PARAMETERIZING THE WEPP MODEL FOR POST-FIRE CONDITIONS IN SEMI-ARID ENVIRONMENTS USING RAINFALL SIMULATOR

By

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A Thesis Submitted to the Faculty of the

SCHOOL OF NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN WATERSHED MANAGEMENT

In the Graduate College

THE UNIVERSITY OF ARIZONA

2006

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ACKNOWLEDGEMENTS

First of all, I would like to thank Jeff Stone for taking me on as a student, always having an open door, and for putting up with my endless questions and concerns. Second, I would like to thank my academic advisor, Dr. Hawkins, for his concern and collaboration throughout the entire process, especially towards the final stages of completion. Third, I would like to thank Dr. Ginger Paige for her support, valuable insight, and vital comments. Finally, I would like to thank Dr. Dave Breshears for his important contributions in enhancing this document.

I would also like to thank everyone at the Southwest Watershed Research Center, especially my co-workers and peers. Not only did their contributions in the field and with data entry benefit my project, but their continual support and encouragement were essential to the completion of my degree.

I would also like to thank my family and friends who were extremely supportive in my endeavors to obtain my master's degree. I want to especially thank my parents, for their love, care and compassion throughout this process. Finally, I want to thank the love of my life, Mark Gruetzman for his patience, undying support and understanding while I worked to accomplish my dreams.

DEDICATION

This work is dedicated to my wonderful parents, Steve and Maggie Wickre. .

Dear Mom and Dad:

This document is dedicated to you because without your undying love and support it would never have been attainable. Thank you for everything you have done for me.

I LOVE YOU BOTH SO MUCH!

Sincerely,

Jennifer E. Wickre

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ABSTRACT

Wildfires are occurring in semi-arid ecosystems due to the combination of drought and human management decisions. Modeling immediate post-fire runoff and erosion impacts, as well as recovery, is challenging due to the lack of known parameter values, parameter estimation equations and adequate models. Current post-fire modeling is focused on forested systems, rather than rangelands, and little research has looked at recovery of systems in the subsequent years following a wildfire. The first two objectives of this research included increasing the database of parameter values and developing parameter estimation equations for modeling post-fire and recovery conditions. The third objective was to evaluate a model on its ability to predict post-fire runoff and erosion rates on semi-arid grassland and oak-woodland ecosystems. The model used was the Water Erosion Prediction Project (WEPP). The approach was to measure post-fire runoff and erosion rates using a multiple intensity rainfall simulator. Simulations were conducted on large (2 m by 6 m) and small (0.6 m by 1.2 m) plots with natural, fire and recovery treatments. The two plot scales were used to analyze differences in erosion processes; rill and interrill erosion. Study areas included two oak-woodland sites and three grassland sites in southeastern Arizona. The results indicated that some sites returned to natural conditions after two years, in terms of erosions response, but did not recover even two years after the fire, in terms of the rainfall-runoff response. Additionally, the data suggested significant differences in the erosion processes between grassland and oak-woodland sites. These results are critical to improving post-fire runoff and erosion modeling in semi-arid ecosystems.

CHAPTER 1

INTRODUCTION

1.1 Overview

Fire is a natural disturbance that has the ability to drastically alter hydrologic and erosion processes. Human management has changed the historical patterns of fire; consequently the long-term absence of fire may produce irreversible changes in structure and function of desert grasslands (McPherson, 1995). These changes in natural fire patterns influenced by human management decisions in addition to the current drought conditions have created environments in which wildfires tend to be more destructive than historically recorded. Therefore, today's wildfires can cause drastic increases in the post-fire rates of runoff and erosion (Johansen et al. 2001a). This is especially true because of the unique climatic conditions of semi-arid environments.

In semi-arid climates, such as southeastern Arizona, one rainy season is the monsoon season which starts in July and ends in September. Monsoons are high intensity, short duration convective thunderstorms. Prior to monsoon season semi-arid grasslands are very dry and senescent biomass accumulates contributing to the fuel load/fire potential. The combination of seasonal dry conditions and accumulated amounts of biomass (which have been enhanced by human management decisions and current drought conditions) can create destructive wildfires; because once a fire is ignited it can spread rapidly. The wildfire causes a change in the structure and function of the rangeland (one example is loss of vegetation cover) which can lead to amplified rates of runoff and erosion when coupled with the high intensity, short-duration thunderstorms.

Modeling post-fire runoff and erosion is used to identify the areas most vulnerable to increased rates of runoff and erosion due to fire. Model users include action agencies such as the United States Forest Service's (USFS) Burned Area Emergency Response (BAER) teams. To improve the current modeling techniques used by the BAER teams in determining post-fire runoff and erosion rates the following three items are needed: an expansion of the current database of post-fire parameter values, development of parameter estimation equations and evaluation of the current models used. This research will address these three items for two semi-arid environments in southeastern Arizona.

1.2 Problem Statement

Research on post-fire impacts has mainly focused on ecosystems other than semi-arid rangelands (Roudy et al. 1978, Wright et al. 1976, Garza and Blackburn 1985, Benavides-Solorio and MacDonald 2001, Robichaud, 2000.). A few studies have looked at post-fire runoff and erosion on semi-arid grassland sites (Emmerich and Cox, 1992; Johansen et al., 2001b; White and Loftin, 2000; Pierson et al., 2001). However no research has been done to look at fire effects on semi-arid oak-woodland sites.

In addition to quantifying the immediate effects of fire on runoff and erosion, little research had looked at the recovery of these sites with time. Vegetation recovers through time following fire but few if any studies have looked at hydrologic and erosion response through time following a fire.

The Erosion Risk Management Tool (ERMiT, Elliot et. al., 2001) is a post-fire management tool, developed by the United States Forest Service (USFS). ERMiT is used to predict runoff and erosion from a fire site following a single storm event. The problem with the current model is that the parameter database is limited and no parameter estimation equations have been developed for post-fire conditions. Parameters need to be estimated for models such as ERMiT under post-fire and subsequent recovery conditions, but minimal data are usually available for parameterization, especially for key vegetation types such as semi-arid grasslands and oak-woodlands in southeastern Arizona.

ERMiT is a model whose interface is online and was created to specifically address the effects of fire. The runoff and erosion components of the ERMiT model are based on the Water Erosion Prediction Project (WEPP, Flanagan and Nearing 1995). WEPP is a hydrologic and erosion simulation model, primarily developed and validated for croplands. The Rangeland Hydrology and Erosion Model (RHEM; Wei et al., submitted) developed in collaboration between the USDA-ARS, Natural Resources Conservation Service (NRCS) and US Forest Service (USFS). RHEM was developed from WEPP but altered slightly to focus on rangelands. The main difference between WEPP and RHEM is that for RHEM the parameterization is separated from the model engine making it easier to use for parameter optimization. Therefore, WEPP is the background model of this research, RHEM is used because it is developed specifically for parameter optimization and ERMiT is the model that needs to be improved for modeling post-fire runoff and erosion. A model evaluation will also be performed on RHEM to test the model ability to predict post-fire runoff and erosion.

The erosion component of WEPP incorporates both interrill and rill erosion. Very few studies have incorporated multiple plot scales to address both types of erosion, especially how these erosion processes changes with a disturbance such as wildfire. Research that incorporates the analysis of both types of erosion is important in developing interrill and rill erosion parameters for modeling post-fire erosion using the WEPP models. The two different plot scales are also important in understanding the two erosion processes that occur at different plot scales and environments. This is especially true if the different environments researched have different deposition patterns as is true of oak-woodland and grassland sites.

In summary, semi-arid grassland and oak-woodland sites are vulnerable to fire yet systematic comparison of post-fire runoff and erosion in these extensive systems is largely lacking, with few if any studies that evaluate time series responses and plot scale dependencies.

1.3 Objectives

The objectives of this research, listed below, are necessary to improve the current technology of modeling post-fire runoff and erosion rates in semi-arid grasslands and oak-woodlands.

(1) To parameterize WEPP runoff and erosion parameters for different soil vegetation complexes for both pre and post fire conditions over several years;

(2) Create parameter estimation equations for users to determine runoff and erosion parameters based on vegetation and ground cover characteristics; and

(3) Evaluate performance of WEPP on post-fire environments

1.4 Approach

In this study, the Walnut Gulch Rainfall Simulator (WGRS), (Paige et al., 2003) was used to measure runoff and erosion on ecological sites in southeastern Arizona. The WGRS is a variable intensity simulator that can apply a range of intensities from 25 to 180 mm/hr. The simulator was used to apply rainfall to three treatments; natural, fire and recovery. Each treatment had two set of plots; four large plots (2 by 6 m) and four small plots (0.6 by 1.2 m). This research focused on the effects of wildfire; therefore pre-fire conditions were not obtainable. Instead natural sites with similar characteristics as the fire sites in terms of slopes, soils and vegetation were chosen to represent the pre-fire treatment. The measured runoff and erosion results from the rainfall simulator experiments were used to develop a database of four identified parameter values for modeling post-fire runoff and erosion using both optimization and calculation techniques. Of the four parameter values one is a runoff parameter (effective hydraulic conductivity, K_e) and three are erosion parameters (interrill erodibility, K_i, and rill erosion parameters; rill erodibility, K_r and critical shear stress, τ_c). The natural, fire, and recovery treatments were analyzed for differences in vegetation and ground cover characteristics in order to develop parameter estimation equations. Finally the identified and estimated parameters were used to evaluate the ability of the model to predict runoff and erosion. A second model evaluation was also completed as suggested by Nearing (2000), which looked at the model effectiveness in predicting erosion when the natural variability in erosion data is accounted for. Figure 1.1 is a flow chart depicting the sequence of steps completed in order to reach the three objectives of this research.

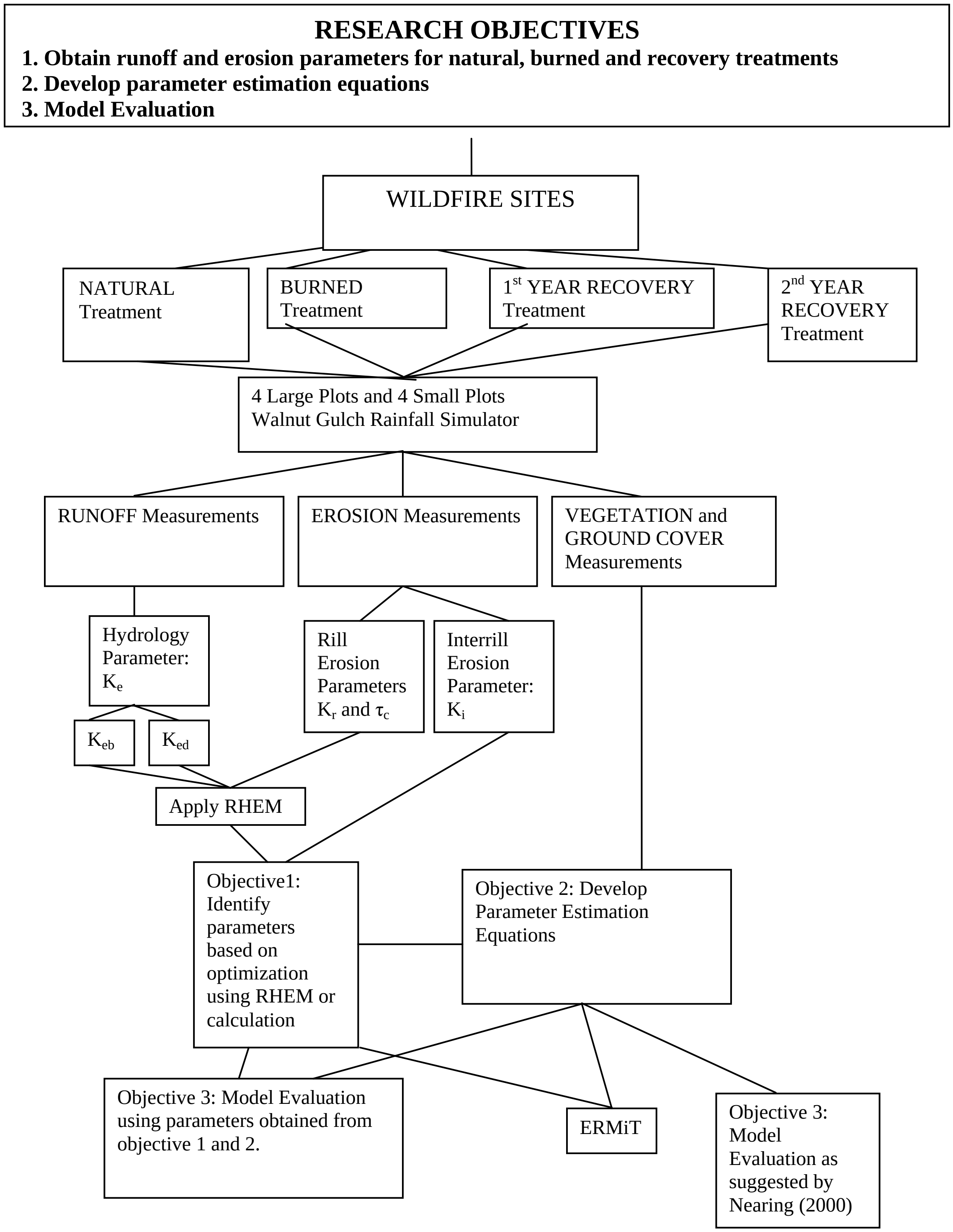


Figure 1.1 Flow chart depicting steps in obtaining research objectives.

1.5 Benefits

Several potential benefits will come out of this research. First, it will help to increase the database of parameters and develop parameter estimation equations for modeling post-fire runoff and erosion rates in semi-arid rangelands. This will enhance the effectiveness of the WEPP, RHEM and ERMiT models. Secondly, the RHEM model will be evaluated for its ability to predict post-fire runoff and erosion rates. Third, different plot scales will be used to create both interrill and rill erosion parameter values and parameter estimation equations. In addition the two plot sizes will help in understanding the different depositional patterns between the two semi-arid environments studied. Finally, this research will help to analyze post-wildfire, as well as subsequent recovery, runoff and erosion rates in semi-arid grassland and oak-woodland vegetation communities.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses post-fire hydrologic and erosion research that has been conducted on semi-arid grasslands, shrublands and woodlands. The first section of this chapter summarizes the techniques and results of several research projects along with their conclusions and hypothesis as to why fire causes changes in runoff and erosion rates. The second section of the literature review is a discussion on the current models and modeling techniques used to predict post-fire runoff and erosion. In particular, the WEPP model is described including results of a sensitivity analysis, governing equations, input files and parameterization of the model. Finally, this chapter includes a brief discussion of the effects of different plot scales on erosion processes.

2.1 Fire Effects on Runoff and Erosion

Grasslands

Johansen et al. (2001b) studied effects of fire at the Waste Isolation Pilot Plant (WIPP) in New Mexico and the Rocky Flats Environmental Technology Site (RFETS) in Colorado. The WIPP site is a grassland site, has sandy soils and slopes of six percent. The RFETS site is also on a grassland, with clayey soils and average slopes of nine percent. Both sites are located in semi-arid climates. A rotating-boom simulator (Swanson, 1962) was used to apply rainfall onto 3 x 10.7 m burned and natural plots. Three simulations were performed on each plot starting with a one hour rainfall application at 60 mm/hr, followed by 24 hour recovery, then two wet runs at 60 mm/hr for half an hour each separated by a half hour recovery period. Canopy cover, ground cover and surface roughness were measured with a point frame on all the plots. Experiments were only conducted on grassland sites; however other vegetation types were incorporated from supplementary literature. These other vegetation types included shrub and woodland systems. The experiment concluded that burning increased the amount of bare soil subjected to raindrop impact and overland flow. Runoff increased on burned plots and was relatively highly correlated with ground cover removal. Increases were not thought to be due to water-repellant soils because at the RFTS site runoff was initially the same for both fire and natural plots. In addition the percent ground cover reduced by fire is expected to be least in the grassland communities because fire tends to burn at a higher intensity and longer in brush and forested systems.

Emmerich and Cox (1992) conducted prescribed burn research on the Santa Rita Experimental Range (SRER) and the Empire-Cienega Resource Conservation Area (ECRCA) in southeastern Arizona, both semi-arid climates. The SRER is a grassland site on gravelly loam soils with slopes of five to six percent. The ECRCA is also a grassland site with gravelly sandy loam soils and slopes of five to seven percent. A rotating boom rainfall simulator was used to apply rainfall to 3.05 by 10.66 m plots. Two rainfall rates were applied to the plot starting with 55 mm/hr for 45 minutes and then a higher rate of 110 mm/hr for 15 minutes. Simulations were conducted following the burn, once in the fall and again in the spring. The data collected illustrated that the fire had no effect on the surface runoff and sediment production immediately (same day) following the burn treatment. This was calculated by comparing the means of the two treatments (control and burn) with a probability level of $P \leq 0.15$. Therefore it was concluded that vegetation cover by itself was not the dominating factor controlling surface runoff and erosion.

In contrast, Emmerich and Cox (1994) used an additional years worth of data to conclude contradictory results. The same sites were used with the same rainfall simulator experimental design but a second burn was done one year after the first burn. Again simulations were run on the second year burn in the fall and again in the spring. On the first treatment assessment it was found that a burn treatment had no effect on runoff and erosion. The deficiency in the first burn treatment having an effect on runoff and erosion was observed to be caused by microdebris dams that formed between grass crowns, which then protected the soil surface from raindrop impact. After the second burn treatment there was a substantial increase in runoff and erosion. It was hypothesized that the change in hydrologic properties was primarily due to soil surface structure. The microdebris dams observed after the first burn were nonexistent during the second treatment. The soil surface under trees and shrubs following a fire maintained a high infiltration rate. Therefore the increase in runoff and sediment production following a burn treatment was primarily influenced by the soil surface structure, while the vegetation interacted with the soil only in preserving high infiltration rates.

Emmerich (1998), using the same data as Emmerich and Cox (1994), again concluded that the primary influence in runoff and sediment loss following a fire was the soil with an interaction with the vegetation. Hence, it is not primarily controlled by vegetation. Significant year and season effects were identified. It was concluded that another primary influence on runoff and erosion following a fire is the season, fall or spring, in which the rainfall event occurred and the number of consistent years in which burning occurred. The general differences were hypothesized to be a result of frost action, soil biological activity and differences in storm types.

White and Loftin (2000) conducted a research experiment to look at sediment yield following a prescribed burn on two semi-arid grassland sites near Albuquerque, New Mexico. One site is a clay loam and the other a fine sandy loam, slopes were not given. A rainfall simulator was not used in this experiment, rather natural rainfall was used on one hectare plots. Sediment was collected from the plots for two years following burn. It was shown that the prescribed burns did not significantly increase sediment yield at the sites. Differences in sediment yield were observed between year one and year two on the unburned sites as well as the burned. Therefore, it was hypothesized that other factors, such as climatic conditions, were influencing erosion rather than only the burn treatment.

Pierson et al. (2001) studied post-fire effects on sagebrush vegetation in the Pine Forest Range near Denio, Nevada. The soils are sandy loams and the slopes between 35 to 40%. An oscillating-arm rainfall simulator was used the year of the fire and one year post-fire. Rainfall was applied to the 0.5 m^2 plots at a rate of 85 mm/h for 60 minutes. Soil moisture, bulk density and soil texture were all measured as well as canopy and ground cover. It was concluded that fire caused an increase in interrill erosion by two fold when comparing burned to unburned conditions. The main cause for the increase was hypothesized to be because fire removed the organic matter and litter from the soil surface. This caused in increase in overland flow because more soil was exposed to raindrop impact and no sediment was trapped behind litter dams. In addition the main impact of the fire on erosion was concentrated on the coppice microsites rather than with the interspaces between shrubs. The year following the fire relatively high erosion rates were still observed

O'Dea and Guertin (2003) conducted research on a prescribed grassland fire on the Audubon Research Ranch near Elgin, Arizona. Data were collected the year of the burn and one year post-fire. The site is on the White House gravelly loam soil with a 1 to 3% slope. Burned plot runoff and erosion rates were measured using both a rainfall simulator and natural rainfall. A rotating-boom simulator was used to apply rainfall to 3 m by 10 m plots. Rainfall was simulated at a rate of 63 mm/hr for 40 minutes. Other measurements taken on the plots were canopy and basal cover as well as bulk density and aggregate stability. Water intake rates were also measured to use as a surrogate measurement of infiltration under unsaturated soil conditions. Informal test with water droplets showed no evidence of post-fire hydrophobic soil conditions. The year of the fire there was no significant difference in runoff between the control and burned plots with natural rainfall, however there was a significant difference in sediment yield. On the plots where the rainfall simulator was applied there was a significant difference in runoff and sediment yield between the burned and unburned plots. The first year recovery data showed that the site seemed to return to unburned conditions. The results showed that the fire caused changes in the structure of the surface soils but did not change aggregate stability. It was hypothesized that reduction in perennial grasses strongly contributed to increases in runoff and erosion.

Shrublands

In the study conducted by Soto and Diaz-Fierros (1998) the effects of controlled and wildfire burns on runoff and erosion for a scrub environment in northwestern Spain were studied. The vegetation is scrub with sandy loam soils and a mean slope of 30%. Natural rainfall was used with nineteen events. Four plots of 4 x 20 meters were observed, two were treated with a prescribed burn. The plots were monitored over a four-year period. Other measurements conducted at the site were canopy cover, biomass, residue, interrill cover and rill cover. The results of this research showed that the burned plots did not lead to an appreciable increase in runoff volumes with respect to the control plots. Soil erosion was clearly higher in the burnt plots the first two years of the experiment. After two years, the erosion was insignificant. From the research it was hypothesized that the two factors most important in determining erosion following a fire were water repellency of the soil surface and the degradation of the soil structure, which affected the hydraulic conductivity and soil erodibility.

An experiment was carried out by Marcos et al. (2000) in a shrub area of Northwest Spain. The climate is subhumid Meditterranean with sandy loam soils and 10% slopes. A drip type rainfall simulator was used to apply rainfall to 1 m^2 plots at a constant intensity of 180 mm/h for a total of five minutes. The plots were simulated on before, immediately and one and a half years after the fire. The cover characteristics for each plot were measured before each simulation. Results of this experiment showed that the both runoff and sediment yield increased after the burn. Although the sediment yield increase after the burn it was not as high as expected. It was hypothesized that the ash on the post-fire soil surface helped to protect the soil surface from raindrop impact. Additionally, the burn was of low-medium severity which could have impacted the sediment yield by leaving enough residual material on the soil surface to protect it. Soil properties also potentially influenced the sediment yield. It was hypothesized that lower runoff rates than expected were found because of the soil surface relatively high organic matter content and percent sand It was also theorized that vegetation cover influenced the amount of soil lost. The lowest soil losses were observed with the oak-woody species and the herbaceous cover treatments.

The research conducted by Ueckert et al. (1978) was done on shrublands in Texas. The research area slopes are less than 1% and on clay soils. A modified Purdue sprinkling infiltrometer was used to apply a rate of 11.4 cm/hr for a 40 minute period to 0.24 m^2 plots. Prior to the application of the infiltrometer all the plots were wetted with 3.4 cm of water. Grass, forb and litter covered was measured along with soil texture, bulk density, total porosity, capillary porosity and noncapillary porosity. Hydraulic conductivity was determined with the constant head method. The results showed that after the burn infiltration rates went down which conversely means runoff rates increased after the burn. It was hypothesized that loss of vegetation and ground cover had the greatest influence on infiltration and runoff. The deficiency of a protective litter layer had a large impact on protecting the soil surface from raindrop impact.

Woodlands

Rainfall simulator experiments were carried out by Johansen, et al. (2001a) in semi-arid intercanopy areas of ponderosa pine forest near Los Alamos, New Mexico. The research was conducted on 4.5 to 7 % slopes with loam soils. Rainfall simulation took place using a rotating-boom rainfall simulator on 3 m by 10.7 m plots. The simulations were performed with a 60mm/h for one hour dry run followed by a 24 hr interval, then the wet run of 0.5 hr and ending with a final very wet run, after a 0.5 hr interval. Two plots were established on two treatments; burned and unburned. The results showed that following the fire both runoff and erosion increased however the increase in sediment yield was more drastic. Vegetation canopy cover, ground cover and surface roughness were measured at 245 points across all four plots. This experiment concluded that observed runoff and sediment yields were well associated with ground cover, which dominated over other variables such as surface roughness or slope. It was found that as percent bare soil increased, there was an increase in sediment yield. However a threshold was reached at approximately 60 to 70 percent, where a continued increase in percent bare soil did not show rising sediment yields. It was hypothesized that the threshold response was do primarily to the reduction in ground cover, but the changes in soil properties following the fire was also important.

The study by Roundy et al. (1978) was carried out in the pinyon-juniper vegetation in arid and semi-arid climates in Utah, where the soils are coarse loamy and the slopes range between 5 and 8 %. Simulated rainfall was applied to 0.9 by 0.9 m plots using a mobile infiltrometer at a rate of 8.38 cm/hr for one hour. Canopy and ground cover was visually measured along with litter depth. Percentage of water repellent area, bulk density, soil moisture content, organic matter content and particle size distribution were all measured on each plot. The results showed that infiltration rates decreased following the burn, therefore runoff increased on the study site. After the burn the sediment production was significantly higher compared to the unburned. It was concluded that due to removal of vegetation and litter cover soil loss from raindrop splash was higher on burned versus unburned coppice dunes. In addition overland flow through interspace would also increase erosion.

The objective of the research done by Hester et al. (1997) was to compare post-fire hydrologic impacts from different vegetation communities. The main communities studied were oak, juniper, bunchgrass and shortgrass. Study sites have silty clay soils with approximately 4% slopes. This research used a drip-type rainfall simulator on eight 0.5 m^2 plots. Simulated rainfall was applied at a rate of 203 mm per hour for 50 minutes. Canopy and ground cover was measured along with surface roughness using a relief meter. Soil texture, organic carbon content, aggregate stability, bulk density and soil moisture were also measured. The experiment showed that fire caused decreased rates of infiltration (increased runoff) on all vegetation types, especially on the oak site because of a hydrophobic layer that developed at the surface. Fire also removed organic cover on the sites causing less protection of soil from raindrop impact and overland flow. Sediment yield was highest on the shortgrass and lowest on the oak and juniper vegetation types. It was hypothesized that this was due to the loss of total organic cover.

Covert et al. (2005) studied three burned watersheds in the Idaho, Montana area following timber harvesting. The vegetation after timber harvesting was ponderosa pine and Douglas fir. The three watersheds have slopes ranging from 40 to 63% slope and sandy loam to loam soils. The ground cover was measured along with burn severity and rainfall. The runoff was measured with pressure transducers and flow depth float measurements at the outlet of the watershed. The watersheds were continuously monitored for up to five years following the burn. The results showed that relatively little differences in runoff were observed the year of the fire. It was hypothesized that this was due to logging management techniques used and the rainfall amounts the year of the burn. Unfortunately with this research the runoff measurement devices were installed after the spring rains the year of the fire so not all the runoff events were included in the analysis.

The above discussion illustrates that there are several diverse conclusions of how an environment is affected by fire. Table 2.1 summarizes the conclusions discussed above, in addition to a synopsis of the research locations and techniques used to obtain those conclusions. One of the prevalent hypotheses was that erosion and runoff increase following a wildfire primarily due to loss of ground cover (Hester et al., 1997; Johansen et al., 2001a; Johansen et al., 2001b; Pierson et al., 2001; Roundy et al., 1978; Uekert et al., 1978). A second hypothesis was that the change comes from the removal of vegetation canopy cover (O’Dea and Guertin, 2003; Roundy et al., 1978; Uekert et al., 1978). Thirdly, the change in soil properties, especially soil structure, causes increases in post-fire runoff and erosion rates (Emmerich and Cox, 1994; Soto and Diaz-Fierros, 1998). Two studies found no significant difference between pre-fire and post-fire rates of runoff and erosion (Emmerich and Cox, 1992; and White and Loftin, 2000). From the summary presented here there is not a complete consensus among researchers if fire does cause changes in the runoff and erosion rates. If the majority of the research is correct and fire does cause an increase in runoff and erosion rates then the primary cause behind the increased rates is still up for debate. Due to the assortment of conclusions reached among several researchers it seems that further research is needed on the impacts of fire.

Table 2.1: A summary of recent literature review for post-fire impacts.

AUTHOR	LOCATION	VEGETATION	RAINFALL[2]	SOILS	SLOPES	PLOT SIZE	HYPOTHESIS[1]
Covert et al. 2005	Montana	Woodland	Natural	Sandy Loam Loam	40 - 63 %	Watershed Scale	Other
Emmerich & Cox 1992	Arizona	Grassland	RF Sim (55 & 110 mm/hr)	Gravelly Loam Sandy Loam	5 - 6 %	3.05 x 10.66m	No significant difference
Emmerich & Cox 1994	Arizona	Grassland	RF Sim (55 & 110 mm/hr)	Gravelly Loam Sandy Loam	5 - 6 %	3.05 x 10.66m	Soil Properties (structure)
Hester et al. 1997	Texas	Woodland	RF Sim (203 mm/hr)	Clayey	4%	0.5 m^2	Ground Cover
Johansen et al. 2001a	New Mexico	Woodland	RF Sim (60 mm/hr)	Loam	4.5 - 7 %	3 x 10.7 m	Ground Cover
Johansen et al. 2001b	New Mexico	Grassland	RF Sim (60 mm/hr)	Clayey	9%	3 x 10.7 m	Ground Cover
O'Dea and Guertin 2003	Arizona	Grassland	RF Sim & Natural (63 mm/hr)	Gravelly Loam	1 - 3%	3 x 10.7 m	Vegetation Cover
Pierson et al. 2001	Nevada	Grassland	RF Sim (85 mm/hr)	Sandy	35 - 40%	0.5 m^2	Ground Cover
Roundy et al. 1978	Utah	Woodland	Infiltrometer	Coarse Loamy	5 - 8%	0.83 m^2	Vegetation & Ground Cover
Solo & Diaz-Fierros 1998	Spain	Shrubland	Natural	Sandy Loam	30%	4 x 20 m	Soil Properties (structure)
Ueckert et al. 1978	Texas	Shrubland	Infiltrometer (84 mm/hr)	Clayey	<1%	--	Vegetation & Ground Cover
White & Loftin 2000	New Mexico	Grassland	Natural	Clay Loam Sandy Loam	--	1 ha	No significant difference

[1] Hypothesis: The primary hypothesis for increases in post-fire runoff and erosion rates; No significant difference symbolizes a significant difference in post-fire runoff and erosion rates was not observed.
[2] Rainfall: RF Sim = rainfall simulator used. Natural = natural rainfall used

2.2 Modeling Fire Response

The first challenge in modeling post-fire runoff and erosion response is choosing a model. The following is a selective list of models used to predict post-fire runoff and/or erosion: WEPP, GeoWEPP (GeoWEPP ArcX 2003; Renschler 2003), Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1965), Revised Universal Soil Loss Equation (RUSLE , Renard et al. 1997), Hillslope Erosion Model (HEM, Lane et al., 1988), HEC-HMS (Hydrologic Modeling System, USACE, 2001) and Geographic Information Systems -based models (ESRI 2000). This next section describes some of the models currently being used to estimate post-fire runoff and erosion response.

In the study conducted by Soto and Diaz-Fierros (1998), the observed results were compared with those predicted by the WEPP model. This was done using the WEPP model in the rangeland run mode and ‘burning’ as a management option and adjusting the vegetation parameters to fit the plot data. Initial soil and vegetation parameters were entered into the WEPP model using measurements from the control plots including effective hydraulic conductivity (K_e). It was found that vegetation recovery and its effects on hydrology and soil erosion were adequately represented by the model, assuming the model was applied to regions with similar soils, vegetation, climate and topography as found in the experiment. However, when using the WEPP model to predict erosion following a wildfire, it was found that the WEPP model underestimated the amount of erosion compared to the results observed in the field. They concluded that WEPP did not include influences of hydrophobic conditions and severity of burn, both of which were associated with degree of post-fire impacts.

Covert et al. (2005) evaluated GeoWEPP (GeoWEPP ArcX 2003; Renschler, 2003) comparing the model predicted runoff to that observed with a rainfall simulator. GeoWEPP is a model that combines WEPP v2002.7 (Flanagan et al., 1995) with Topography Parameterization software (TOPAZ, Garbrecht and Marz, 1997) within the ArcView 3.2 GIS (ESRI, 2000) program to predict runoff and erosion at the hillslope and watershed scale. The results of the research showed that the predictive ability of the GeoWEPP model for runoff in small, harvested and burned forest watersheds was poor. The model tended to overestimate runoff rates. The research also evaluated the WEPP v98.4, model which is a modified version of the WEPP model for forested soils by Wu et al. (2000). The WEPP model did a better job at predicting runoff compared to the GeoWEPP model. However, on average the WEPP model overpredicted seasonal runoff. Inconsistencies were found between the sites implying that further modification to the model is needed.

MacDonald et al. (2000) used a modified GIS-based version of RUSLE with the addition of a hydrophobicity risk model called HY-RISK. The parameters used to estimate HY-RISK were vegetation type, fire severity and soil texture. The analysis was combined with slope, soil erodibilty factors, and a factor representing soil moisture following the removal of vegetation. All these parameters were combined to assess the post-fire surface erosion risk at hillslope and catchment scale. Data layers were obtained from such sources as STATSGO, AVHRR (Advanced Very High Resolution Radiometer coverage); the slopes file was created using a 90-m DEM. The litter loadings and consumption were predicted to estimate the fire severity based on every vegetation and land cover type combination. Soil wetness was predicted for each dominant vegetation type. This model was not calibrated or validated for the Colorado area it was assessing. It was created to show the highest impacted areas if a fire was to occur. The authors noted several limitations of the model used. First of all, it did not consider multiple severity of wildfire with relation to the dominant vegetation types. Second, it did not contain a deterministic or stochastic rainfall component to look at the impact of an individual storm on post-fire erosion rates. Third it did not address the persistence of a fire-induced hydrophobic layer. Finally, it did not analyze the decrease in erosion following recovering vegetation at the site.

Wilson et al. (2001) used HEM-GIS to model the effect of fire on runoff and erosion immediately following the Cerro Grande fire in 2000. USLE was not used because of the limitations in the model sediment routing. WEPP and KINEROS (Kinematic Runoff and Erosion Model) were also not chosen due to limitations in time and parameterization needs. HEM requires a runoff volume input that was obtained using the SCS Curve Number (CN) method (USDA-SCS, 1956). With this research it was found that current hillslope erosion prediction technology is limited by either (a) the inability to apply technology across large tracts of diverse terrain or (b) the inability to route eroded sediment from source areas into streams along hillslope flow-pathways, although these limitations were not applicable to HEM. The author’s experience with HEM-GIS showed that the predicted runoff and erosion corresponded well with the few observations available.

McLin et al. (2001) used a combination of HEC-HMS, HEC-RAS and ArcView GIS for floodplain analysis of pre and post burned watersheds. The CN method was used to predict runoff. This technique was used because it allowed for changes in land use patterns for future applications. The model was calibrated at several channel locations where the observed and predicted hydrographs were matched. Then the calibrated model was used to identify critical areas of soil loss. The CN values used for the post-fire areas yielded simulated hydrograph peaks that compared favorably with observed values.

Beeson et al. (2001) used an ecohydrological model called SPLASH (Simulator for Processes of Landscapes: Surface/Subsurface Hydrology) to map vulnerability areas following the Cerro Grande fire in 2000. SPLASH simulates overland flow using Manning equation and water is routed based on areas of steepest descent found with a DEM. The Green-Ampt equation is used to calculate infiltration. Pre and post fire conditions were modeled using the 2 and 100 year rainfall return periods. The model was then compared to runoff predictions made with the curve-number method. It was found that the predictions at the subcatchment scale using the SPLASH model were well correlated to the curve-number method ($r=0.56$ and $P<0.01$).

