Erosion and Erodibility from Off Highway Vehicle Trails in Alberta's Southern Rocky Mountains

by

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Abstract

Runoff, sediment production, and erodibility from off highway vehicle (OHV) trails was studied using rainfall simulation experiments and natural rainfall observations in Alberta's south-west Rocky Mountains to evaluate the suitability of models such as Universal Soil Loss Equation (USLE) to support management of OHV trails networks by identifying problem areas for mitigation. Sediment production from rainfall simulation on small 1 m^2 plots (< 2 yr. return period 20 min. precipitation of 22.5 mm hr^{-1}) ranged from 0.01-6.4 tonnes ha^{-1} of trail surface while natural storms on larger trail segments produced 0.9-43.3 tonnes ha^{-1} from larger storm events ranging from 35.6-146.3 mm (peak 30 min. intensity 4.6-24.4 mm hr^{-1}). Both studies showed that trail use intensity was a chief factor governing both runoff and erosion with greater erosion from trails with greater intensity of OHV use. Rainfall simulations showed that usage rates, reflected in trail organic matter content, affect runoff pathways through compaction and reduction of infiltration on high-use trails, and through greater surface roughness, and increased infiltration on low-use trails. Natural rainfall observations likewise showed variable patterns of erosion, reflecting variable physical trail characteristics and use rate intensity with trails receiving greater use producing greater rates of erosion than current models such as USLE predict. While, sediment availability and erodibility were strongly affected by OHV use, soil properties commonly used to predict erodibility and required to model erosion using a broad suite of erosion models, substantially under-predicted erodibility on higher use trails. However, natural rainfall observations also showed a simple linear response between erosion and event precipitation for high-use trails, suggesting that regionally specific precipitation-erosion relationships may offer an interim solution to erosion prediction from OHV trail networks.

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Chapter 1 Introduction

Off highway vehicle (OHV) trails are a popular method of recreation in Alberta. Users are represented by various groups and organizations with approximately 150,000 OHVs registered in Alberta in 2013 (Alberta Transportation, Office of Traffic Safety, 2013). A recent socio-economic evaluation in the Crowsnest Pass of South Western Alberta showed there are an approximate 13,000 visits to the area annually for OHV recreational use, with visitors coming from as far as Saskatchewan, spending approximately $300 in the area per weekend visit, and having a willingness to spend almost double that (Prescott 2016). However, there has been growing attention on potential ecological impacts of OHV use and associated trail systems in sensitive areas. Of particular concern is the potential for these trails to effectively deliver sediment laden runoff to first order streams.

Fine sediment inputs are a management concern in most jurisdictions and best management practices are often employed to reduce the likelihood of sediment entering aquatic systems (Bilotta & Brazier, 2008). Increased sedimentation in streams can affect aquatic life through a range of changes to aquatic ecosystems. These include; alteration of temperature and pH (Bilotta & Brazier, 2008), the possibility of increased toxicity in water from upstream pesticides and heavy metals (Dawson & Macklin, 1998; Kronvang, et al., 2003), decreased oxygen availability (Greig, et al., 2005), reduced capability of organisms to hunt/forage (Chapman, et al., 2014), the drift and alteration of benthic macroinvertebrate communities (Culp, et al., 1985), and filling of refugia and spawning habitat (Curry & MacNeill, 2004; Bilotta & Brazier, 2008; Chapman, et al., 2014). Through a synthesis of numerous studies on fish mortality due to sedimentation Chapman et al. (2014) concluded high sediment inputs result in impaired feeding behavior, spawning success, and reduced species richness for fresh water fish species in lotic environments. While generally similar conclusions regarding impacts of suspended solids (SS) on aquatic life were outlined by Bilotta and Brazier (2008), they argued that considerable uncertainty still exists in defining limits of SS as a management objective because of high variability reported among studies they reviewed.

Regardless of uncertainty, fine sediment remains a concern for water resources management and numerous studies have focused on runoff, sediment inputs, and soil loss from forest roads and skid trails. A 2012 study in the Crowsnest pass region of south west Alberta found that a watershed impacted by historic forestry operations had higher concentrations of suspended solids and embeddedness of the streambed decades after harvesting had occurred. Nutrient loading (phosphorus) associated with fine sediments from forest operations increased production of benthic periphyton Chlorophyll α in the disturbed watershed (Smith Creek) by greater than 11.6 times that of the reference watershed (Star Creek) (Hawthorn, 2014). This illustrates the need for additional research to improve knowledge of land use impacts on sediment to improve watershed management. In particular, very little information presently exists on impacts of OHV trails on sediment production and what types of trails are prone to erosion, this information is essential for meeting management objectives to limit sediment impacts in areas with recreational OHV use.

The majority of the research on erosion from linear features has centered on roads. A range of studies have examined how erosion is affected by usage rates (traffic intensity) on unpaved forest roads (Ziegler, et al., 2000; Sheridan, et al., 2006) types of roads (Sheridan and Noske, 2007), infiltration capacities (Sosa-Perez & MacDonald, 2017), the accuracy of road erosion model parameters (Sheridan, et al., 2008), and road maintenance regimes (Luce & Black, 2001). Many of these studies show that increases in traffic can increase erosion from 2-100 times that of an unused or lightly used road (Reid & Dunne, 1984; Bilby, et al., 1989; Luce & Black, 1999; Ziegler, et al., 2000). Roads are often engineered to control runoff and erosion; existing research on roads can only provide crude insights into potential impacts of OHV trails because undeveloped trails do not generally have similar erosion control measures.

While comparatively little research has specifically focused on erosion from OHV trails, some limited descriptive insights into erosional or hydrologic impacts associated with OHV trails have been described in several regions of North America (Marion and Olive, 2009; Ricker et al., 2008; Sack and da Luz Jr., 2003; and Arp and Simons, 2012). However, several studies have provided more detailed insights into erosional processes specifically associated with OHV trail systems. A comprehensive study of erosion from OHV trails across 7 U.S. states (Meadows et al., 2008) showed low-use use OHV trails had 2-6 times greater total erosion and 2-3 times greater interrill erodibility than undisturbed soils, and that moderate trail use intensity had roughly 2 times greater erosion compared to lower trail use classes. A recent study on infiltration rates between used and rehabilitated OHV trails by Sosa-Perez and McDonald (2017) showed an increase in erosion by a factor of 3 for OHV trails receiving greater use. Thus, OHV trail use rate is likely a significant factor in determining the amount and predictability of erosion from these features.

In addition to documenting erosional impacts of OHV trails, models predicting erosion from OHV trails may be a cost-effective management tool to minimize impacts of trail networks by identifying trails with high erosion potential. However, very little research presently exists to support adapting sediment models used for predicting erosion from roads to OHV trails. Only one study (to my knowledge) by Welsh (2008) has explored adapting road sediment models to OHV trails and concluded that neither of two existing road erosion models (WEPP and SEDMODL2) were accurate at predicting sediment loss from OHV trails and roads in the Upper South Platte River Watershed. Furthermore, even for models used on undeveloped roads, prediction of erosion is often inaccurate, and that very little validation of erosion models and their parameters has been done in jurisdictions outside the United States (Sheridan, et al., 2008; Wang, et al., 2013; Saygin, et al., 2018).

The high erosion documented by the forest road and OHV trail specific studies outlined above suggest that rates of OHV use on recreational trails is likely a concern for watershed management. Furthermore, high variability of erosion reported from these studies indicates that further research is needed to better understand the underlying factors driving this variation. This information is needed to support development of erosion models with sufficient accuracy to support their use for management applications.

One potential approach may be to explore use of early generalized soil erosion models used for soil conservation. The Universal Soil Loss Equation (USLE) was developed by Wischmeier and Smith in the 1960s, following decades of study devoted to soil conservation in agricultural contexts (Wischmeier & Smith, 1978). It was intended as a tool to predict soil loss from agricultural operations but has since been expanded to other forms which include the Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) and is widely used for erosion control in management, transportation, and construction (Agriculture and Agri-Food Canada , 1997). USLE uses a simple equation to calculate the total soil loss of a standardized plot over a particular range of characteristics (background and history of the USLE is outlined in Chapter 2). Furthermore, while more contemporary erosion models such as WEPP, GRAIP and many others extend the representation of basic factors controlling erosion described in USLE to include stochastic processes needed to apply predictions across a broader range of temporal/spatial scales, unlike USLE their accuracy has not been extensively verified (Agriculture and Agri-Food Canada , 1997) (Agriculture and Agri-Food Canada , 1997).A well-established simpler erosion model such as USLE may be better suited to exploring the primary factors governing erosion and their interaction on OHV trails.

There is very little research that presently exists on erosion from OHV trails in Canada or elsewhere, nor have there been any significant attempts to develop prediction tools or models to enable developing management strategies to mitigate potential impacts of OHV trail erosion on streams.

1.2 Research Goals

Accordingly, the main goal of this work was to characterize the total erosion occurring on recreational trails in the eastern slopes region of Alberta and evaluate the characteristics of trails associated with variation (greater or lesser) erosion. An allied goal was to explore the potential of simple erosion models such as USLE to predict erosion from trail segments to help identify locations of higher erosion which would enable the use of simple models to manage OHV trail networks to mitigate impacts of OHV trails on headwaters streams in Alberta's eastern slopes.

