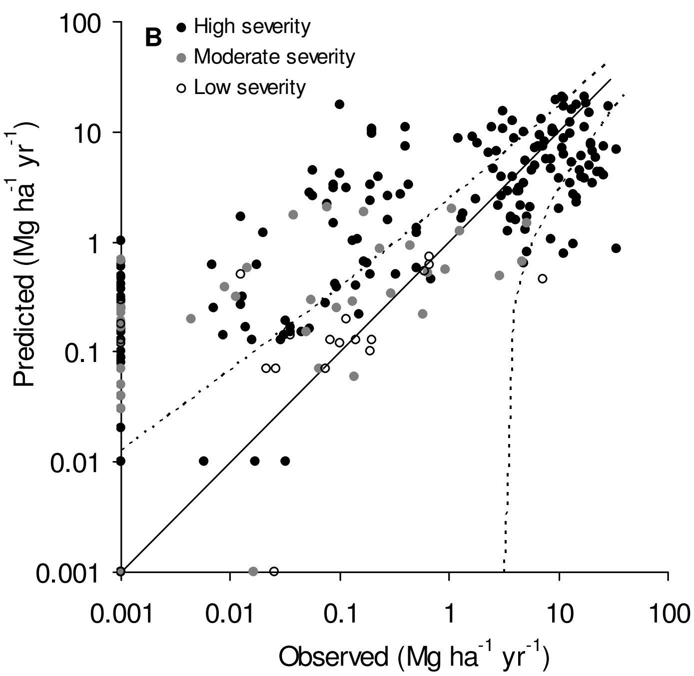

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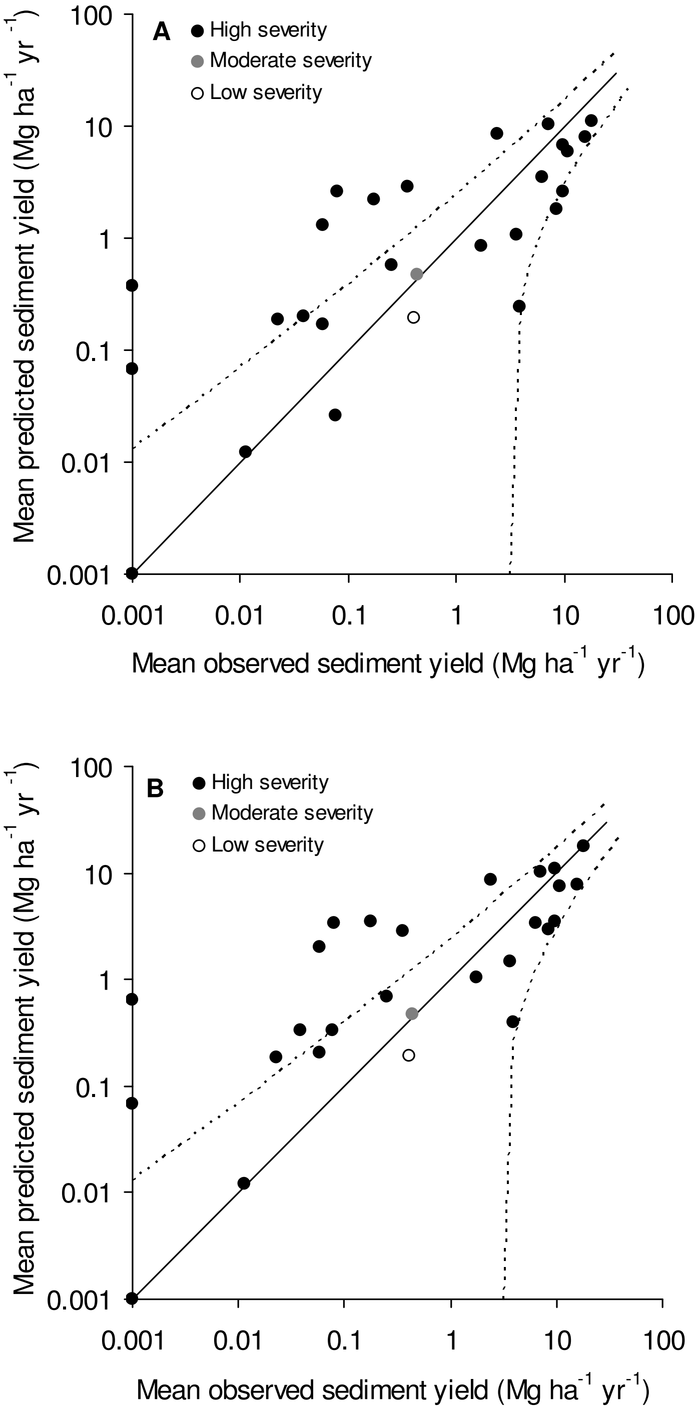

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