2.3 WEPP Model

Model

The WEPP erosion model is a continuous simulation computer program which predicts soil loss and sediment deposition from overland flow on hillslopes; soil loss and sediment deposition from concentrated flow in small channels and sediment deposition in impoundments. In addition to the erosion components, it also includes a climate component which uses a stochastic generator to provide daily weather information, a hydrology component which is based on a modified Green-Ampt infiltration equation and solutions of the kinematic wave equations, a daily water balance component, a plant growth and residue decomposition component and an irrigation component. The WEPP model computes spatial and temporal distributions of soil loss and deposition, and provides explicit estimates of when and where in a watershed or on a hillslope that erosion is occurring so that management techniques, including fire, can be selected to most effectively control soil loss and sediment yield (Flanagan and Nearing, 1995).

Erosion Risk Management Tool (ERMiT, Elliot et al., 2001) is part of the Disturbed WEPP technology. ERMiT provides probabilistic estimates of single-storm post-fire hillslope erosion by incorporating variability in rainfall characteristics, burn severity and soil characteristics into each prediction. Users specify climate parameters (based on location), vegetation type (forest, range, chaparral), soil type (clay loam, silt loam, sandy loam, loam), topography (slope length and gradient) and burn severity class (low, moderate, high) (Robichaud, 2005). The outputs from the model are given based on return period rainfall. It also gives probabilistic estimates of erosion reduction to be expected from three treatments; seeding, straw mulching and untreated. It does not account for spatial and temporal variability of fire effects on soil and erosion processes (Robichaud and Miller, 1999)

RHEM (Wei et al., submitted) is the rangeland hillslope single storm version of the WEPP model developed in cooperation with the USDA-ARS, NRCS and the USFS.

The main difference between WEPP and RHEM is that RHEM separates the model engine (physical-based part) from the parameterization (empirical simulations of seven parameters). The model has almost the same hydrology and erosion techniques as used in WEPP. The modifications to the model are as follows; 1) RHEM only accounts for the surface soil layer, it does not have the restrictive layer infiltration routines in it; 2) RHEM currently does not have rainfall interception component; 3) the adjustment factor for total transport capacity for sandy soils in WEPP is taken out; 4) approximate method for peak runoff calculating in WEPP is taken out (kinematic wave method is used); and 5) aggregate classes used to calculate sediment enrichment are input values in RHEM.

Sensitivity Analysis

Tiscareno – Lopez (1991) made several conclusions upon completion of the sensitivity analysis of the WEPP model. Runoff volume was very sensitive to rainfall characteristics (amount, duration and peak intensity) and parameters that regulate water infiltration (K_e and soil water content). K_e was the most important parameter in terms of model sensitivity in predicting runoff volume and peak runoff. Erosion predictions were also sensitive to rainfall characteristics (amount, duration and peak intensity). The most sensitive parameters were τ_c, K_i and K_r. Sediment detachment was more sensitive to K_r and K_i for large rainfall events in which the depth of flow in the rill areas overcomes the threshold shear stress value.

Governing WEPP equations

RHEM was used for model parameterization and evaluation. Its governing equations are explained below in equations 2.1 to 2.7. RHEM computes net detachment and deposition using the steady state sediment continuity equation,

$$\partial G/\partial x = D_f + D_i \quad (2.1)$$

where x represents distance downslope (m), G is sediment load ($kgs^{-1}m^{-1}$), D_i is interrill sediment delivery to the rill ($kgs^{-1}m^{-2}$), and D_f is rill erosion rate ($kgs^{-1}m^{-2}$). Interrill sediment delivery, D_i, is considered to be independent of x, and is always positive. Rill erosion, D_f, is positive for detachment and negative for deposition.

Interrill sediment delivery is calculated as

$$D_i = K_i I_e \sigma_{ir} (R_s/w) \quad (2.2)$$

where K_i is interrill erodibility ($kg\text{-}s/m^4$), I_e is effective rainfall intensity (m/s), σ_{ir} is the interrill runoff rate (m/s), R_s is the spacing of the rills (m), and w is the rill width (m).

Net soil detachment in rills is calculated for the case when hydraulic shear stress exceeds the critical shear stress of the soil and when sediment load is less than sediment transport capacity. For the case of rill detachment

$$D_f = D_c (1 - G/T_c) \quad (2.3)$$

where D_c is detachment capacity by rill flow ($kgs^{-1}m^{-2}$), and T_c is sediment transport capacity in the rill ($kgs^{-1}m^{-1}$). When hydraulic shear stress of the rill flow exceeds the critical shear stress for the soil, detachment capacity, D_c, is expressed as

$$D_c = K_r\,(\tau_f - \tau_c) \tag{2.4}$$

where K_r (sm^{-1}) is a rill erodibility parameter, τ_f is flow shear stress acting on the soil particles (Pa), and τ_c is critical shear stress of the soil (Pa).

In RHEM the infiltration rate is computed using the Green and Ampt equation (Green and Ampt, 1911).

$$f = K_e\,(1+(N_s/\mathrm{F})) \tag{2.5}$$

where f is the infiltration rate (mm/hr; $f = dF/dt$), K_e is the effective hydraulic conductivity (mm/hr), N_s is the effective matric potential (mm), F is accumulated infiltration depth (mm), and t is time (hr).

RHEM uses the kinematic wave model as a routing function to transform rainfall excess into flow depths on a flow surface (Stone et al., 1995). The kinematic equation for flow on a plane are the continuity equation

$$\partial h/\partial t + \partial q/\partial x = v \tag{2.6}$$

and a depth-discharge relationship

$$q = \alpha\, h^m \tag{2.7}$$

where v is rainfall excess (ms^{-1}), h is depth of flow (m), q is discharge per unit width of the plane (m^2s^{-1}), α is depth discharge coefficient ($m^{0.5}s^{-1}$), m is depth-discharge exponent and x is distance from top of plane (m).

The Chezy relationship is used for overland flow routing in WEPP so

$$\alpha = C\, S_o^{0.5} \tag{2.8}$$

where C is the Chezy coefficient ($m^{0.5}s^{-1}$), S_o is slope and m is 1.5. The initial conditions are h(x,0) = h(0,t) = 0.

Input files

RHEM requires four input files; a storm file, soil file, slope file, and an initial condition file. There are two types of storm files, breakpoint and disaggregation. For the breakpoint file, real time and total cumulative rainfall at that time are needed. With the nonbreakpoint file the following are needed; rainfall amount, duration of rainfall, ratio of time to rainfall peak/rainfall duration (t_p) and ratio of maximum rainfall intensity/average rainfall intensity (i_p). The soil file requires the following inputs: N_s, K_e, K_i, K_r, τ_c, friction factors, and aggregate classes. Soil physical properties needed are the same as those used in WEPP, see Flanagan and Nearing (1995) for complete details. The slope file requires number of overland flow elements, hillslope width, hillslope width and steepness of slope. The initial condition file requires intercanopy and canopy cover, total canopy cover, random roughness and initial soil moisture.

Parameterization

Parameterization in hydrologic and erosion models is used to increase accuracy in model output. Model parameterization includes both parameter identification and parameter estimation steps. Although process-based models are conceptually superior to empirical models, their accuracy is still dependent on the accuracy of their input parameters. Unless the most accurate set of parameter values associated with an identification data set can be found, a reasonable degree of confidence cannot be placed in the accuracy of model predictions (Freedman et al., 2001).

Nearing et al. (1989) completed a two parameter optimization to determine K_r and τ_c. A five step procedure was outlined as follows: (1) choose initial best guess values of Kr and τc as input, (2) the program then uses the erosion model to calculate sediment loads for an array of K_r and τ_c values around the central values, (3) the least squares objective function was calculated for each point on the array, (4) the minimum of the function was found, (5) the central K_r and τ_c were reset to correspond to the minimum point of the array. The steps were repeated so that the program calculated a new array of the objective function around new values with a finer grid. The accuracy of the method was dependent upon the number of times that the grid size was reduced, which was approximately five times. Interdependence was found among the parameters: however, it was determined that the dependence did not cause problems in identifying parameters or question the validity of the model structure with respect to parameterization. A model evaluation was done comparing the measured sediment load versus the predicted from parameters derived with the optimization technique; R^2 values of 0.86 to 0.99 were obtained. The model evaluation was done on the individual steady state sediment yield values and not the sediment yield values from the entire event. In conclusion, it was found that the model represented the data accurately.

Risse et al. (1994) conducted a study to derive and evaluate K_e parameter values with a variety of methods. The objective of the study was to determine which method was most suitable for estimating K_e values. The conclusion was that the calibration method of deriving K_e values was better than any of the different methods for estimating K_e values based on soil properties. The calibration method consisted of two steps; the first was to determine an objective function and the second was to complete an optimization. The optimization consisted of running the WEPP model on an event basis until the minimum K_e value was found. Risse et al. (1994) also concluded that the optimized Ke values tended to overpredict runoff on the small events and underpredict runoff on the larger events.

Model Evaluation

Nearing et al. (1999) conducted research to try and quantify the unexplained variability in soil erosion data in order to improve current techniques of evaluating erosion models. Current techniques of model evaluation do not always consider the natural variability found in measured soil erosion data. One way to evaluate a model is to calculate the difference between the measured erosion and the model predicted erosion values. It is expected that a portion of the difference between the measured and predicted erosion will be due to model error and another portion will be due to unexplained variance of the measured data. Nearing et al. (1999) used data from the USDA-ARS National Soil Erosion Research Laboratory, which included 797 replicated plot pairs for 2061 storms on 13 sites. The plots ranged from 2 to 8 m in width with a length of 22 m, the slopes ranged from 3 to 16%. Differences between the plots were calculated as

$$R_{diff} = (M_2 - M_1)/(M_2 + M_1) \qquad (2.9)$$

where M_1 and M_2 were the paired values of soil loss from the replicated plots and R_{diff} was the calculated differences with a range of -1 to +1. The results showed that R_{diff} decreases with increasing measured soil loss. For example, with large values of measured soil loss there would be smaller differences values of R_{diff}. It was then assumed that soil loss magnitude was the principal factor in explaining variance in soil loss data. In conclusion, when comparing measured versus predicted erosion values for a model evaluation it is important to note that there is a large variability in the measured erosion values, especially if the measured soil loss values are relatively small.

The research done by Nearing (2000) analyzed replicated plot data and presented methodology to allow model evaluators to take natural variability (within treatment) of erosion plots into account when testing models. One way to evaluate a model is to compare measured versus the model predicted erosion values. However, there is an unexpected variability in the measured erosion values, strongly correlated to magnitude of soil loss, which must be taken into account (Nearing et al., 1999). The suggested model evaluation procedure was as follows:

(1) List the measured and predicted data pairs

(2) Calculate the relative difference between measured and predicted soil loss, R_{diffs} as

$$R_{diffs} = (O - M)/(O + M) \qquad (2.10)$$

where O is the predicted erosion value form a simulation of the model, and M is the measured value of erosion. R_{diffs} ranges from -1 to +1.

(3) Compute the 90 or 95 occurrence interval as given by equation 2.11

$$R_{diffocc} = m \log_{10}(M) + b \qquad (2.11)$$

where $R_{diffocc}$ is the relative difference in values representing the 90 to 95 percent frequency of occurrence intervals, m is the coefficient and b is the intercept. Values for m and b were given by Nearing (2000) to compute $R_{diffocc}$. Using the data in Nearing

(2000), a 90 and 95 percent frequency of occurrence was found using a cumulative probability distribution function. The result of determining the 90 and 95 percent occurrence intervals was values of *m* and *b* to calculate equation 2.11.

(4) Determine the number of predictions for which the R_{diffs} value fell within the interval

(5) Calculate model effectiveness coefficient, *e*, as the fraction of acceptable predictions for the data set.

This procedure was then applied to two studies; one of which was the USLE data set from Risse et al. (1993) and the other the Zhang et al. (1996) study of the WEPP model. It was found that the model effectiveness coefficient, *e*, for the USLE data was 0.56, while the WEPP had an e value of 0.66. It was hypothesized that a calibrated model would perform better than an e = 0.6. This research proposed this method that was not intended to be the complete answer to model evaluation but rather an objective measure to account for natural availability in measured erosion data.

2.4 Effects of Scale

Davenport et al. (1998) developed a conceptual model of soil erosion in pinon-juniper ecosystems. Part of the conceptual model addressed the differences in runoff between the patch and the hillslope scale. It predicted that runoff at the hillslope scale was much less than on the patch scale because of storage within the hillslope. In addition, the connectivity of the patches on a hillslope helped determine relative runoff rates. For example, adjacent patches with high storage rates caused a decrease in runoff per unit area with increasing spatial scale. Furthermore an area with a greater number of connected bare patches yielded more runoff.

In support of the Davenport et al. (1998) research, Reid et al. (1999) compared two scales and three vegetation types; canopy, vegetated intercanopy and bare intercanopy. Each of the three vegetation plots had both a large plot (6 to 8 m) and a small plot (1 m). The site has soils of sandy loam or loam texture with an average slope of 5%. Natural rainfall created runoff which was then measured at the base of each plot. The results showed that runoff and erosion were lowest for the canopy patches, higher for the vegetated intercanopy patches and highest for the bare intercanopy patches. The bare patches generated approximately three times more sediment than the vegetated patches. The hypothesis was that bare areas were sources for sediment while the vegetated areas acted as sinks. There was more runoff at the smaller scale compared to the large scale plots. This result supported the hypothesis that at the larger scales, most of the runoff generated was not measured because it never reached the collection area at the end of the plot.

Wilcox et al. (2003) conducted additional research to Reid et al. (1999) using the 1 m scale, the 6-8 m plot size and then an additional 3 m by 10.7 m plot. The research was conducted on semi-arid pinon-juniper woodland, slopes of 5% and sandy loam or loam soils. Natural rainfall created the runoff which was then collected in a similar manner to Reid et al. (1999). It was found that as the scale of measurement increased, both the frequency and the magnitude of runoff and erosion decreased. There was more than a 5000 percent decrease in cumulative runoff with increasing scale and more than a

15000 percent decrease in cumulative erosion. A large, high intensity storm generated runoff at the microplot scale close to 100% of the rainfall while only 6% at the large scale. The hypothesis was that at the large scale water and sediment were being stored on the plot; the water was being transferred from upslope bare patches to downslope vegetated patches.

CHAPTER 3

METHODS AND MATERIALS

This chapter discusses the steps used to obtain the three objectives of this research. To re-iterate, the objectives of this research are as follows; (1) to develop a database of post-fire runoff and erosion parameters; (2) to create parameter estimation equations; and (3) to evaluate the performance of a model on post-fire environments. In order to obtain these three objectives of this research several steps were needed, as depicted in the flow chart (Figure 1.1). The first step was to collect runoff and erosion data using a multiple intensity rainfall simulator. Rainfall simulation experiments were conducted on three treatments; natural, recent fire and recovery. The rainfall simulator experiment is described first in this chapter. The description includes a discussion of the wildfire sites; followed by a description of the rainfall simulator, the rainfall simulator experimental design and additional measurements needed to obtain the research objectives. The second step was to use the rainfall simulator data to parameterize the hydrology and erosion components of the Rangeland Hydrology and Erosion Model (RHEM; Wei et al., submitted). The parameters include one runoff parameter; K_e, hydraulic conductivity (mm/hr), and three erosion parameters, K_i, interrill erodibility (kg-s/m^4), K_r, rill erodibility (s/m) and τ_c, critical shear stress (Pa). The steps for the model parameterization are described in this chapter following the description of the rainfall simulator experiment. Also described are the techniques used to develop parameter estimation equations. Finally, a description of the model evaluation done on RHEM is also included in this chapter.

3.1 Rainfall Simulator Experiment

3.1.1 Location and Site Description

Rainfall simulator experiments, using the Walnut Gulch Rainfall Simulator, were conducted on six wildfire sites in southeastern Arizona shown on the map in Figure 3.1. Each wildfire site had three treatments; natural, fire and recovery. This research looked at the effects of wildfire; therefore pre-fire conditions on the burned sites were not obtainable. Instead nearby natural sites with similar characteristics as the fire sites in terms of slopes, soils and vegetation were chosen to represent the pre-fire treatment. The rainfall simulator experiments were also conducted on the wildfire sites for two years after the burn to analyze recovery treatments. The two vegetation communities studied were grassland and oak-woodland.

These post-fire experiments were conducted on three ecological sites (ES); Loamy Upland, Limy Slopes and Clay Loam Uplands. An ES is the main resource identification unit used by the NRCS for planning and evaluation (USDA-NRCS, 2003). It is an area of land with specific physical characteristics that differ in its ability to produce a distinctive kind and amount of vegetation. Each ES has characteristic soils, hydrology, climate, fire regime and native plant communities. The characteristics for each site are listed in Table 3.1. There were only two soil textures among the sites; sandy loam and clay loam.

For each ecological site there were two sets of plots each consisting of four large plots (2 x 6.1 meters) and four small plots (0.6 m by 1.2 m). The two different plot sizes allowed for comparison of erosion processes. The large plots were used to collect the following data: infiltration, runoff and total erosion processes. Total erosion processes included soil detachment by raindrop impact, flow detachment, transport and deposition. On the small plots only erosion by raindrop impact was measured. Previous research has shown, and it was assumed here, that the small plots were too small for rill erosion processes to be active. In addition the small plots were too short for potential runoff-runon effects to be activated; therefore runoff was measured only on the large plots.

Fire severity can be described as the degree (low, moderate or severe) to which a site has been disturbed by fire. Although the severity of the wildfire was considered in this research it was not measured. The following descriptions of the fire sites include description of the wildfire severity.

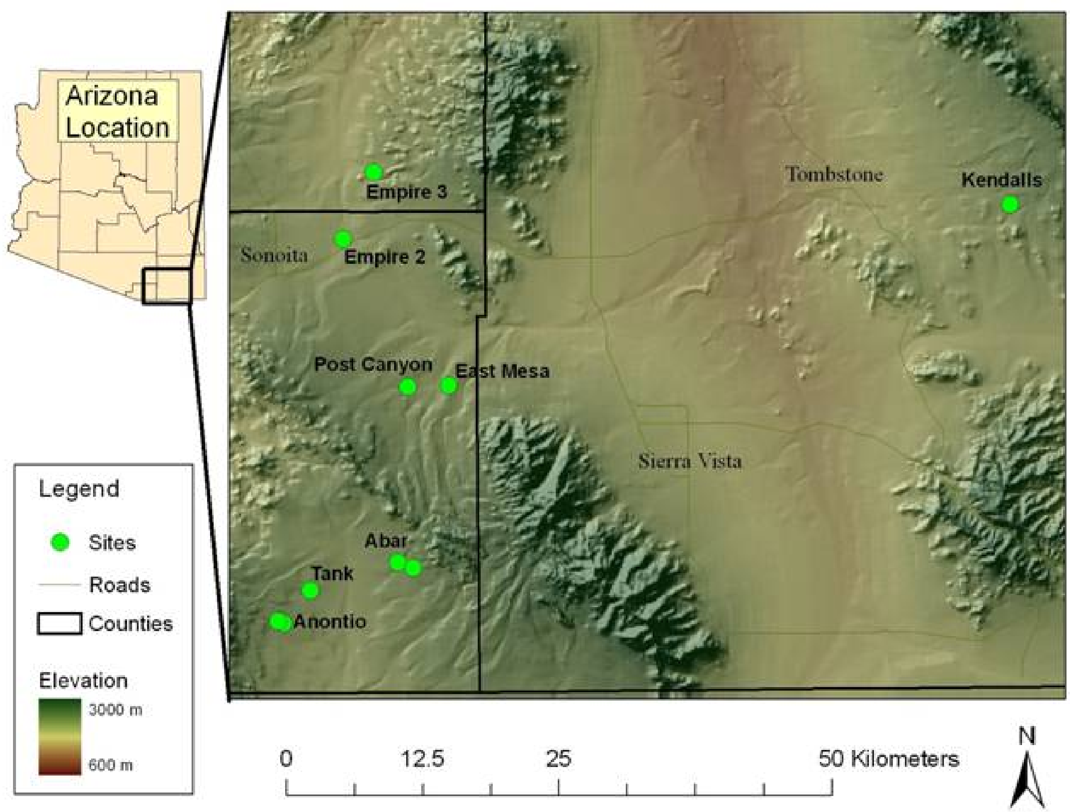


Figure 3.1: Map of all the rainfall simulator sites located in southeastern Arizona.

Table 3.1: The descriptions for all of the rainfall simulator sites, as well as the site abbreviations.

Site	Abbre.[1]	ES[2]	Vegetation[3]	Soils[4]	Slope (%)	Fire	Yr. of Fire[5]
Abar	AB	LU	Oak	Whitehouse	8 - 10	Abar	2003
Abar Natural	ABN	LU	Oak	Whitehouse	9 - 14	Natural	NA
Antonio	ANTB	LU	Oak	Whitehouse	13 - 17	Antonio	2005
Antonio Natural	ANTN	LU	Oak	Whitehouse	16 - 19	Natural	NA
Empire 3	ER3	LU	Grass	Whitehouse	11 - 16	Empire	2005
Empire 3 Natural	ER3N	LU	Grass	Whitehouse	12 - 14	Natural	NA
East Mesa	EM	LiS	Grass	Blacktail	12 - 15	Ryan	2002
Post Canyon	PC	LU	Grass	Terrarosa	8 - 9	Ryan	2002
Kendall	K	LiS, LU	Grass	Stronghold/Elgin	11 - 15	Natural	NA
Tank	TF	CLU	Grass	Signal	28 - 30	Tank	2004
Tank Natural	TFN	CLU	Grass	Signal	21 - 24	Tank	2004

[1]Abbre. = Abbreviation. The site abbreviation used throughout text.
[2]ES = Ecological Site Description; LU = Loamy Upland, LiS = Limy Slopes, CLU = Clay Loam Upland
[3]Vegetation; Oak = Oak-woodland, Grass = Grassland
[4]Soil; All the soils are sandy loams except for the Signal soil which is a clay loam.
[5]Yr. of Fire = Year the fire burned

Ryan Fire

The Ryan Fire occurred in the spring of 2002 and impacted 38,000 hectares of land managed by the Audubon Society, The Research Ranch (TRR). Two burned sites are being studied from this large fire, East Mesa (EM) and Post Canyon (PC). EM site burned at a moderate severity, while PC had a low severity burn. Ecological site descriptions defined EM as LiS (Limy Slopes) and PC as LU (Loamy Upland). The EM site has a slope of 11 to 15 percent and the PC site is eight to nine percent, both are grassland sites.

The natural sites to compare to the burned EM and PC sites are at Kendall, a subwatershed of the USDA-ARS Walnut Gulch Experimental Watershed. The plots at Kendall are classified as both LU (Loamy Upland) and LiS (Limy Slopes).

A-Bar Fire

In May of 2003 the A-Bar fire was a moderate severity burn and affected 600 acres of Coronado National Forest. The site is an oak-woodland community located in the San Raphael Valley, east of Patagonia in southeastern Arizona. This site is not currently being grazed. The A-Bar (AB) site is a LU (Loamy Upland) and has a range of slope from eight to ten percent.

Tank Fire

The Tank fire was a low severity burn and occurred in June of 2004 on USFS land. The site is currently being grazed. The Tank Fire (TF) site is classified as CLU (Clay Loam Upland) and is a grassland site. The slopes range from 30% for the burned site to 20% for the unburned site.

Antonio Fire

The Antonio fire was a low severity burn and occurred in June 2005. The Antonio (ANT) site is on USFS land and located in the San Raphael Valley near the Mexico border. It is currently being grazed. The slopes range between 13 and 17 percent for the burned and 16 to 19 for the natural. ANT is an oak-woodland site and classified as LU (Loamy Upland).

Empire Fire

The Empire fire was a low severity burn that occurred in June 2005. The Empire 3 (ER3) site is located on the Empire Ranch, the Las Cienegas Natural Conservation Area, managed by the Bureau of Land Management (BLM) near Sonoita, AZ. Rainfall simulations were conducted on the site the following week after the fire was contained. The fire was a low severity burn. This site is currently being grazed. The slopes are between 11 and 16 percent for the burned and 12 to 14 percent for the natural site. ER3 is a grassland site and classified as a LU (Loamy Upland).

3.1.2 Rainfall Simulator

Figure 3.2: Walnut Gulch Rainfall Simulator at Tank Fire site in 2004.

Rainfall Simulator Experimental Design

All the experiments were conducted in the same manner using the WGRS, a variable intensity rainfall simulator (Paige et al., 2003). The WGRS is shown in Figure 3.2, while the rainfall applications are shown in Figure 3.3. The first step was to perform a dry run on the plot, which consisted of an intensity of 63.5 mm/hr for a duration of 45 minutes. Following a 45 minute to one hour of drying time a wet run was conducted, which had varying intensities starting at 63.5 mm/hr to a maximum of 177.8 mm/hr. Immediately following was a second wet run that starts at intensity at 50.8 mm/hr and ended at 25.4 mm/hr. The second wet run is applied to measure runoff rates at the lower intensity rainfall rates. The full range of runoff is obtained with the combination of the wet run and the second wet run. Each intensity of the wet run was applied until steady state runoff was observed for a minimum of 5 minutes.

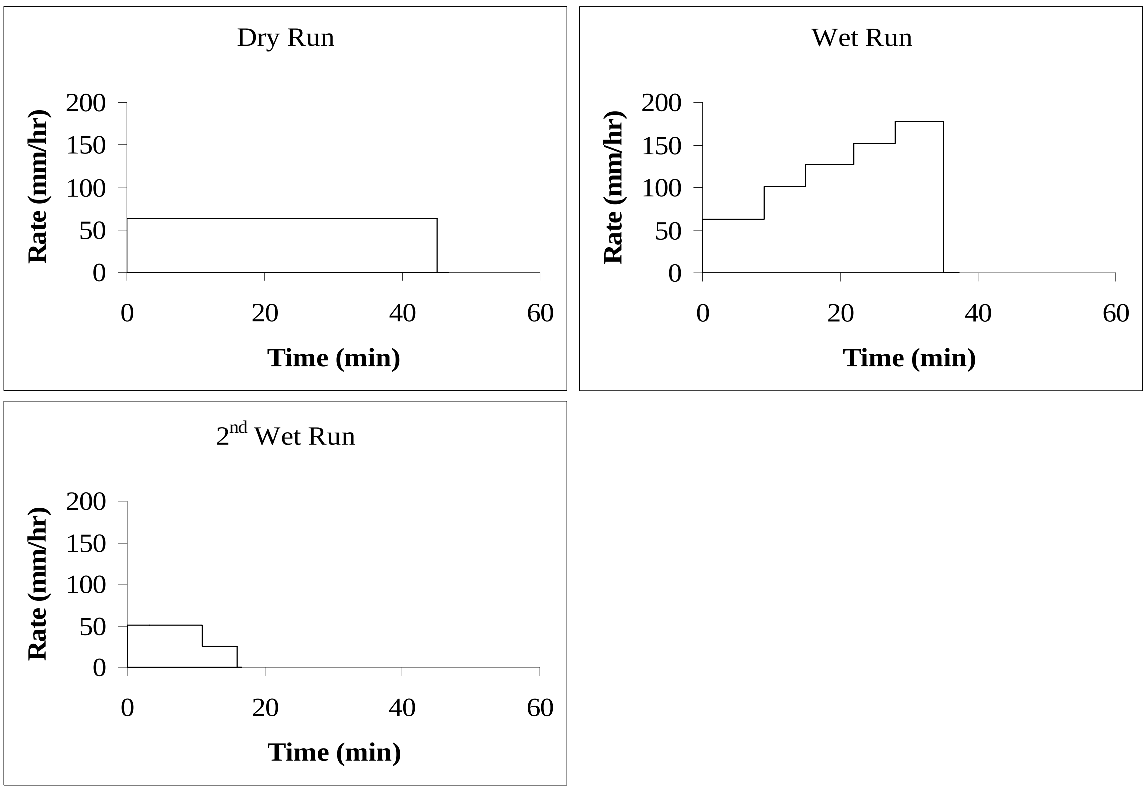


Figure 3.3: The WGRS rainfall application for the dry, wet and second wet runs.

Measurements

Runoff from the plot was measured using a pre-calibrated runoff measuring flume (Simanton et al., 1991). The water level in the flume was measured manually using a staff gage. A flow-rating curve was then used to convert the measured water level to a discharge rate. Grab samples were taken at the end of the flume to compute sediment concentration in the runoff from the plot. Soil moisture readings were taken before the dry and the wet runs using the gravimetric method.

The plot surface and vegetation canopy characteristics were measured as well. Gap, fetch and point measurements were taken for each plot. Gap is a measure of the bare spaces between canopy (canopy gap) and basal (basal gap) cover, parallel and perpendicular to the slope. Fetch measures the radial distance from one plant to the nearest plants at 15 points across the plot. Point measures total canopy and ground cover, both inside and outside the canopy cover, using a 15 cm by 20 cm grid with a total of 400 points covering the entire plot. Canopy cover is defined as grass, shrub, tree, forb or cactus cover. Basal vegetation, gravel, rock, litter, ash or bare soil are the measured ground cover characteristics.

3.2 Modeling

The RHEM model (Wei et al., submitted) is a modification of the WEPP model and was used in this research to complete the parameter identification steps to obtain the first objective of this research. A model evaluation was also done on the RHEM model. The main difference between the RHEM model and the WEPP model is that the RHEM model was modified so that the model engine (physical-based part) was separated from the parameterization (empirical simulations of 7 parameters). This modification made the RHEM model an easier model to use for the parameter identification step. In addition the RHEM model hydrology and erosion components were altered slightly to make it more suitable for rangeland conditions. The results of this research will expand the Erosion

Risk Management Tool (ERMiT, Elliot et al., 2001). ERMiT is part of the Disturbed WEPP technology, meaning it is developed from the WEPP model with an online interface. ERMiT provides probabilistic estimates of single-storm post-fire runoff and erosion by incorporating variability in rainfall characteristics, burn severity and soil characteristics into each prediction.

Parameterization in hydrologic and erosion models is used to increase accuracy in model output. To parameterize a model, both parameter identification and estimation processes are completed. The parameter identification process uses both optimization and calculations techniques to obtain a database of parameter values. The parameter estimation process develops equations to estimate input variables from easily measured physical characteristics. The sensitivity analysis done by Tiscareno-Lopez (1991) identified the most sensitive parameters; those that result in the largest percent change in model output, which are K_e, K_i, K_r and τ_c.

3.2.1 Parameter Identification

Parameter identification techniques are used to develop a database of parameter values to increase accuracy of model predictions. In this research two different techniques were used to complete the parameter identification process; optimization and calculation. K_e, K_r and τ_c values were identified with optimization procedures, while calculations were used to identify K_i values. The parameter identification process for the four most sensitive parameters (K_e, K_i, K_r and τ_c) in the WEPP model is described below.

Hydraulic Conductivity

Effective Hydraulic Conductivity, K_e (mm/hr), was optimized using the runoff volume from the wet run of the rainfall simulator experiments. The wet run was used because it was the multiple intensity run; it had a range of intensities from 63.5 mm/hr to 177.8 mm/hr. To optimize for runoff volume K_e values were adjusted until the model predicted runoff volume matched the observed.

The model was run with two types of rainfall input files; breakpoint and disaggregated rainfall. A K_e value was obtained for each type of rainfall input file; breakpoint K_e (K_{eb}), and disaggregated K_e (K_{ed}). For the breakpoint rainfall input file the rainfall data from the rainfall simulator experiment is used to create a hyetograph, as shown in Figure 3.4. This means that for the breakpoint rainfall input file the parameters needed are time and total cumulative rainfall at that time that define a single rainfall event. The disaggregated input file is rainfall data from the rainfall simulator experiment, reconditioned to fit the WEPP storm file where the following are needed; rainfall amount, duration of rainfall, ratio of time to rainfall peak/rainfall duration (t_p) and ratio of maximum rainfall intensity/average rainfall intensity (i_p). The disaggregated rainfall input file uses the information above to create a hyetograph with a set number of rainfall intensity steps as shown in Figure 3.5. The model then predicts a runoff hydrograph from the hyetograph it created. The model predicted hydrograph has approximately the same runoff volume as the hydrograph measured with the rainfall simulator.

Optimization routines were done for both K_{ed} and K_{eb} parameters. K_{ed} was determined because it was assumed that the model will be typically operated with this type of rainfall input. On the other hand, because some users will want to use the breakpoint rainfall file input a database of K_{eb} values was also developed. Each site was given a K_{ed} value for each treatment that was acquired by averaging the K_{ed} values from the four large plots. Other variables that were directly measured during the rainfall simulation that affect hydraulic conductivity are: initial soil moisture, intercanopy and canopy vegetation and ground cover.

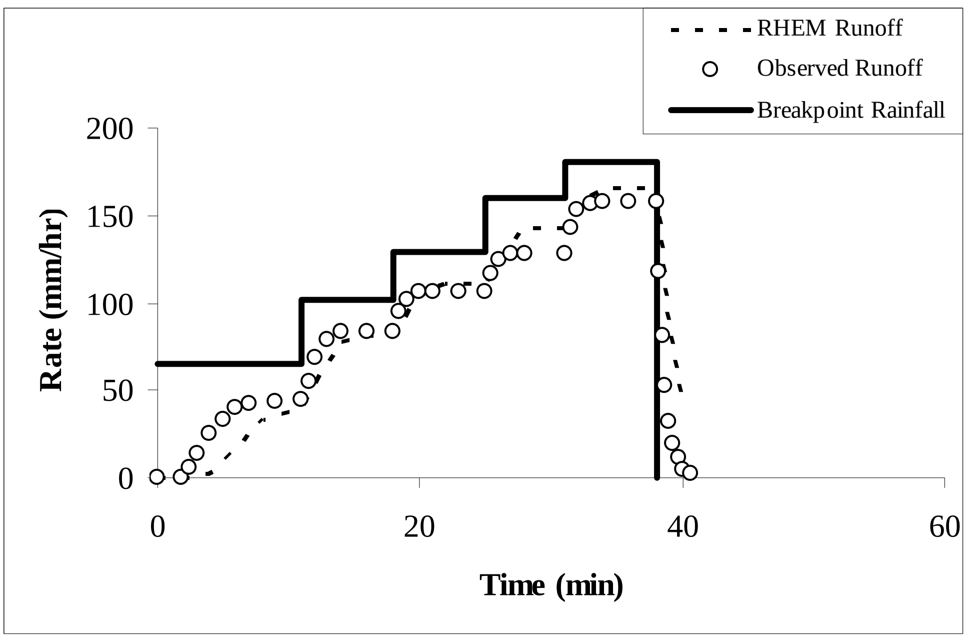


Figure 3.4: Runoff volume predicted by RHEM model using breakpoint rainfall data. The RHEM runoff is the model predicted runoff.