1.3 Research Objectives and Organization of Thesis Chapters

Chapter 2 outlines the history and development of the USLE and how this model uses the fundamental factors controlling soil erosion for management and prediction. Its intent is to provide a broad overview of both erosional processes and their representation in USLE including how the parameters of USLE are typically derived and equations governing their estimation.

Chapter 3 describes a rainfall simulation study that was conducted to explore runoff, erosion, and erodibility (K) from OHV trails under representative high intensity rainfall in Alberta's southwest Rocky Mountain region. The specific objectives of this study were to a) characterize runoff, total erosion, and K using rainfall simulation on trails of contrasting physical characteristics (slope, soil texture, water content), and organic matter content/trail use intensity,

b) explore the relative sensitivity of total erosion and sediment production to variation in trail physical characteristics and trail use intensity, and c) evaluate the accuracy of commonly used approaches for predicting K using generalized nomograph approaches based on soil properties against actual field measured K.

Chapter 4 describes a field study documenting erosion from OHV trails under conditions of natural rainfall from larger trail segments of variable width, length, and physical characteristics. Specific objectives of this study were to a) characterize total erosion and K under natural rainfall conditions among trails of contrasting physical characteristics (slope, trail surface stoniness and canopy cover) and organic matter content/trail use intensity, b) explore the sensitivity of total erosion and sediment production from singular events and as seasonal averages as it responds to variation in trail physical characteristics and trail use intensity, and c) evaluate the accuracy of rainfall simulated measures of K and total sediment generation against the natural rainfall observations

Chapter 5 outlines a synthesis of results of these studies in the context of both previous research and information needed for management of this issue in Alberta. Additional questions that arose from the results of these studies and suggestions for future research to answer some of the more interesting patterns of response observed in the present studies are also outlined.

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Chapter 2 Overview of the Universal Soil Loss Equation

2.1 Introduction

In this chapter, I review the main components of the universal soil loss equation, its history and purpose, how the components are most often derived, and how these were applied in this study.

The Universal Soil Loss Equation (USLE) is a model developed to predict sheet and rill erosion by rainfall. The procedure was developed from long term erosion plot experiments conducted in the early half of the 20th century and expanded using rainfall simulation studies in the 1960s (United Sates Department of Agriculture, 2016). While originally developed to predict erosion from agricultural fields, the USLE has been applied to predict rainfall mediated erosion from a very broad range physiographic regions and precipitation regimes. Because USLE consists of a simple representation of the key physical soil, precipitation, and landform factors governing rainfall driven erosion, this empirical model has been employed to predict erosion worldwide. This includes many studies from outside of North America where it was developed. It has been used in West Africa along the Ivory Coast (Roose, 1976) to assess soil loss in the Nyabarongo River Catchment of Rwanda, Southern Uganda (Karamage, et al., 2016), in Japan for management in mountainous forested regions (Kithara, et al., 2000) and agricultural plots (Shiono, et al., 2002), in India using GIS techniques (Parveen & Kumar, 2012; Bera, 2017) and numerous studies in China (Wang, et al., 2013). While the USLE has been most extensively applied in a broad range of agricultural research applications, because of its focus on physical factors governing erosion, it has also been extensively applied for forestry and engineering practices. It is the recommended method for predicting erosion control requirements by; Alberta Transportation (Alberta Transportation , 2011), the BC ministry of Forests (Carr, et al., 1991), the Ontario ministry of Agriculture, Food, and Rural Affairs (Stone & Hilborn, 2015), and is widely used by government agencies around the world. It can be used with GIS and a number of other modeling tools and techniques. The applications of USLE have extended further since the original model was expanded in subsequent formulations (USLE-2, RUSLE, RULSE-2, and MUSLE).

While the ULSE has not been previously evaluated in the context of erosion prediction on OHV trail networks, the model describes the dominant factors affecting rainfall mediated soil erosion including erosive energy from rainfall and its interaction with the dominant soil and surface properties governing erosion.

The basic format of the Universal Soil Loss Equation (USLE) is;

Equation 2-1 A= R K LS C P

where,

A Total soil loss for the plot area in question. The units for A are mass/area given to match those used for both R and K values (see below).

R Erosivity or the erosive power of the storm(s) over a specified time period.

K Erodibility factor or the inherent erodible nature of a particular soil type.

LS Slope length factor or the factor used to scale the ratio of soil loss on any slope and length comparable to that of the standard plot of 22.1m long and 9% slope used in USLE development.

C Cover-management factor or the factor used to represent the amount of interference caused by environmental features which stop rainfall from having direct contact with the soil that will be eroded.

P Support practice factor or ratio of soil loss from alternative cropping practices with that of row cropping (not used in this study).

2.2 Historical Context and Evolution of Agricultural Soil Loss Models

The focus on soil conservation research increased rapidly after the “dust bowl” and great depression in the United States. Researchers in the Corn Belt of the United States of America began the development of mathematical tools for estimating soil loss (United Sates Department of Agriculture, 2016). The first of these was the slope-practice equation of Zingg (1940) which was later modified from a simple relation of soil loss to slope and length of the plot (LS) to include most of the conservation (C), soil (K), and practice factors (P) associated with current soil loss models (Laflen & Flanagan, 2013). This collaborative effort was undertaken by varied researchers of the northern United States as well as members of the Soil Conservation Service (SCS) and later the National Runoff and Soil Loss Data Center (NRSLC) of the Agricultural Research Service (ARS). Further revisions included addition of a rainfall factor (R) to expand its application to agricultural operations in other regions by 1946; the resulting model becoming known as the Musgrave Equation (Meyer, 1984).

In the 1950s, under the direction of Walt Wischmeier, an intense analysis of the existing data sets began in an attempt to build a model that could be used across the United States. Since soil conservation and erosion prediction had become a national collaboration amongst many researchers in the U.S.A. through the National Runoff and Soil Loss Data Center and Purdue University, with projects in 49 different areas, the data sets had greater than 10,000 plot-years of observational data regarding soil loss and runoff. Later, rainfall simulation experiments in 16 different states explored the major factors suggested by the previous equations, evaluated their accuracy, and revised their representation in the model to the present the Universal Soil Loss Equation. The USLE was first presented in Agricultural Handbook Number 282 in 1965 by Wischmeier and Smith and updated in Handbook 537 in 1978 (United Sates Department of Agriculture, 2016).

2.3 Subsequent Developments of USLE

2.3.1 The Revised Universal Soil Loss Equation or RUSLE

USLE was revised in the 1980s by Renard et al. The revised version of USLE, RUSLE, attempts to improve upon the factors that have been demonstrated to be the most important for affecting erosion. These tend to include; the accuracy of isoerodant maps for the R factor (only applicable to the United States and portions of Canada), the seasonal variations in K factors, the slope steepness factor (S), and several permutations of the cover-management factor. The LS factors were significantly modified in RUSLE to represent the idea that rill formation is less likely to occur on slopes shorter than 4 meters (Renard, et al., 1991).

2.3.2 The Modified Universal Soil Loss Equation or MUSLE

The Modified Universal Soil Loss Equation (MUSLE) is a variation of USLE developed in 1975 by Williams (Laflen & Flanagan, 2013). MUSLE uses runoff rather than rainfall amounts to determine erosion (Williams, 1975). It replaces R factor with an energy factor obtained from the combination of an energy constant, the amount of surface runoff (in m^3), and the peak runoff (m^3/s).

2.3.3 USLE Incorporation into Other Models

Since its initial conception, the USLE has undergone considerable evolution, yet still remains one of the most useful approaches for researchers studying soil loss. More recent erosion prediction models including Water Erosion Prediction Project (WEPP), Soil and Water Assessment Tool (SWAT), Geomorphic Road Analysis and Inventory Package (GRAIP) retain many of the key elements from the original and later USLE formulations to represent erosional processes, despite being more contemporary models (Laflen & Flanagan, 2013). There is little doubt that the USLE has contributed significantly to both the study and prediction of soil loss and conservation throughout the world.

2.4 Deriving the Variables to Apply the USLE

The input variables required to apply the USLE are most often estimated for a region using a combination of either historical data (precipitation), generalized relationships between the USLE input parameters and readily available information on soil properties or general erosivity maps created for the U.S. and Canada from historical data (Wischmeier & Smith, 1978) where these former data are unavailable. While generalized relationships between soil texture, organic matter content, soil structure, and permeability can be used to estimate erodibility (K) from nomographs for any particular region more regionally specific data for K can be used if available.

2.4.1 The Total Soil Loss or A

In the USLE, total soil loss for the plot is represented by the factor A (Wischmeier & Smith, 1978). Its metric units are most easily expressed in tonnes ha^{-1}. It is usually presented as an annual loss but can be expressed in any units that may also be used for the R and K factors (Foster, et al., 1981). A is usually either mathematically generated as a prediction or it is measured physically to compare against predictions.

2.4.2 The Rainfall Erosivity Factor or R

R is the total erosive power of an individual storm, annual sum of storms, and/or average of annual sums over a substantial period (>22 years). In the USLE calculations the R factor are usually prepared for an annual time period. This is done by summing the erosive energy of each storm, greater than 12mm and separated by other events by at least 6 hours, for an entire year (Wischmeier & Smith, 1978). For generalizing R over broader areas of North America, a 22-year precipitation record was used to develop isoerodent (R) maps for both the U.S. and Canada, however, many regions of Canada are not well represented in these maps (Figure 1-1).

Erosivity (R) is calculated as the total kinetic energy (E_k) of the storm multiplied by its maximum 30-minute intensity (I_{30}) as follows;

Equation 2-2 $$R = EI_{30}$$

where E_k is the kinetic energy of the storm and is represented in equation 2-3 below;

Equation 2-3 $$E_k = e_k v_k$$

where unit energy or e_k for lower intensity storms is given in equation 2-4 below;

Equation 2-4 $$e_k = 0.119 + 0.0873 \log_{10} (i_m)$$

where $i_m \leq$ 76mm/h and is represented in mm/hr.and v_k is the total depth of water in mm that has fallen (Foster, et al. 1981).

Note that there are two equations designated for finding the unit energy or e_k of a storm. Both reflect relationships on the interaction between energy, rain drop size, and terminal velocity (Laws & Parsons, 1943).

The combined equation for R is:

Equation 2-5 $$R = e_k v_k I_{30}$$

2.4.3 The Soil Erodibility Factor or K

K values or the soil erodibility factor are based upon the natural tendency of the particular soil type to be eroded. In the USLE both an equation and a simplified method can be used to obtain K values. Most often the K value is determined by the simplified nomograph approach. While both are determined from soil texture, organic matter %, soil structure class, and permeability, the nomograph approach uses a graphic representation rather than an equation (Wischmeier & Smith, 1978). There have been many other methods of estimating K used by other researchers, all with varying success (Figure 1-2).

A single equation can also be used to estimate K values from the soil properties above;

Equation 2-6

$$(2.1*10^{-4})*(12-a)*(s3*(100-u))^{1.14})+((3.25)*(w-2)+(2.5*(x-3))))/100$$

where a is the organic content (%), s is the percent silt and very fine sand content, u is the percent clay content, w is the soil structure class, and x is the permeability (Wischmeier & Smith, 1978). This estimates K in imperial units and should then be multiplied by 0.1317 to convert to metric units (Foster, et al.1981).

2.4.4 The Slope Length Factor or LS

The Slope Length factor or LS is the factor that is used to standardize the soil loss of any slope to that of the original 22.1m and 9% slope plots that were initially used in the early studies (Wischmeier & Smith, 1978). Since the two characteristics of slope and length have been determined to affect erosion together the separate factors of L and S are most often combined. In both USLE and RUSLE Handbooks LS can be determined from tables or by equation (Wischmeier & Smith, 1978; Renard, et al., 1991).

LS is given by equation 2-7;

Equation 2-7 $$LS = (\lambda/72.6)^m * (65.41 \sin^2\Theta + 4.56 \sin \Theta + 0.065)$$

where λ = length of slope in feet, Θ = angle of the slope, and m = 0.5 (a constant when all slopes are greater than 5%)

Converted to a metric, excel friendly version that uses percent slope the equation provided by Stone and Hilborn (2015), appears in equation 2-8;

Equation 2-8 $$LS = [0.065 + 0.0456 (\%slope) + 0.006541 (\%slope)^2]*(\lambda \div 22.1)^m$$

2.4.5 The Cover-management Factor

Variable approaches to estimating the cover-management factor (overhead or ground cover preventing direct rainfall contact with soils) are used depending on specific land management practices. In many applications these can be directly estimated from % overhead or ground cover, or from published handbooks for the USLE. For example, Agricultural Handbook 537 outlines cover-management factors for wide range of land use applications (i.e. construction sites, idle lands, rangelands, etc.) (Wischmeier & Smith, 1978).

2.4.6 A Note about Individual Storms and Short Observation Periods

Agricultural Handbook 537 cautions against using the USLE to calculate erosional losses for individual storms since the equation and many of its factors were developed to estimate annual averages whereas individual storms and environmental characteristics may vary to such an extent between storms that accuracy is reduced (Wischmeier & Smith, 1978). However, it is suggested that this can be accomplished by providing ratios for seasonal variation of these driving factors. The use of controlled input rainfall simulation, timed runoff samples, and measures of soil water content in this study were developed with this in mind and should address these concerns adequately.

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Figure 2-1 Example of an Isoerodent map of R values (Agriculture and Agri-Food Canada , 1997).

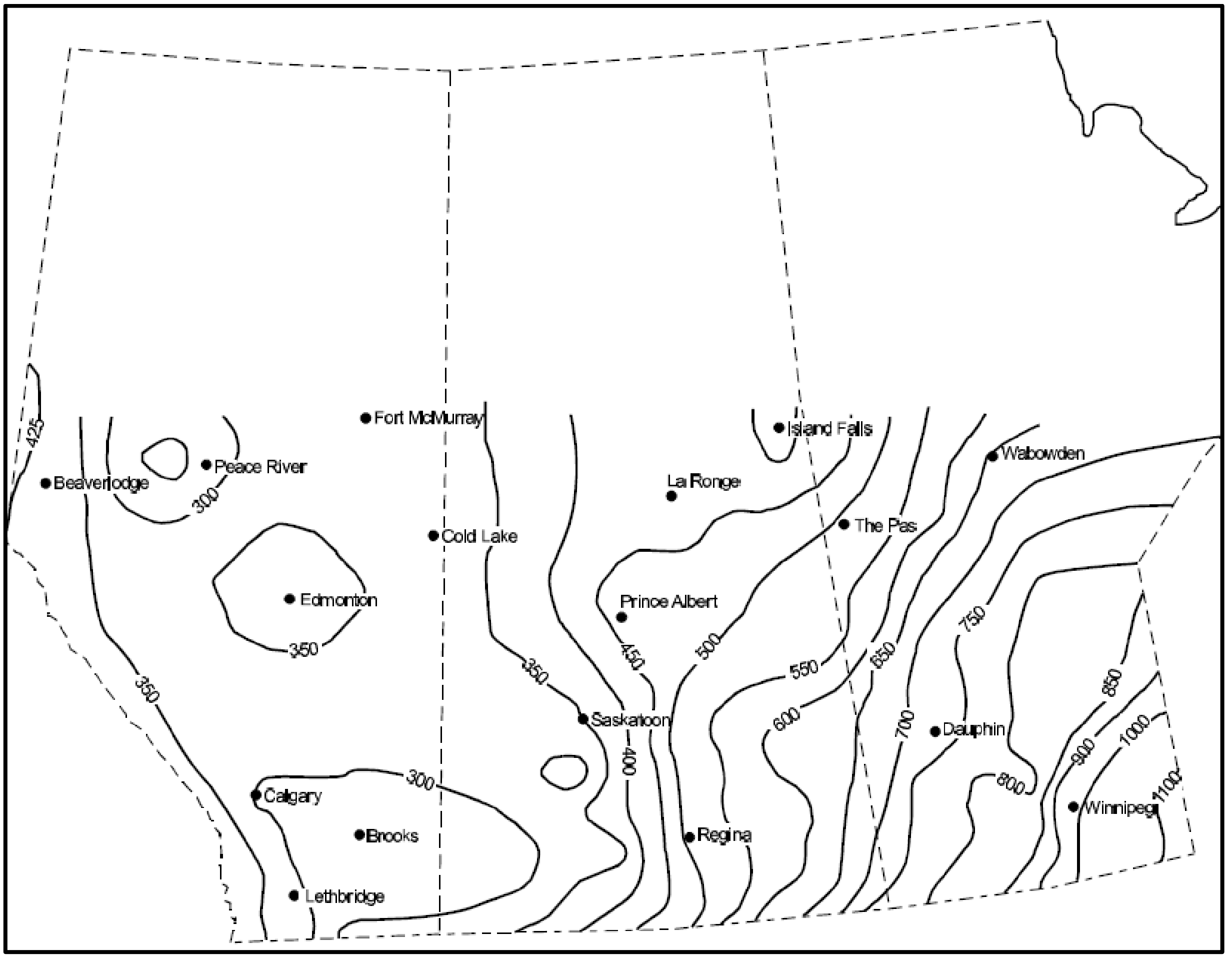
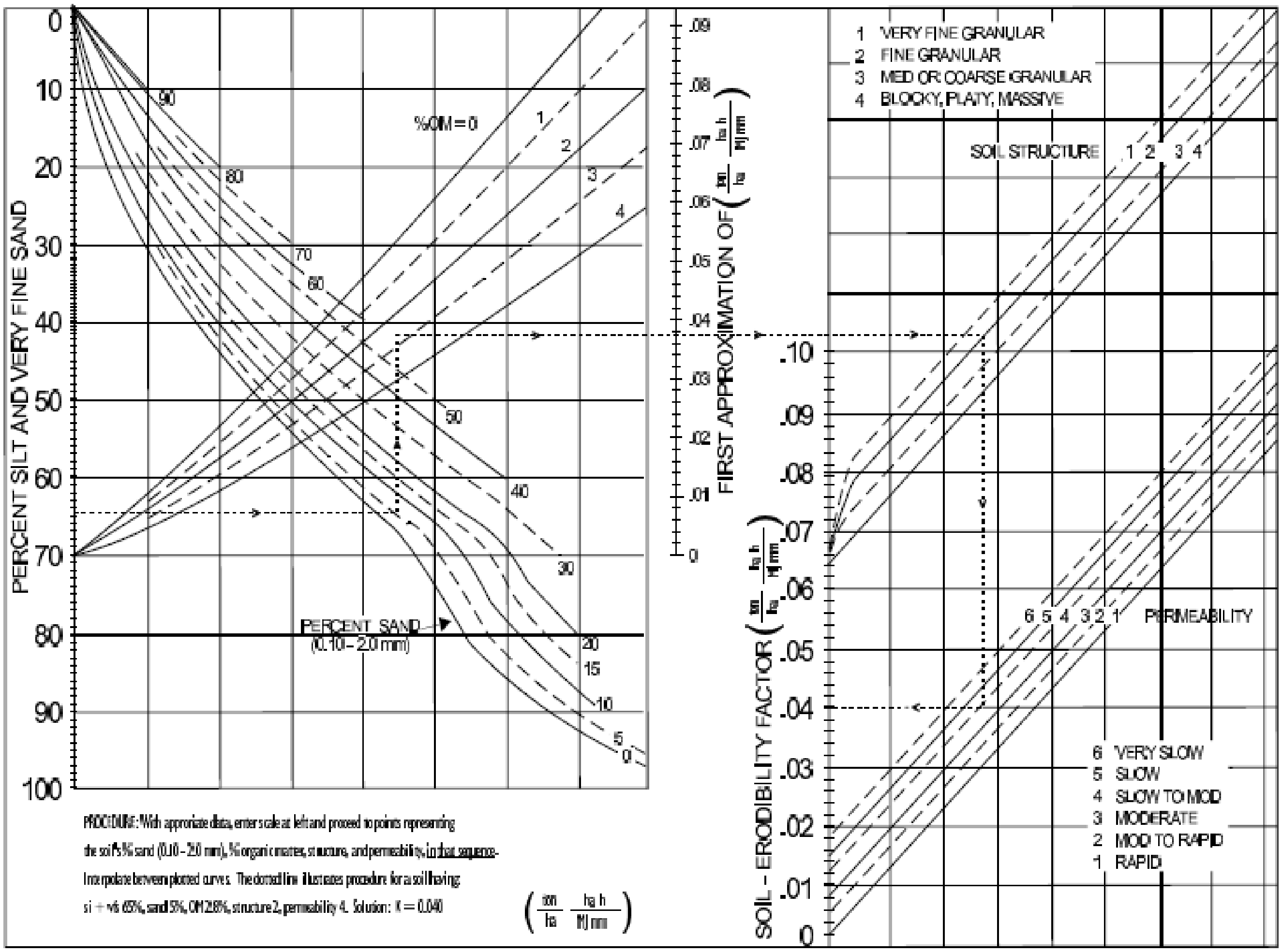