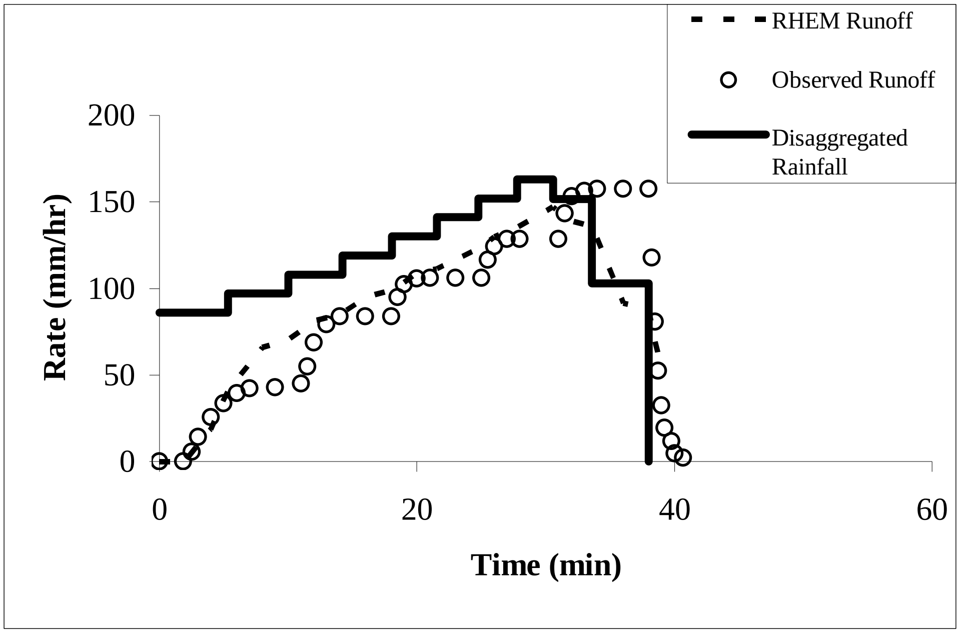


Figure 3.5: Runoff volume predicted by RHEM model using disaggregated rainfall data. The RHEM runoff is the model predicted runoff.

Interrill Erodibility

Interrill erodibility, K_i, values were calculated for each rainfall intensity, at steady state runoff, by rearranging the interrill sediment delivery equation (eq. 2.2) as:

$$K_i = D_i/(I_e*\sigma_{ir}) \quad (3.1)$$

I_e is the effective rainfall intensity (*m/s*), σ_{ir} is the interrill runoff rate (*m/s*), and D_i is the interrill sediment delivery ($kgs^{-1}m^{-2}$) and is defined as:

$$D_i = q_s/A \quad (3.2)$$

where q_s is sediment discharge rate (*kg-s*) for each intensity and *A* is area (m^2) of the plot.

The data from the small plot rainfall simulator erosion measurements were used to determine K_i. One K_i value was determined for each site using an average of the four small plots by calculating an average across the multiple intensity run for the four small plots.

Rill Erodibility and Critical Shear Stress

Rill erosion was calculated when sediment load was less than the sediment transport capacity using equation 2.3. In calculating detachment capacity, equation 2.4, both rill erodibility and critical shear stress are used. Therefore the two parameters are dependent and in order to obtain rill erodibility and critical shear stress values a two parameter optimization was required.

To obtain the two rill erosion parameters a two parameter optimization was completed as used by Nearing et al. (1989). The first step was to define a realistic range for the K_r and τ_c values; this was defined as the parameter space. The second step was to divide the range of the two parameter spaces into thirty intervals each, for a total of 900 different combinations of K_r and τ_c. The model was run within the parameter space (the 900 combinations of K_r and τ_c) for each steady state sediment discharge rate. The third step was to compute the least squares objective function for each point in the parameter space. The fourth step was to plot the objective function contours in the parameter space to visually identify the minimum values. The final step, depending on the shape of the contours, was to narrow the range of the parameter space and re-run the model until there is no significant change in the objective function.

With this technique, multiple paired values of K_r and τ_c (within a narrow range) can be used to obtain the same minimum sediment discharge rate. From that narrow range average K_r and τ_c values were found for each plot for which the rill erosion process was active.

3.2.2 Parameter Estimation

Parameter estimation equations are used in modeling to determine model input parameter values from readily obtainable physical characteristics. In this research parameter estimation equations were developed to estimate the four runoff and erosion parameters from site vegetation and ground cover characteristics. There were three objectives of the parameter estimation process. The first was to determine parameter estimation equations for all the fire sites. Second, to analyze equations established with the WEPP project (Flanagan and Nearing, 1995) to determine if they were a good estimate of parameter values of the natural sites. The WEPP equations were considered a good estimate of parameter values if they produced results close to the identified parameter values. If the WEPP parameter estimation equations were not a good estimate of parameter values then new equations needed to be developed. The final objective was to establish an equation for site recovery.

The parameter estimation equations were determined using a stepwise regression. A stepwise regression creates a multiple linear regression from a given data set based on independent variables that are significantly correlated to the response variable. The result was a combination of independent variables that yielded a relatively high R^2 value when evaluating the difference between the model predicted and the observed response variables. To prevent spuriously correlations in the resultant regression equations, the parameter values were plotted against the treatment physical characteristics. Relationships that yielded a R^2 value but were due to outliers or a high number of zero values were removed from the regression. A high number of zero values were found because of differences in treatments (for example, ground cover under canopy on fire treatment or ash cover on recovery treatment). Displaying the response variables against the independent variables was also necessary to determine if a substantially stronger relationship was obtainable that was not necessarily linear. For example, a strong exponential relationship was shown between K_e and GAPc (canopy gap).

The recommended parameter estimation equations are shown in the results section. However, upon completion of the stepwise regression it was found that multiple combinations of parameter values yielded high R^2 values. Listed in the appendix are tables of multiple parameter estimation equations where the best equation to use can be determined by the user, whether they are looking for an equation that yields the highest R^2 value or an equation with a relatively high R^2 but with a limited number of required parameter values..

The vegetation and slope independent variables used in this research come from measurements conducted with the rainfall simulator experiments. A list of the input variables and their abbreviations used in the parameter estimation steps are presented in Table 3.2. The variables in Table 3.2 are in units of percent, except gap which was measured in cm.

Table 3.2: Abbreviations for measured independent variables used to create parameter estimation equations.

Abbrev.	Characteristic
G	Ground Cover
R	Rock Cover
L	Litter Cover
B	Basal Cover
A	Ash Cover
C	Canopy Cover
S	Shrub
Gs	Grass
F	Forb
t	Total
i	Under Canopy
r	Intercanopy Space
GAPb	GAP Basal
GAPc	GAP Canopy
S_o	Slope
$Ln(S_o)$	Natural Log (Slope)

Units are percent
Exception: Gap units are cm.

Hydraulic Conductivity

Parameter estimation equations were found for both breakpoint and disaggregated hydraulic conductivity values K_{eb} and K_{ed}. Equations were developed for four treatments: oak-woodland burned, oak-woodland and grasslands natural as well as recovery from the burn for both oak-woodlands and grasslands.

Interrill Erodibility

Interrill erodibility parameter estimation equations were developed for three treatments: burned, natural and recovery for both oak-woodland and grassland vegetation sites. Parameter estimation equations created with WEPP included multiplying an adjustment factor by the baseline condition K_i value to get an adjusted K_i value. Originally the baseline K_i value represented the K_i value based on soil properties and the baseline value was adjusted for cover and treatment. However, this did not work with these data because there was not a wide enough range in soil textures to determine baseline K_i values. Therefore K_i parameter estimation equations were developed to calculate K_i values based only on vegetation and ground cover characteristics, as well as slope.

Rill Erodibility and Critical Shear Stress

The stepwise regression method was also applied to rill erosion parameters and site characteristics to create parameter estimation equations for each rill erosion parameter. Both rill erosion parameters needed a separate parameter estimation equation. Parameter estimation equations for rill erosion parameters were only developed for the burned treatment on oak-woodlands.

3.2.3 Model Evaluation

Model evaluation is the process of testing model output to establish that the error or prediction is at an acceptable level. An evaluation of the RHEM model was done using the parameters found through the optimization and estimation techniques. The first step was to use the identified parameters found with the calculation and optimization techniques. With the identified parameters the model was rerun and the model predicted runoff and erosion values were compared to those observed from the rainfall simulator experiments. The second step was to repeat the first step except with the values from the parameter estimation equations. Goodness of fit statistics were used to analyze the results of both the first and second steps. The goodness of fit statistics used are as follows; adjusted R^2 values (adj. R^2), Nash-Sutcliffe (NS, Nash and Sutcliffe, 1970), root mean square error (RMSE, Willmott, 1981) and the standard error (SE). The adjusted R^2 represents the calculated R^2 value adjusted for the number of parameters used. The difference between the R^2 value and the Nash-Sutcliffe value is that the R^2 value calculates the error (differences between the observed and predicted response variables) around the best-fit regression line while the Nash-Sutcliffe values calculates the error around the 1:1 line. The adjusted R^2 is calculated as:

$$adjustedR^2 = 1 - \left[\frac{(n-1)}{(n-k)} \left(1 - R^2\right) \right] \quad (3.3)$$

where *n* is the number of nonmissing observations and *k* is the number of fitted parameters in the model. The units for R^2 and $adjustedR^2$ are non-dimensional. R^2 is calculated as:

$$R^2 = \frac{\sum_{i=1}^{n} (Oi - Pi)^2}{\sum_{i=1}^{n} Oi^2 - n\left(\overline{Oi}\right)^2} \quad (3.4)$$

The Nash-Sutcliffe efficiency, E is calculated as:

$$E = 1 - \frac{\sum_{i=1}^{n}(Oi - Pi)^2}{\sum_{i=1}^{n}(Oi - \overline{O})^2} \tag{3.5}$$

where *P* is predicted values and *O* is observed values. *E* is a dimensionless variable that has a range from -∞ to 1.0, where 1.0 is a perfect fit.

The RMSE is calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \tag{3.6}$$

where *N* is the number of paired observations. The units for RMSE are the same units as the predicted and observed values.

Hydraulic Conductivity

A model evaluation of the identified and estimated hydraulic conductivity values was completed by comparing the model predicted runoff volume with the observed runoff volume from the rainfall simulator. The first step was to use the K_{ed} and K_{eb} values for each plot and compare predicted peak discharge with the observed peak discharge values. The second step was to run the model for every plot using the site average K_{ed} value. The third and fourth steps used K_{ed} values found with the recommended parameter estimation equations. The third step used the estimated K_{ed} values for each plot, while the fourth step used the estimated site average estimated K_{ed}

values. Goodness of fit statistics were used to evaluate the output results. The model evaluation was conducted at two levels, the first compared all results and the second separated the output into treatments: fire, natural and recovery. This was done to determine if a better fit was obtainable if the data were separated by treatments.

Interrill Erodibility, Rill Erodibility and Critical Shear Stress

In order to evaluate the ability of the model to predict total sediment yield, both interrill and rill erosion parameters had to be combined. The model evaluation consisted of two steps, the first used the identified K_i, K_r and τ_c and the second used the estimated values. If rill erosion was not observed on the site, inputs for the rill erosion parameters were set to approximately zero (0.0001), because the model does not allow for zero values of rill erosion parameters. An additional analysis was done to look at how the estimated parameters predicted soil loss compared to the observed values using the model evaluation technique developed by Nearing (2000) and described in chapter two. The objective of this method was to include the natural variability of measured erosion data into the model evaluation.

CHAPTER 4

RESULTS

This chapter presents the results of the rainfall simulator experiments and the following modeling steps; parameter identification, parameter estimation and model evaluation. The rainfall simulator results are presented first to help explain the outcomes from the modeling steps. The rainfall simulator results include the runoff, erosion and vegetation results. This section contains figures and tables representing the results by site, while the results for the individual plots are located in the appendix. In the tables, NA means "not available."

4.1. Rainfall Simulator Results

4.1.1 Runoff Results

In order to compare the results among plots with different rainfall applications the runoff volumes were normalized by dividing the runoff volume, Q (mm) by the total rainfall, P (mm).

The observed runoff data from the rainfall simulator experiments are shown in Figure 4.1 and Table 4.1. A significant difference was found between burned and natural treatments for the AB and PC sites (Table 4.1). The site with the greatest difference in normalized runoff volume between natural and burned treatments was the PC site, with a 70 percent increase. In contrast, the ER3 site had the smallest difference between natural and burned treatments with a six percent decrease in normalized runoff volume. There was a significant increase in normalized runoff volume for the AB and PC sites the first year post-fire. The second year post-fire the runoff was not significantly different from the first-year post-fire. The EM and TF sites did not show significant differences in runoff between treatments.

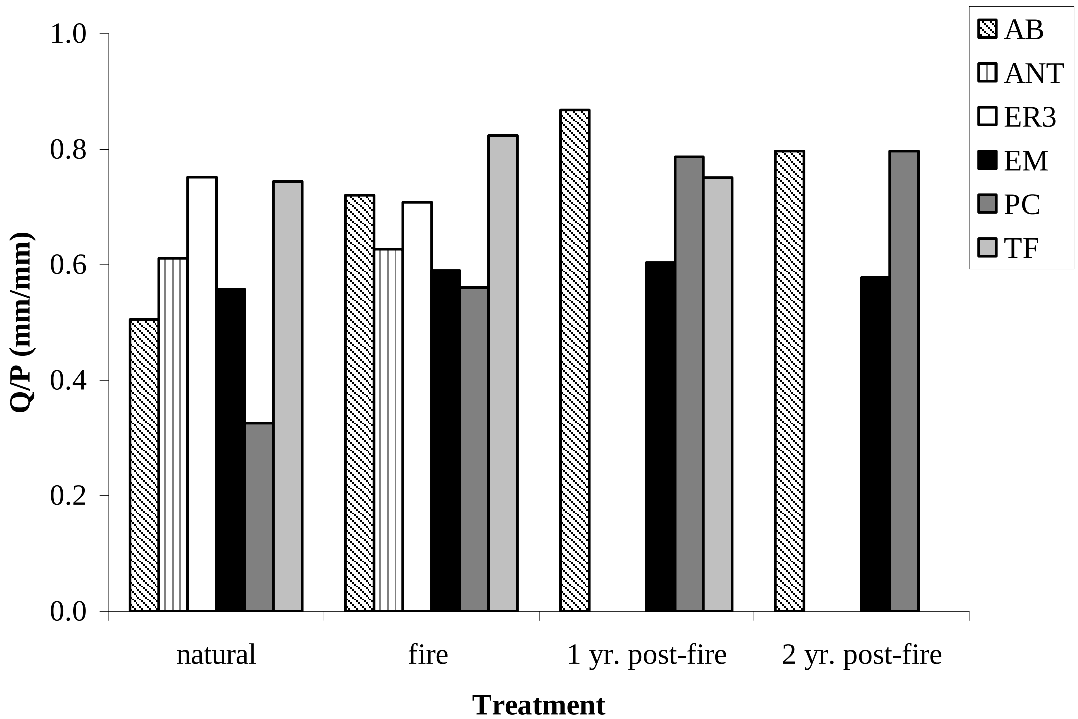


Figure 4.1. The average observed runoff ratio for natural, fire and recovery treatments on all the rainfall simulator sites.

Table 4.1. Average normalized runoff results for all rainfall simulator sites and treatments. Values within a row with the same letter indicate no significant difference using a t-test at p <= 0.10.

Q/P (mm/mm)				
Site	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
AB	0.51[a]	0.72[b]	0.87[c]	0.80[bc]
ANT	0.61[a]	0.63[a]	NA	NA
ER3	0.75[a]	0.71[a]	NA	NA
EM	0.56[a]	0.59[a]	0.60[a]	0.58[a]
PC	0.33[a]	0.56[b]	0.79[c]	0.80[c]
TF	0.74[a]	0.82[a]	0.75[a]	NA

The minimum sample size (N) for each site was (4), except EM(3) and PC (2).

The normalized runoff results were separated into vegetation types (Figure 4.2). There was not a significant difference in runoff between any of the treatments for the grassland sites. For the oak-woodland sites there was a significant increase in normalized runoff from the natural to the burned treatment. There was another significant increase in normalized runoff between the year of the fire and one year post-fire. The first and second year post-fire rates were not significantly different; however the second year post-fire rates had significantly high normalized runoff values compared to the natural conditions.

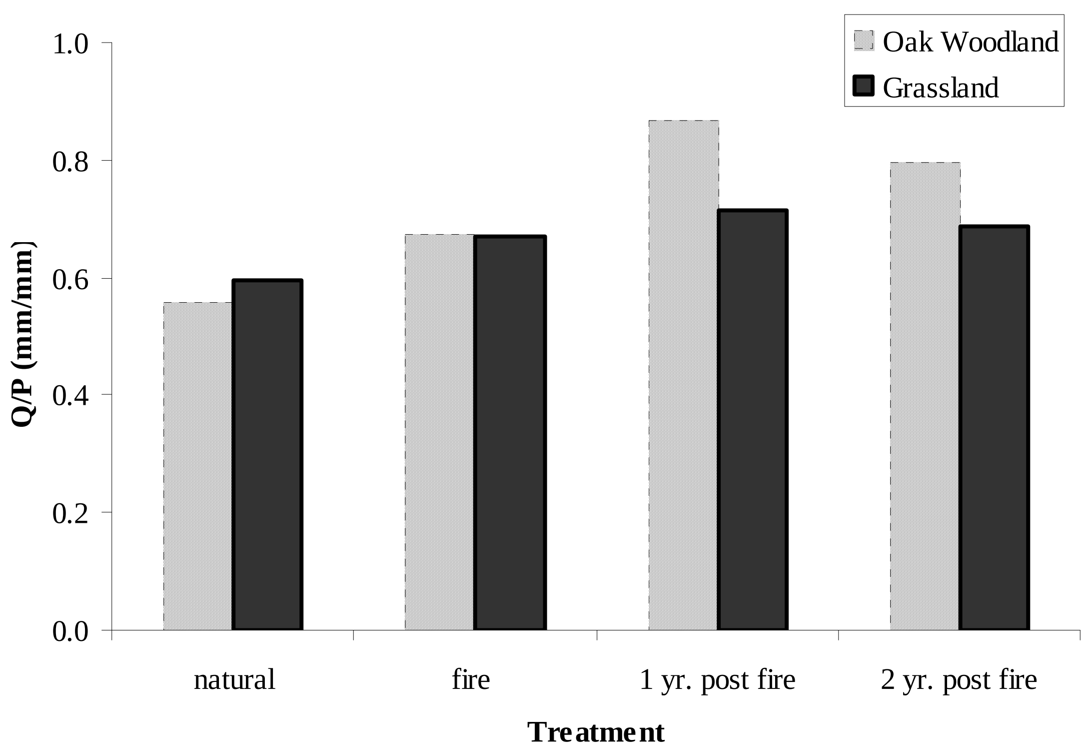


Figure 4.2. The average observed runoff ratio for natural, fire and recovery treatments on grassland and oak-woodland sites.

Table 4.2. The average normalized runoff volume for all treatments on semi-arid grasslands and oak-woodlands. Values within a row with the same letter indicate no significant difference using a students t-test at p <= 0.10.

Q/P (mm/mm)				
Vegetation Type	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
Grassland	0.59[a]	0.67[a]	0.71[a]	0.69[a]
Oak-woodland	0.56[a]	0.67[b]	0.87[c]	0.80[bc]

The minimum sample size (N) for grasslands was (13) and oak-woodlands (8).

4.1.2 Erosion Results

The sediment yield was normalized, in order to make comparisons among sites, by dividing the sediment yield, SY (T/ha) by runoff volume, Q (mm), times the plot slope, S_o (unitless). Sediment yield was normalized for runoff because runoff varied among plots. Sediment yield was also normalized for slope because it is important in transport capacity of sediment off the plot and is also important because of large differences in slope among sites. For example TF burned which has a range of slopes from 28 to 30% compared to 8 to 10% for the AB burned site. Sediment discharge was calculated by multiplying the runoff rate, q (mm/hr) by concentration, C (% weight) for each sediment sample taken systematically throughout the rainfall simulator experiment. Sediment yield is the total amount of sediment collected.

The observed erosion results for all rainfall simulator sites are shown in Figure 4.3. Results in Table 4.3 show there was a significant increase in erosion following the burn for all the sites. The erosion rates then decreased the first year post-fire and continued to decrease the second year post-fire. There was not a significant difference in normalized sediment yield between natural and the second year post-fire. Therefore the sites have approached natural conditions after two years. The PC site had the greatest change in normalized sediment yield values between natural and burned with a 2500 percent increase, while the ER3 site had only a 130 percent increase.

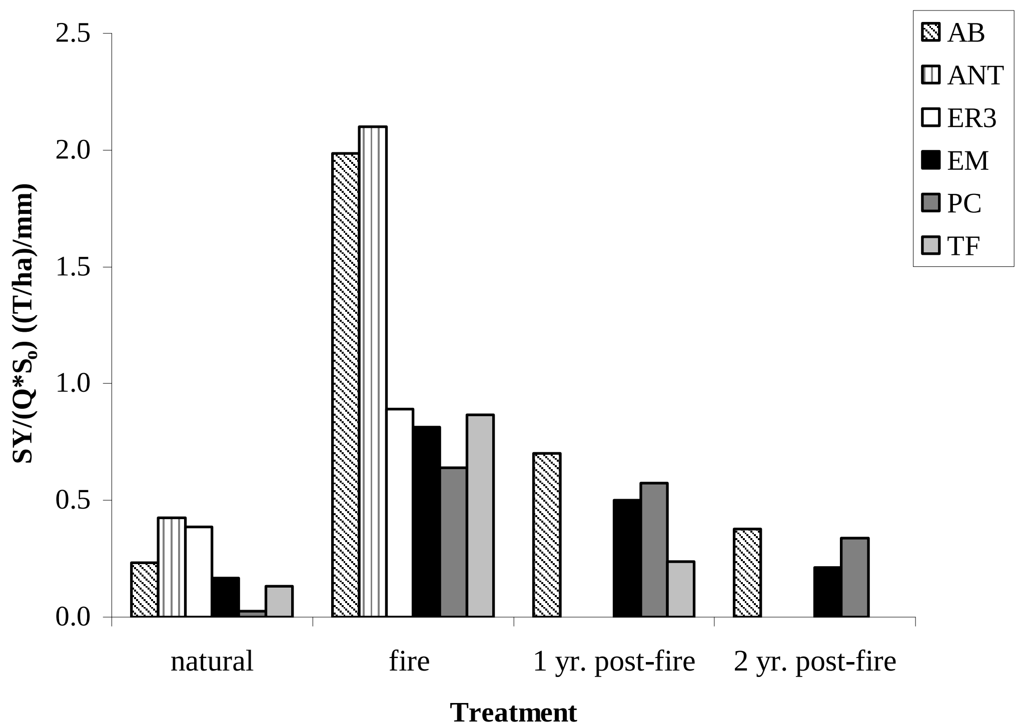


Figure 4.3. The average normalized sediment yield for natural, fire and recovery treatments on all rainfall simulator sites.

Table 4.3. Average normalized sediment yield results for all rainfall simulator sites and treatments. Values within a row with the same letter indicate no significant difference using a students t-test at $p <= 0.10$.

$SY/(QS_o)$ ((T/ha)/mm)				
Site	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
AB	0.23^{a}	1.99^{b}	0.70^{c}	0.38^{a}
ANT	043^{a}	2.10^{b}	NA	NA
ER3	0.39^{a}	0.89^{b}	NA	NA
EM	0.17^{a}	0.81^{b}	0.50^{c}	0.21^{a}
PC	0.03^{a}	0.64^{b}	0.57^{b}	0.34^{ab}
TF	0.13^{a}	0.87^{b}	0.24^{c}	NA

The minimum sample size (N) for each site was (4), except EM(3) and PC (2).

In Figure 4.4, the erosion results are separated by vegetation type. The normalized sediment yield for the oak-woodland increased by a factor of 5.2 immediately after the fire, while the sediment yield for the grasslands increased by a factor of 3.5. The sediment yield decreased the first and second year post-fire for both vegetation types.

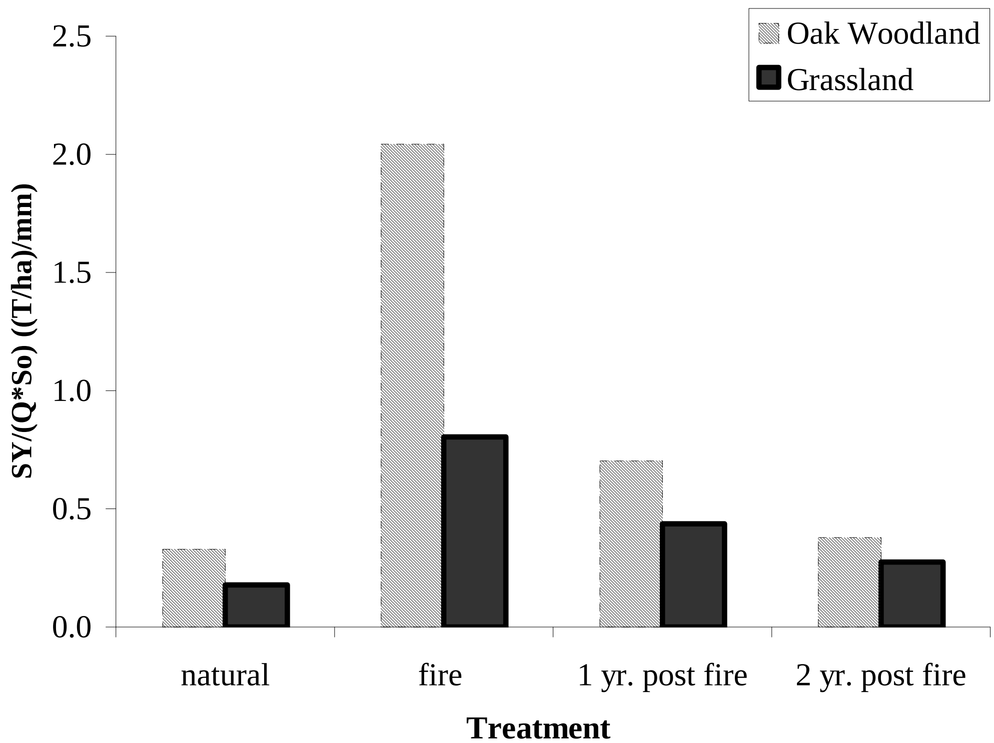


Figure 4.4. Average normalized sediment yield for natural, fire and recovery treatments on grassland and oak-woodland sites.

Table 4.4. Average normalized sediment yield values for all treatments on semi-arid grasslands and oak-woodlands. Values within a row with the same letter indicate no significant difference using a students t-test at $p <= 0.10$.

$SY/(QS_o)$ ((T/ha)/mm)				
Vegetation Type	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
Grassland	0.18^a	0.80^b	0.44^c	0.28^a
Oak-woodland	0.33^a	2.04^b	0.70^c	0.38^a

The minimum sample size (N) for grasslands was (13) and oak-woodlands (8).

A comparison of the normalized SY among the small and large plots for both burned and natural treatments was done (Figure 4.5). SY was plotted against steady state runoff discharge in order to remove differences in SY due to discrepancies in the runoff rate (q, mm/hr). SY was normalized for slope and time, t (hr). SY was normalized by time (t) to ensure that differences in sediment yield were not due to differences in duration of intensity in the wet run of the rainfall simulator experiments. The R^2 values shown in Figure 4.5 were obtained by a linear regression analysis on the log transforms of the independent and dependent variables.

The large plots are used to collect total erosion. Total erosion included the following processes: soil detachment by raindrop impact, flow detachment, transport and deposition. On the small plots only erosion by raindrop impact was measured. Previous research has shown that the small plots are too small for rill erosion processes to be active. The methodology behind the comparison between the large and small plots has allowed for the following assumptions: (1) if the small plot erosion is greater than the large plot, depositions is occurring on the large plot; (2) if the small plot erosion is equal to the large plot, erosion a threshold has been reached where flow detachment is occurring on large plot: (3) if erosion on the small plot is less than the large plot, flow detachment is occurring on the large plot, meaning that the flow has excess capacity to transport the raindrop detached sediment as well as detached sediment by flowing water.

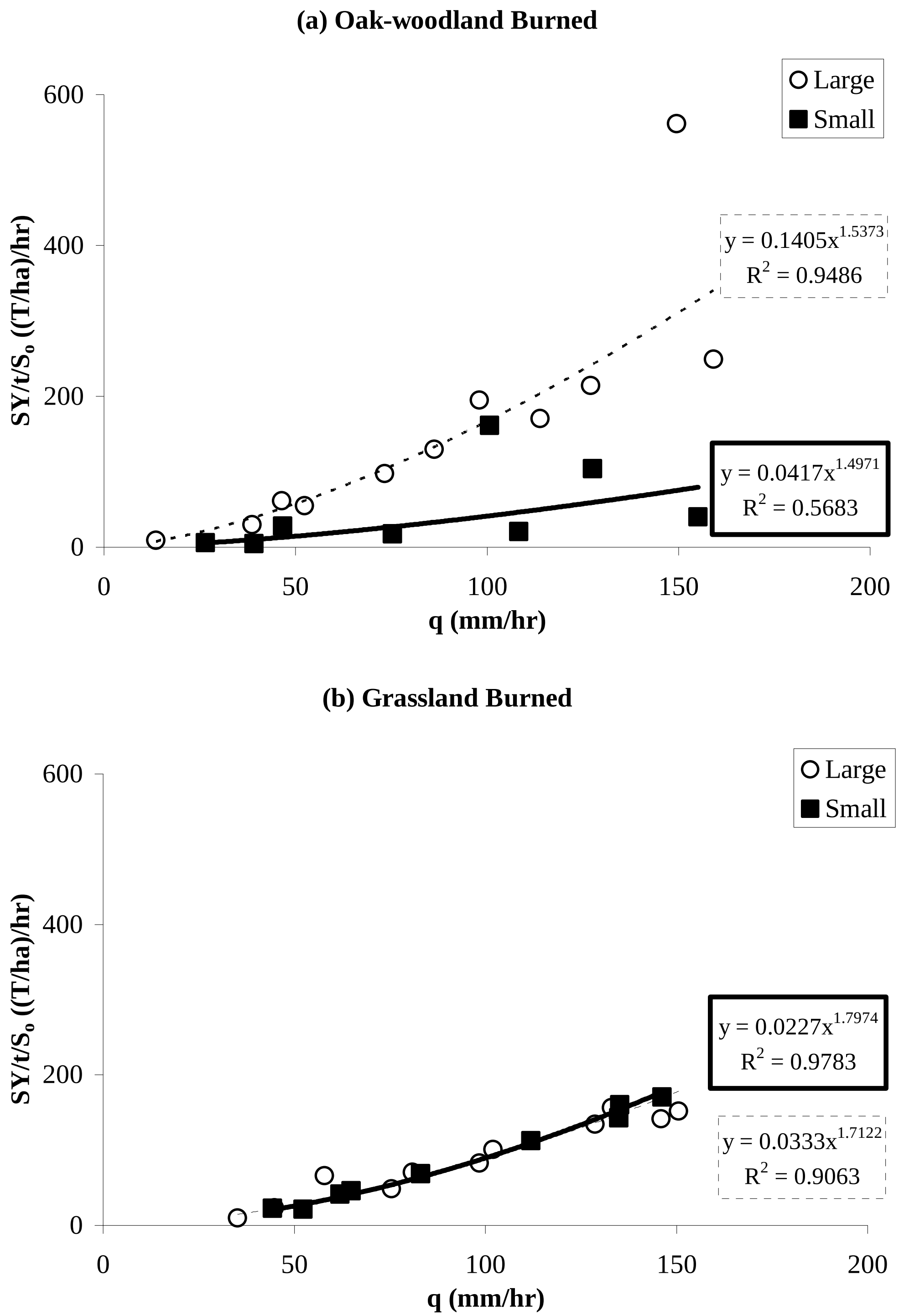


Figure 4.5. Normalized sediment yield versus runoff rate of the large and small plots for grasslands and oak-woodlands burned and natural treatments.

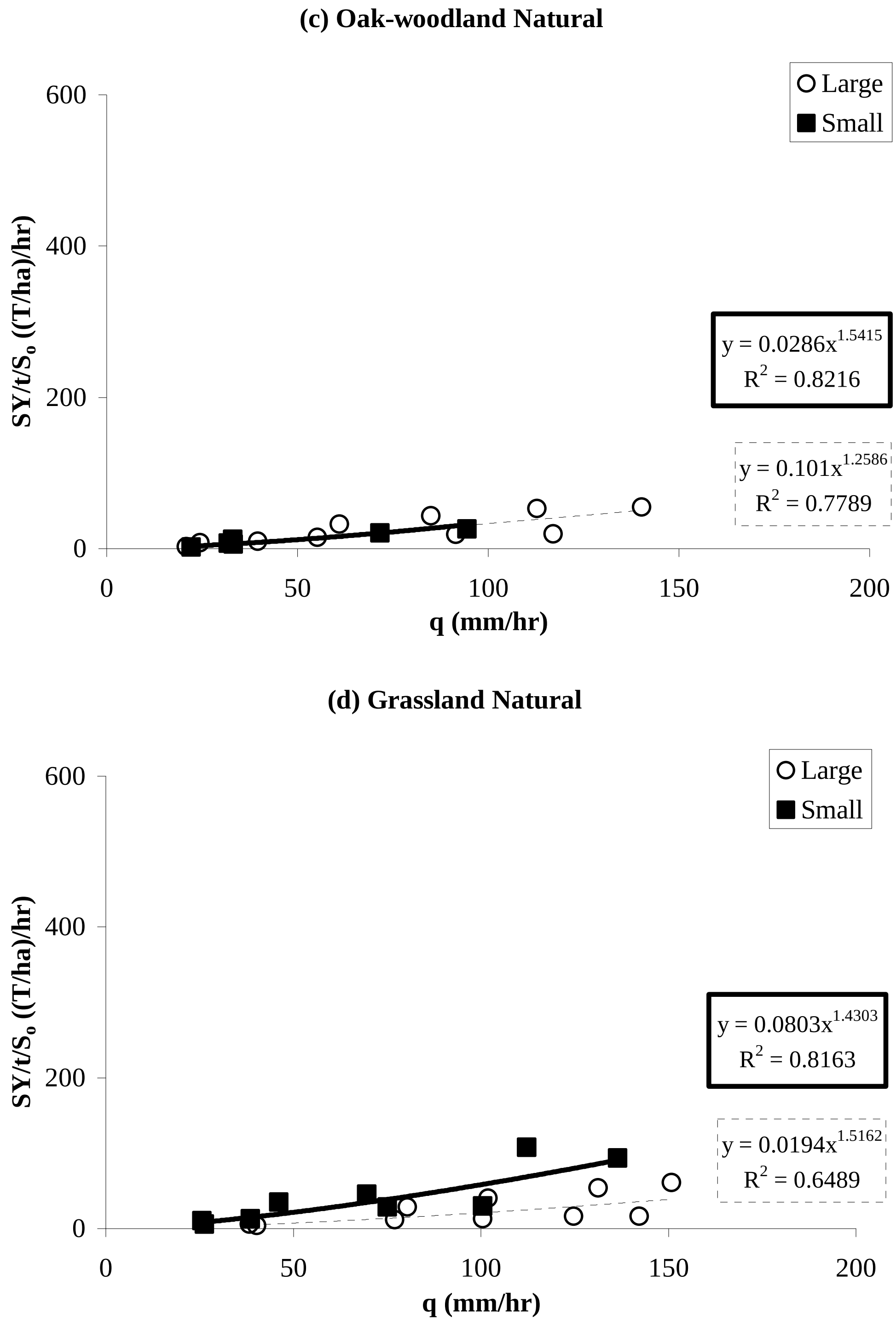


Figure 4.5. Normalized sediment yield versus runoff rate of the large and small plots for grasslands and oak-woodlands burned and natural treatments.