Figure 2-2 Soil Erodibility Nomograph (Foster, et al., 1981)



Chapter 3 Rainfall Simulation

3.1 Introduction

Off highway vehicle (OHV) trails have the potential to efficiently deliver sediment during runoff events to streams. In the Southern Rockies of Alberta, OHV use is a popular recreational activity. The increasing usage in these highly sensitive areas has highlighted the need for greater understanding of the implications of trail and vehicle impacts on aquatic environments. Management objectives for maintaining downstream water quality and ecological integrity rely on the capability to predict the magnitude of soil erosion from individual or networks of OHV trails. While soil erosion can be assessed using models or by direct measurement, this has never been done on OHV trails in the Eastern Slopes of Alberta's Rockies.

Numerous models predicting soil loss and erosion have been developed for use on agricultural plots, construction sites, and roads including: WEPP (water erosion prediction project), GRAIP (Geomorphic Road Analysis and Inventory Package), and simpler tools like the Universal Soil Loss Equation (USLE) and its numerous variations. WEPP is a process-based modelling system that provides soil loss predictions from the range of hillslopes to entire watersheds. It requires an extensive set of input parameters and includes components for prediction of both erosion but also plant growth simulations and its role in regulating water balances. However, WEPP has been described as "too onerous" for some uses in Canada due to the significant inputs required thus researchers and government agencies have long chosen to continue to use the USLE or the RUSLE models as provided in RUSLEFAQ (Van Vliet, 2001; Wall, et al., 2002). Similar to WEPP, GRAIP is a suite of tools for predicting soil loss, specifically from the effects of roads in forested watershed. It has a number of capabilities that include analysis for the assessment of areas that require management interventions such as culverts, fish passage and stream diversion, and others (Rocky Mountain Research Station Air Water and Aquatic Environments Program, 2018). However, general lack of availability of input parameters also limits use of GRAIP in many regions. The Universal Soil Loss Equation (USLE) is a widely used tool for predicting the total soil loss and erosion resulting from rainfall (Wischmeier & Smith, 1978). It is commonly used in agriculture, transportation, and construction (USLE is more generally described in chapter 2). The USLE may have greater applicability in predicting erosion from OHV trails largely because a) it consists of a simple, generalized, and flexible representation of key functional variables regulating rainfall driven soil erosion, and b) it has been extensively evaluated and successfully applied across a diverse range of environments. Thus, the USLE was the most promising choice of simple erosion prediction tools for this study.

The parameters used in the USLE were developed over several decades, much of which involved rainfall simulation (see Chapter 2). One of the key input parameters for the USLE is an estimate of erodibility (K) which represents the inherent erodibility of a soil type under standard plot conditions used in the original erosion experiments used in formulating the USLE (Wischmeier & Smith, 1978). General estimates of erodibility were originally developed from long term agricultural plots and validated using rainfall simulation in the mid-western agricultural regions of the United States. These experiments produced the basic relationships that served as the foundation for generalized approaches to estimate erodibility using nomographs or simple equations as a function of soil texture, organic matter content, soil structural class, and permeability (see Chapter 2). These, in turn, have been used to produce broad spatially distributed estimates of soil erodibility across broad regions of the United States. However, Bryan (2000) argued that broad application of erodibility estimates to soils, climatic, and land use settings outside of the agricultural settings where the initial erodibility values for the USLE were estimated may result in highly uncertain erosion estimates. Erodibility studies in China showed that field verification of erodibility (K) values was not common. Thus though the USLE's use may be widespread, but there is very little validation of model predictions (Wang, et al., 2013). While erodibility values have been experimentally determined for several agricultural regions in Canada, use of the USLE to predict erosion from OHV trails in mountainous environments (soils, climates, physiographic settings) would require either uncertain estimates of erodibility (K) from these generalized nomographs or equations, or experimental determination of erodibility in this setting.

Considerable applied research on erosion from roads has focused on rates of total erosion or infiltration rates on forest roads rather than on investigations of generalized erodibility rates. Rainfall simulation experiments by Ziegler et al. (2000) reported 10 times more sediment production from roads receiving greater use and suggested this finding was a result of their diminished infiltration capacities and greater sediment availability. Similar findings have been reported from rainfall simulation experiments on unpaved forest roads worldwide (Reid & Dunne, 1984; Croke, et al., 1999; Wang, et al., 2013). However, specific research on erodibility from forestry roads is more limited. Sheridan et al. (2005) reported K from roads with heavier traffic intensity was 3-4 times greater than on roads with less traffic. However, the correspondence of greater K with soil properties that might be affected by traffic was less clear; they found generally poor correspondence between measured K and K predicted from soil properties resulting in either under or overestimated rates of erosion on forest roads (Sheridan et al., 2008).

While research on erosion from forestry roads may serve as useful analogs to potential erosion from OHV trails, the similarity of erosion processes among these two types of linear features is uncertain. Limited existing research on un-maintained roads, similar to OHV trails, suggests erosion from un-maintained roads without graveled surfaces can produce 3-5 times greater sediment than graveled roads (Sheridan & Noske, 2007). OHV traffic on un-maintained roads can further increase erosion, where erosion from roads used by OHVs was more recently reported to be 3 times greater than that of decommissioned roads (Sosa-Perez & MacDonald, 2017). The most comprehensive study on erosion from OHV trails from six U.S. states reported that runoff volumes from high intensity rainfall simulation (4 inches hr^{-1}) was 2-4 times greater from OHV trails with higher rates of OHV traffic compared to undisturbed forest soils (Meadows et al. 2008). These same simulations showed that infiltration (which plays an important role in controlling runoff and erosion) was highly dependent on the degree of soil disturbance and trail use intensity. Similarly, measures of interrill erodibility (erodibility coeffients used in WEPP) on OHV trails were greater than those of undisturbed soils. In particular, these studies highlight the general finding that OHV use may increase erodibility in forest and range settings, but the impacts on K or soil properties governing erodibility are unclear and would need to be specifically characterized in in order to predict erosion from OHV trails in Alberta's eastern slopes.