Figure 4.5 showed the following conclusions; a) the large plots have a greater sediment yield than small plots in the oak-woodland burned graph (Figure 4.5a), b) there was little difference between the two plot sizes for the grassland burned graph (Figure 4.5b), c) this was also true for the oak-woodland natural graph (Figure 4.5c), and d) however, there was more sediment yield from the small plots than the large plots in the grassland natural graph (Figure 4.5d).

4.1.3 Rainfall Simulator Measurements

Additional measurements that were taken with the rainfall simulator experiments include the following: slope, canopy cover and ground cover (Table 4.5 and 4.6). Figures 4.6 through 4.8 show the relationship between normalized sediment yield and slope, canopy and ground cover measurements.

Table 4.5 shows the percent canopy and ground cover results for all rainfall simulator sites and treatments. The year of the fire canopy cover decreases to approximately zero percent canopy cover. The recovery treatments show increases in canopy cover. Figure 4.6 shows that normalized sediment yield decreases as canopy cover increases. There are both increases and decreases in ground cover the year of the fire. Figure 4.7 shows that there is not a trend in the relationship between ground cover and normalized sediment yield values.

Table 4.6 shows the average slope values for the burned and natural treatments for all the rainfall simulator sites. The TF site has the largest slopes with an average of 22 percent for the unburned and 29 percent for the burned plots. All other rainfall simulator sites have average slopes between 9 and 16 percent. Figure 4.8 is a comparison between normalized sediment yield (normalized for runoff volume) and average percent slope for both burned and natural treatments. The general trend is that as slope increases, normalized sediment yield increases.

Table 4.5. The canopy and ground cover for natural, fire and recovery treatments on all rainfall simulator sites.

		CANOPY COVER (%)		GROUND COVER (%)	
Site	Treatment	AVG	SD	AVG	SD
AB	natural	76.00	7.79	71.50	10.02
	fire	0.00	0.00	67.00	21.06
	1 yr. post fire	25.75	15.44	60.00	8.52
	2 yr. post fire	23.13	6.88	59.50	6.88
ANT	natural	27.06	2.30	54.81	13.50
	fire	2.85	1.98	39.59	12.01
ER3	natural	25.88	7.20	58.19	4.25
	fire	5.25	1.51	42.39	1.54
EM	natural	63.51	2.72	60.26	4.70
	fire	2.67	1.91	75.58	1.53
	1 yr. post fire	66.25	21.50	49.56	12.81
	2 yr. post fire	54.50	2.38	55.00	2.16
PC	natural	88.34	3.81	81.92	7.07
	fire	7.25	4.24	72.63	13.61
	1 yr. post fire	21.67	1.53	35.33	2.08
	2 yr. post fire	58.00	6.16	33.50	5.20
TF	natural	83.25	7.23	54.25	0.96
	fire	0.00	0.00	60.75	4.86
	1 yr. post fire	31.82	3.33	57.27	5.39

AVG = Average; SD = Standard Deviation

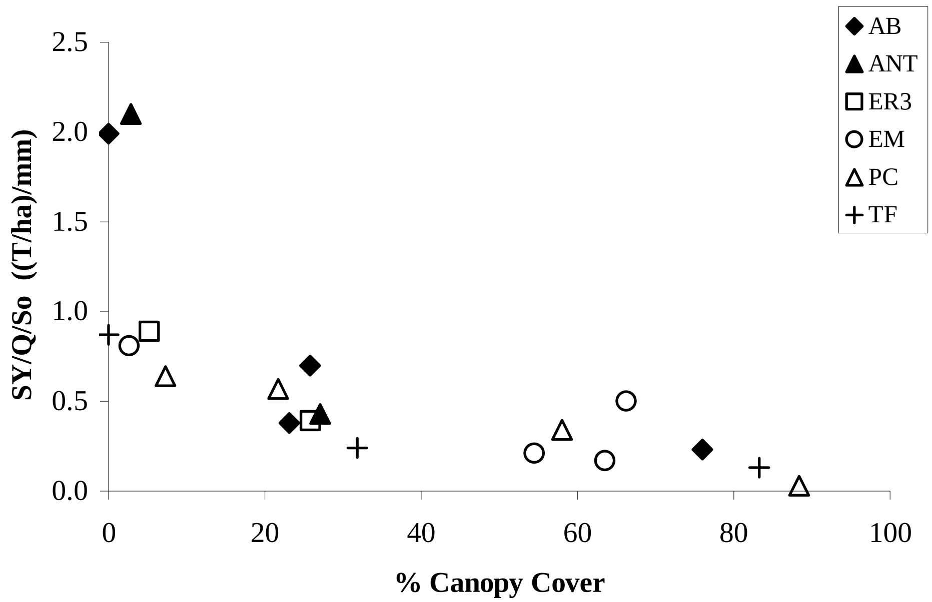


Figure 4.6. The normalized sediment yield versus canopy cover for all rainfall simulator sites and treatments.

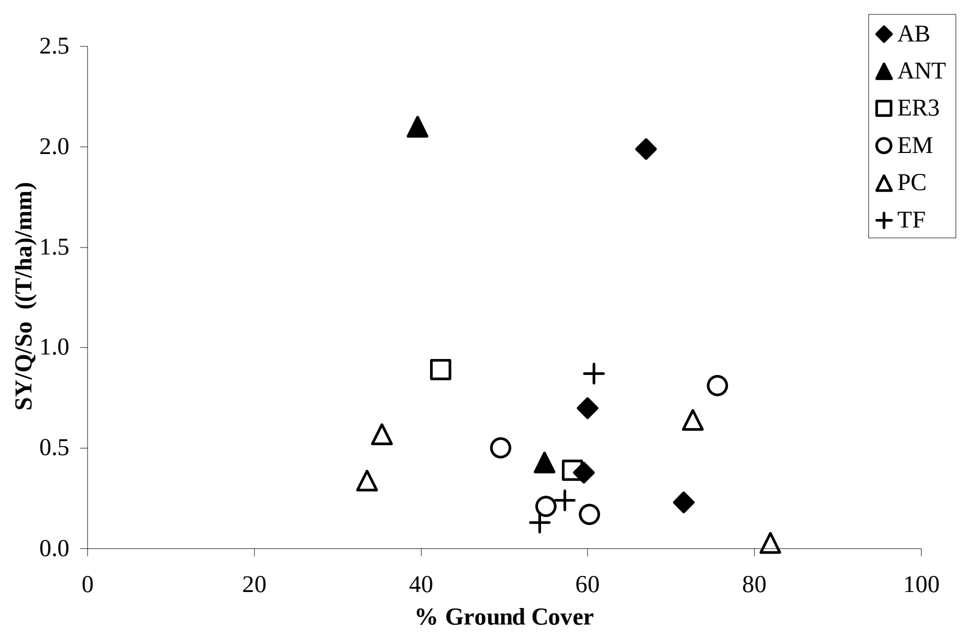


Figure 4.7. The normalized sediment yield versus ground cover for all rainfall simulator sites and treatments.

Table 4.6. The slopes for the natural and fire treatments on all rainfall simulator sites. The units are percent.

		SLOPE (%)	
Site	Treatment	AVG	SD
AB	natural	11.26	2.49
	fire	9.26	0.93
ANT	natural	16.54	1.62
	fire	15.69	2.13
ER3	natural	13.50	1.00
	fire	13.25	2.06
EM	natural	13.73	1.80
	fire	12.75	1.50
PC	natural	11.30	0.42
	fire	8.75	0.50
TF	natural	21.95	1.29
	fire	28.88	0.88

The units are percent.
AVG = Average; SD = Standard Deviation

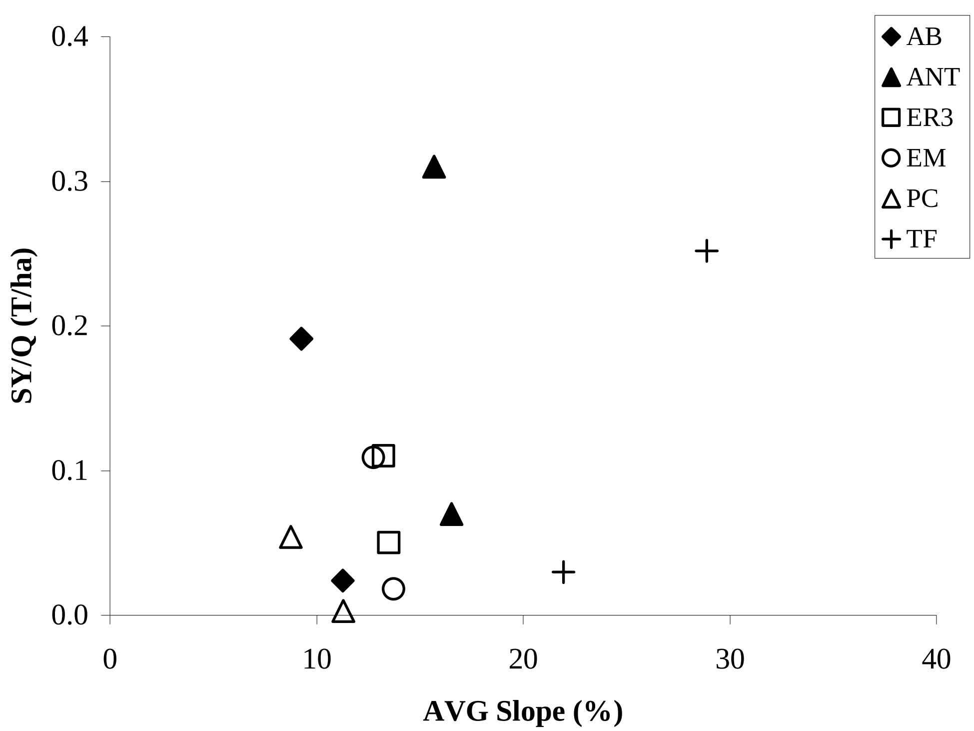


Figure 4.8. Sediment yield versus average slope for all rainfall simulator sites burned and natural treatments.

4.2 Model Results

4.2.1 Parameter Identification

Hydraulic Conductivity

Parameter values for effective hydraulic conductivity, K_e, were found by adjusting Ke values until the model predicted runoff volume matched the observed runoff volume, using both breakpoint and disaggregated rainfall data. Individual site disaggregated K_e (K_{ed}) values are shown in Figure 4.9 and the mean and standard deviation for the site K_{ed} values are listed in Table A5. The AB site had the largest change in K_e values between fire and natural conditions, a 70 percent decrease in K_e from natural to fire. The lowest was ANT with a 10 percent decrease in K_e between natural and fire treatments.

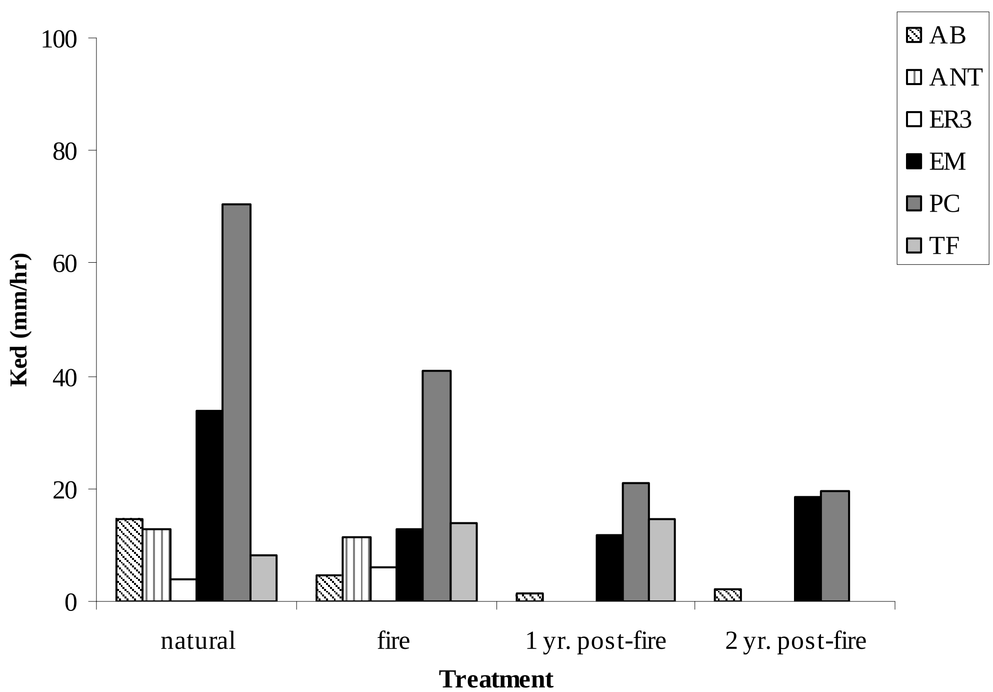


Figure 4.9. The average K_{ed} values for all rainfall simulator sites and treatments. The solid bars are the grasslands while the patterned bars represent the oak-woodlands.

Table 4.7. Average K_{ed} values for all rainfall simulator sites and treatments. Values within a row with the same letter indicate no significant difference using a students t-test at p <= 0.10.

K_{ed} (mm/hr)				
Site	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
AB	15^{a}	5^{b}	2^{c}	2^{c}
ANT	13^{a}	12^{a}	NA	NA
ER3	4^{a}	6^{a}	NA	NA
EM	34^{a}	13^{b}	12^{b}	19^{b}
PC	71^{a}	41^{a}	21^{b}	20^{b}
TF	8^{a}	14^{a}	15^{a}	NA

The minimum sample size (N) for each site was (4), except EM(3) and PC (2).

Figure 4.10 shows average K_{ed} values over time for the two vegetation types. The results showed a decrease in K_{ed} values the year of the fire, an increase in runoff. There was approximately a 60 percent decrease in K_{ed} values after the fire for both vegetation types. The first year post-fire K_{ed} values continued to decrease, but started to increase the second year post-fire. A significant difference was detected between the burned and natural K_{ed} values for oak-woodlands only. The null hypothesis was that the burned K_{ed} values were not similar to the natural. This null hypothesis was accepted with a p-value of 0.03. The data were significantly different at the 95% confidence interval.

Table 4.8. Average K_{ed} values for all treatments on grasslands and oak-woodlands. Values within a row with the same letter indicate no significant difference using students t-test at p <= 0.10.

K_{ed} (mm/hr)				
Vegetation Type	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
Grassland	30^{a}	18^{ab}	16^{b}	19^{b}
Oak-woodland	14^{a}	8^{b}	2^{c}	2^{c}

The minimum sample size (N) for grasslands was (13) and oak-woodlands (8).

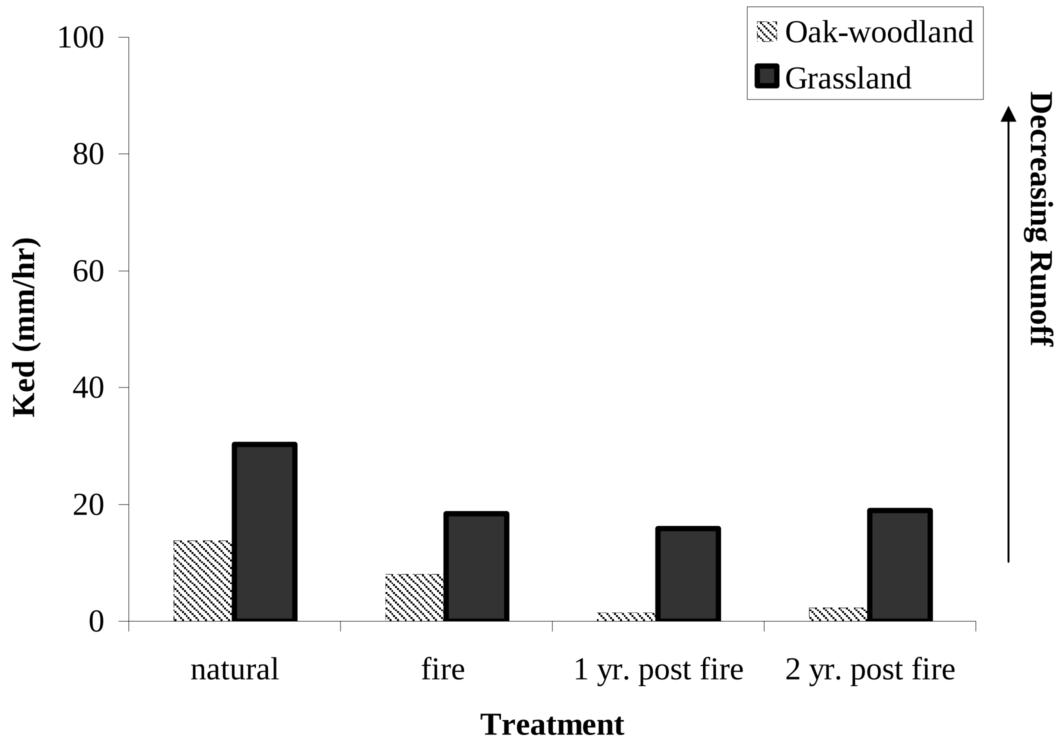


Figure 4.10. Average K_{ed} values for grasslands and oak-woodlands for natural, fire and recovery treatments. As K_{ed} increases runoff decreases. The gray thick line represents the grassland sites, while the black dashed line is signifying the oak-woodlands.

Interrill Erodibility

K_i values were calculated from the small plot data using equation 3.1. K_i values were calculated on a plot basis and then were averaged to get a site K_i value. K_i values increased after the fire because K_i is positively correlated with erosion. Figure 4.11 shows the average K_i values for each site; the means and standard deviations of each site are given in Table A6. The largest increase in K_i values was between natural and fire treatments for the TF site, with a 250 percent increase. The smallest change in K_i was on the ER3 site. There are not enough data to complete t-tests on the K_i values to determine significant differences between treatments for each vegetation type as well as among the sites. This is because K_i values were calculated as a site average rather than a K_i value for every plot and also because small plot data were not collected for EM and PC in the natural and fire treatments.

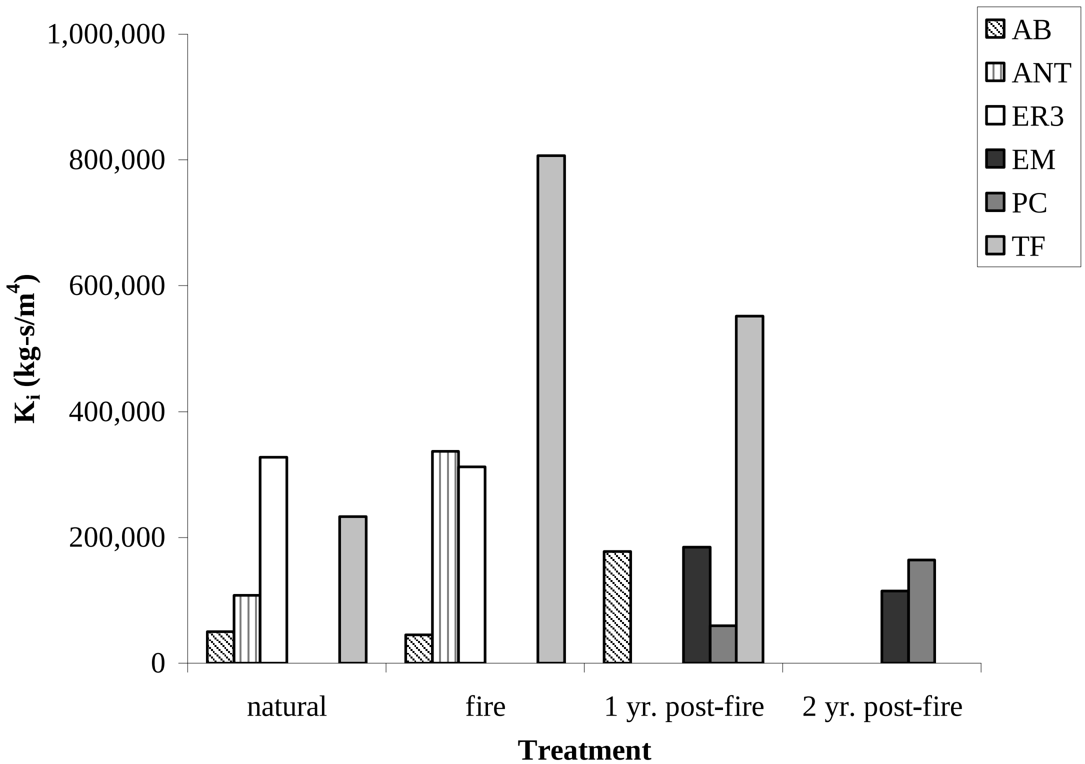


Figure 4.11. Average K_i values for all rainfall simulator sites and treatments. The solid bars are the grasslands while the patterned bars represent the oak-woodlands.

Figure 4.12 shows the differences in K_i between burned and natural treatments and recovery time for both vegetation types. There was a 140 percent increase in K_i values for oak-woodlands and a 100 percent increase for grasslands. The difference between pre and post fire conditions was significant with a p-value of 0.0339 at a 95% confidence interval.

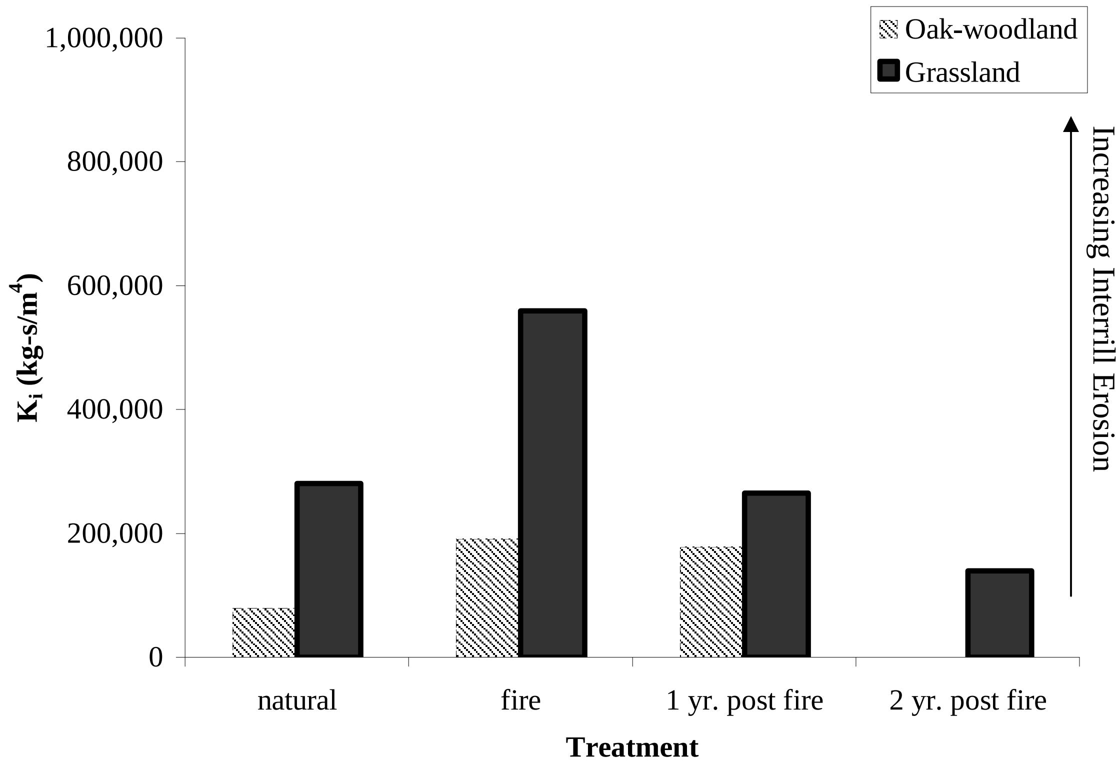


Figure 4.12. The K_i values for grasslands and oak-woodlands for natural, fire and recovery treatments. As K_i increase interrill erosion also increases.

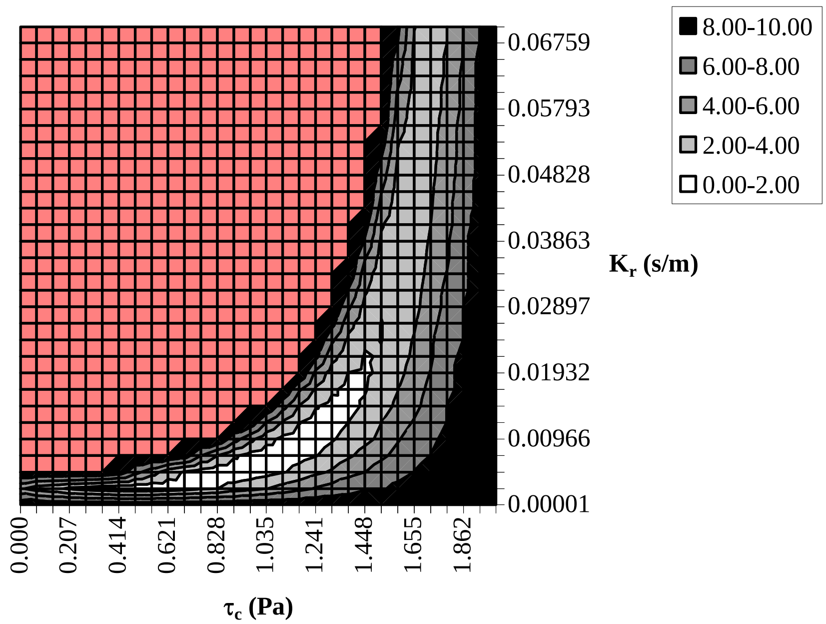
Rill Erodibility and Critical Shear Stress

K_r and τ_c values were determined using a two parameter optimization approach comparing the predicted and the observed sediment discharge values for each intensity on the large rainfall simulator plots only. For the two parameter optimization, the model was run with 30 values of K_r and 30 values of τ_c giving 900 combinations. The sum of the least squares equations for the 900 combinations of K_r and τ_c were plotted on a contour map. The model was rerun until a narrower range of K_r and τ_c was not obtainable. An example of the results of the two parameter optimization procedure by which response surfaces were narrowed to obtain the minimum K_r and τ_c for a plot is shown in Figure 4.13. Figure 4.14 shows a response surface of a plot where a minimum K_r and τ_c value were not obtainable; the two parameter optimization to find a minimum K_r and τ_c did not work in all cases. Table 4.9 summarizes the sites for which parameter values were obtainable. Table 4.9 also shows at which sites and treatments rill erosion processes were active according to the comparison of large plots versus small plots as in Figure 4.5 and Figure A1. Again the assumption is that if the large plots had more sediment yield compared to the small plots rill erosion processes were occurring. Rill erosion processes were active on AB and ANT burned treatments only. However, K_r and τ_c were obtainable on all the grassland burned treatments as well as natural oak-woodland and 1 yr. post-fire for the AB site.

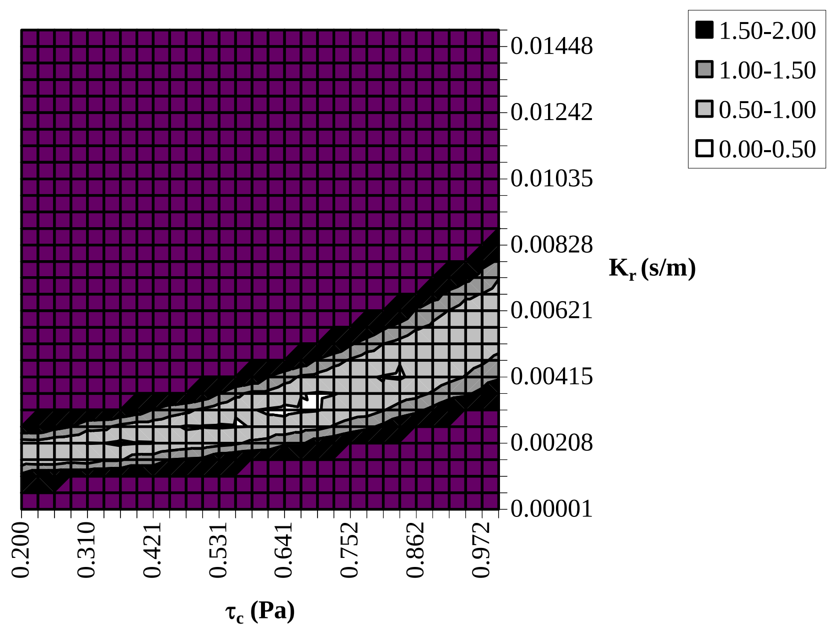
Table 4.9. Results of the two parameter optimization for K_r and τ_c.

Site	Treatment	Rill process active?	K_r & t_c obtainable?
AB	natural	N	Y
	fire	**Y**	Y
	1 yr. post-fire	N	Y
	2 yr. post-fire	N	N
ANT	natural	**Y**	Y
	fire	N	Y
ER3	natural	N	N
	fire	N	Y
EM	natural	N	N
	fire	N	Y
	1 yr. post-fire	N	N
	2 yr. post-fire	N	N
PC	natural	N	N
	fire	N	Y
	1 yr. post-fire	N	N
	2 yr. post-fire	N	N
TF	natural	N	N
	fire	N	Y
	1 yr. post-fire	N	N

Y stands for yes K_r and τ_c were obtainable for that site and treatment. Whether rill erosion processes were active were determined by results of Figure 4.5 and A1. If rill erosion processes occurred, a Y is in the column labeled "Rill process active?" If K_r and τ_c were obtainable a, Y is in the column labeled "K_r and τ_c obtainable?"

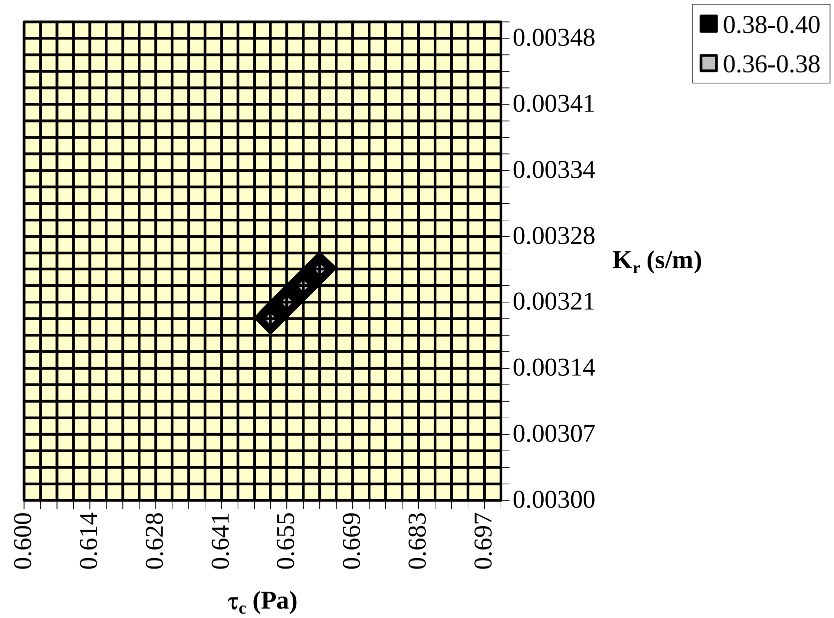


(a)

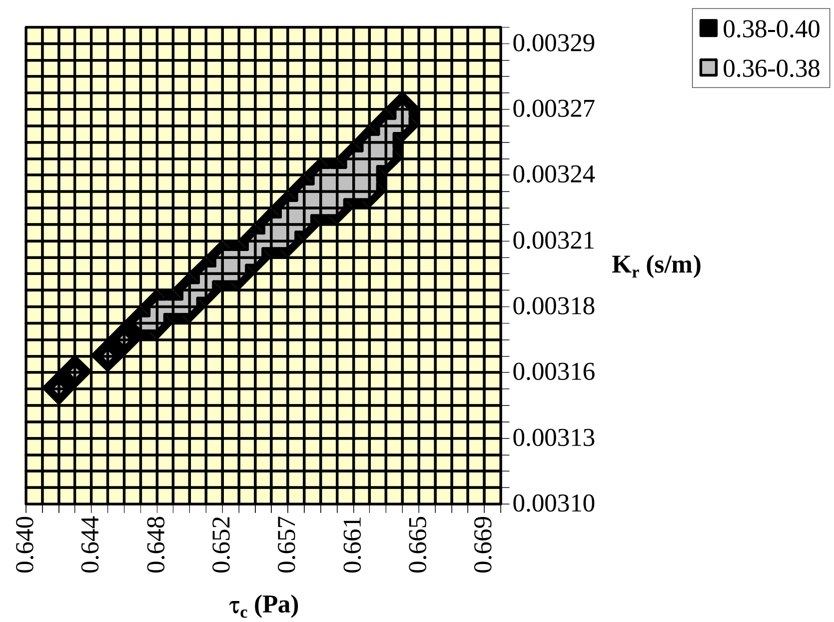


(b)

Figure 4.13. Sequential response surface for the ANT burned site plot two. The range of K_r varies from (0.00001 to 0.070) for graph a to (0.00310 to 0.00330) for the graph d, while τ_c varies from (0.000 to 2.000) to (0.640 to 0.670).



(c)



(d)

Figure 4.13. Sequential response surface for the ANT burned site plot two. The range of K_r varies from (0.00001 to 0.070) for graph a to (0.00310 to 0.00330) for the graph d, while τ_c varies from (0.000 to 2.000) to (0.640 to 0.670).

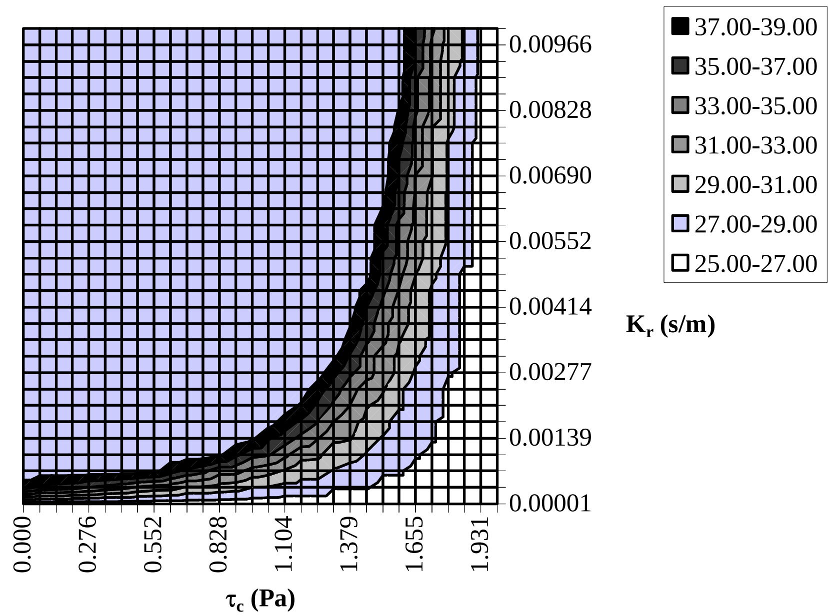


Figure 4.14. Response surface for the TF natural plot 1. K_r ranges from 0.00001 to 0.001, while τ_c ranges from 0.000 to 2.000.

The following two figures, Figure 4.15 and Figure 4.16, show the results for site average K_r and τ_c. The increase in K_r was approximately 1000 percent at both the AB and ANT sites. τ_c values increased by 1400 percent for the ANT site and 900 percent for the AB site. Changes in rill erosion by vegetation type are shown in Figures 4.17 and 4.18. These graphs show an increase in rill erosion following the wildfires; however, the increase was significantly greater in the oak-woodland vegetation type. There was a 1000 percent increase in K_r values the year of the fire for the oak-woodlands and a 1400 percent increase in τ_c. After the fire, there was a decrease in K_r and τ_c values to near natural conditions. T-tests were only applied to burned and natural treatments for the oak-woodland vegetation type, because K_r and τ_c values were only obtainable for these sites. There was a significant difference for both K_r and τ_c.

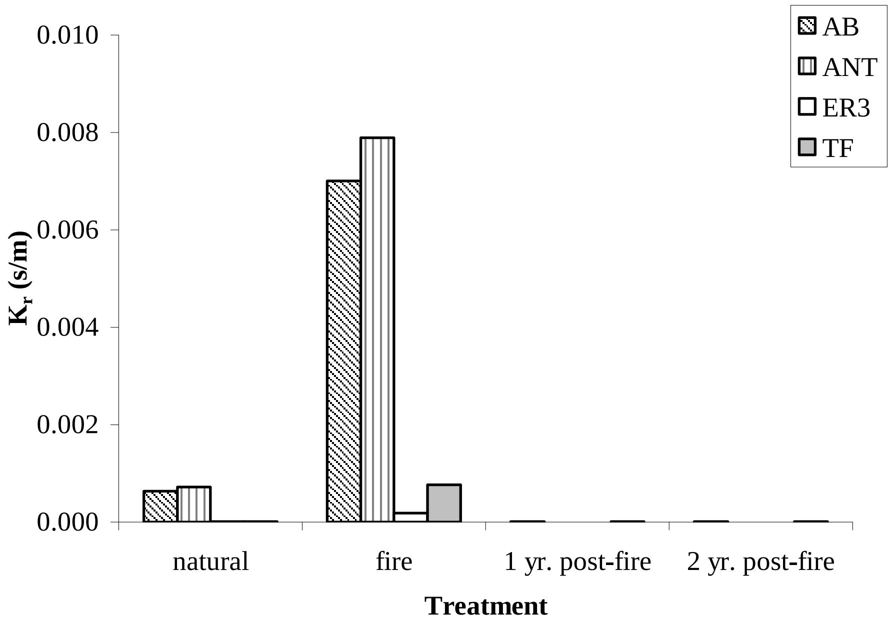


Figure 4.15. Average K_r values for rainfall simulator sites where rill erosion was observed. Oak-woodland sites are AB and ANT while the grassland sites are ER3 and TF.

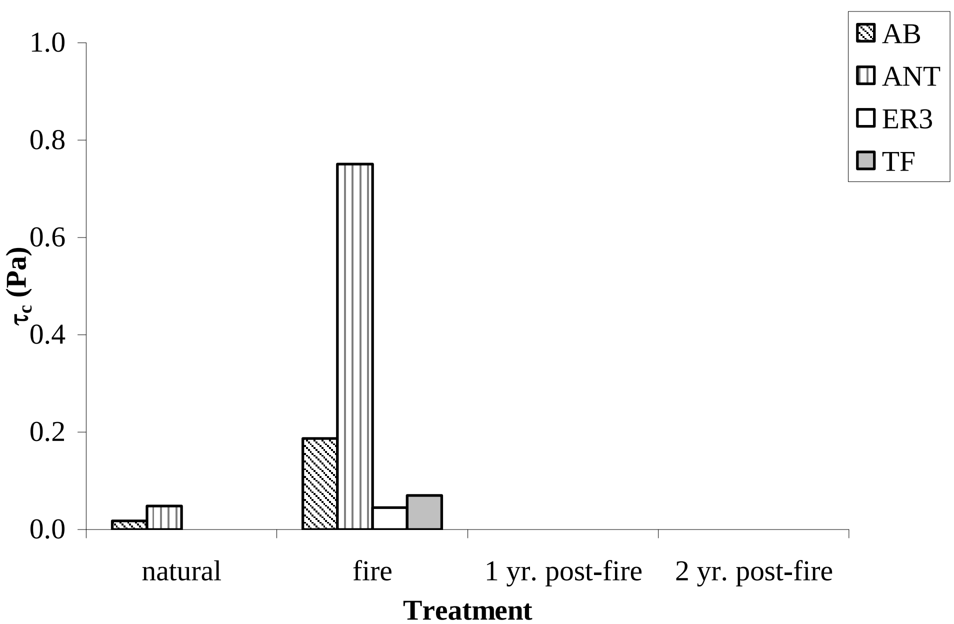


Figure 4.16. Average τ_c values for sites where rill erosion was observed. Oak-woodland sites are AB and ANT while the grassland sites are ER3 and TF.

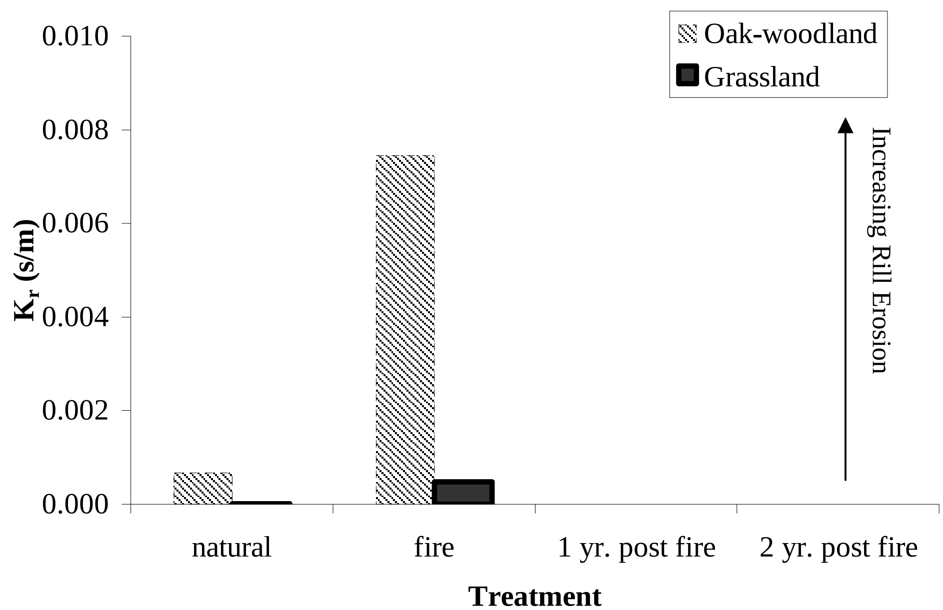


Figure 4.17. Kr values for oak-woodlands and grasslands for natural, fire and recovery treatments. As Kr increases rill erosion increases. The gray thick line represents the grassland sites, while the black dashed line is signifying the oak-woodlands.

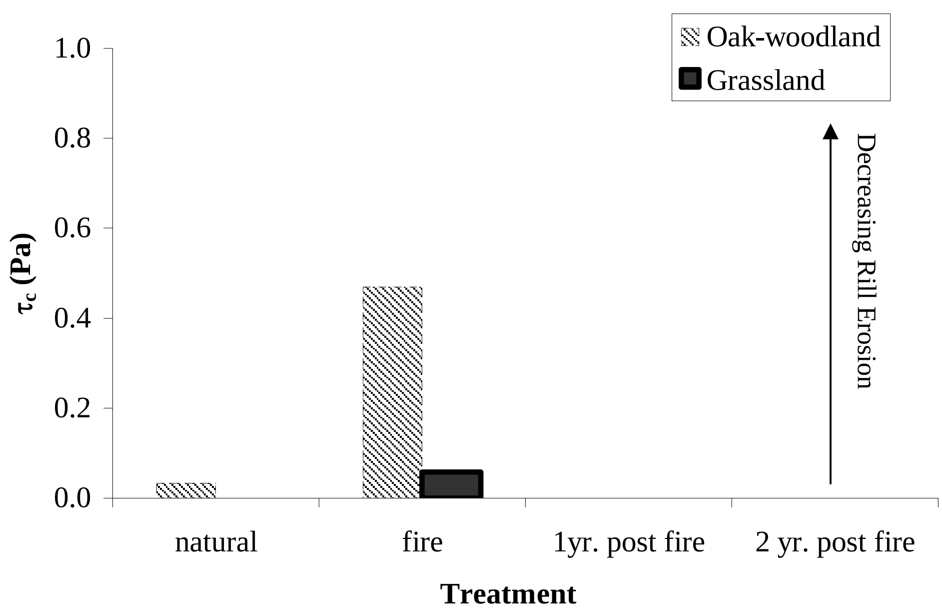


Figure 4.18. The τ_c values for oak-woodland and grasslands for natural, fire and recovery treatments. As τ_c increases rill erosion decreases. The gray thick line represents the grassland sites, while the black dashed line is signifying the oak-woodlands

4.2.2 Parameter Estimation

Parameter estimation equations were created for both runoff and erosion parameters. The recommended parameter estimation equations are listed in Table 4.10 through 4.12. The K_{ed} values of the parameter estimation equations were compared to the parameter identification values for K_{ed} and K_i (Figure 4.19 and 4.20). The units for the input variables are percent.

Hydraulic Conductivity

Four equations were created for determining K_e values. Equations were created for both K_{eb} (breakpoint K_e) and K_{ed} (disaggregated K_e); however, results were not significantly different between two types of K_e. Therefore the recommended parameter estimation equations for K_{ed} are shown in Table 4.10.

Table 4.10. Parameter estimation equations created to determine the runoff parameters K_{ed} separated by fire, natural and recovery treatments for oak-woodlands (oak) and grasslands (grass).

Treatment	Vegetation Type	Equation for K_{ed} (mm/hr)	Adj. R^2	RMSE	N
FIRE	Oak	$K_{ed} = 4.65 + 0.21Lt$	0.66	2.59	8
FIRE and NATURAL	Grass	$K_{ed} = -7.43 + 0.85Li + 2.30Bi$	0.85	8.97	26
NATURAL	Oak	$K_{ed} = 13.82 + 0.29Li - 0.39Rr$	0.77	2.30	8
RECOVERY	Grass and Oak	$K_{ed} = 26.25 - 0.07GAPc - 0.42Rr$	0.46	6.60	27

The units are mm/hr.
N is the sample size for each equation.
Bi – Under canopy basal cover (percent)
GAPc – Canopy gap cover (cm)
Li – Under canopy litter cover (percent)
Lt – Total litter cover (percent)
Rr – Intercanopy rock cover (percent)

The estimation equation for the fire treatment in oak-woodlands contained litter cover as the only input variable. For the natural treatments, total basal cover and total under canopy ground cover were in the parameter estimation equation. A better relationship was obtained when the natural treatment was separated by vegetation type, rather than lumped together. The estimation equations for the natural treatment in grasslands and oak-woodlands contained the following; under canopy litter cover, under canopy basal cover and intercanopy rock cover. The recovery treatment equations contained canopy gap, intercanopy rock cover and total rock cover. Parameter values calculated by the estimation equations for K_{ed} are shown below in Figures 4.19, where the calculated values were compared to the parameter values found with optimization technique. The estimated K_{ed} values were calculated with the suggested parameter estimation equations (Table 4.10). The optimized and estimated K_{ed} values were highly correlated, R^2 values of approximately 0.8. The natural treatment had the strongest relationship between estimated and predicted K_{ed} values, followed by the fire treatment. The recovery treatment had the poorest relationship between estimated and predicted K_{ed} values.

K_e values were calculated from the parameter estimation equations given in the WEPP documentation. The estimated K_e values calculated from WEPP were then compared to the optimized K_e values found with this research. This comparison resulted in an R^2 value of 0.004 (Figure A3).

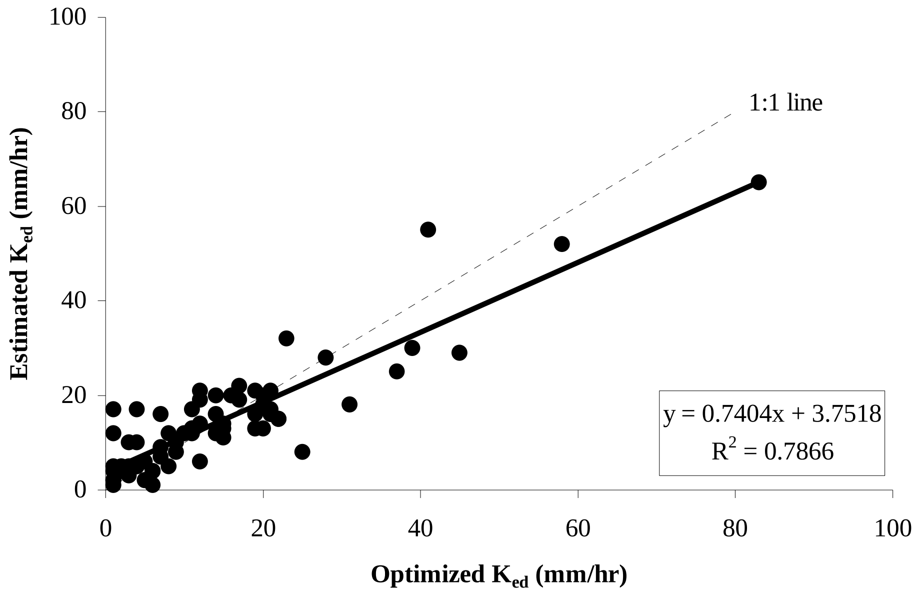


Figure 4.19. K_{ed} values found with optimization technique compared to K_{ed} values calculated with parameter estimation equations.

Interrill Erodibility

Interrill erodibility parameter estimation equations were created for three treatments (Table 4.11). The parameter estimation equations were not further separated into vegetation type because this did not strengthen the analysis. The relationship between K_i and input variables was logarithmic. The same input variables, total ground cover and natural logarithm of the slope, were correlated with K_i for both fire and natural treatments. In the parameter estimation equation for the recovery treatment, slope was the only input variable used.

Table 4.11. Parameter estimation equations used to calculate K_i separated by fire, natural and recovery treatments.

Treatment	Equations for K_i (kg-s/m^4)	Adj. R^2	RMSE	N
FIRE	$\ln(K_i) = 9.41 - 0.02Gt + 1.54\ln(So)$	0.82	0.48	21
NATURAL	$\ln(K_i) = 13.00 + 0.72\ln(So) - 0.06Gt$	0.56	0.62	21
RECOVERY	$K_i = 913927.19 + 346815.15*\ln(So)$	0.61	108788	27

The units are kg-s/m^4.
N is the sample size for each equation.
ln(So) – Natural Log of Slope (percent)
Gt – Total ground cover (percent)

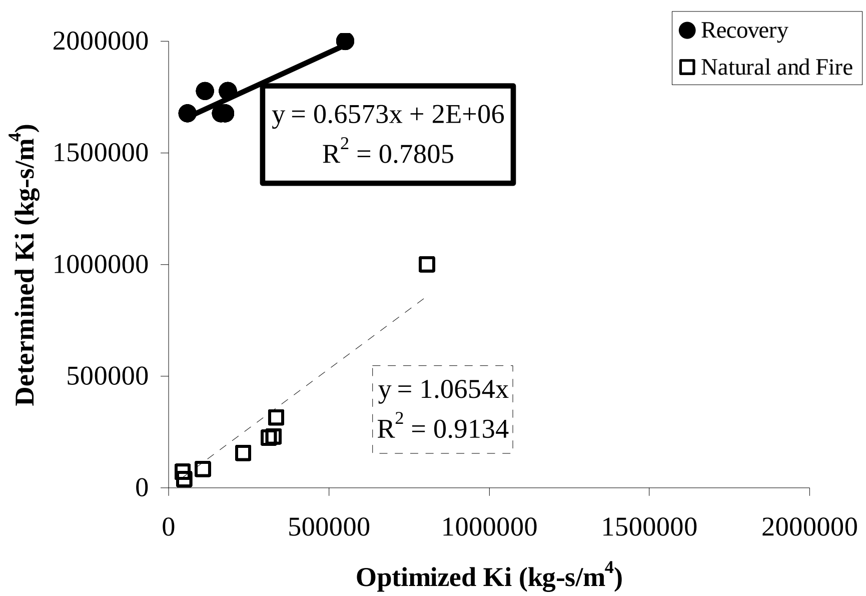


Figure 4.20. K_i values found through optimization technique compared to K_i values calculated by estimation equations. The closed circles represent the recovery treatments while the open squares are the natural and fire treatments.

K_i values were calculated with the recommended parameter estimation equations from Table 4.11. The estimated parameter values were compared to the parameter values found with the optimization technique (Figure 4.20). The R^2 values were higher, showing a stronger relationship between estimated and identified Ki values, for burned and natural treatments compared to the recovery treatment.

K_i values were calculated from the parameter estimation equations given in the WEPP documentation. The estimated K_i values calculated from WEPP were then compared to the identified K_i values found with this research. This comparison resulted in an R^2 value of 0.13 (Figure A4).

Rill Erodibility and critical shear stress

Parameter estimation equations were created for each rill erosion parameter. However this was only done for the burned treatment on oak-woodland sites because rill erosion was only observed on those sites (Table 4.12). Total rock cover and basal cover were the principal input variables for estimating K_r. Total ground cover was the only input variable needed for estimating τ_c.

The recommended equations in Table 4.12 were used to calculate parameter values for the burned treatment on the AB and ANT sites. A figure comparing estimated and identified parameter values was not included because parameter estimation equations were only applied to two sites. The values calculated by the parameter estimation equations are in Table A14 and A15.

Table 4.12. Parameter estimation equations used to calculate rill erosion parameters K_r and τ_c.

Parameter	Equations for Rill Erosion Parameters	Adj. R^2	RMSE	N
K_r (s/m)	$K_r = 0.01 - 0.0003Rt$	0.53	0.00	6
τ_c (Pa)	$\log(\tau_c) = 5.53 - 0.13Gt$	0.99	0.31	6

The units are s/m and Pa.
N is the sample size for each equation.
Gt – Total ground cover (percent)
Rt – Total rock cover (percent)

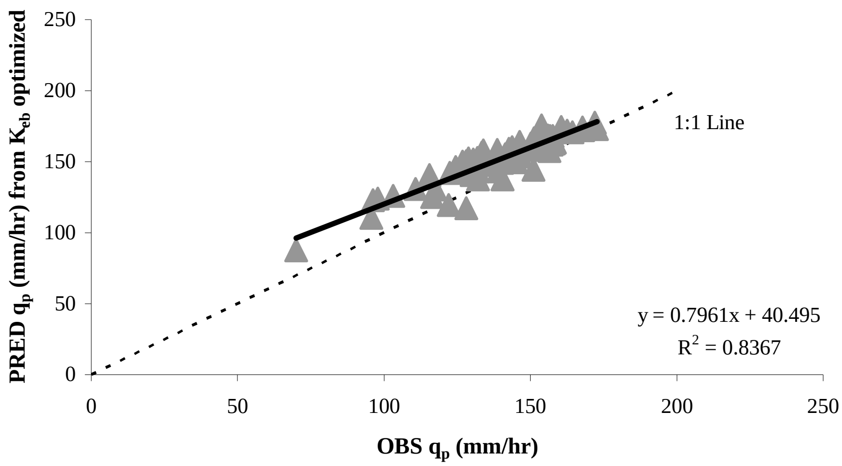
4.2.3 Model Evaluation

An evaluation of the RHEM model was done using the parameters found through the optimization and estimation techniques. The predicted values (found through both the optimization and estimation techniques) were compared to the observed values for both runoff and erosion parameters (Figures 4.21 – 4.26). Goodness of fit statistics were also used to analyze the results of the observed and predicted parameter values (Tables 4.13 to 4.16). A model evaluation was also completed as suggested by Nearing (2000); (Figure 4.27).

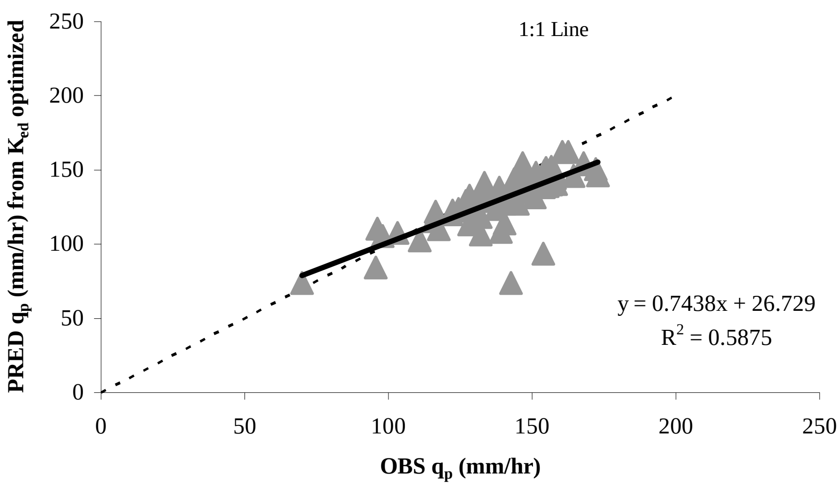
Hydraulic Conductivity

Model evaluation was conducted using K_{eb} and K_{ed} parameters determined from both the optimization and estimation procedures. The model was evaluated based on both its prediction of runoff volume and peak discharge. The R^2 values from the model evaluation were not significant at the 95% confidence level between K_{eb} and K_{ed} except when the optimized K_{eb} and K_{ed} values were used to evaluate the prediction of peak discharge. Therefore, both K_{eb} and K_{ed} results were shown for the first step, otherwise only K_{ed} results were shown.

The first step in model evaluation for K_e was to use optimized K_{eb} and K_{ed} values and compare the predicted peak discharge with the observed peak discharge for the individual plots (Figure 4.21 and Table 4.13). A better relationship was found when K_{eb} parameter values were used compared to K_{ed} for almost all treatments except natural treatment where both parameters had similar R^2 value. The second step was to use the average site K_e values found with the optimization routine and predict the individual plot runoff volume. The model predicted runoff volume was then compared to the observed value for each plot (Figure 4.22 and Table 4.14). When the data were separated into treatment the correlation was strongest with the natural treatment, recovery treatment and fire treatment in that order for both K_{ed} and K_{eb}.

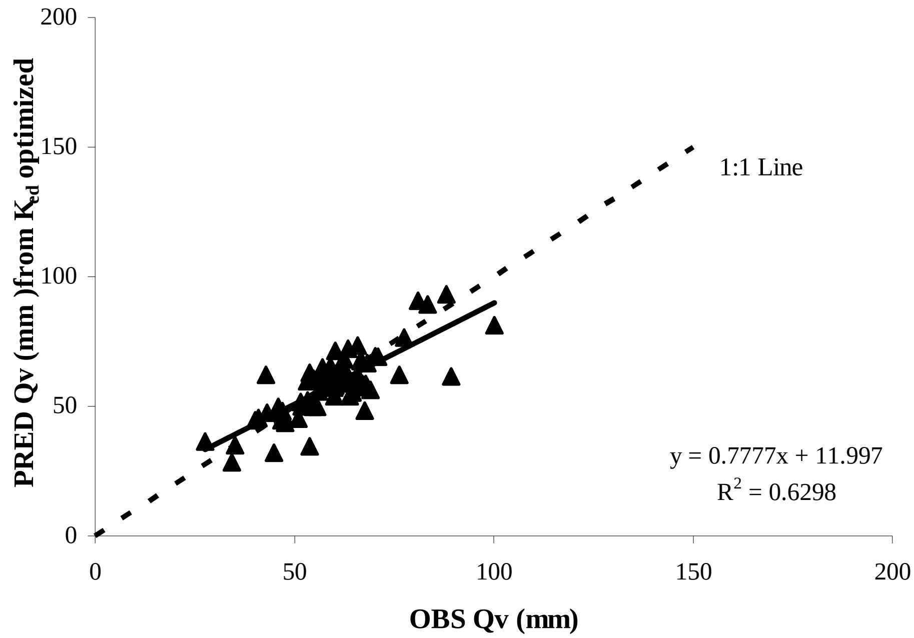


(a)



(b)

Figure 4.21. Model evaluation for peak discharge from optimized K_{eb} and K_{ed} values for each plot. Graph a is the results from K_{eb}, while K_{ed} results are shown in Graph b.



(a)

Figure 4.22. Model evaluation for runoff volume with site average K_{ed} values from optimization.

The third and fourth steps were to use the parameter estimation values to estimate runoff volume. The third step took the parameter values found for each plot with the estimation equations and used those values to rerun the model, comparing the predicted runoff volume with the observed runoff volume (Figure 4.23 – 4.24 and Table 4.15). The final step was to use the average K_e value found for each site from the parameter estimation equations. The model was rerun for every plot using the site average K_e value. Then the predicted runoff volume was compared to the observed runoff volume for each plot. Relatively higher R^2 were achieved when the individual plot estimation values were used compared to the site average estimate K_{ed} values, except in the natural treatment where R^2 values are relatively high for both.

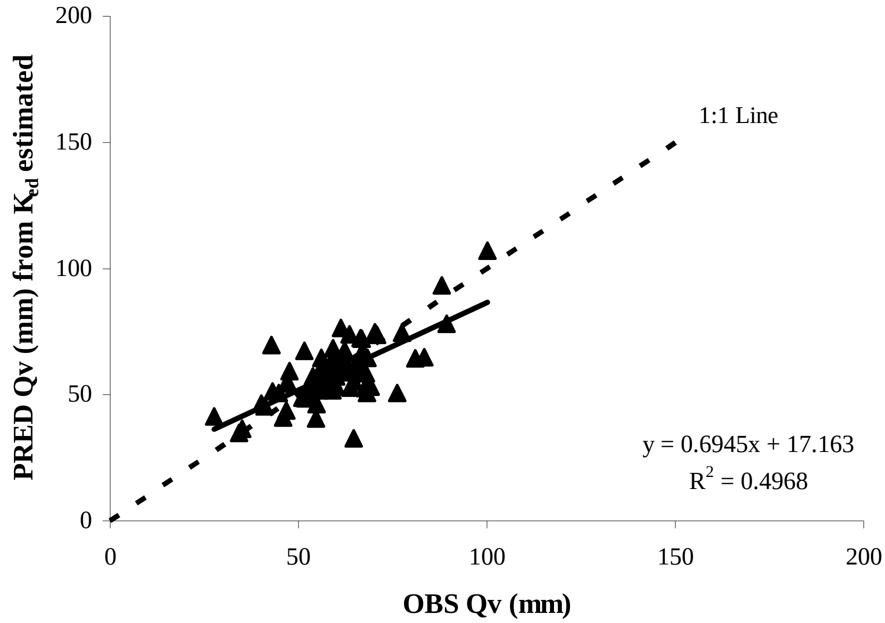


Figure 4.23. Model evaluation for runoff volume with individual plot K_{ed} values from parameter estimation.

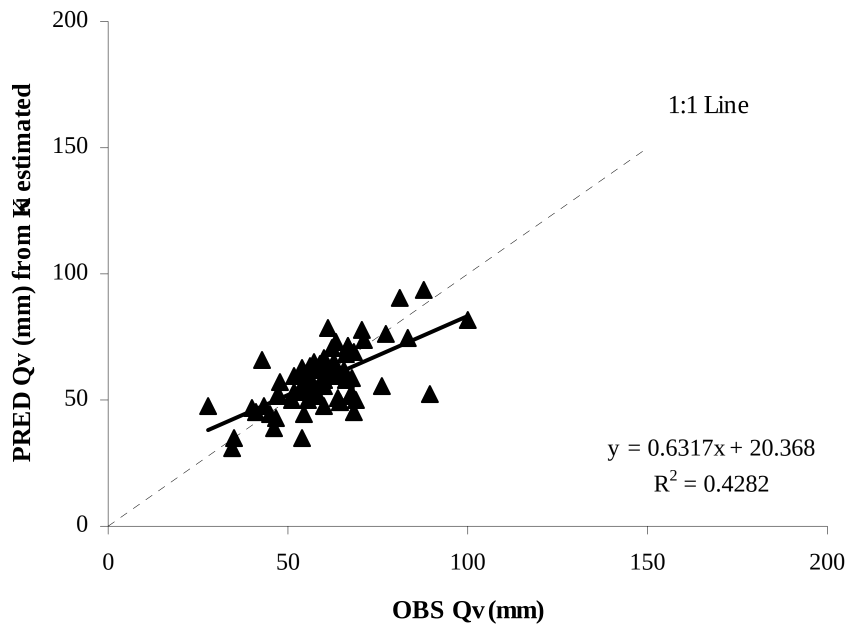


Figure 4.24. Model evaluation for runoff volume with site average K_{ed} values from parameter estimation.

Table 4.13. Model evaluation for peak discharge using the plot K_{ed} values found with optimization technique.

	K_{eb} (mm/hr)				K_{ed} (mm/hr)			
Treatment	**R^2**	**NS test**	**RMSE**	**SE**	**R^2**	**NS test**	**RMSE**	**SE**
All	0.84	0.46	14.35	3.12	0.59	0.33	16.01	3.27
Natural	0.84	0.51	16.61	7.09	0.82	0.76	11.59	6.74
Fire	0.59	-0.22	12.10	3.35	0.20	-2.00	18.96	3.91
Recovery	0.93	0.38	14.07	4.28	0.53	0.15	16.47	5.13

The units are mm/hr.

Table 4.14. Model evaluation for runoff volume using the site average optimized K_{ed} values.

	K_{ed} (mm/hr)			
Treatment	**R^2**	**NS test**	**RMSE**	**SE**
All	0.63	0.59	8.14	2.13
Natural	0.73	0.71	8.92	5.11
Fire	0.45	0.40	8.16	2.93
Recovery	0.59	0.47	7.45	2.92

The units are mm.

Table 4.15. Model evaluation for runoff volume using the K_{ed} values found with the parameter estimation equations. This was done for each plot first using the calculated estimation values for each plot and then with the site average values.

		K_{ed} (mm/hr)			
	Treatment	**R^2**	**NS test**	**RMSE**	**SE**
Individual Plot Values	All	0.50	0.41	9.70	2.13
	Natural	0.73	0.72	8.86	5.04
	Fire	0.40	0.34	8.57	3.09
	Recovery	0.24	-0.15	11.04	2.91
Site Average Values	All	0.43	0.32	10.45	2.11
	Natural	0.66	0.65	9.88	4.94
	Fire	0.12	-0.17	11.38	3.06
	Recovery	0.35	0.03	10.13	2.93

The units are mm.

Interrill Erodibility, Rill erodibility and critical shear stress

In order to evaluate the ability of the model to accurately predict soil loss, K_i, K_r and τ_c parameters had to be combined. This means that all three erosion parameters were used simultaneously to obtain total sediment yield. The first step was to use the identified K_i, K_r and τ_c values. The second step was to use the K_i, K_r and τ_c calculated with the parameter estimation equations. The predicted soil loss was compared to the observed soil loss from both the first and second steps (Figure 4.25 – 4.26). Goodness of fit statistics were first applied to all the results, comparing the observed and predicted values (Table 4.16). The results were then separated into natural, fire and recovery treatments to determine if stronger relationships were obtainable. Stronger correlations were obtained when identified parameters were used rather than the estimated parameter values. When the identified parameters were used the highest R^2 value, 0.59, was obtained when all the results were combined, prior to being separated into treatments. A high R^2 value was also obtained with the results from the fire treatment. In contrast, with the estimated parameters the fire treatment had the highest R^2 with a value of 0.37.

Table 4.16. Model evaluation for total sediment yields using both parameters found with optimization technique (identified parameters) and those parameters calculated with parameter estimation equations (estimated parameters).

	Identified Parameters				**Estimated Parameters**			
Treatment	**R^2**	**NS test**	**RMSE**	**SE**	**R^2**	**NS test**	**RMSE**	**SE**
All	0.59	0.62	0.38	0.10	0.01	-3.95	1.37	0.14
Natural	0.07	-0.45	0.29	0.22	0.05	-0.10	0.25	0.22
Fire	0.56	0.53	0.55	0.08	0.37	0.35	0.64	0.07
Recovery	0.09	-1.65	0.40	0.08	0.10	-126.76	2.75	0.20

The units are kg/m^2.

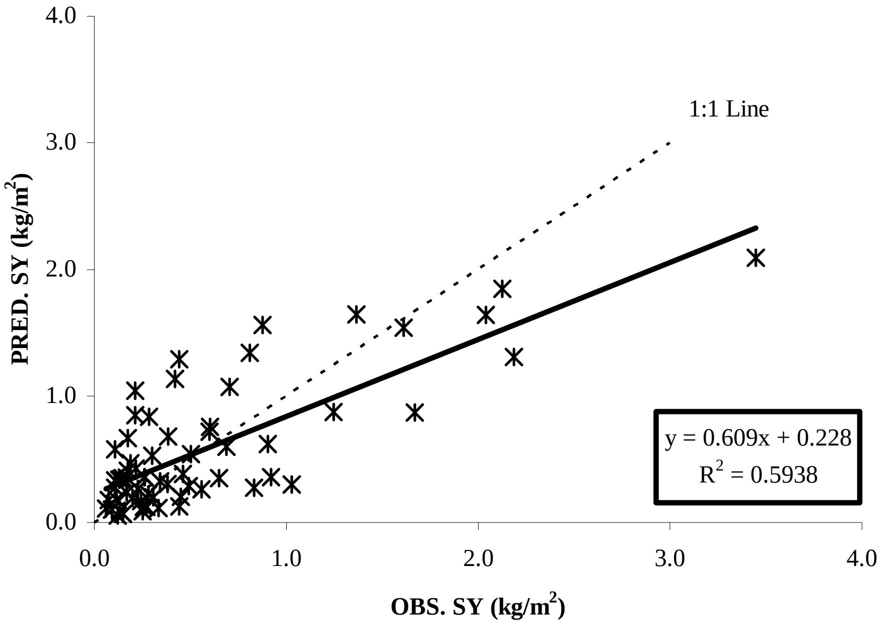


Figure 4.25. Results of model evaluation where observed and predicted sediment yield values are compared with identified erosion parameters.

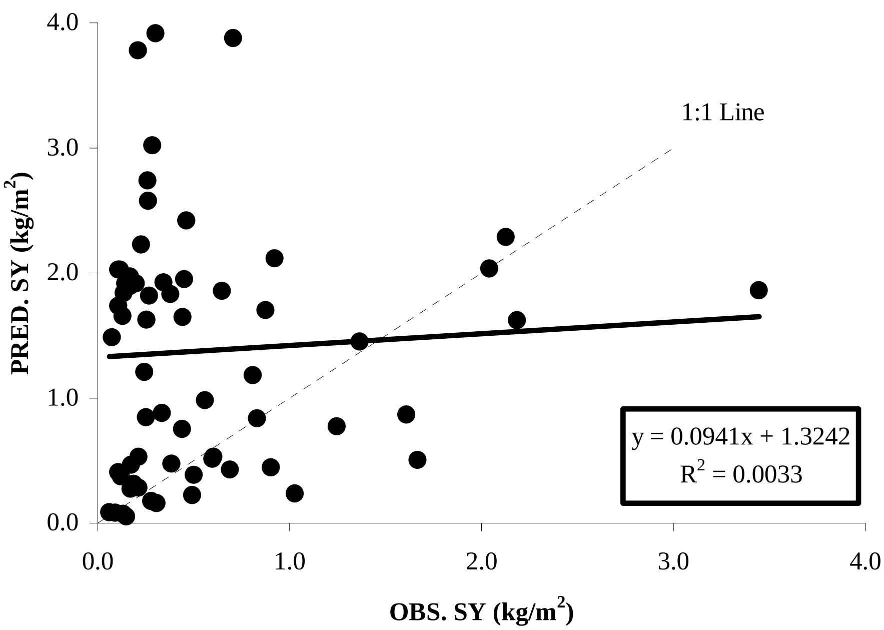


Figure 4.26. Results of model evaluation where observed and predicted sediment yield values are compared using parameters from estimation equations.