Accordingly, the broad objectives of this study were to characterize erosion from OHV trails in Alberta's Rocky Mountain region and explore the variation in both sediment production and erodibility (K) as a function of physical trail characteristics and trail use intensity in Alberta's southwest Rocky Mountain region. Specific objectives of this study were to a) evaluate runoff and sediment production, and erodibility (K) using rainfall simulation on OHV trails of with variable physical characteristics (slope, organic matter content, soil texture, water content) and trail use intensity, and b) evaluate the accuracy of commonly used approaches to predict erodibility (K) using generalized nomograph approaches based on soil physical properties

3.2 Methods

3.2.1 Study Area

This study was completed in the Crowsnest Pass in South Western Alberta (49°37N, 114°40W) (Figure 3-1). It is located within the Montane Cordillera ecozone and the Northern Continental Divide ecoregion (Ecological Stratification Working Group, 1999). Land use in the area is dominated by forestry, mining, rangeland, and recreational usage, with some oil and gas extraction. The region is within a 2.5-hour drive from Calgary, as well as many smaller municipalities of Southern Alberta; more than 1.2 million people have the opportunity to use it as a recreational area, along with the broader eastern slopes region in southwest Alberta (City of Calgary, 2016). The trail systems in this region are situated on both public and private land, are heavily used, and have the potential to deliver sediment to tributaries of the Crowsnest River.

3.2.1.1Climate

The study region has a cool continental climate, with a mean annual temperature of 3.6 ºC ranging from average July/August temperatures of 14.3 ºC to -7.4 ºC in December (Government of Canada, 2016). Average annual precipitation for the region is 582.1 mm (1981-2010), with 30% falling as snow. Mean monthly precipitation ranges from 70 mm in June to 35 mm in December (Government of Canada, 2016). Based on records from the Southern Rockies Watershed Project (SRWP) network of climate stations, average short duration (1 hr.) summer rainstorms in the study region are 11.7 mm with peak rainfall intensity of 13.1 mm hr^{-1} ranging to approximately 50 mm total precipitation with mean peak rainfall intensity of ~ 2 mm $hr^{-1}$for longer-duration (24 hr.) storms.

3.2.1.2 Topography, Geology and Soils

The greater study region is situated along the Flathead and High Rock ranges (south and north of highway 3, respectively). Elevation in the study region ranges from 1375-1500 meters above sea level. Geologic setting of higher elevation regions within the study area consists of Paleozoic bedrock shales, sandstones and carbonates of the Cambrian, dolomite and limestone of the Devonian, carbonate and shale of the Mississippian, sandstone and shale of the Jurassic and Cretaceous respectively (OWC, 2012). Most of the study trail sections were located on lower and middle elevations of the Alberta group formation consisting of mainly shale of the Late Cretaceous period and the Blairmore group, of the Early Cretaceous, consisting of mudstone, sandstone, and siltstone (Hamilton, et al., 1998; Glass, 1997). Surface soils comprising OHV trails are most commonly Brunisols with poorly developed horizons, though some trail sections were also situated on organic/peaty or coarse colluvial deposits

3.2.2 Study Design

A controlled process-based rainfall simulation study was employed to explore the variation in runoff, erosion, and erodibility as a function of physical trail characteristics and trail use intensity. Trails in the North York, Star, and the Allison creek regions were selected as broadly representative of variability in these characteristics in the study region. Twenty three rainfall simulation experiments were carried out over the summer season of 2015 in three periods from June 29 -July 9, August 19-August 23, and Sept 17-18 using consistent rainfall intensity and precipitation depth. Total and peak runoff, time to runoff initiation, sediment concentration, total erosion, and sediment load (mass/volume runoff) during rainfall simulations were recorded and related to plot and trail characteristics.

While the study was not initially designed to consider OHV traffic intensity as a factor to be evaluated, preliminary analysis indicated trail use intensity as indicated by the presence or absence of significant litter/grass cover on trails was a strong factor governing variation in erosion response and was thus included as a factor in the study (see 3.2.4.2).

3.2.2.1 Rainfall Simulator Construction

A rainfall simulator was constructed using a pump to supply water to a nozzle mounted on an elevated wooden platform attached to the tripod legs. Pressure monitoring and valves were used to control rainfall depth and intensity for plot scale rainfall simulations (Covert & Jordan, 2009). A 4 stroke Honda Wx10 water pump was used with a 125 L enclosed water barrel as a water source. A spray nozzle (¼ inch HH-WSQ, Spraying Systems Co., Wheaton, IL, USA) with a ball valve was used to stabilize water output pressure to 3-4 p.s.i. which was the minimum possible pressure that could cover the entire plot while maintaining drop sizes comparable to those in natural rainstorms. The simulator was capable of simulating a low intensity storm (see 2.3.2.3 below) with average drop size diameters ranging from 0.8-2 mm. It was necessary to use a windbreak during rainfall simulation and keep rain directed towards the center of the plot using a wind shield surrounding the simulator constructed from a dome tent with the bottom removed after Foltz *et al.* (2009) (Figures 3-3 and 3-4).

Runoff and sediment generation was measured during rainfall simulations using a fixed rectangular plot frame (1.25 x 0.8 m; 1.0 m^2) constructed from steel angle iron nailed to the trail surface with 8 in framing nails. Layers of foam were used under the steel frames to ensure a watertight seal between the ground and steel plot edges (Figure 3-6). A sheet metal pan with a circular outlet was used at the bottom of the plot to collect water and sediment during rainfall simulations after Sheridan et al. (2008). The pan was sealed against the ground surface using closed cell latex foam and nailed to the ground. A clear plastic cover over the pan was used to exclude rainfall on the pan from runoff measurements.

3.2.2.2 Rainfall simulator calibration

Prior to use, the simulator was calibrated for rainfall intensity, rainfall depth, and average drop size to ensure that simulation fell within the natural range for low intensity storms (Laws & Parsons, 1943). Pump speed and pressure were adjusted to produce approximately 7.5 mm of precipitation in 20 min (equivalent to ~22.5 mm hr^{-1}. rainfall intensity; see 3.2.2.3). Ten replicate rainfall simulations were used to confirm reproducibility of the target rainfall depth and intensity, and characterize the distribution of rain drop sizes produced by the simulator. Nine tin cans placed evenly within the 1 m^2 plot frame were used to measure rainfall depth (by weighing) and calculate rainfall intensity during the calibration runs. A constant pump speed and pressure (3-4 p.s.i.) were used during both calibration and subsequent plot measurements.

Total rainfall during the ten simulated storms ranged from 6.5-8 mm though most calibration runs (8) fell within 7.0-7.8mm, over a 20 min. period producing an average rainfall intensity of 22.5 mm.hr (19.5-24 mm hr^{-1}). Drop size distribution was measured using an oil drop method using oil filled petri dishes and a camera to measure drop size at impact (Eigel & Moore, 1983). Oil filled petri dishes were subjected to simulated rain for a few seconds; the dishes were then placed on a black background with a camera mounted above enabling measurement of drop sizes. Rain drops ranged from 0.8-2 mm with the majority falling within the 1.0 to 1.4 mm range (Figure 3-5).

3.2.2.3 Rainfall intensity and erosivity (R Factor USLE)

Historic rainfall data (2005-2013) from SRWP rain gauge networks in Star and North York Cks. was used to characterize average summer rainfall intensity in the study region using intensity-duration-frequency (IDF) analysis (Silins, unpublished). Rolling 20 minute total rainfall data was used for rainfall intensity-duration-frequency (IDF) analysis to characterize the frequency of storms of varying intensity in this region. Based on this analysis, a 1-2 yr. return period 20 min. storm is between 13.6-23.4 mm hr^{-1} in this region While the early objective was to attempt to simulate a high but regionally common rainfall intensity, based on practical limitations in the lowest steady pump flow rates that could be maintained, a target rainfall depth of ~7.5 mm over 20 min. (rainfall intensity of ~22.5 $mmhr^{-1}$, 1.9 yr. return period storm) was selected for rainfall simulation measurements in this study. On average, a storm of this magnitude would be expected to occur every ~2 years or would have a ~50% annual probability of occurrence in this region.

The corresponding R factor (erosivity) for this rainfall intensity was subsequently calculated from Eq. 2.5 (Chapter 2) as:

Equation 2-5 $R = e_k v_k I_{30}$

$= (0.119 + 0.0873 \log_{10}(22.5885) * 7.5295) * 22.5885 = 40.34 \text{ MJ mm ha}^{-1} \text{ hr}^{-1}$

3.2.3 Rainfall Simulation

Rainfall simulations on recreational trail plots were conducted during dry days in June, July, August, and September 2015. Measurements required approximately 3 hr/plot including plot set up, measurements, and plot disassembly. Microsite selection criteria for each plot included sufficient trail area to accommodate the pan and plot edges, and avoiding extensively stony sites or plots with exposed tree roots to enable plot establishment. Minor plot preparation including digging small pits for the sample collection bottles, and leveling trail sections on plot borders to ensure a watertight seal between the plot border and ground surface was possible. Soil removed from digging pits for sample bottle locations was used to determine antecedent soil moisture, soil texture class, particle size distribution and organic content on the plot. Samples were stored in airtight container, frozen, and then processed in the lab for soil moisture content and sent to Natural Resources Analytical Laboratory (Dept. of Renewable Resources, University of Alberta) for organic content and particle size distribution analysis.

The slope angle (from horizontal) was measured at the 4 plot corners using a level to establish an average slope. A visual survey was used to estimate % cover of plot surface material size classes (boulder, cobble, and finer entrainable sizes), % organic material including roots on each plot.

Rainfall simulation occurred over a 20 min. period, starting as soon as water began to fall on the plot. The time to runoff initiation from the start of the simulation was recorded and samples were collected at the plot outlet 4, 8, 12, 16, and 20 min. from the start of the rainfall in 600ml bottles. The time to fill each bottle was also recorded. After stopping the rainfall simulator, sediment remaining in the pan was collected.