An additional evaluation was done to account for the natural variability in measured erosion data. This method was presented by Nearing (2000). This additional evaluation was done to compare observed versus predicted soil loss using estimated parameter values. A discussion and list of the steps were outlined in chapter two. Figure 4.27 presents a plot of the R_{diffs}, calculated with equation 2.10 versus measured soil loss. The final steps of the suggested model evaluation was to calculate a model effectiveness coefficient, *e* (Nearing, 2000). The *e* value calculated for all rainfall simulator sites and treatments was 0.63 at a 95% confidence interval. Figure 4.27 compares the R_{diffs} values calculated with equation 2.10 and the measured soil loss from the rainfall simulator experiments. R_{diffs} values are both positive and negative showing that the model tended to both over-predict (positive R_{diffs} values) and under-predict (negative R_{diffs} values) soil loss. However, the model tended to over-predict more than under-predict soil loss.

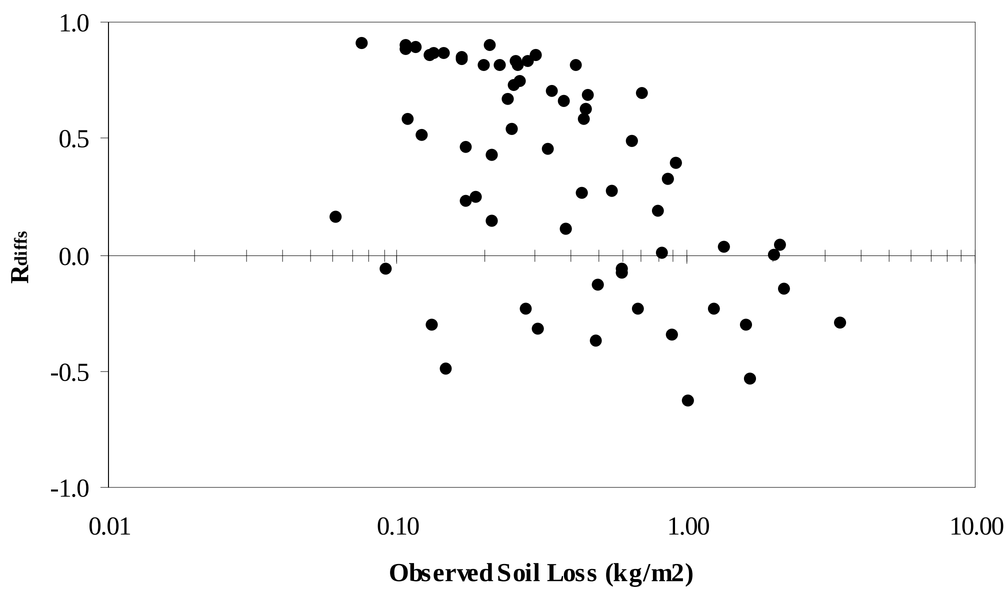


Figure 4.27. Comparison of observed soil loss to R_{diffs} calculated with equation 2.10.

CHAPTER 5

DISCUSSION

This chapter discusses the modeling results first. The objectives of this research include creating a database of parameter values, developing parameter estimation equations and completing a model evaluation. Therefore the results of these objectives will be discussed first. A discussion of the rainfall simulator results, as they relate to the objectives of this research, will follow the discussion of the modeling results.

5.1 Discussion of Model Results

5.1.1 Parameter Identification

Hydraulic Conductivity

The wildfires only caused a statistically significant decrease in K_e for the oak-woodlands. There was not a significant difference between the natural and fire K_e values for the grassland sites. This follows the research results that runoff did not significantly increase after a fire for semi-arid grasslands (Emmerich and Cox, 1992). It is assumed that the TF had an initially low K_e values as the soil at the site is a clay loam. The PC site did not show a significant difference in K_e values after the fire. However, the EM site did show a significant difference in K_e values after the fire (Table 4.7). This is assumed to be because the natural plots for these sites did not accurately represent the natural conditions for EM and PC.

This research showed that even two years post-fire, the AB and EM sites had not returned to natural conditions. There was a significant difference in K_e values for natural and second year post-fire treatments for the AB and PC site, indicating that these sites have not returned to natural conditions. Additional research is needed to determine when oak-woodland and grassland sites return to their natural K_e values.

Interrill Erodibility

Although runoff increased after a fire for the oak-woodland sites, the more drastic post-fire impact was on erosion. K_i values increased following fire, as expected (Pierson et al., 2001). The TF site had the greatest increase in K_i values after the fire (Figure 4.11). ANT also showed a large increase in K_i after the fire. AB and ER3 did not have a great difference between natural and fire treatments. There cannot be a comparison between natural and fire treatments for the EM and PC sites as data was not collected for those treatments.

There were both increases and decreases between K_i values for the first and second year post-fire treatment. For the AB site, K_i values increased the first year post-fire and were close to the average K_i values for the fire treatment of the two oak-woodland sites. The K_i values for the EM site decreased between the first and second year post-fire. On the other hand there was an increase in K_i values between first and second year post-fire for the PC site.

The differences in K_i values between the two types of vegetation were noteworthy (Figure 4.12). First, the grassland sites had a higher natural K_i value compared to the oak-woodland sites. Second, the grasslands had a more drastic increase in K_i compared to the oak-woodland. These results, in addition to the results of the comparison between large and small plots (Figure 4.5); indicate that interrill erosion could be the dominant erosion process for burned grassland sites.

Rill Erodibility and Critical Shear Stress

In comparison to the K_i results, where grasslands had the more drastic post-fire impact, the results of the K_r and τ_c parameter optimization showed that erosion processes on oak-woodlands were more impacted by fire (Figure 4.15 through 4.18). Both rill erosion parameters increased after the burn especially on the oak-woodland sites. Recovery values for K_r and τ_c approached zero for all sites. Figures 4.16 and 4.18 show that τ_c increased as K_r increased. However, according to Equation 2.4, if D_c is constant or near constant, then the variables K_r and τ_c are inversely related.

With the two parameter optimization technique it was difficult to determine K_r and τ_c values for all treatments other than the burned sites (Table 4.9). Sediment yield at different scales were compared in order to understand why this occurred (Figure 4.5). With the small and large plot comparison it is hypothesized that the reason for the difficulties in the parameter optimization technique were because rill erosion only occurred on the oak-woodland sites the year of the fire. Small and large plot data for the AB site the first year after the burn were also compared (Figure A1). Because the small and large plot data were the same it indicates that rill erosion did not occur on the oak-woodland site in the first year post-fire. The data in Figure 4.5 support observations in the field that rill erosion only occurred on oak-woodland sites the year of the fire.

A two parameter optimization routine was conducted as outlined by Nearing et al., (1989). The result of the two parameter optimization was a response surface of the least squares objective function. The response surface allowed the minimum of the objective function to be easily detected and the shape of the response surface gave an indication of the sensitivity of the model to the input parameters. As discussed in Nearing et al. (1989), an elongation of the response surface at the 45 degree angle to the axis indicated interdependence of the parameters. The most favorable response surface shape with regards to sensitivity and independence was circular. Figure 4.13a shows elongation at the 45 degree angle which indicated interdependence of K_r and τ_c. This interdependence was evident at even the narrow ranges of K_r and τ_c (Figure 4.13b-d). A response surface like the one shown in Figure 4.13 was obtained for all the burned sites and the oak-woodland natural sites. A circular response surface was not obtained. The other response surface obtained was shown in Figure 4.14; for these plots, rill erosion parameters were not obtainable. It is assumed that a response surface like the one in Figure 4.14 was obtained because rill processes were not active for those sites. There are two indications that there could be problems with the current model predicting post-fire erosion in semi-arid environments. First, no circular response surfaces were obtained. In addition, in some cases response surfaces with no minimum K_r and τ_c values were found.

A two parameter optimization for rill erosion parameters for fire conditions has never been done before. Nearing et al. (1989) conducted a two parameter optimization for rill erosion parameters using bare (bare, meaning vegetation was removed from the plot) plot data. The results from the Nearing et al. (1989) research were compared to this research to see if the bare plot data could be used to expand this research. Figure A5 shows the comparison of the fire treatment to the bare plots with the WEPP research. The results suggest that there was a difference in K_r and τ_c values between the two treatments so the WEPP bare plot data were not included in the analysis.

5.1.2 Parameter Estimation

Recommended parameter estimation equations were created for all four runoff and erosion parameters to estimate natural, fire and recovery parameters from known site characteristics. The equations in Tables 4.10 to 4.12 are the recommended parameter estimation equations to calculate runoff and erosion parameters.

Correlations between the input variables and the parameter values are shown in Tables A18 through A22. The values in bold font are those variables which were used in the parameter estimation equation. In most cases, the input variable with the strongest correlation to its parameter value was used in the parameter estimation equations. The input variable with the highest R^2 was not always used in the parameter estimation equation due to outliers, etc. as explained previously. Correlations between independent variables were also found. For example total rock cover, Rt, and intercanopy space rock cover, Rr, are highly interrelated especially on burned sites. These results were considered in determining the recommended parameter estimation equations.

Hydraulic Conductivity

Parameter estimation equations for K_{ed} are shown in Table 4.10. To re-iterate, equations were developed for both K_{eb} and K_{ed}; however, results were not significantly different between two types of K_e. Therefore K_{ed} will be referred to K_e throughout the rest of this text. The final input variables in the parameter estimation equations were distinctive for each treatment. For example the parameter estimation equations had distinct input variables for each of the fire treatments. The equation for the fire treatment on oak-woodlands had total litter cover as the input variables. These results follow the research done by Johansen et al. (2001b) that showed that runoff increased on burned plots generally correlated with ground cover removal. In the natural treatments, the ground cover characteristics were the principal components of the parameter estimation equations. The parameter estimation equations contained under canopy basal cover and undercanopy litter cover for the natural treatment on grasslands. On the other hand, the parameter estimation equations for the natural treatment on oak-woodlands contained under canopy litter cover and intercanopy space rock cover. In comparing the parameter estimation equations among treatments, the recovery treatment did not have a strong relationship. The reason for the lower R^2 value for the recovery treatment needs further research.

Listed below (equations 5.1 to 5.4) are the four recommended equations for calculating K_e for different treatments on semi-arid grassland and oak-woodlands. These equations are given in Table 4.10 with goodness of fit statistics.

The recommended parameter estimation equation to be used when calculating K_e (*mm/hr*) values from site characteristics for burned oak-woodlands is

$$K_e = 4.65 + 0.21Lt \qquad (5.1)$$

where *Lt* (*percent*) is total litter cover. There is not a recommended parameter estimation equation for burned grassland sites as there was not a significant difference between natural and fire treatments for grasslands. Therefore, equation 5.2 should be used for both burned and natural conditions in semi-arid grasslands.

$$K_e = -7.43 + 0.85Li + 2.30Bi \qquad (5.2)$$

where *Li* (*percent*) is under canopy litter cover and *Bi* (*percent*) is under canopy basal cover. Equation 5.3 is the recommended equation to calculate K_e values for natural conditions on semi-arid oak-woodland sites.

$$K_e = 13.82 + 0.29Li - 0.39Rr \qquad (5.3)$$

where *Li* (*percent*) is under canopy litter cover and *Rr* (*percent*) is intercanopy space rock cover. Equation 5.4 is the recommended equation to calculate K_e values for one to two years post-fire on semi-arid grassland and oak-woodland sites.

$$K_e = 26.25 - 0.07GAPc - 0.42Rr \qquad (5.4)$$

where *GAPc* (*cm*) is canopy gap and *Rr* (*percent*) is intercanopy space rock cover. It is not recommended to use equation 5.4 to calculate K_e values for more than two years post-fire. This is because this research does not have the data to support it. Research will be continued to determine how long it takes semi-arid grasslands and oak-woodlands to recover from fire and return to natural K_e values.

For the WEPP model, two equations were developed to estimate K_e based on rainfall simulator experiments from across the western United States (Alberts et al., 1995). If the intercanopy surface cover is less than 45% then the following input variables are used; cation exchange capacity of the soil, root biomass in the top 10 cm of the soil, intercanopy space basal cover and under canopy litter cover. If the intercanopy surface cover is greater than 45% the following input variables are used; percent sand, fraction organic matter, random roughness, undercanopy litter cover, root biomass in top 10 cm of the soil and under canopy basal cover. In comparison to results from this research, the under canopy litter cover variable was one of the variables in the equations for both the natural treatments on both grassland and oak-woodlands. In addition, the under canopy basal cover in the WEPP equations was an input variable for determining K_e values for the natural treatment in grasslands. The parameter estimation equations in the WEPP documentation were applied to the data from this research. When the estimated parameter values from the WEPP equations were compared to the optimized K_e values from this research an R^2 of 0.004 was obtained (Figure A3). It is assumed that a low R^2 was obtained because of limited variability among the sites vegetation and soil physical characteristics. This research did not have the wide variation in geographic area as the WEPP study did.

Interrill Erodibility

Slope was an input variable in the parameter estimation equations for K_i because it was highly correlated to K_i values (Figure A2). However gap measurements were not included as possible input variables for K_i parameter estimation equations as gap measurements were not taken on small plots.

Unlike the K_e equations, stronger relationships were obtained when the treatments were not separated by vegetation type. This was especially true with the natural treatments, therefore parameter estimation equations were not created for these treatments. Total ground cover and slope were the two parameters used in both the fire and natural treatment equations. That post-fire erosion was highly correlated with decreases in total ground cover which follows the research done by Roundy et al. (1978) and Johansen et al. (2001b). Pierson et al. (2001) also concluded that increased rates of interrill erosion after a fire were correlated to decrease litter cover.

Listed below (Equations 5.5 to 5.6) are the recommended equations for calculating K_i ($kg\text{-}s/m^4$) values for natural, fire and recovery treatments. These are as found in Table 4.11, which also gives the goodness-of-fit statistics.

Equation 5.5 is the recommended equation for calculating burned K_i ($kg\text{-}s/m^4$) values for semi-arid grasslands and oak-woodlands.

$$\ln(K_i) = 9.41 - 0.02Gt + 1.54 ln(S_o) \qquad (5.5)$$

where Gt (*percent*) is total ground cover and $ln\ (S_o)$ (*percent*) is the natural log of the slope. Equation 5.6 is the recommended equation for calculating natural K_i values for semi-arid grasslands and oak-woodlands.

$$\ln(K_i) = 13.00 + 0.72\ ln(S_o) - 0.06Gt \qquad (5.6)$$

where $ln(S_o)$ (*percent*) is the natural log of the slope and Gt (*percent*)is the total ground cover. There is not a recommendation for calculating K_i values for recovery period because the RMSE of the recovery parameter estimation equation was too high (Table 4.11).

The equations to estimate K_i values in the WEPP project used under canopy ground cover and canopy cover. With WEPP there was also an equation for estimating baseline K_i values. The variables used for calculating baseline K_i were percent sand, fraction of organic matter and the volumetric water content. However, physical soil properties of the sites were not used to create parameter estimation equations for this research because there was limited variability in surface soils between sites. This was also the reason for such a low R^2 value when comparing the estimated K_i values from the WEPP parameter estimation equations to the identified K_i values (Figure A4).

Rill erodibility and critical shear stress

Rill erosion parameter equations were only determined for the fire treatment in oak-woodlands where rill erosion is observed. Equations 5.7 and 5.8 are the recommended equations for calculating post-fire K_r and τ_c values on semi-arid oak-woodlands. These are found in Table 4.12 which also gives the goodness-of-fit statistics.

$$K_r = 0.01 - 0.0003Rt \qquad (5.7)$$

$$\log_{10}(\tau_c) = 5.53 - 0.13Gt \qquad (5.8)$$

where *Rt* (*percent*)is total rock cover and *Gt* (*percent*)is total ground cover.

The input variable for the K_r equations was total rock cover. For τ_c the input variable was total ground cover. This suggests that for determining rill erosion ground cover characteristics are important (Roundy et al., 1978 and Johansen et al., 2001b). The

WEPP equation for estimating K_r used the following input variables: soil clay content, organic matter content, dry soil bulk density and root biomass in the top 10 cm of the soil surface. The τ_c WEPP equation included percent sand, organic matter content and dry soil bulk density. Physical soil properties of the sites were not used to create parameter estimation equations for K_r and τ_c because there was limited variability in surface soils between the sites.

5.1.3 Model Evaluation

Hydraulic Conductivity

A model evaluation of runoff volume was completed testing the site average optimized K_e values. The estimated K_e values were tested as well; both the individual plot estimated K_e values as well as the site average estimated K_e values. In addition, the model was evaluated based on its prediction of peak discharge using the individual plot K_e values optimized for runoff volume (Table 4.13 and Figure 4.21).

The results of the model evaluation for peak discharge showed that there was a difference between using the two different K_e values. A stronger relationship was achieved when K_{eb} was used (0.8367). This was because of the different model inputs into the rainfall files used during the parameter optimization. For the K_{eb} rainfall file the exact hyetograph of the rainfall was given. With the K_{ed} rainfall file the model used inputs to predict a rainfall hyetograph. With a more accurate rainfall file, as with the K_{eb} storm file, the model predicted the runoff hydrograph better and therefore the model predicted peak discharge was closer to the observed peak discharge from the rainfall simulator experiment.

The model evaluation for runoff volume used a site average K_{ed} value found with averaging the K_{ed} values from the optimization routine that was completed on each plot. The result was that the model did a relatively good job of predicting the runoff volume, with an R^2 of 0.63.

A model evaluation was also completed using the estimated K_{ed} values found from the parameter estimation equations. There was a stronger relationship when the estimated K_{ed} values of the individual plots were used compared to the site average estimated K_{ed} values. There was a stronger relationship when the estimated K_{ed} values for the natural treatment were used. The model output was not as accurate with the estimated parameters for predicting the fire and recovery treatmtents.

In comparing the results of the model evaluation using the optimized versus estimated K_{ed} values, R^2 values for the model evaluation on the natural treatment were the same (Table 4.14 and 4.15). However, the standard error values were relatively high (5.11) when the optimized K_{ed} values were used compared to 5.04 with the estimated K_{ed} values.

With WEPP a model evaluation was done using the K_e parameter values calculated with the parameter estimation equations. The results of the model evaluation were an R^2 value of 0.63. In comparison, the R^2 values were lower for model evaluation using the parameter estimation equations developed in this research.

Interrill Erodibility, Rill Erodibility and Critical Shear Stress

The fact that the identified parameters did the better job of modeling sediment yield compared to the estimated parameters (Table 4.16) was not surprising. However, what was not expected was how poorly the relationship were for using both identified and estimated parameter values. The treatment with the highest R^2 was the fire, but this was anticipated as only optimized K_r values were used for this treatment.

In Nearing et al. (1989), the observed results were matched with the model predicted values for the two parameter optimization. High R^2 values of approximately 0.95 were found. A lower R^2 value, compared to the results from Nearing et al. (1989), was to be expected. This was because Nearing et al. (1989) compared simulated and observed steady state sediment yield values. In this study, the model evaluation for sediment yield was completed using the total event sediment yield.

The reason for the poor relationships in predicting total sediment yield is discussed below. For some plots K_i values were too high in order to get a response surface in which optimum K_r and τ_c values could be obtained, which caused a problem in assessing the model ability to predict erosion. The small plots were not a direct replicate of an individual large plot, therefore the calculated site average K_i value was used. This may have caused the interrill erosion values to be inaccurately represented. If the K_i values were too high than there was not enough transport for sediment detachment in the rill and therefore it was difficult to obtain rill erosion parameter values.

The results from the evaluation using Nearing (2000) on RHEM gave a model effectiveness coefficient of 0.63 using a 95% confidence interval. The Nearing (2000) model evaluation was used on USLE data (Risse et al., 1993) and WEPP data (Zhang et al., 1996). The model effectiveness coefficient, *e*, for the USLE data was 0.56 and 0.66 for the WEPP model. Therefore, the RHEM model is comparable to USLE and WEPP in its ability to accurately predict erosion.

5.2 Discussion of Rainfall Simulator Results

Rainfall simulator experiments were applied to three treatments; natural, fire and recovery. It should be noted that because this research looked at the effects of wildfire, the natural treatment was not the pre-fire condition, rather a site for the natural treatment was chosen based on similar characteristics to the burned sites. The fire treatment was simulated on for multiple years post-fire to look at the effects of runoff and erosion with the recovery treatment. The natural treatment sites were only simulated on once. It was assumed that the hydrology and erosion of the natural sites did not vary with time based on research from Goodrich (1990).

5.2.1 Runoff Results

There was a significant increase in runoff after the burn for the oak-woodland sites which concurred with other research (Johansen et al., 2001a). However, there was not a significant increase in runoff after the burn for the grassland sites which concurs with Emmerich and Cox (1992). This is reflected in the modeling results, where there was a significant decrease in K_{ed} values for oak-woodland sites only (Table 4.8).

Table 4.1 shows that there was a significant difference between natural and fire treatments for the AB and PC sites only. The other rainfall simulator sites did not show significant difference at the 95% confidence level. In the modeling results, the AB site showed a significant decrease in K_{ed} values between the natural and fire treatments. However the PC site did not. Table A5 shows the standard deviation and the average K_{ed} value for each rainfall simulator site and treatment. The PC site had a high standard deviation for its natural treatment. However there was a significant difference in K_{ed} values for the EM site, but the EM site did not show significant differences between treatments in the observed runoff results. This could be attributed to the fact that for the EM and PC sites, natural plots were located at the Walnut Gulch watershed in Tombstone, AZ. These natural plots may not have been a good representation of the natural conditions for those sites.

The ANT and ER3 sites did not show a significant increase in runoff after the burn, which may be attributed to the fact these sites were grazed prior to the burn. The TF also did not show a significant increase in runoff after the burn which is hypothesized to be due to the fact that it is a clay loam soil, while the other soils are sandy soils. This is also true of the modeling results. There was not a significant difference in K_{ed} values for the ANT, ER3 and TF sites.

With the first year post-fire treatment there was a significant increase in runoff for the AB and PC sites only. For the same treatments, there was a significant decrease in K_{ed} values for the AB and PC sites as well. A significant difference in runoff and K_{ed} values between the first and second year post-fire was not detected for any of the other sites, excluding AB and PC. There was a significant difference between natural and second year post-fire treatments for the AB and PC sites indicating that these sites have not yet returned to natural conditions.

5.2.2 Erosion Results

Although there was a significant increase in runoff for two rainfall simulator sites after the burn, the more drastic post-fire impact was in the sediment yield results. There was a significant increase in sediment yield after the burn. This follows the research by Johansen et al., (2001a) and Roundy et al., (1998).

Comparing the erosion results between vegetation types, the more drastic increase in erosion, immediately after the fire, occurred in the oak-woodlands (Figure 4.3). This follows the modeling results where rill erosion only occurred on the oak-woodland sites; in addition interrill erosion parameter values were highest on the grassland sites after the burn.

The grasslands and oak-woodlands appeared to take two years to return to natural erosion rates (Table 4.4). Research done on shrublands in Spain by Soto and Diaz-Fierros (1998) also found that erosion was not significantly different from the control plots after two years post-fire. The AB, PC and EM sites seemed to return to natural erosion rates two years after the fire; there was not a significant difference between natural and two year post-fire sediment yield values for these sites.

Two plot scales of data were collected with the rainfall simulator experiments. This means that erosion rates could be compared to look at how distinct erosion processes occurred not only between vegetation types but also between plot scales. The two plot scales were also used to explain the modeling results. Figure 4.5 contains four graphs which were separated by vegetation type and treatment. Starting with the oak-woodland natural (Figure 4.5c) there was not much sediment loss and no scale dependency as both large and small plots had about the same SY. This was why rill erosion parameters were difficult to obtain on the oak-woodland sites prior to the burn. On the other hand the grassland natural (Figure 4.5d) showed that although the sediment loss was still low there was a difference between scales. The small plots had a greater SY than the large plots. This was probably due to detachment of sediment from raindrop impact being the dominant process and on the larger scale the detached soil was deposited. This was also shown in the modeling results; rill erosion parameters values were not obtainable and K_i values were higher for the natural treatment on the grassland sites. The oak-woodland burned sites (Figure 4.5a) showed substantial sediment loss and a large difference due to scale. There was more sediment lost on the large plots compared to the small plots. This was attributed to where rill erosion was occurring, because the large plots had larger sediment yield values compared to small plots. This was also shown in the modeling results where rill erosion results were obtainable for all oak-woodland sites after the burn. Finally, the grassland burned sites (Figure 4.5b) showed high rates of SY but no scale dependency. For this comparison, as both scales showed about the same amount sediment yield, there was deposition occurring at the large plot scale, which probably means rill erosion was not occurring. This was why rill erosion parameters were difficult to obtain for the grassland sites after the burn. In order to confirm the assumptions stated here more research is needed.

In the literature review of this paper three references were cited for scale dependent erosion responses; Davenport et al. (1998), Wilcox et al. (2003) and Reid et al. (1999). These three papers emphasized how patches of bare soil are highly correlated with erosion rates; for example, erosion at the hillslope scale was much less than on the patch scale because of storage occurring at the hillslope scale. This prediction can be supported by the results of the small and large plot comparison for the grassland natural treatment (Figure 4.5d), where there was less erosion on the large plots because deposition/storage was occurring.

In addition, the three papers suggested a greater number of connected bare soil patches yielded more erosion. This too corresponds to the results of the large and small plot comparison here. A fire causes a loss of vegetation and hence bare soil patches become more connected. The small and large comparison for the grassland sites after the burn, (Figure 4.5b), showed that the small plot erosion equaled the large plot erosion. Therefore after the fire the bare patches on the large plot increased, because of this there was a decrease in soil deposition/storage on the large plots and erosion rates were equal to those of the small plots.

The suggestions by Davenport et al. (1998), Wilcox et al. (2003) and Reid et al. (1999) also relate to the results of the small and large plot comparison for the burned and natural oak-woodland sites found here. For the oak-woodland natural treatment, (Figure 4.5c), the small and large plot erosion was equal. This indicates that there were more connected patches of bare soil and hence less storage on the large plots for the oak-woodland natural sites compared to the grassland natural sites. This agrees with results here since the grassland natural sites had more homogeneous cover compared to the oak-woodland natural sites. The fire increased the amount of connected patches of bare soil on the oak-woodland sites, as it did on the grassland sites. The small and large plot comparison for the oak-woodland sites after the burn, (Figure 4.5a), showed that erosion was greater on the large plots compared to the small plots. This again emphasizes the result that after a fire there is a decrease in storage from the natural conditions that could possibly be due to an increase in the connectedness of bare soil patches as suggested by Davenport et al. (1998), Wilcox et al. (2003) and Reid et al. (1999).

5.2.3 Rainfall Simulator Measurements

Rainfall simulator measurements (canopy cover, ground cover and slope) were compared to observed normalized sediment yield values (Figure 4.6 to 4.7). Figure 4.6 shows that as canopy cover increases normalized sediment yield decreases. This follows research of Roundy et al. (1978) and Ueckert et al. (1978). These results show that there is a correlation between the removal of canopy cover due to fire and an increase in post-fire sediment yield. However there was not as strong of a relationship between sediment yield and percent ground cover (Figure 4.7). If Figure 4.7 was separated by treatments rather than by sites a better correlation may be found between normalized sediment yield and percent ground cover.

The erosion parameter estimation equations all contained ground cover characteristics. The results of the model evaluation shows that the estimated parameter values did a poor job of predicting total sediment yield values. Obviously the parameter estimation equations developed with this research do not incorporate all the variables needed to accurately predict total sediment yield. Previous WEPP research developed erosion parameter estimation equations using ground cover and soil physical characteristics as variables in the parameter estimation equations. This research did not incorporate physical soil characteristics as variables into the erosion parameter estimation equations due to the lack of variability between the rainfall simulator site soils.

Figure 4.8 shows the relationship between normalized sediment yield and slope for each rainfall simulator site. As shown the TF site had sediment yield values comparable to the oak-woodland sites. This is attributed to the fact that the slopes at the TF were larger than any other site. This is why the sediment yield values throughout this paper were normalized for slope. The TF site had the larger slopes and had the highest K_i values. A strong relationship was detected between K_i values and slope (Figure A2). For these reasons slope was included into the K_i parameter estimation equations.

In order to compare this research to other post-fire research in semi-arid areas the results of this research were combined with results of other research compiled by Johansen et al. (2001a) (Table 5.1). Figure 5.1 is a comparison between sediment yield and percent bare soil for the research results compiled in Table 5.1. Only the large plot data from Table 5.1 was used for Figure 5.1. This was done in order to ensure that similar erosion processes were occurring among the different research sites. The trend in

Figure 5.1 is that as percent bare soil increases, sediment yield increases. Percent bare soil is calculated as shown in equation 5.9.

$$100\% - \%\text{Total Ground Cover} = \%\text{Bare Soil} \qquad (5.9)$$

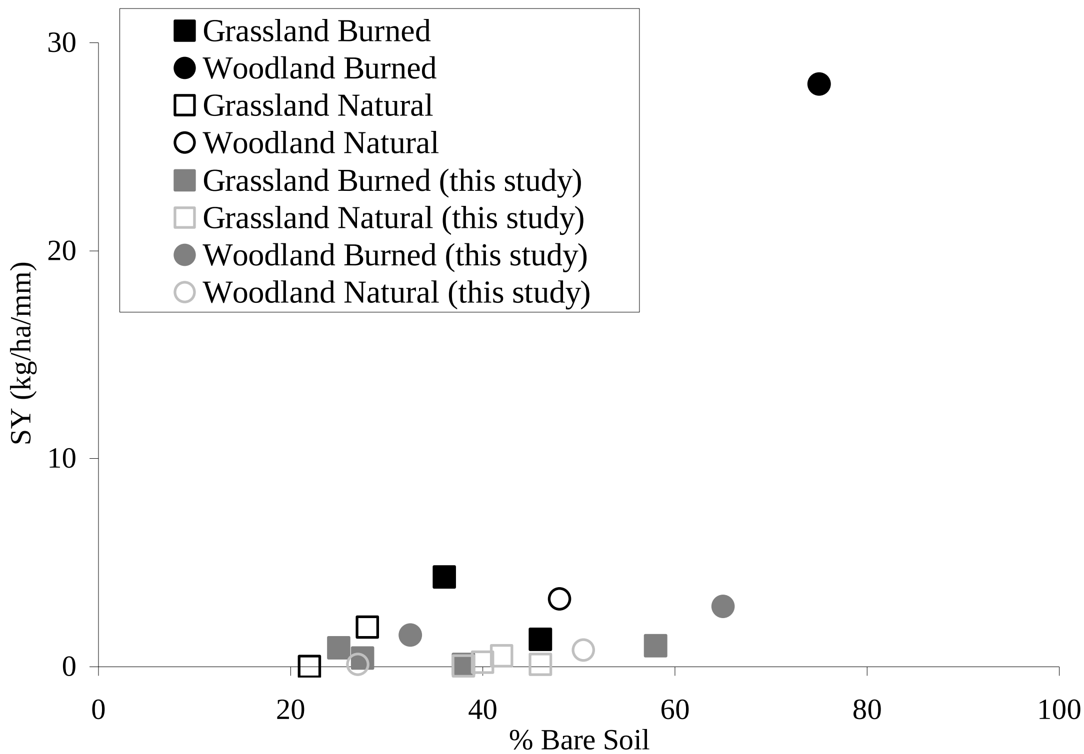


Figure 5.1. Sediment yield versus percent bare soil for combined post-fire research in semi-arid environments.

Table 5.1. The combined results of post-fire research in semi-arid areas using a rainfall rate. Created in collaboration with work conducted by Johansen et al. (2001a).

REFERENCE	LOCATION	VEGETATION	RAINFALL	SOILS	SLOPES	PLOT SIZE	SY (kg ha^{-1} mm^{-1})		BARE SOIL (%)	
							Burned	**Unburned**	**Burned**	**Unburned**
Emmerich & Cox 1992	Arizona (Santa Rita)	Grassland	RF Sim (55 & 110 mm/hr)	Gravelly Loam	5 - 6 %	3.05 x 10.66m	0.4 - 0.6	0.3 - 0.4	--	--
Emmerich & Cox 1992	Arizona (Empire)	Grassland	RF Sim (55 & 110 mm/hr)	Gravelly Sandy Loam	5 - 7 %	3.05 x 10.66m	1.6 - 4.2	1.3 - 2.4	--	--
Hester et al. 1997	Texas	Woodland	RF Sim (203 mm/hr)	Clayey	4%	0.5 m^2	22.2	0.01	100%	0%
Hester et al. 1997	Texas	Grassland	RF Sim (203 mm/hr)	Clayey	4%	0.5 m^2	22. 0	1.5	100%	32%
Johansen et al. 2001a	New Mexico	Woodland	RF Sim (60 mm/hr)	Loam	4.5 - 7 %	3 x 10.7 m	28.2 - 113.3	2.3 - 4.2	69 - 80%	38 - 58%
Johansen et al. 2001b	New Mexico (RFETS)	Grassland	RF Sim (60 mm/hr)	Clayey	9%	3 x 10.7 m	4.3	1.9	36%	28%
Johansen et al. 2001b	New Mexico (WIPP)	Grassland	RF Sim (60 mm/hr)	Sandy	9%	3 x 10.7 m	1.3	0	46%	22%
Knight et al. 1983	Texas	Shrubland	RF Sim (203 mm/hr)	Sandy Loam	--	0.4 m^2	6	7.1	16%	19%
Knight et al. 1983	Texas	Shrubland	RF Sim (203 mm/hr)	Clay Loam	--	0.4 m^2	12.7	19.2	12%	11%
Pierson et al. 2001	Nevada	Grassland	RF Sim (85 mm/hr)	Sandy	35 - 40%	0.5 m^2	0.4	0.12	99%	6%
Roundy et al. 1978	Utah	Woodland	Infiltrometer (84 mm/hr)	Coarse Loamy, mixed	5 - 8%	0.83 m^2	4.0 - 9.7	1.6 - 3.3	19 - 80%	1 - 17%

Tabel 5.1 Continued.

REFERENCE	LOCATION	VEGETATION	RAINFALL	SOILS	SLOPES	PLOT SIZE	SY (kg ha^{-1} mm^{-1})		BARE SOIL (%)	
							Burned	**Unburned**	**Burned**	**Unburned**
This Study	Arizona (AB)	Woodland	RF Sim (63.7 - 180 mm/hr)	Sandy Loam	8 - 14%	2 x 6 m	1.5	0.1	14 - 50%	16 - 38%
This Study	Arizona (ANT)	Woodland	RF Sim (63.7 - 180 mm/hr)	Sandy Loam	13 - 19%	2 x 6 m	2.9	0.8	52 - 78%	36 - 65%
This Study	Arizona (ER3)	Grassland	RF Sim (63.7 - 180 mm/hr)	Sandy Loam	11 - 16%	2 x 6 m	1.0	0.5	56 - 60%	38 - 47%
This Study	Arizona (EM)	Grassland	RF Sim (63.7 - 180 mm/hr)	Sandy Loam	12 - 15%	2 x 6 m	0.9	0.2	23 -26%	36 - 45%
This Study	Arizona (PC)	Grassland	RF Sim (63.7 - 180 mm/hr)	Sandy Loam	8 - 9%	2 x 6 m	0.4	0.02	18 - 37%	36 - 39%
This Study	Arizona (TF)	Grassland	RF Sim (63.7 - 180 mm/hr)	Clay Loam	20 - 30%	2 x 6 m	0.1	0.1	33 - 44%	45 - 47%

Rainfall: RF Sim = rainfall simulator used. Natural = natural rainfall used

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

The objectives of this research were as follows: (1) To parameterize WEPP runoff and erosion parameters for different soil vegetation complexes for both pre and post fire conditions over several years; (2) Create parameter estimation equations for users to determine runoff and erosion parameters based on vegetation and ground cover characteristics; and (3) Evaluate performance of WEPP on post-fire environments.

These objectives were met by using data from an experiment which used a variable intensity rainfall simulator on three treatments: burned, natural and recovery. The measured runoff and erosion rates and amounts were used to parameterize the effective hydraulic conductivity term of the infiltration model and the interrrill, rill, and critical shear parameters of the steady state erosion equation. The identified parameters were then correlated with site vegetation and soil surface characteristics to develop parameter estimation equations. Finally, an evaluation was done of the model performance in simulating runoff and erosion using both identified and estimated parameters.

The combination of the modeling and rainfall simulator results has addressed some of the research gaps in understanding post-fire runoff and erosion.

The rainfall simulator results showed:

1. Runoff significantly increased immediately after the fire for the oak-woodland sites, but not in the grassland sites.

2. Sediment yield significantly increased immediately after the fire for all sites, this was especially true of the oak-woodland sites.

3. Runoff increased significantly in the first year post-fire for the AB and PC sites only.

4. There was a no significant difference between natural and second year post-fire sediment yield values. This means that sediment yield returned to natural values after two years post-fire for all sites; however runoff did not.

The two plot scale comparisons showed:

1. Deposition was occurring on the large plots at the grassland sites immediately after the fire, signifying that the grassland sites were at a threshold between raindrop and runoff detachment.

2. Rill erosion only seemed to occur on the oak-woodland sites immediately after the fire.

The parameter identification showed:

1. K_e values significantly decreased after the fire for the oak-woodland sites.

2. K_e values significantly decreased in the first year post-fire for oak-woodland sites.

3. K_i values significantly increased after the fire when both vegetation types were combined.

4. Rill erosion parameters significantly increased after the fire for oak-woodland sites

The parameter estimation showed:

1. Recommended K_e parameter estimation equations only needed to be established for both the natural and burned treatments for oak-woodland sites.

2. K_i parameter estimation equations established for burned and natural treatments could be applied to both vegetation types.

3. The recommended parameter estimation equations from the WEPP project did not work well with this research because there was limited variability of surface soil properties among sites.

The model evaluation showed:

1. The model did a better job of predicting runoff compared to predicting erosion, especially if identified parameter values were used.

2. The model was poor at predicting erosion using both the identified and estimated parameters from this research.

3. When the natural variability of soil erosion was accounted for by the procedure outlined in Nearing et al. (2000), the RHEM did a good job at predicting erosion compared to the USLE and WEPP.

Research results are informative to not only future WEPP users but also to fire managers. One implications of this research to future model users is that a database of parameter values has been established to use when operating WEPP for post-fire, and subsequent recovery, runoff and erosion in semi-arid grasslands and oak-woodlands. This could increase the accuracy of predictions by model users for southeastern Arizona rangelands. Additionally, this research has shown that the current WEPP model may not be proficient at accurately predicting erosion processes in semi-arid ecosystems. One implication of this research to future fire managers is that although runoff and erosion increase after a fire, the critical issue is how drastically erosion increases especially in the oak-woodland sites. Furthermore, first and second year post-fire are also important to monitor and manage because some data showed that runoff could increase during this time.

With this research we now have a better understanding of impacts of fire on semi-arid grasslands and oak-woodland ecosystems in southeastern Arizona; as well as recovery of runoff and erosion rates after the fire. In addition better modeling tools have been established such as a database of parameter values and parameter estimation equations. Finally, two plot scales were used to show how different erosion processes are important in modeling post-fire runoff and erosion rates.

6.2 Recommendations for Future Research

Although research objectives were met, questions have been raised throughout the process of achieving those objectives that provide some insight as to future work that can be done to improve this study and/or lead to new insights to the hydrologic effects of burning on rangelands.

1. Continue experiments to examine the long-term post-fire recovery identifying when the sites completely return to natural conditions.
2. Incorporate soil physical characteristics into the parameter estimation equations. This could involve adding to the current measurements taken with the rainfall simulator experiment.
3. Apply the parameter values and/or parameter estimation equations and rerun the model for other burned and recovering semi-arid grassland and oak-woodland areas to evaluate effectiveness of research results.
4. The small versus large plot comparison (Figure 4.5) showed that different erosion processes were occurring between grassland and oak-woodland sites. More research could be conducted to determine how the spatial vegetation patterns and/or surface soil characteristics affected the outcome.
5. Although grazing was not a primary focus of this research, it was noted that grazing could have had an impact on the runoff and erosion response after the fire. This may be for the following reasons; grazing removes vegetation cover (allowing more soil to be exposed to raindrop impact and reduces heat intensity upon burning) and causes compaction of the soil surface (more runoff could occur). The data collected with the rainfall simulator experiments could be part of a future research project to look at the combined effects of grazing and wildfire on runoff and erosion.
6. Apply additional research to Table 5.1 to expand the literature review of how sediment yield compares to percent bare soil in semi-arid rangelands.
7. Incorporate an analysis that quantifies how fire intensity effects runoff/erosion results

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ABBREVIATIONS AND SYMBOLS

NAME	DESCRIPTION	UNITS	DIMENSIONS
AB	Abar Site		
ANT	Antonio Site		
ANTN	Antonio Natural Site		
AZ	Arizona		
BAER	Burned Area Emergency Response		
BLM	Bureau of Land Management		
CLU	Clay Loam Upland		
CN	Curve Number	--	--
EM	East Mesa Site		
ER3	Empire 3 Site		
ER3N	Empire 3 Natural Site		
ERMiT	Erosion Risk Management Tool		
ES	Ecological Sites		
GIS	Geographic Information System		
HEM	Hillslope Erosion Model		
K	Kendalls Site		
LiS	Limey Slopes		
LS	Loamy Slopes		
LU	Loamy Upland		
NA	Not Available		
NRCS	Natural Resource Conservation Service		
PC	Post Canyon Site		
RHEM	Rangeland Hillslope Erosion Model		
RUSLE	Revised USLE		
TF	Tank Fire Site		
TFN	Tank Fire Natural Site		
TRR	The Research Ranch		
USDA	United States Department of Agriculture		
USFS	United States Forest Service		
USLE	Universal Soil Loss Equation		
WEPP	Water Erosion Prediction Project		
WGRS	Walnut Gulch Rainfall Simulator		
A	Area	m^2	*A*
A	Ash Cover	%	--
B	Basal Cover	%	--
*Bi**	Under Canopy Basal Cover	%	--
C	Chezy Coefficient	$m^{0.5} s^{-1}$	*l/t*
C	Canopy Cover	%	--
Dc	Detachment Capacity	$kg/s/m^2$	*m/t/A*
Df	Rill Erosion Rate	$kg/s/m^2$	*m/t/A*
Di	Interrill Sediment Delivery	$kg/s/m^2$	*m/t/A*
e	Model Effectiveness Coefficient	--	--
E	Nash Sutcliffe Efficiency	--	--

NAME	DESCRIPTION	UNITS	DIMENSIONS
f	infiltration rate	*mm/hr*	*l/t*
F	Accumulated Infiltration Depth	*mm*	*l*
F	Forb	*%*	--
G	Sediment Load	*kg/s/m*	*m/t/l*
G	Ground Cover	*%*	--
GAPb	Basal GAP Cover	*%*	--
*GAPc**	Canopy GAP Cover	*%*	--
Gs	Grass	*%*	--
*Gt**	Total Ground Cover	*%*	--
h	Depth of Flow	*m*	*l*
i	Under Canopy	*%*	--
I_e	Effective Rainfall Intensity	*m/s*	*l/t*
i_p	Ratio of rainfall intensity/average intensity	*mm/hr*	*l/t*
K_e	Effective Hydraulic Conductivity	*mm/hr*	*l/t*
K_{eb}	Breakpoint K_e	*mm/hr*	*l/t*
K_{ed}	Disaggregated K_e	*mm/hr*	*l/t*
K_i	Interrill Erodibility	$kg\text{-}s/m^4$	*m-t/A*
K_r	Rill Erodibility	*s/m*	*t/l*
L	Litter Cover	*%*	--
*Li**	Under Canopy Litter Cover	*%*	--
ln	Natural Logarithm	--	--
*ln(So)**	Natural Logarithm of Slope	*%*	--
*Lt**	Total Litter Cover	*%*	--
m	Depth Discharge Exponent	--	--
M	Measured Erosion	*T/ha*	*m/A*
N	Number of Paired Observations	--	--
Ns	Effective Matric Potential	*mm*	*l*
NS test	Nash-Sutcliffe test	--	--
O	Observed Values	*T/ha*	*m/A*
P	Rainfall Amount	*mm*	*l*
Q	Runoff	*mm*	*l*
q	Runoff Discharge	*mm/hr*	*l/t*
q_s	Sediment Discharge Rate	*kg/s*	*m/t*
R	Rock Cover	*%*	--
r	Intercanopy Space	*%*	--
R^2	Square Root	--	--
R_{diff}	Relative Difference	--	--
$R_{diffocc}$	Relative Difference between occurrence intervals	--	--
R_{diffs}	Relative Difference between M and P	--	--

NAME	DESCRIPTION	UNITS	DIMENSIONS
RMSE	Root Mean Square Error	--	--
*Rr**	Intercanopy Space Rock Cover	*%*	--
Rs	Spacing of Rills	*m*	*l*
*Rt**	Total Rock Cover	*%*	--
S	Shrub	*%*	--
SE	Standard Error	--	--
So	Slope	--	--
SY	Sediment Yield	*T/ha*	*m/A*
t	Time	*hr*	*t*
t	Total (in conjuction with vegetation characteristics)	*%*	--
Tc	Sediment Transport Capacity	*kg/s/m*	*m/t/l*
t_p	Ratio of time rainfall peak/rainfall duration	*hr*	*t*
w	Rill Width	*m*	*l*
x	Distance Downslope	*m*	*l*
α	Depth Discharge Coefficient	--	--
σ_{ir}	Interrill Runoff Rate	*m/s*	*l/t*
τ_c	Critical Shear Stress	*Pa*	*P*
τ_f	Flow Shear Stress	*Pa*	*P*

* denotes variables used in parameter estimation equations

APPENDIX

Table A1. Normalized runoff volume and sediment yield for all rainfall simulator sites and treatments.

Site	Treatment	Q/I	SY/QS_o
		(mm/mm)	((T/ha)/mm)
AB	natural	0.505	0.234
	fire	0.721	1.986
	1 yr. post-fire	0.868	0.702
	2 yr. post-fire	0.797	0.378
ANT	natural	0.61	0.43
	fire	0.63	2.10
	1 yr. post-fire	NA	NA
	2 yr. post-fire	NA	NA
ER3	natural	0.75	0.39
	fire	0.71	0.89
	1 yr. post-fire	NA	NA
	2 yr. post-fire	NA	NA
EM	natural	0.558	0.167
	fire	0.590	0.813
	1 yr. post-fire	0.604	0.501
	2 yr. post-fire	0.578	0.213
PC	natural	0.326	0.025
	fire	0.561	0.639
	1 yr. post-fire	0.787	0.573
	2 yr. post-fire	0.797	0.338
TF	natural	0.744	0.134
	fire	0.824	0.867
	1 yr. post-fire	0.751	0.237
	2 yr. post-fire	NA	NA

Table A2. Normalized runoff and sediment yield for all rainfall simulator plots and treatments.

Site	Plot	Treatment	Q/I	SY/QSo
			(mm/mm)	((T/ha)/mm)
AB	1	natural	0.44	0.46
	2		0.66	0.27
	3		0.48	0.09
	4		0.45	0.12
	1	fire	0.63	4.02
	2		0.73	2.86
	3		0.72	0.40
	4		0.80	0.66
	1	1 yr. post-fire	0.89	0.68
	2		0.92	1.58
	3		0.75	0.28
	4		0.91	0.27
	1	2 yr. post-fire	0.79	0.43
	2		0.93	0.43
	3		0.70	0.29
	4		0.77	0.37
ANT	1	natural	0.65	0.70
	2		0.60	0.36
	3		0.60	0.29
	4		0.59	0.35
	1	fire	0.55	1.48
	2		0.48	1.18
	3		0.70	1.27
	4		0.78	4.47
ER3	1	natural	0.85	0.65
	2		0.77	0.53
	3		0.72	0.21
	4		0.67	0.15
	1	fire	0.70	0.77
	2		0.75	1.40
	3		0.66	0.75
	4		0.72	0.66

Table A2 CONTINUED

Site	Plot	Treatment	Q/I	SY/QSo
			(mm/mm)	((T/ha)/mm)
EM	K3	natural	0.55	0.07
	K7		0.70	0.28
	K8		0.43	0.15
	1	fire	0.69	0.74
	2		0.50	0.89
	1	1 yr. post-fire	0.64	0.59
	2		0.43	0.35
	3		0.74	0.56
	4		0.55	0.07
	1	2 yr. post-fire	0.59	0.23
	2		0.54	0.17
	3		0.56	0.13
	4		0.62	0.33
PC	K4	natural	0.36	0.02
	K5		0.29	0.03
	1	fire	0.78	0.59
	2		0.79	0.45
	1	1 yr. post-fire	0.78	0.59
	2		0.79	0.45
	3		0.79	0.68
	4		0.36	0.02
	1	2 yr. post-fire	0.67	0.29
	2		0.85	0.19
	3		0.84	0.64
	4		0.83	0.24
TF	1	natural	0.68	0.16
	2		0.66	0.15
	3		0.92	0.08
	4		0.72	0.14
	1	fire	0.76	1.06
	2		0.95	0.85
	3		0.87	1.04
	4		0.72	0.53
	1	1 yr. post-fire	0.71	0.23
	2		0.86	0.21
	3		0.78	0.37
	4		0.65	0.14

Table A3: Normalized runoff and sediment yield for small plot data for natural, fire and recovery treatments.

Site	Treatment	Q/I (mm/mm)	SY/(Q*So) ((T/ha)/mm)
AB	natural	0.02	79.66
	fire	0.10	117.18
	1 yr. recovery	0.05	528.68
ANT	natural	0.05	122.34
	fire	0.07	491.78
ER3	natural	0.08	417.18
	fire	0.07	558.28
EM	1 yr. recovery	0.05	349.50
	2 yr. recovery	0.05	191.39
PC	1 yr. recovery	0.05	213.38
	2 yr. recovery	0.07	428.93
TF	natural	0.05	198.09
	fire	0.08	743.01
	1 yr. recovery	0.09	422.28

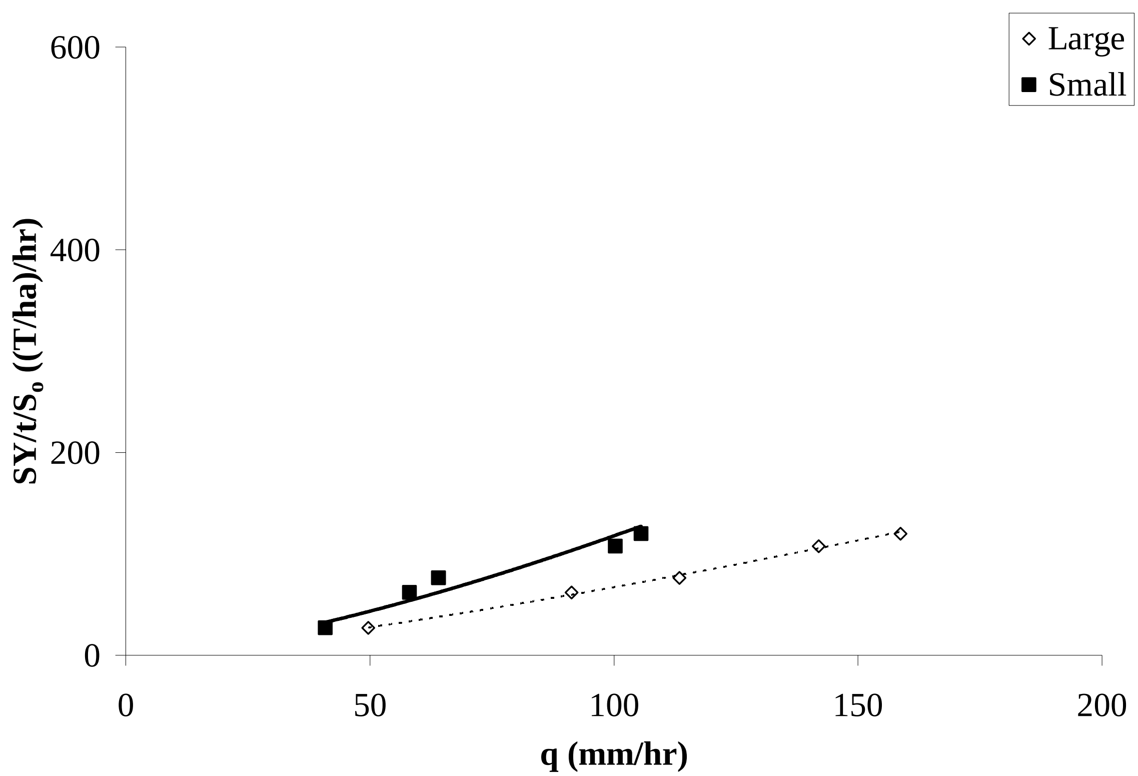

Figure A1. Large Plot versus Small Plot for AB 1 yr post-fire (2004). The open circles are the large plots and the closed squares are the small plots.

Table A4. K_{ed} values for all rainfall simulator plots and treatments.

K_{ed} (mm/hr)				
Site	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
AB_01	15	8	1	2
AB_02	5	4	1	1
AB_03	19	4	3	3
AB_04	20	2	1	3
ANT_01	12	11	NYC	NYC
ANT_02	15	15	NYC	NYC
ANT_03	14	11	NYC	NYC
ANT_04	10	9	NYC	NYC
ER3_01	1	6	NYC	NYC
ER3_02	3	6	NYC	NYC
ER3_03	5	6	NYC	NYC
ER3_04	7	6	NYC	NYC
EM_01	41	17	11	21
EM_02	21	9	25	19
EM_03	39	12	4	20
EM_04	NA	NA	7	14
PC_01	58	37	22	31
PC_02	83	45	22	14
PC_03	NA	NA	NA	16
PC_04	NA	NA	19	17
TF_01	12	23	21	NYC
TF_02	12	1	11	NYC
TF_03	1	4	7	NYC
TF_04	8	28	20	NYC

Table A5. The average K_{ed} values for all rainfall simulator sites and treatments. The numbers in parenthesis are the standard deviations.

K_{ed} (mm/hr)				
	Natural	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
AB	15	5	2	2
	(7)	(3)	(1)	(1)
ANT	13	12	NA	NA
	(2)	(3)		
ER3	4	6	NA	NA
	(3)	(0)		
EM	34	13	12	19
	(11)	(4)	(9)	(3)
PC	71	41	21	20
	(18)	(6)	(2)	(8)
TF	8	14	15	NA
	(5)	(13)	(7)	

Table A6. The average K_i values for all rainfall simulator sites and treatments. The numbers in parenthesis are the standard deviations.

K_i (kg-s/m^4)				
	Natural	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
AB	50,386	45,061	177,874	NA
	(17268)	(5581)	(32892)	
ANT	108,195	336,921	NA	NA
	(13163)	(251002)		
ER3	327,565	312,468	NA	NA
	(128189)	(29209)		
EM	NA	NA	184,889	114,981
			(21570)	(19462)
PC	NA	NA	59,553	163,853
			(16070)	(17167)
TF	233,216	807,001	551,763	NA
	(111546)	(93148)	(157008)	

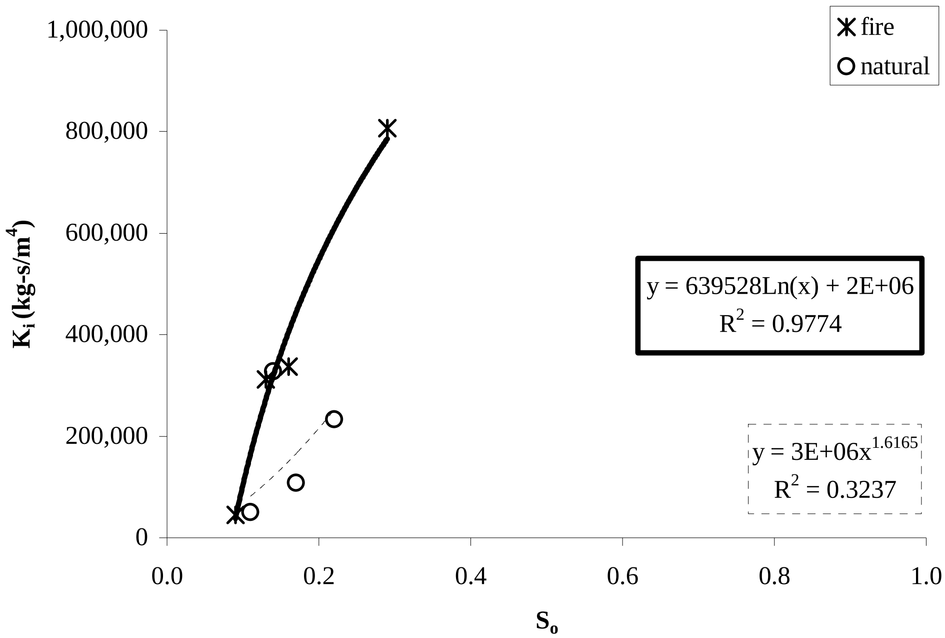

Figure A2. The relationship between K_i values and Slope (S_o). The x represents the fire sites and the open circles represent the natural sites.

Table A7. The average K_r and τ_c values for all rainfall simulator sites and treatments. The numbers in parenthesis are the standard deviations.

K_r (s/m)			**τ_c (Pa)**		
	Natural	**Fire**		**Natural**	**Fire**
AB	0.0000	0.0000	**AB**	0.0180	0.1871
	(0.0000)	(0.0054)		(0.0000)	(0.2564)
ANT	0.0007	0.0079	**ANT**	0.0482	0.7513
	(0.0011)	(0.1353)		(0.0414)	(0.1353)
ER3	NA	0.0000	**ER3**	NA	0.0452
		(0.0003)			(0.0304)
TF	NA	0.0000	**TF**	NA	0.0703
		(0.0008)			(0.0202)

Table A8. The K_r and τ_c values for all rainfall simulator plots and treatments

Site	Plot	Treatment	K_r	t_c
			(s/m)	(Pa)
AB	1	Natural	0.00063	0.01802
	2		NA	NA
	3		NA	NA
	4		NA	NA
	1	Fire	0.01113	0.00370
	2		0.01186	0.00233
	3		0.00074	0.19547
	4		0.00429	0.54687
ANT	1	Natural	0.00201	0.00252
	2		0.00014	0.08316
	3		0.00001	0.05879
	4		NA	NA
	1	Fire	0.01257	0.84702
	2		0.00321	0.65562
	3		NA	NA
	4		NA	NA
ER3	1	Natural	NA	NA
	1	Fire	0.00002	0.00006
	2		0.00070	0.06535
	3		0.00001	0.05413
	4		0.00001	0.06116
EM	1	Natural	0.00070	0.06535
	1	Fire	0.08834	0.04414
	2		0.01739	0.69310
PC	1	Natural	NA	NA
	1	Fire	0.01082	0.22758
	2		0.29862	0.10651
TF	1	Natural	NA	NA
	1	Fire	0.00151	0.07763
	2		0.00150	0.06809
	3		0.00004	0.09182
	4		0.00002	0.04382

Table A9. Parameter estimation equations created to determine the runoff parameters K_{ed} separated by fire, natural and recovery treatments as well as vegetation type.

Treatment	Equation No.	Equation for K_{ed} (mm/hr)	Adj. R^2	RMSE
FIRE	1	Ked = 7.59 - 0.18*Rt* + 0.34*Lt*	0.41	8.97
	2	Ked = 2.94 + 0.38*Lt*	0.42	8.86
FIRE GRASS	1	Ked = 48.56 - 1.50*Rr*	0.62	8.59
	2	Ked = 48.58 - 1.47*Rt*	0.61	8.63
	3	Ked = 45.22 + 0.04*Lt* - 1.41*Rr*	0.58	8.98
	4	Ked = 45.06 + 0.05*Lt* - 1.38*Rt*	0.58	9.03
FIRE OAKS	1	Ked = 4.65 + 0.21*Lt*	0.66	2.59
	2	Ked = 5.08 + 0.18L*r*	0.53	3.03
	3	Ked = 15.63 - 0.03*GAPb*	0.46	3.25
NATURAL	1	Ked = -10.29 + 2.78*Bt* + 0.34*Git*	0.68	10.58
	2	Ked = -6.77 + 4.07*Bt*	0.60	11.80
NATURAL GRASS	1	Ked = -7.43 + 0.85*Li* + 2.30*Bi*	0.85	8.97
	2	Ked = -8.55 + 0.50*Bt* + 2.09*Bi* + 0.79*Li*	0.84	9.38
	3	Ked = -0.75 + 3.20*Bi*	0.73	12.08
	4	Ked = -18.06 + 3.47*Bt* + 0.74*Lt*	0.70	12.72
NATURAL OAKS	1	Ked = 13.82 + 0.29*Li* - 0.39*Rr*	0.77	2.30
	2	Ked = 9.21 + 0.31*Li*	0.47	3.51
RECOVERY	1	Ked = 26.25 - 0.07*GAPc* - 0.42*Rr*	0.46	6.60
	2	Ked = 27.02 - 0.11*GAPc* - 0.29*Rt*	0.43	6.80
	3	Ked = 23.79e^-0.02*GAPc*	0.43	0.87

Table A10. Parameter estimation equations created to determine the runoff parameters K_i separated by fire, natural and recovery treatments as well as vegetation type.

Treatment	Equation No.	Equations for K_i (kg-s/m^4)	Adj. R^2	RMSE
FIRE	1	LN(Ki) = 9.41 - 0.02*Gt* + 1.54*LN(So)*	0.82	0.48
	2	LN(Ki) = 15.05 - 0.05*Gt*	0.67	0.65
FIRE OAKS	1	LN(Ki) = 5.02 - 0.01*Gt* + 2.85*LN(So)*	0.81	0.46
	2	LN(Ki) = 4.33 + 2.99*LN(So)* - 0.01*Rt*	0.81	0.47
	3	LN(Ki) = 6.47 - 0.01*Gt* +2.41*LN(So)* - 0.01*Rt*	0.79	0.50
	4	LN(Ki) = 14.23 - 0.04*Gt*	0.54	0.73
FIRE GRASS	1	LN(Ki) = 10.28 + 1.03*LN(So)* - 0.01*Rt*	0.70	0.34
	2	LN(Ki) = 14.10 - 0.03*Rt*	0.53	0.42
NATURAL	1	LN(Ki) = 13.00 + 0.72*LN(So)* - 0.06*Gt*	0.56	0.62
	2	LN(Ki) = 15.16 - 0.06*Gt*	0.56	0.62
RECOVERY	1	Ki = 913927.19+ 346815.15**LN(So)*	0.61	108788

Table A11. Parameter estimation equations created to determine the runoff parameters K_r and τ_c separated by fire, natural and recovery treatments as well as vegetation type.

Parameter	Equation No.	Equations for Rill Erosion Parameters	Adj. R^2	RMSE
K_r (s/m)	1	LOG(Kr) = -4.08 - 0.92*Bt*	0.69	0.62
	2	Kr = 0.01 - 0.004*Bt*	0.55	0.00
	3	Kr = 0.01 - 0.0003*Rt*	0.53	0.00
	4	Kr = 0.01 - 0.0003*Rr*	0.51	0.00
τ_c (Pa)	1	LOG(τc) = 5.53 - 0.13*Gt*	0.99	0.31
	2	τc = 1.32 - 0.02*Gt*	0.75	0.18

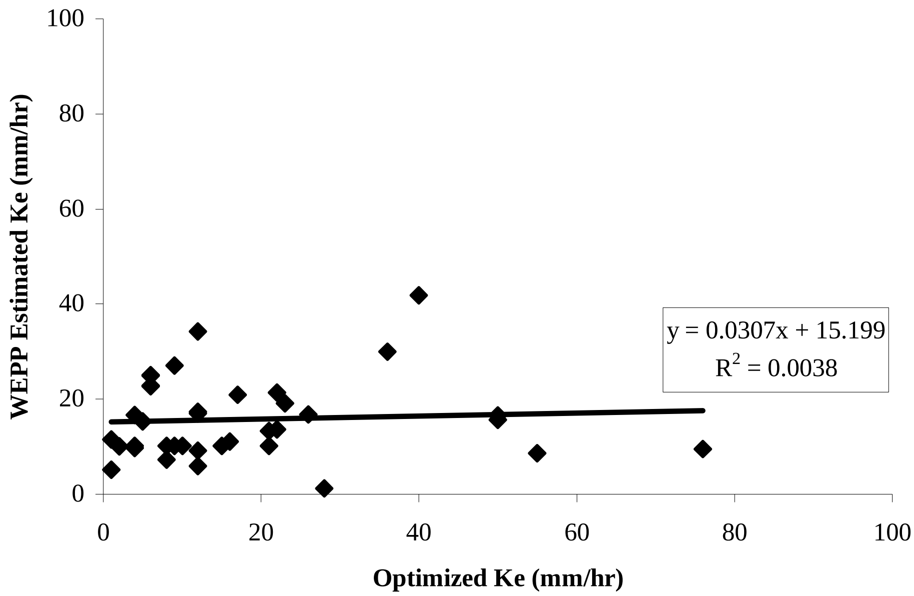

Figure A3. Comparison of the K_e values calculated with the parameter estimation equations from the WEPP documentation to optimized K_e values from this research.

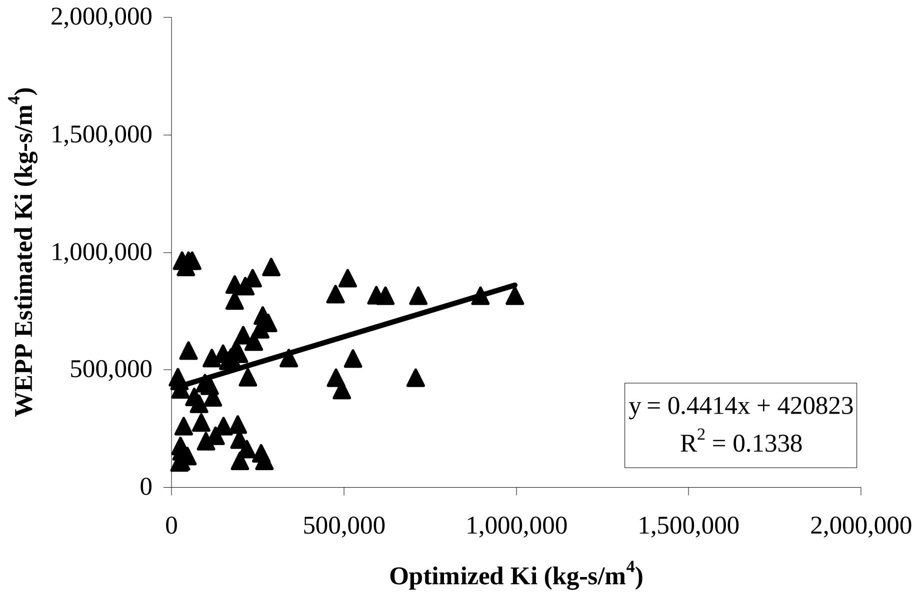

Figure A4. Comparison of the K_i values calculated with the parameter estimation equations from the WEPP documentation to identified K_i values from this research.

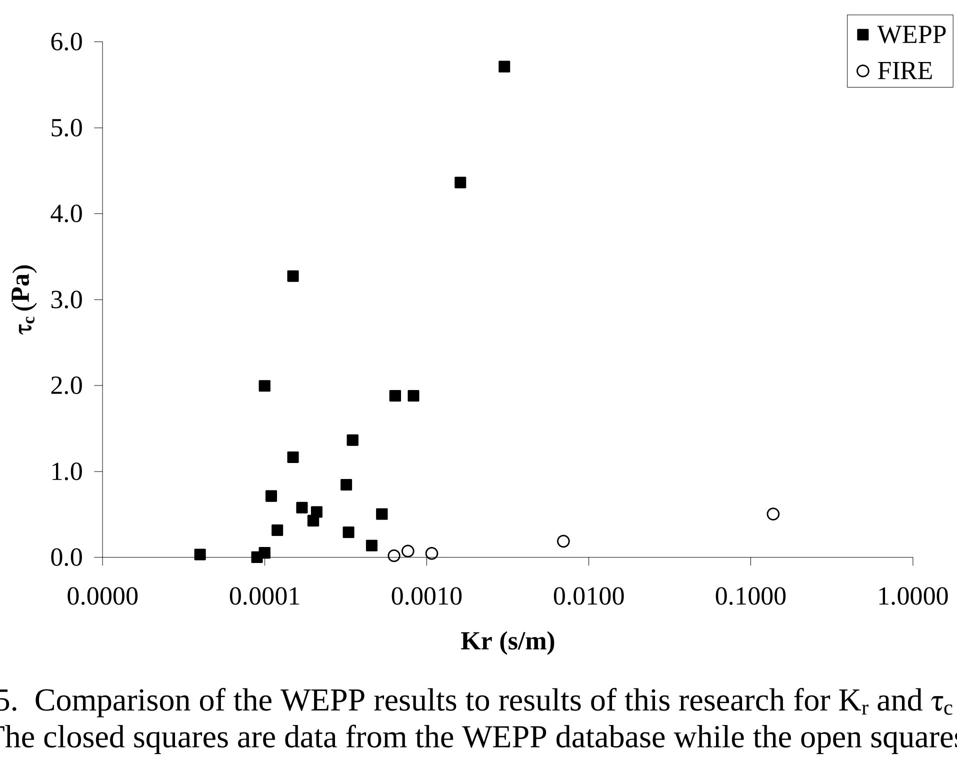

Figure A5. Comparison of the WEPP results to results of this research for K_r and τ_c values. The closed squares are data from the WEPP database while the open squares are the results of this research.

Table A12. The K_{ed} and K_{eb} values found with parameter estimation equations.

K_{ed} (mm/hr)				
Site	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
AB	15	5	4	6
ANT	13	11	NA	NA
EM	34	18	10	10
ER3	4	3	NA	NA
PC	58	27	16	19
TF	13	20	18	NA

Table A13. The K_i values found with parameter estimation equations.

K_i (kg-s/m^4)				
Site	**Natural**	**Fire**	**1 Yr. Post-fire**	**2 Yr. Post-fire**
AB	39,077	71,930	1,675,958	NA
ANT	84,484	313,500	NA	NA
EM	NA	NA	1,775,730	1,775,730
ER3	228,947	223,124	NA	NA
PC	NA	NA	1,675,958	1,675,958
TF	155,127	1,000,696	2,000,000	NA

Table A14. K_r values calculated with parameter estimation equations.

K_r (s/m)				
Site	**Natural**	**Fire**	**1 Yr. Recovery**	**2 Yr. Recovery**
AB	0	0.0028	0	0
ANT	0	0.0068	NA	NA
EM	0	0	0	0
ER3	0	0	NA	NA
PC	0	0	0	0
TF	0	0	0	NA

Table A15. τ_c values calculated with parameter estimation equations.

τ_c (Pa)				
Site	**Natural**	**Fire**	**1 Yr. Recovery**	**2 Yr. Recovery**
AB	0	0.2475	0	0
ANT	0	0.8514	NA	NA
EM	0	0	0	0
ER3	0	0	NA	NA
PC	0	0	0	0
TF	0	0	0	NA

Table A16: Results of rainfall simulator measurements conducted on small plots for all treatments and sites.