3.2.4 Measurement, Sample Analysis, and Statistical Analysis

3.2.4.1 Sample Preparation and Analysis

3.2.4.1.1 Slope-length (LS) factor (USLE)

The length and area of each plot was kept consistent (125 cm in length by 80 cm wide). The slope was measured on site at each corner in both directions (inward and down) and the average of all the downward slopes was used to determine plot slope for calculation of the LS factor from equation 2-8 (chapter 2), (Wischmeier & Smith, 1978; Wall, et al., 2002; Stone & Hilborn, 2015).

3.2.4.1.2 Cover-management Factor (USLE)

Cover-management factor was estimated at each plot by visual inspection based on the proportion of plot area where soils would be exposed to direct raindrop impact (range from 1.0 [fully exposed] – 0 [fully covered]). Most sites did not have any cover which is expressed as a 1.0 in the USLE equation. There were three sites that had significant organic ground cover, needles in particular; these were assigned a cover-management factor of 0.45 based on the percentage of plot area covered as determined by visual inspection (Wall, et al., 2002).

3.2.4.1.3 Percent Soil Water Content

Percent soil water content (gravimetric water content) was measured on each plot as an indication of antecedent moisture conditions at the time of rainfall simulation (see 3.2.3). Soils sampled on each plot prior to rainfall simulation were stored in sealed bags stored in coolers in the field and later frozen and stored until analysis. In the laboratory, soils were thawed and weighed (in pre-weighed tins) to determine fresh weight, oven dried at 108 degrees Celsius for 3 days and re-weighed to determine dry weight. Gravimetric soil water content was calculated using equation 3-1,

Equation 3-1

$$\text{Soil water content (\%)} = ((\text{wet weight} - \text{dry weight})/\text{dry weight}) * 100$$

3.2.4.1.4 Texture Class, Particle size distribution, and Organic Matter Content

Organic matter content of oven dried samples from water content analyses was determined through loss on ignition of a 5-mg oven dry sub-sample. Samples that had higher than 5% organic content were digested and then particle size distribution was determined using the hydrometer method (Klute, Arnold (Ed.), 1986). Soil textural class was determined from percentage sand, silt, and clay.

3.2.4.1.5 Total and Peak Runoff

The runoff discharge (Ls^{-1}) was calculated by taking 5 sequential runoff samples (4, 8, 12, 16, and 20 min. after start of each rainfall simulation) at the outlet of runoff frame with runoff rate based on the time taken to fill each 600 ml sample bottle. The relationship between runoff rate as a function of time was used to calculate total runoff volume by integrating area under the curve of this relationship, whereas peak runoff was determined from the highest rate of runoff observed from the sequential runoff samples for each plot.

3.2.4.1.5 Sediment Load (A)

The volume of each runoff sample was measured before drying (evaporating) samples in pre-weighed tins. To reduce time for evaporation, clean water was syphoned from the top of the tins after the samples had settled for one week. After the remaining water had evaporated, samples were oven dried for 3 days at 108 degrees Celsius and to measure final dry weight. Sediment load (mgs^{-1}) was calculated for all 5 runoff samples from each plot. Sediment load from all plots showed a clear ascending limb, peak and descending limb of sediment production over time. The total sediment generated from each plot was calculated from the relationship between sediment load (mgs^{-1}) and time (s) by integrating area under the curve of this relationship.

Any sediment remaining in the pan after each rainfall simulation was collected and frozen. This was brought back to the lab and thawed before being dried in pre-weighed tins in the oven for 3 days at 108 degrees Celsius. The total pan sediment weight was recorded for each simulation and added to the total runoff sediment weight for calculation of total sediment (A, see below).

3.2.4.1.6 Measured and Predicted Erodibility (K)

The USLE equation 2-1 (Chapter 2) was rearranged (equation 3-2 below) to solve for erodibility to enable measuring K from erosion measurements during rainfall simulation as follows;

Equation 2-1 $A = R*K*LS*C$

Equation 3-2 $K = A/(R*LS*C)$

where,

A = total sediment produced from runoff ($t\ ha^{-1}$)

R = rainfall erosivity factor ($MJ\ mm\ ha^{-1}\ hr^{-1}$)

LS = slope length factor

C = cover-management factor

Equation 3-2 was used to calculate experimentally measured erodibility (K, $t\ hr.\ MJ^{-1}\ mm^{-1}$) for each plot based on sediment (A) generated by the rainfall energy (R) and plot characteristics (LS and C) during rainfall simulation. A companion estimate of erodibility predicted from plot soil properties (organic matter content %, texture [silt and fine sand%], structural class, and permeability class) was also determined from plot soil properties using equation 2-6 (Chapter 2) to enable comparing measured K against K predicted from soil properties are the most commonly used approaches (standard nomograph) in USLE erosion estimates.

3.2.4.2 Statistical Analysis

During preliminary exploratory analysis, it was clearly evident that two distinct patterns of runoff and erosion were present across OHV trails in this study. Trails with greater forest litter, and grass cover on the trail surface showed a clearly differing pattern of runoff and erosion than those with less organic matter cover. Trails with low litter/grass cover were associated with trails that had received greater previous OHV traffic. Thus, organic matter content was used as a proxy indicator of previous OHV traffic intensity enabling separation of plots between low-use and higher use trail categories as a factor in the analysis. Analysis of both trail characteristics and runoff/erosion parameters was performed for both a) all plots pooled, and b) separated by trail use category.

Variables from both plots on high-use trails and pooled (all trails) variables were found to be not normally distributed, whereas variables from low-use use plots were normally distributed based on Shapiro-Wilk normality tests. Differences in runoff and erosion parameters between high and low-use use plots were compared using non-parametric Wilcoxon-Mann-Whitney rank sum tests using a confidence interval of 95%. The relationship between erosion parameters and trail characteristics were explored using linear regression to evaluate primary OHV trail factors regulating erosion. Experimentally measured erodibility was compared to predicted erodibility among high and low-use trail categories using both linear regression and Wilcoxon-Mann-Whitney rank sum tests using a confidence interval of 95%.

3.3 Results

Of the 23 rainfall simulation plots, four plots were excluded including two initial plots where sampling procedures were still being developed and corrected and two additional plots where pump flow rate or plot sediment leakage problems resulted in unreliable results that were omitted from analysis.

3.3.1 Trail Characteristics

While trail characteristics were variable across plots, most plot characteristics (other than slope) were moderately-strongly related to differences in organic matter content (OM) between high and low-use trails. Mean plot slope was 14.4% (5.24 - 32.0%) and was generally uniformly distributed across trail use categories (Table 3-1). However, mean OM of low-use trails was 16.1% (3.1 - 57.3%) compared to 2.8% (1.1-3.9 %) on high-use trails ($p = 0.003$, Table 3-1). Differences in OM among trail use categories were also associated with differences in soil water content and particle size distribution among high and low-use trails. Soil water content was strongly related to OM on both low-use trails and pooled (all) plots ($r^2 \geq 0.9$, Table 3-2) which was not surprising since OM (needles and duff) can retain substantial moisture. Mean antecedent soil water content was 8.96 and 21.9% for high and low-use trails respectively (Table 3-1). Mean primary textural classes across all plots were 60.1% sand, 24.1% silt, and 11.7% clay (Table 3-1), however, differences in OM % was also associated with soil texture on both low-use trails and pooled (all) plots ($r^2 \geq 0.53$, $p<0.068$, Table 3-2). OM was positively associated with % silt and clay, but negatively related to % sand for these two trail use categories. High-use trails were dominated by coarser textured soils (63.2% sand compared to 43.8% in low-use trails), while low-use trails were dominated by finer textured soils (combined clay + silt fractions was 36.8% for high-use trails compared to 56.2% in low-use trails, Table 3-1).

3.3.2 Runoff and Sediment Production

3.3.2.1 Timing of Runoff, Total Runoff, and Peak Runoff

Runoff variables from simulated storms varied moderately-strongly among trail use categories (Table 3-3). Mean time to initiation of runoff took 56 s longer on low-use trails (160 s) compared to high-use trails (103 s, $p = 0.028$). More rapid runoff response on high-use trails was also associated with approximately 2 times greater total and peak runoff; mean total runoff was 8.70 and 3.76 x 10^{-3} m^3 ($p = 0.002$) and peak runoff was 10.55 and 5.51 x 10^{-6} m^3 ($p = 0.003$) for high and low-use trails, respectively. Because the rainfall intensity and storm duration were constant for all rainfall simulations, differences in infiltration among trail use categories inversely paralleled differences in total runoff above (i.e. lower infiltration on high-use trails, data not shown).

While all three runoff variables were linearly related to variation in OM across high and low-use trails (Table 3-2), because OM also co-varied with other trail characteristics such as texture and soil moisture, the relationships of runoff variables with trail characteristics was variably linear or non-linear among low-use, high-use, and pooled plots (Table 3-4). For example, weaker, but significant negative linear relationships (Table 3-2) between OM and peak discharge ($r^2 = 0.36$) and total runoff ($r^2 = 0.24$) were better described as non-linear relationships in some cases (i.e. for peak discharge, Table 3-4). However, the general relationship of all runoff variables with trail characteristics were consistent with the observation of more rapid initiation of runoff, and greater total and peak runoff on trails with greater traffic use (less OM%). Runoff generation was also affected by variation in trail slope, but these relationships were much stronger on high-use trails ($r^2 = 0.84$) where very low-use OM (duff/grass cover) had a weaker modifying effect on infiltration and generation of total runoff. In contrast, on low-use trails with greater OM, the relationship between slope and runoff was much weaker ($r^2 = 0.38$).

3.3.2.2 Sediment Production

Differences in runoff were also strongly associated with differences in sediment load among trail use categories. High-use trails generated nearly 10 times greater sediment (A) than low-use trails (2.10 and 0.22 t ha^{-1} for high and low-use trails respectively, $p < 0.001$, Table 3-3).

Despite the relatively strong association of trail characteristic that would be expected to regulate erosion between trail use categories, and in turn, the moderate association of these differences with differential runoff responses between trail use categories, relationships between many of the individual trail characteristics with total sediment production were not strong. For example, while soil texture classes, OM, and soil water content differed among trail use categories and these, in turn, were associated with differences in runoff variables between low-use and high-use trails, variation in soil texture classes (% sand, silt, clay), soil moisture, and OM were not meaningfully related to variation in sediment production across (pooled) or within trail use categories (Table 3-5, Figure 3-6, Figure 3-7). Rather, variation in sediment production with trail characteristics showed the relationship of erosional responses with trail characteristics reflected two different response populations between low-use and high-use trails, rather than a gradient of erosional responses controlled by gradient in trail characteristics across trail use categories. However, somewhat stronger relationships of sediment production with runoff variables were evident. Sediment load was strongly related to all runoff variables (time to runoff initiation, total and peak-runoff) across trail use categories ($p < 0.045$), however, relationships with runoff were generally not evident within either the low-use or high-use trail groups (Tables 3-4 and 3-5, Figure 3-8). Sediment production was most strongly related to trail slope ($p = 0.005$) where the strength of this relationship was primarily driven by very strong relationships between sediment load with slope in high-use trails ($p < 0.001$) but was not similarly evident ($p = 0.139$) in low-use trails (Tables 3-4 and 3-5, Figure 3-8).

3.3.3 Erodibility

3.3.3.1 Field measured erodibility

Variation in field measured erodibility (K) among trail use categories strongly paralleled the pattern of differences observed for sediment production. Erodibility of high-use trails was over 10 times greater than that observed on low-use trails (0.090 and 0.008 t hr. MJ^{-1} mm^{-1} for high and low-use trails respectively, $p < 0.001$, Table 3-3).

Variation in erodibility among trail use categories was more strongly related to variation in most trail characteristics that would be expected to affect inherent erodibility of soils (particle detachment from rainfall splash erosion). K was linearly related to both trail OM ($p < 0.026$) and soil moisture content ($p < 0.057$) on low-use trails (Tables 3-4 and 3-6, Figure 3-9). Similarly, K was linearly related to variation in % sand and clay size fractions across all plots ($p < 0.04$, Table 3-6) but not within trail use categories where the variation in textural classes was less than that observed across categories (Figure 3-10). Lastly, K was also linearly related to variation in all runoff variables (particularly for pooled plots) likely reflecting the combination of factors related to OM/soil moisture and soil texture above (Tables 3-5 and 3-6, Figure 3-11). However, it is important to note that despite the finding of significant linear relationships between K and trail characteristics expected to regulate inherent soil erodibility, the clearest variation in erodibility was between the two populations of trail use categories, rather than strong continuous relationships with trail properties across trail use categories.

3.3.3.2 Predicted erodibility

The inherent erodibility predicted from measured soil properties on trails was both lower and less variable than field measured K. In particular, median predicted K was 5.4 times lower than measured K on high-use trails (0.090 and 0.020 t hr. MJ^{-1} mm^{-1} on high and low-use trails respectively, $p < 0.001$), whereas no difference in the distribution of predicted and measured K was evident in low-use trails ($p = 0.456$, Table 3-3, Figure 3-12).Variation in predicted K was much lower than that observed for measured K and no meaningful relationships were evident between measured and predicted K either within or across (pooled) trail use categories (Figure 3-13).

3.4 Discussion

The primary objectives of this research were to characterize erosion from OHV trails in Alberta's Rocky Mountain region and investigate variation in sediment production and erodibility (K) as a function of physical trail characteristics and trail use intensity. More specifically, to evaluate runoff, sediment production, and erodibility (K) on OHV trails of with variable physical characteristics and trail use intensity, and to evaluate the commonly used method of obtaining erodibility (K) -using the generalized nomograph approach of USLE, in order to assess the accuracy of USLE for predicting erosion.

Overall, runoff, sediment load and erodibility from OHV trails were much higher than anticipated. Rainfall intensity used in this research was representative of high, but more commonly occurring storms (22.5 mm hr^{-1}, <2 yr. return period storm) which resulted in mean sediment production of 1.67 tonnes ha^{-1}. These findings are approximately consistent with estimates from the very few previous studies that have documented erosion from OHV trails, though variation in rainfall intensity and duration among studies limits such comparisons. For example, using rainfall simulation of larger, longer duration storms (44 mm hr^{-1} over 45 min.), Sosa-Perez and MacDonald (2017) observed mean sediment production from 0.43 tonnes ha^{-1} on unsealed roads where OHV traffic was excluded in Colorado, USA. After 80 OHV passes, erosion rates tripled to 1.29 tonnes ha^{-1} approximately similar to that observed in this study. Differences in parent geological material and soils (granitic in Colorado compared to sedimentary in south west Alberta) is likely source of variation among these studies. Similarly, in a comprehensive study of OHV trail erosion across 7 U.S. states, while sediment production of up to 20 tonnes ha^{-1} was reported using simulation of very high precipitation (100 mm hr^{-1}, 30 min.), high variability was observed across regions of differing soils, trail physical characteristics, and trail use intensity.

Traffic intensity has been previously identified as an important modifier of variation in erosion from forestry roads (Reid & Dunne, 1984; Ziegler, et al., 2000; Luce & Black, 2001). In the present study, I found sediment production from high-use trails to be approximately 10 times greater than that of low-use trails. Indeed, when rainfall simulation results were evaluated for low-use and high-use trail intensity classes (based on OM% as a proxy indicator), moderate to strong variation in runoff, sediment production, and erodibility were evident across these trail use categories. While similarly strong effects of trail use intensity (low, high) on sediment production from footpaths (walking trails) and roads have been reported Ziegler et al. (2000), some studies have reported significant but slightly weaker effects of traffic on erosion from roads. Both Sheridan et al. (2008) and Sosa-Perez and MacDonald (2017) found that erosion increased by only 4 and 3 times respectively between simulations on their highly used and lightly or unused roads. Again, the differences in the effects of vehicle traffic on erosion among studies likely relate more closely to the physical characteristics of the roads and trails and how these, in turn, affect erosion mechanisms.

The primary difference in the physical characteristics of our high-use and low-use trails was related to their ability to generate runoff. Flow related factors are considered dominant factors driving erosion (Bryan, 2000). Early models for predicting erosion started out as simple slope length equations and evolved to include storm energy and runoff related parameters (Meyer, 1984). More recent studies have continued to confirm the importance of surface characteristics associated with runoff including slope and infiltration capacity (Bilby, et al., 1989; Luce & Black, 1999). For plots in this study, organic matter was observed to be a good proxy for determining traffic intensity and which explained much of the variability in runoff and sediment production from study plots. This was largely because variation in organic matter was strongly associated with other physical factors more directly regulating runoff generation and erosion. For example, heavily compacted trails are not conducive to plant growth, have lower infiltration rates, and less surface roughness limiting runoff (Voorhees, et al., 1979; Unger & Kaspar, 1994; Bryan, 2000).

On low-use trails there were strong negative relationships between organic matter content and both peak discharge and total runoff (Table 3-6), that in turn, were associated with much lower sediment production. These trails were less compacted, had higher infiltration rates, and had greater fraction of vegetation (grass and moss) that all act to limit runoff and erosion (Heede, 1984; Croke, et al., 1999; Bryan, 2000). This general finding is also consistent with many studies showing lower rates of erosion from the undisturbed forests compared to that from road surfaces (Ziegler & Giambellucca, 1998; Luce & Black, 2001; Pan & Shangguan, 2006). In contrast, variation in runoff, sediment production, and erodibility from high-use trails with low OM% was more closely related to other physical trail conditions such as plot slope. Because of the lack of plant / duff cover on high-use trails that would otherwise affect surface roughness and flow velocity, plot slope was an important factor on high-use trails as it regulates runoff power, shear stress, and energy erode and transport entrainable sediments. Other studies have reported greater erosion and sediment transport with increasing slope because of its negative association with infiltration rates (Fox, et al., 1997).