Site	Plot	Treatment	Gt	Rt	Lt	Bt	At	Git	Grt	Ct
AB	**1**	**natural**	69.44	40.28	19.44	9.72	0.00	25.00	44.44	37.50
	2		80.56	31.94	36.11	12.50	0.00	44.45	36.11	54.17
	4		62.50	40.28	18.06	4.17	0.00	26.39	36.11	38.89
AB	**1**	**fire**	98.61	27.78	0.00	0.00	70.83	0.00	27.78	0.00
	2		88.89	25.00	0.00	0.00	63.89	0.00	25.00	0.00
	3		87.50	75.00	0.00	0.00	12.50	0.00	75.00	0.00
	4		56.94	44.44	0.00	0.00	12.50	0.00	44.44	1.39
AB	**1**	**1 yr. recovery**	29.17	29.17	0.00	0.00	0.00	1.39	27.78	12.50
	2		44.44	40.28	2.78	1.39	0.00	11.11	33.34	27.78
	3		34.72	29.17	2.78	1.39	1.39	5.56	27.78	20.83
	4		29.17	27.78	1.39	0.00	0.00	2.78	26.39	2.78
ANT	**1**	**natural**	72.00	2.00	66.00	4.00	0.00	16.00	56.00	24.00
	2		74.00	22.00	46.00	6.00	0.00	16.00	58.00	20.00
	3		54.00	14.00	38.00	2.00	0.00	6.00	48.00	16.00
	4		56.00	16.00	38.00	2.00	0.00	14.00	42.00	32.00
ANT	**1**	**fire**	40.28	23.61	16.67	0.00	0.00	2.78	37.50	5.55
	2		50.00	26.39	23.61	0.00	0.00	0.00	50.00	1.39
	3		52.78	9.72	43.06	0.00	0.00	6.95	45.83	19.44
	4		63.89	13.89	50.00	0.00	0.00	2.78	61.11	6.94
ER3	**1**	**natural**	44.00	42.00	2.00	0.00	0.00	6.00	38.00	14.00
	2		52.00	38.00	10.00	4.00	0.00	10.00	42.00	18.00
	3		38.00	30.00	4.00	4.00	0.00	4.00	34.00	14.00
	4		40.00	24.00	14.00	2.00	0.00	2.00	38.00	6.00
ER3	**1**	**fire**	58.00	48.00	6.00	4.00	0.00	6.00	52.00	10.00
	2		60.00	46.00	12.00	2.00	0.00	2.00	58.00	2.00
	3		48.00	36.00	8.00	4.00	0.00	2.00	46.00	4.00
	4		44.00	32.00	8.00	4.00	0.00	0.00	44.00	4.00

Table A16 CONTINUED

Site	Plot	Treatment	Gt	Rt	Lt	Bt	At	Git	Grt	Ct
EM	**1**	**1 yr. recovery**	43.06	23.61	18.06	1.39	0.00	4.17	38.89	23.61
	2		54.17	34.72	18.06	1.39	0.00	5.56	48.61	15.28
	3		47.22	40.28	6.94	0.00	0.00	4.17	43.05	15.28
	4		50.00	34.72	15.28	0.00	0.00	2.78	47.22	13.89
EM	**1**	**2 yr. recovery**	58.33	52.78	4.17	1.39	0.00	43.09	52.78	13.89
	2		43.06	38.89	4.17	0.00	0.00	13.89	29.17	56.94
	4		45.83	36.11	6.94	2.78	0.00	6.94	38.89	34.72
PC	**1**	**1 yr. recovery**	33.33	18.06	12.50	2.78	0.00	2.78	30.56	26.39
	2		29.17	12.50	9.72	6.94	0.00	9.72	19.44	23.61
	3		26.39	6.94	18.06	1.39	0.00	2.78	23.62	13.89
	4		30.56	5.56	23.61	1.39	0.00	0.00	30.56	19.44
PC	**1**	**2 yr. recovery**	44.44	18.06	11.11	15.28	0.00	16.67	27.77	48.61
	2		43.06	31.94	2.78	8.33	0.00	11.11	31.94	44.44
	3		31.94	25.00	2.78	4.17	0.00	11.11	20.84	26.39
	4		48.61	30.56	12.50	5.56	0.00	26.40	22.22	54.17
TF	**1**	**natural**	52.78	29.17	15.28	8.33	0.00	34.72	18.05	63.89
	2		56.94	34.72	15.28	6.94	0.00	36.11	20.83	62.50
	3		58.33	40.28	9.72	8.33	0.00	22.22	36.11	47.22
	4		51.39	25.00	15.28	11.11	0.00	26.38	24.99	59.72
TF	**1**	**fire**	54.17	30.56	13.89	8.33	0.00	0.00	52.78	0.00
	2		31.94	11.11	11.11	6.94	0.00	0.00	29.16	0.00
	3		40.28	25.00	5.56	9.72	0.00	0.00	40.28	0.00
	4		31.94	11.11	13.89	6.94	0.00	0.00	31.94	0.00
TF	**1**	**1 yr. recovery**	36.00	22.00	8.00	6.00	0.00	6.00	30.00	28.00
	2		50.00	32.00	14.00	4.00	0.00	10.00	46.00	18.00
	3		62.00	36.00	20.00	6.00	0.00	8.00	54.00	12.00
	4		60.00	34.00	24.00	2.00	0.00	8.00	52.00	20.00

Table A16 CONTINUED

Site	Plot	Treatment	St	Gst	Ft	Lr	Rr	Br	Li	Ri	Bi
AB	**1**	**natural**	0.00	33.33	4.17	12.50	23.61	8.33	6.94	16.67	1.39
	2		0.00	54.17	0.00	9.72	13.89	12.50	26.39	18.06	0.00
	4		0.00	38.89	0.00	9.72	22.22	4.17	8.33	18.06	0.00
AB	**1**	**fire**	0.00	0.00	0.00	0.00	27.78	0.00	0.00	0.00	0.00
	2		0.00	0.00	0.00	0.00	25.00	0.00	0.00	0.00	0.00
	3		0.00	0.00	0.00	0.00	75.00	0.00	0.00	0.00	0.00
	4		1.39	0.00	0.00	0.00	44.44	0.00	0.00	0.00	0.00
AB	**1**	**1 yr. recovery**	0.00	5.56	6.94	0.00	27.78	0.00	0.00	1.39	0.00
	2		0.00	18.06	9.72	2.78	29.17	1.39	0.00	11.11	0.00
	3		0.00	18.06	2.78	2.78	23.61	1.39	0.00	5.56	0.00
	4		0.00	0.00	2.78	1.39	25.00	0.00	0.00	2.78	0.00
ANT	**1**	**natural**	4.00	16.00	4.00	54.00	2.00	0.00	12.00	0.00	4.00
	2		0.00	16.00	4.00	40.00	18.00	0.00	6.00	4.00	6.00
	3		0.00	8.00	8.00	34.00	14.00	0.00	4.00	0.00	2.00
	4		0.00	20.00	12.00	30.00	12.00	0.00	8.00	4.00	2.00
ANT	**1**	**fire**	0.00	4.17	1.39	15.28	22.22	0.00	1.39	1.39	0.00
	2		0.00	1.39	0.00	23.61	26.39	0.00	0.00	0.00	0.00
	3		19.44	0.00	0.00	37.50	8.33	0.00	5.56	1.39	0.00
	4		4.17	1.39	1.39	48.61	12.50	0.00	1.39	1.39	0.00
ER3	**1**	**natural**	2.00	12.00	0.00	2.00	36.00	0.00	0.00	6.00	0.00
	2		0.00	18.00	0.00	6.00	36.00	0.00	4.00	2.00	4.00
	3		0.00	14.00	0.00	4.00	30.00	0.00	0.00	0.00	4.00
	4		0.00	6.00	0.00	14.00	24.00	0.00	0.00	0.00	2.00
ER3	**1**	**fire**	0.00	10.00	0.00	6.00	46.00	0.00	0.00	2.00	4.00
	2		0.00	2.00	0.00	12.00	46.00	0.00	0.00	0.00	2.00
	3		0.00	4.00	0.00	6.00	36.00	4.00	2.00	0.00	0.00
	4		0.00	4.00	0.00	8.00	32.00	4.00	0.00	0.00	0.00

Table A16 CONTINUED

Site	Plot	Treatment	St	Gst	Ft	Lr	Rr	Br	Li	Ri	Bi
EM	**1**	**1 yr. recovery**	0.00	13.89	9.72	13.89	23.61	1.39	4.17	0.00	0.00
	2		0.00	13.89	1.39	13.89	33.33	1.39	4.17	1.39	0.00
	3		0.00	8.33	6.94	6.94	36.11	0.00	0.00	4.17	0.00
	4		0.00	1.39	12.50	13.89	33.33	0.00	1.39	1.39	0.00
EM	**1**	**2 yr. recovery**	0.00	8.33	1.39	2.78	48.61	1.39	1.39	41.70	0.00
	2		0.00	45.83	11.11	4.17	25.00	0.00	0.00	13.89	0.00
	4		0.00	30.56	4.17	6.94	29.17	2.78	0.00	6.94	0.00
PC	**1**	**1 yr. recovery**	0.00	26.39	0.00	11.11	16.67	2.78	1.39	1.39	0.00
	2		0.00	23.61	0.00	8.33	11.11	0.00	1.39	1.39	6.94
	3		0.00	13.89	0.00	16.67	5.56	1.39	1.39	1.39	0.00
	4		12.50	6.94	0.00	23.61	5.56	1.39	0.00	0.00	0.00
PC	**1**	**2 yr. recovery**	26.39	22.22	0.00	6.94	8.33	12.50	4.17	9.72	2.78
	2		0.00	44.44	0.00	1.39	22.22	8.33	1.39	9.72	0.00
	3		0.00	20.83	5.56	2.78	16.67	1.39	0.00	8.33	2.78
	4		2.78	48.61	2.78	6.94	12.50	2.78	5.56	18.06	2.78
TF	**1**	**natural**	0.00	62.50	1.39	0.00	9.72	8.33	15.28	19.44	0.00
	2		0.00	61.11	1.39	2.78	11.11	6.94	12.50	23.61	0.00
	3		0.00	44.44	2.78	2.78	25.00	8.33	6.94	15.28	0.00
	4		0.00	55.56	4.17	8.33	5.55	11.11	6.94	19.44	0.00
TF	**1**	**fire**	0.00	0.00	0.00	13.89	30.56	8.33	0.00	0.00	0.00
	2		0.00	0.00	0.00	11.11	11.11	6.94	0.00	0.00	0.00
	3		0.00	0.00	0.00	5.56	25.00	9.72	0.00	0.00	0.00
	4		0.00	0.00	0.00	13.89	11.11	6.94	0.00	0.00	0.00
TF	**1**	**1 yr. recovery**	0.00	26.00	2.00	6.00	20.00	4.00	2.00	2.00	2.00
	2		0.00	18.00	0.00	14.00	32.00	0.00	0.00	6.00	4.00
	3		0.00	12.00	0.00	20.00	34.00	0.00	0.00	2.00	6.00
	4		0.00	16.00	4.00	20.00	32.00	0.00	4.00	2.00	2.00

Units are percent
Exception: Gap units are cm.

Table A17. Vegetation measurements conducted on rainfall simulator large plots.

Site	Plot	Treatment	Gt	Rt	Lt	Bt	At	Git	Grt	Ct	St	Gst
AB	**1**	**natural**	62.00	27.00	35.00	1.00	0.00	33.50	28.25	71.00	37.00	31.00
	2		65.00	40.00	19.00	6.00	0.00	28.75	36.50	70.00	4.00	63.00
	3		84.00	36.00	40.00	8.00	0.00	63.25	20.75	87.00	1.00	83.00
	4		75.00	27.00	41.00	7.00	0.00	45.50	29.00	76.00	12.00	62.00
AB	**1**	**fire**	84.00	21.00	0.00	1.00	62.00	0.00	23.80	0.00	0.00	0.00
	2		86.00	11.00	0.00	0.00	75.00	0.00	12.50	0.00	0.00	0.00
	3		53.00	38.00	0.00	3.00	7.00	0.00	45.30	0.00	0.00	0.00
	4		45.00	31.00	0.00	2.00	12.00	0.25	32.00	0.00	0.00	0.00
AB	**1**	**1 yr. recovery**	60.00	54.00	3.00	1.00	2.00	11.50	47.25	17.00	3.00	4.00
	2		55.00	29.00	5.00	1.00	9.00	5.00	41.00	11.00	2.00	4.00
	3		72.00	65.00	3.00	4.00	0.00	17.75	53.75	29.00	4.00	16.00
	4		53.00	45.00	5.00	3.00	0.00	18.00	35.50	46.00	18.00	18.00
AB	**1**	**2 yr. recovery**	64.50	53.50	9.00	2.00	0.00	15.75	48.50	20.00	3.50	15.50
	2		52.50	44.00	7.75	0.75	0.00	7.50	44.50	15.00	2.50	10.50
	3		66.25	55.50	5.25	5.50	0.00	19.75	48.00	27.50	0.75	22.25
	4		54.75	38.50	14.25	2.00	0.00	15.75	38.50	30.00	6.75	22.50
ANT	**1**	**natural**	64.50	12.00	48.75	3.75	0.00	19.25	45.25	24.75	11.25	13.00
	2		62.00	15.75	42.75	3.50	0.00	19.50	42.50	26.50	13.25	11.50
	3		35.00	9.00	50.25	5.75	0.00	1.50	57.25	26.75	0.75	21.50
	4		57.75	11.25	41.00	5.50	0.00	1.00	21.25	30.25	0.50	20.50
ANT	**1**	**fire**	40.86	5.43	34.57	0.86	0.00	2.58	38.28	3.14	0.00	2.86
	2		48.50	16.00	31.50	1.00	0.00	4.00	44.50	5.50	0.00	4.50
	3		46.75	5.50	41.25	0.00	0.00	1.50	57.25	1.75	0.25	1.25
	4		22.25	5.75	15.50	1.00	0.00	1.00	21.25	1.00	0.00	1.00
ER3	**1**	**natural**	53.00	38.00	11.75	3.25	0.00	0.00	0.00	20.50	4.75	15.50
	2		56.50	35.25	17.50	3.75	0.00	0.00	0.00	19.75	5.00	14.75
	3		61.00	46.25	8.75	6.00	0.00	0.00	0.00	28.25	1.50	26.75
	4		62.25	37.25	16.50	8.50	0.00	0.00	0.00	35.00	3.75	30.00
ER3	**1**	**fire**	44.00	30.25	8.00	5.75	0.00	4.00	40.00	6.00	0.00	6.00
	2		42.50	30.25	8.25	4.00	0.00	2.75	39.75	4.25	0.25	4.00
	3		42.75	32.75	4.75	5.25	0.00	3.75	39.00	7.00	0.00	7.00
	4		40.29	30.00	6.86	3.43	0.00	2.28	38.00	3.75	0.25	3.50

Table A17 CONTINUED

Site	Plot	Treatment	Gt	Rt	Lt	Bt	At	Git	Grt	Ct	St	Gst
EM	**K3**	**natural**	64.36	32.82	20.26	11.28	0.00	57.98	16.70	66.41	0.51	51.79
	K7		61.28	37.44	19.49	4.36	0.00	41.53	20.28	63.08	14.62	18.79
	K8		55.13	27.69	21.54	5.90	0.00	47.18	11.80	61.03	2.31	29.74
EM	**1**	**fire**	74.25	18.50	54.00	1.75	0.00	0.75	73.50	4.75	0.00	4.75
	2		75.25	26.00	47.00	2.25	0.00	1.75	73.50	2.25	0.50	1.50
	3		77.25	18.75	54.50	4.00	0.00	10.00	73.30	1.00	0.50	0.25
EM	**1**	**1 yr. recovery**	36.00	23.00	9.00	4.00	0.00	0.75	34.50	61.00	0.00	60.00
	2		44.00	37.00	6.00	1.00	0.00	2.00	41.50	53.00	4.00	36.00
	3		66.00	38.00	26.00	2.00	0.00	11.75	54.25	98.00	10.00	88.00
	4		52.25	35.25	54.00	3.50	0.00	3.50	58.00	53.00	0.00	48.50
EM	**1**	**2 yr. recovery**	55.00	33.00	16.00	6.00	0.00	27.50	27.25	56.00	0.00	54.00
	2		57.00	46.00	8.00	3.00	0.00	25.50	32.00	56.00	0.00	51.00
	3		56.00	38.00	13.00	5.00	0.00	23.00	33.50	51.00	0.00	47.00
	4		52.00	25.00	13.00	4.00	0.00	25.75	26.25	55.00	0.00	50.00
PC	**K4**	**natural**	86.92	31.28	44.62	11.03	0.00	75.64	11.27	85.64	18.72	48.97
	K5		76.92	21.28	37.69	17.95	0.00	73.08	3.85	91.03	7.18	76.41
PC	**1**	**fire**	63.00	16.50	41.75	4.75	0.00	5.50	57.50	4.25	0.50	3.00
	2		82.25	13.25	62.75	6.25	0.00	3.75	78.50	10.25	0.25	9.75
PC	**1**	**1 yr. recovery**	37.00	23.00	9.00	5.00	0.00	2.50	34.00	22.00	0.00	21.00
	2		36.00	24.00	8.00	4.00	0.00	2.50	32.75	23.00	1.00	21.00
	4		33.00	20.00	6.00	7.00	0.00	2.00	30.25	20.00	3.00	17.00
PC	**1**	**2 yr. recovery**	37.00	28.00	6.00	3.00	0.00	11.50	24.25	51.00	0.00	50.00
	2		26.00	16.00	7.00	3.00	0.00	9.00	17.50	57.00	1.00	55.00
	3		34.00	24.00	4.00	6.00	0.00	20.25	14.00	66.00	5.00	58.00
	4		37.00	22.00	7.00	8.00	0.00	14.75	21.25	58.00	5.00	51.00

Table A17 CONTINUED

Site	Plot	Treatment	Gt	Rt	Lt	Bt	At	Git	Grt	Ct	St	Gst
TF	**1**	**natural**	54.00	31.00	18.00	5.00	0.00	37.00	17.50	77.00	0.00	67.00
	2		55.00	29.00	20.00	6.00	0.00	39.25	6.78	77.00	0.00	70.00
	3		55.00	28.00	23.00	4.00	0.00	43.75	11.00	90.00	1.00	76.00
	4		53.00	32.00	16.00	5.00	0.00	39.50	13.50	89.00	0.00	75.00
TF	**1**	**fire**	58.00	12.00	41.00	3.00	2.00	0.25	55.50	0.00	0.00	0.00
	2		67.00	30.00	22.00	12.00	3.00	0.00	64.00	0.00	0.00	0.00
	3		56.00	21.00	23.00	6.00	6.00	0.00	50.75	0.00	0.00	0.00
	4		62.00	14.00	27.00	18.00	3.00	0.00	59.25	0.00	0.00	0.00
TF	**1**	**1 yr. recovery**	64.57	11.43	48.00	5.14	0.00	24.57	40.00	34.57	0.00	28.57
	2		57.89	25.26	24.74	7.89	0.00	19.99	37.63	34.74	0.00	33.42
	3		54.29	26.00	23.14	4.57	0.57	16.28	36.86	29.71	0.86	26.57
	4		52.31	12.05	35.38	4.87	0.00	15.38	36.92	28.25	1.00	24.75

Table A17 CONTINUED

Site	Plot	Treatment	Ft	GAPc	GAPb	Lr	Rr	Br	Li	Ri	Bi
AB	**1**	**natural**	3.00	39.00	114.00	11.00	16.50	0.75	23.50	9.75	0.25
	2		4.00	20.00	45.00	12.00	24.00	0.50	7.00	16.50	5.25
	3		3.00	13.00	45.00	8.25	4.75	7.75	31.50	31.50	0.25
	4		3.00	12.00	46.00	14.50	8.50	6.00	26.25	18.50	0.75
AB	**1**	**fire**	0.00	280.00	293.00	1.30	21.50	1.00	0.00	0.00	0.00
	2		0.00	258.00	324.00	2.00	10.50	0.00	0.00	0.00	0.00
	3		0.00	187.00	400.00	0.00	42.55	2.75	0.00	0.00	0.00
	4		0.00	280.00	324.00	0.75	29.75	1.50	0.00	0.25	0.00
AB	**1**	**1 yr. recovery**	10.00	137.00	499.00	1.50	44.50	1.25	1.75	9.75	0.00
	2		5.00	146.00	589.00	4.75	35.00	1.25	0.25	4.75	0.00
	3		10.00	34.00	103.00	3.75	48.00	2.00	1.50	15.75	0.50
	4		9.00	39.00	147.00	2.25	30.00	3.25	1.00	16.25	0.75
AB	**1**	**2 yr. recovery**	1.00	61.36	20.20	5.50	43.00	0.00	3.50	10.25	2.00
	2		2.00	95.32	29.86	6.25	38.25	0.00	1.50	5.25	0.75
	3		4.50	29.79	24.89	3.00	45.00	0.00	2.25	11.25	6.25
	4		0.75	39.16	45.77	7.50	31.00	0.00	6.00	7.75	2.00
ANT	**1**	**natural**	0.50	23.80	47.67	34.50	10.50	0.25	14.25	1.50	3.50
	2		1.75	56.75	99.26	28.75	13.75	0.00	14.00	2.00	3.50
	3		4.50	36.75	90.90	51.75	5.50	0.00	1.50	0.00	0.00
	4		9.25	53.17	103.76	15.50	5.75	0.00	0.00	0.00	1.00
ANT	**1**	**fire**	0.29	74.57	97.21	33.14	5.14	0.00	1.43	0.29	0.86
	2		1.00	72.47	92.79	29.25	15.25	0.00	2.25	0.75	1.00
	3		0.25	599.38	349.75	51.75	5.50	0.00	1.50	0.00	0.00
	4		0.00	253.64	279.70	15.50	5.75	0.00	0.00	0.00	1.00
ER3	**1**	**natural**	0.25	48.09	24.52	9.75	25.25	0.00	2.00	5.25	3.25
	2		0.00	69.16	53.13	12.00	24.50	1.25	5.50	4.00	2.50
	3		0.00	37.60	15.94	5.50	31.00	3.00	3.25	9.75	2.75
	4		1.25	34.22	16.03	11.25	26.25	3.25	5.25	9.50	5.25
ER3	**1**	**fire**	0.00	279.70	20.72	7.50	29.50	3.00	0.50	0.75	2.75
	2		0.00	311.00	21.97	7.75	29.50	2.50	0.50	0.75	1.50
	3		0.00	311.00	24.21	4.75	32.00	2.25	0.00	0.75	3.00
	4		0.00	279.50	51.57	6.86	29.43	1.71	0.00	0.57	1.71

Table A17 CONTINUED

Site	Plot	Treatment	Ft	GAPc	GAPb	Lr	Rr	Br	Li	Ri	Bi
EM	**K3**	**natural**	14.10	23.07	56.92	5.40	11.30	0.00	14.90	21.54	21.54
	K7		29.49	23.59	61.94	5.38	14.90	0.00	14.10	22.56	4.87
	K8		28.97	27.82	54.42	3.59	8.21	0.00	17.95	19.49	9.74
EM	**1**	**fire**	0.00	350.00	58.70	53.75	18.00	1.75	0.25	0.50	0.00
	2		0.25	350.00	137.95	45.50	25.75	2.25	1.50	0.25	0.00
	3		0.25	350.00	80.27	52.00	18.30	3.00	3.00	2.00	5.00
EM	**1**	**1 yr. recovery**	1.00	52.24	90.69	8.50	22.50	3.50	0.00	0.75	0.00
	2		13.00	48.33	62.81	5.50	34.75	1.25	0.25	1.75	0.00
	3		0.00	55.58	124.27	24.00	28.75	1.50	2.75	9.00	0.00
	4		4.50	88.00	253.50	24.75	32.25	1.00	1.25	2.25	0.00
EM	**1**	**2 yr. recovery**	2.00	44.00	67.00	6.00	15.75	5.50	9.25	17.75	0.50
	2		5.00	34.00	50.00	3.25	25.50	3.25	5.00	20.50	0.00
	3		4.00	45.00	65.00	4.50	23.75	5.25	8.75	14.25	0.00
	4		5.00	34.00	99.00	4.75	18.50	3.00	8.50	16.75	0.50
PC	**K4**	**natural**	17.95	26.37	53.42	4.10	6.92	0.25	40.51	24.36	10.77
	K5		7.44	22.83	45.68	1.03	2.82	0.00	36.67	18.46	17.95
PC	**1**	**fire**	0.75	350.00	30.00	37.00	16.00	4.50	4.75	0.50	0.25
	2		0.25	350.00	49.86	60.50	13.00	5.00	2.25	0.25	1.25
PC	**1**	**1 yr. recovery**	0.00	31.00	56.00	8.25	21.25	4.50	0.50	2.00	0.00
	2		0.00	25.00	42.00	7.00	21.75	4.00	0.75	1.75	0.00
	4		0.00	31.00	51.00	5.25	18.25	6.75	0.25	1.75	0.00
PC	**1**	**2 yr. recovery**	1.00	17.00	27.00	4.75	17.25	2.25	0.75	10.25	0.50
	2		1.00	20.00	25.00	4.75	10.50	2.25	2.25	6.00	0.75
	3		2.00	41.00	59.00	3.00	8.50	2.50	1.25	15.75	3.25
	4		2.00	27.00	37.00	4.25	13.25	3.75	3.00	8.00	3.75

Table A17 CONTINUED

Site	Plot	Treatment	Ft	GAPc	GAPb	Lr	Rr	Br	Li	Ri	Bi
TF	**1**	**natural**	10.00	18.62	61.75	4.50	8.50	4.50	13.50	22.75	0.75
	2		7.00	21.77	52.94	5.75	1.03	0.00	14.50	18.75	6.00
	3		13.00	23.84	86.00	4.25	6.25	0.50	18.75	21.25	3.75
	4		14.00	25.53	58.30	2.50	9.50	1.50	13.25	22.75	3.50
TF	**1**	**fire**	0.00	350.00	97.52	41.25	11.25	3.00	0.25	0.00	0.00
	2		0.00	350.00	37.18	22.50	29.25	12.25	0.00	0.00	0.00
	3		0.00	192.64	72.17	23.50	21.00	6.25	0.00	0.00	0.00
	4		0.00	350.00	27.74	26.75	14.00	18.50	0.00	0.00	0.00
TF	**1**	**1 yr. recovery**	6.00	22.90	33.21	31.43	8.57	0.00	16.57	2.86	5.14
	2		1.32	20.53	24.40	17.89	19.74	0.00	6.84	5.26	7.89
	3		2.29	25.56	28.22	16.00	20.86	0.00	6.57	5.14	4.57
	4		2.50	27.98	30.46	26.92	10.00	0.00	8.46	2.05	4.87

Units are percent
Exception: Gap units are cm.

Table A18: Table of correlation values between K_{ed} and input variables separated by treatments.

Treatment	Ked	Gt	Rt	Lt	Bt	At	Git	Grt	CC	SC
Fire All	1.00	0.31	**-0.45**	**0.67**	0.26	-0.24	0.28	0.51	0.46	0.33
Fire Grasslands	1.00	0.50	**-0.80**	**0.64**	0.13	-0.19	0.14	0.47	0.35	0.24
Fire Oak-woodlands	1.00	-0.30	-0.60	**0.84**	-0.44	-0.42	0.88	0.43	0.88	0.28
Natural All	1.00	0.48	-0.15	0.29	**0.79**	0.00	**0.73**	-0.52	0.42	0.15
Natural Grasslands	1.00	0.71	-0.58	**0.74**	**0.84**	0.00	0.85	-0.59	0.47	0.40
Natural Oak-woodlands	1.00	0.37	0.00	0.52	0.17	0.00	0.55	-0.20	0.32	0.21
Recovery All	1.00	-0.53	-0.58	0.06	0.39	-0.31	0.01	-0.58	0.24	-0.43
Recovery Grasslands	1.00	-0.31	-0.10	-0.39	-0.03	-0.35	-0.10	-0.42	-0.37	-0.30

Treatment	GC	FC	GAPc	GAPb	Lr	Rr	Br	Li	Ri	Bi
Fire All	0.42	0.43	0.22	-0.36	0.63	-0.45	0.28	0.60	0.01	-0.06
Fire Grasslands	0.30	0.58	0.49	-0.05	0.62	**-0.81**	0.18	0.58	-0.17	-0.22
Fire Oak-woodlands	0.87	0.80	-0.13	**-0.73**	**0.77**	-0.59	-0.63	0.86	0.56	0.69
Natural All	0.22	0.48	-0.32	-0.03	-0.27	-0.45	-0.18	0.68	0.39	0.80
Natural Grasslands	0.23	0.47	-0.42	0.13	-0.58	-0.52	-0.45	**0.78**	0.47	**0.87**
Natural Oak-woodlands	0.25	-0.33	-0.25	-0.05	-0.05	**-0.59**	0.71	**0.74**	0.38	-0.67
Recovery All	0.34	-0.16	**-0.55**	-0.43	0.07	**-0.68**	0.47	0.21	-0.11	-0.06
Recovery Grasslands	-0.40	0.22	**-0.44**	-0.49	-0.39	-0.21	0.32	0.01	0.07	-0.14

Units are percent

Exception: Gap units are cm.

Table A19. Table of correlations for K_{ed} between all input variables.

	K_{ed}	**Gt**	**Rt**	**Lt**	**Bt**	**At**	**Git**	**Grt**	**Ct**	**St**
K_{ed}	1.00									
Gt	0.21	1.00								
Rt	-0.28	0.17	1.00							
Lt	0.37	0.41	-0.50	1.00						
Bt	0.55	0.23	-0.04	0.18	1.00					
At	-0.14	0.34	-0.16	-0.24	-0.22	1.00				
Git	0.51	0.39	0.24	0.16	0.46	-0.20	1.00			
Grt	-0.23	0.18	-0.01	0.40	-0.16	-0.17	-0.59	1.00		
Ct	0.32	0.09	0.25	0.03	0.28	-0.26	0.79	-0.60	1.00	
St	0.12	0.22	0.14	0.14	-0.01	-0.11	0.38	-0.16	0.36	1.00
Gst	0.25	0.02	0.20	0.00	0.29	-0.24	0.68	-0.56	0.95	0.12
Ft	0.36	0.15	0.25	0.00	0.15	-0.13	0.61	-0.43	0.52	0.24
GAPc	-0.08	0.13	-0.32	0.19	-0.12	0.24	-0.51	0.56	-0.68	-0.27
GAPb	-0.27	0.03	-0.02	-0.16	-0.42	0.42	-0.26	0.07	-0.28	-0.04
Lr	0.11	0.19	-0.56	0.82	-0.07	-0.16	-0.33	0.73	-0.39	-0.11
Rr	-0.50	0.00	0.74	-0.51	-0.28	-0.02	-0.38	0.42	-0.33	-0.05
Br	0.07	0.04	-0.04	-0.03	0.51	-0.07	-0.14	0.24	-0.11	-0.16
Li	0.53	0.44	0.02	0.36	0.43	-0.16	0.92	-0.50	0.68	0.47
Ri	0.28	0.27	0.47	-0.10	0.29	-0.20	0.88	-0.58	0.82	0.27
Bi	0.57	0.25	0.05	0.13	0.55	-0.14	0.67	-0.39	0.38	0.13

Table A19 CONTINUED

	Gst	Ft	GAPc	GAPb	Lr	Rr	Br	Li	Ri	Bi
K_{ed}										
Gt										
Rt										
Lt										
Bt										
At										
Git										
Grt										
Ct										
St										
Gst	1.00									
Ft	0.31	1.00								
GAPc	-0.63	-0.38	1.00							
GAPb	-0.31	-0.03	0.32	1.00						
Lr	-0.36	-0.30	0.51	-0.05	1.00					
Rr	-0.33	-0.17	0.07	0.21	-0.29	1.00				
Br	-0.04	-0.24	0.23	-0.19	0.05	0.01	1.00			
Li	0.56	0.47	-0.42	-0.24	-0.17	-0.48	-0.11	1.00		
Ri	0.74	0.62	-0.55	-0.20	-0.47	-0.20	-0.04	0.68	1.00	
Bi	0.30	0.44	-0.27	-0.25	-0.15	-0.27	-0.33	0.55	0.41	1.00

Units are percent
Exception: Gap units are cm.

Table A20: Table of correlation values between K_i and input variables separated by treatments.

Treatment	Ki	Gt	Rt	Lt	Bt	At	Git	Grt	CC	SC
Fire All	1.00	**-0.73**	-0.44	0.04	0.81	-0.47	-0.21	-0.27	-0.21	-0.20
Fire Grasslands	1.00	-0.59	**-0.76**	0.37	0.80	0.00	-0.67	-0.57	-0.67	0.00
Fire Oak-woodlands	1.00	**-0.75**	**-0.41**	0.37	0.00	-0.51	0.37	-0.10	0.29	0.01
Natural All	1.00	**-0.77**	0.07	-0.52	-0.27	0.00	-0.44	-0.35	-0.26	-0.13
Natural Grasslands	1.00	-0.44	-0.49	0.27	-0.38	0.00	-0.50	0.40	-0.54	-0.29
Natural Oak-woodlands	1.00	-0.56	-0.45	0.17	-0.42	0.00	-0.57	0.18	-0.52	0.14
Recovery All	1.00	0.42	0.20	0.27	0.08	-0.04	-0.09	0.50	-0.26	-0.09
Recovery Grasslands	1.00	0.50	0.23	0.32	0.08	0.00	-0.08	0.53	-0.27	-0.09

Treatment	GC	FC	Lr	Rr	Br	Li	Ri	Bi	So	Ln(So)
Fire All	-0.05	0.02	0.06	-0.43	0.82	-0.18	-0.11	-0.12	0.90	0.89
Fire Grasslands	-0.67	0.00	0.43	**-0.76**	0.81	-0.46	-0.37	-0.56	0.88	0.88
Fire Oak-woodlands	0.95	0.67	0.37	-0.42	0.00	0.26	0.62	0.00	0.81	0.81
Natural All	-0.19	-0.32	-0.37	0.29	-0.20	-0.49	-0.25	-0.04	0.22	0.25
Natural Grasslands	-0.53	-0.39	0.90	0.16	-0.48	-0.43	-0.54	0.48	-0.51	-0.51
Natural Oak-woodlands	-0.55	0.43	0.30	-0.29	-0.31	-0.33	-0.52	-0.05	0.38	0.38
Recovery All	-0.22	-0.04	0.38	0.32	-0.16	-0.17	-0.12	0.38	0.85	0.79
Recovery Grasslands	-0.22	-0.03	0.43	0.33	-0.16	-0.19	-0.11	0.39	0.88	0.84

Units are percent
Exception: Gap units are cm.

Table A21. Table of correlation values between K_r, τ_c and input variables

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Parameter	Gt	Rt	Lt	Bt	At	Git	Grt	CC	SC
K_r (s/m)	0.48	**-0.79**	0.15	**-0.80**	0.58	-0.08	-0.69	-0.10	0.00
τ_c (Pa)	**-0.89**	-0.29	0.81	0.06	-0.84	0.77	0.63	0.72	0.00

Parameter	GC	FC	GAPc	GAPb	Lr	Rr	Br	Li	Ri	Bi
K_r (s/m)	-0.07	-0.25	0.11	-0.26	0.17	-0.78	-0.65	-0.07	-0.30	0.04
τ_c (Pa)	0.74	0.58	-0.74	-0.75	0.81	-0.32	-0.30	0.74	0.74	0.80

Units are percent

Exception: Gap units are cm.