Predictability of erosion relies on accurate modelling parameters. However, the predicted erodibility (K) based on soil texture, organic matter content, soil structural class for many of our plots were far less than the measured using rainfall simulation. This was mainly driven by the greater sediment loss occurring on high-use trails. Similar findings showing divergence of predicted and measured K on higher intensity of use OHV trails was reported by Meadows et al. (2008). This result suggests that using the USLE without field-verified erodibility measurements could significantly under predict the amount of soil loss from OHV trails in the southern Rockies. Field verification of erodibility values is not common for regions that employ the ULSE and its variants for sediment management and research (Wang et al., 2013). Lack of reliability of USLE predicted erodibility was also reported by Sheridan et al. (2008) while exploring alternate expressions for erodibility (none of which were accurate) from experiments on simulation plots to predict erosion from long term plots. This represents a potentially significant limitation to use of USLE or allied models based on USLE relationships for the broad prediction.

While K predicted from soil properties only marginally lower than measured K on low-use trails, K predicted from soil properties underestimated measured erodibility by approximately 5.5-fold. Erodibility for many erosion models is based on the particle size distribution and bulk soil characteristics. The fraction of silt and fine sand is positively associated with K, whereas clay and sand fractions describe resistance to erosion (Wischmeier & Smith, 1978). In this study, trails with greater clay were indeed, associated with reduced K, while there was a weak positive relationship between K and sand. However, while K predicted from soil properties was nearly 2 times greater for high-use trails than low-use trails, K predicted from soil properties was still underestimated by 5.5 times. Furthermore, the finding of courser textured soils on high-use trails (39% greater sand fraction and 31% lower combined silt-clay fractions) suggests historic erosion has already eroded the fine, more easily transported sediments from the high-use compared to the low-use trails. Because sustained higher flow velocities are required to transport larger sediment particles, this may suggest downslope transport distances of sediments from high-use trails may be substantially less than that of sediments from lower use trails, likely because transport of fine sediments from high-use trails has already occurred in the past.

This may be related to both greater sediment availability and runoff on higher trail use plots. Some researchers have speculated that trail and road usage increases the available sediment of unpaved road surfaces where mechanical action of traffic loosens sediment while compacted road/trail surfaces increase runoff (Voorhees, et al., 1979; Ziegler, et al., 2000). However, the influence of this factor is not represented in either USLE nor the relationships used to predict K from soil properties. While more recent efforts to model erosion using alternative representation of factors governing erosional processes has occurred (Saygin, et al., 2018), additional research is needed to further understand the modifying of vehicle traffic on K before applying USLE or allied models to erosion prediction from road or trail networks.

3.4 Conclusion

The results of this research show that traffic or rates of OHV trail use is one of the primary factors regulating the generation of runoff, sediment production, and variability of erodibility from OHV trails in Alberta's eastern slopes region. Sediment production was strongly driven by factors governing runoff which differed substantially between high and low-use intensity trails.

For high-use trails the slope of the plot governed runoff and sediment generation, whereas on low-use trails organic matter content reduced erosion rates regardless of the plot's slope. Traffic related variability in erosion resulted in high-use trails generating 10 times more sediment than low-use trails. However, because courser sediment fractions were more dominant on high-use trails, risk of longer distance sediment transport to receiving streams may be somewhat lower than that from low-use trails.

The amount of organic content on trails was useful in classifying trails into high or low recreational vehicle use categories. In this study 4-5% OM content was used as a rough limit for defining high and low-use tails. This should likely be confirmed in future studies.

Our interpretation is that for recreational trails in the Southern Rockies, broadly used models such as the USLE or allied models based on the USLE employing estimates of inherent erodibility (K) do not produce reliable estimates of erosion. While K predicted from soil properties may produce reasonable estimates of erosion from lower use intensity trails, K and sediment production may be significantly underestimated on trails with greater OHV use largely because of the modifying effect of vehicle traffic on K and erosion. Because neither of these are presently represented in commonly used approaches for predicting erosion, modelling of sediment loss from OHV trails with some models may be of highly limited value.

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Table 3-1 Plot and trail characteristics.

Site	Plot	Slope (%)	SWC (%)	OM (%)	Sand (%)	Silt (%)	Clay (%)	Soil Type
				High Use Trails				
1*	2	13.61	4.58	1.52	82.55	11.25	6.20	loamysand
1	3	10.51	2.97	2.77	66.50	20.31	13.19	sandyloam
1	4	32.01	5.00	2.34	67.52	20.35	12.13	sandyloam
2	1	10.07	11.83	2.11	63.55	28.90	7.55	siltysand
2	2	19.44	11.76	3.78	63.21	23.34	13.46	sandyloam
7	1	5.24	7.09	3.42	72.51	17.08	10.41	sandyloam
7	2	10.95	9.94	3.58	68.81	19.04	12.15	sandyloam
8	1	15.84	4.57	3.13	47.45	38.36	14.19	loam
9	1	25.40	6.39	2.51	48.44	30.81	20.75	loam
10	1	8.75	7.17	1.09	76.03	16.21	7.76	loamysand
11	1	8.75	12.12	2.40	74.66	17.33	8.00	siltysand
13	1	24.01	17.35	3.65	43.98	42.55	13.47	loam
14	1	7.43	15.75	3.90	45.99	42.09	11.92	loam
Mean		14.77	8.96	2.78	63.17	25.20	11.63	
Median		10.95	7.17	2.77	66.50	20.35	12.13	
Max		32.01	17.35	3.90	82.55	42.55	20.75	
Min		5.24	2.97	1.09	43.98	11.25	6.20	
				Low Use Trails				
2	3	5.68	9.08	3.06	69.64	19.98	10.39	sandyloam
3*	1	13.17	12.96	7.11	45.40	32.58	22.02	loam
3*	2	14.50	10.81	9.13	40.54	43.59	15.86	loam
4	1	17.63	19.46	15.91	54.81	23.89	21.30	sandyclayloam
4	2	18.53	13.20	14.28	42.60	40.08	17.32	loam
4	3	16.73	72.34	57.25	0.10	67.65	32.25	peat
5	1	26.79	12.95	10.36	70.12	16.67	13.21	sandyloam
5	2	18.53	19.24	20.61	21.22	45.10	33.68	clayloam
6	1	17.18	9.05	4.29	51.69	27.34	20.96	loam
12*	1	11.39	40.19	19.36	41.56	32.31	26.14	clayloam
Mean		16.01	21.93	16.14	43.77	34.92	21.31	
Median		16.96	13.08	12.32	44.00	32.44	21.13	
Max		26.79	72.34	57.25	70.12	67.65	33.68	
Min		5.68	9.05	3.06	0.10	16.67	10.39	
				All Trails (pooled)				
Mean		14.36	8.54	7.56	60.08	24.14	11.63	
Median		14.50	11.76	3.65	54.81	27.34	13.46	
Max		32.01	72.34	57.25	82.55	67.65	33.68	
Min		5.24	2.97	1.09	19.98	10.39	6.20	

* Sites with asterisks were included in analysis of plot characteristics but omitted from analysis of rainfall simulation results (see section 3.3)

Table 3-2 Relationships between percent organic matter content and plot, soil characteristics, runoff variables, sediment production, and measured K. Bold indicates relationships with α < 0.1.

Variable	*Type*	*df*	*Adjusted r^2*	*P value*
Percent Soil Water Content	All trails	18	**0.899**	**<0.001**
	High use	11	0.096	0.172
	Low use	6	**0.960**	**<0.001**
Percent Sand on Plot	All trails	18	**0.635**	**<0.001**
	High use	11	0.159	0.110
	Low use	6	**0.721**	**0.010**
Percent Silt on Plot	All trails	18	**0.525**	**<0.001**
	High use	11	0.125	0.140
	Low use	6	**0.767**	**0.006**
Percent Clay on Plot	All trails	18	**0.563**	**<0.001**
	High use	11	0.034	0.267
	Low use	6	**0.516**	**0.068**
Time to Runoff	All trails	18	0.000	0.887
	High use	11	0.000	0.942
	Low use	6	0.000	0.523
Total Runoff	All trails	18	**0.237**	**0.020**
	High use	11	**0.261**	**0.052**
	Low use	6	0.196	0.177
Peak Runoff	All trails	18	**0.362**	**0.004**
	High use	11	0.080	0.192
	Low use	6	**0.624**	**0.021**
Sediment Load	All trails	18	0.059	0.163
	High use	11	0.000	0.919
	Low use	6	0.135	0.223
Measured K	All trails	18	**0.230**	**0.020**
	High use	11	0.000	0.877
	Low use	6	**0.593**	**0.026**

Table 3-3 Runoff response, USLE input parameters, sediment load, and measured and predicted K from rainfall simulation experiments.

Site number	Plot number	Time to Q (s)	Total Q (m^3 x 10^{-3})	Q Peak (m^3 s^{-1} x 10^{-6})	R (MJ mm ha^{-1} hr^{-1})	C	LS	Sediment load (t ha^{-1})	Measured K (t hr MJ^{-1} mm^{-1})	Predicted K (t hr MJ^{-1} mm^{-1})
					High Use Trails					
1	3	478	3.384	5.430	40.34	1.00	0.30	0.167	0.014	0.011
1	4	41	9.245	15.583	40.34	1.00	1.96	6.365	0.081	0.015
2	1	80	11.127	13.975	40.34	1.00	0.28	0.938	0.082	0.023
2	2	44	13.003	14.641	40.34	1.00	0.81	3.740	0.114	0.012
7	1	106	8.313	9.049	40.34	1.00	0.11	0.578	0.125	0.018
7	2	110	8.216	12.000	40.34	1.00	0.32	1.474	0.114	0.014
8	1	53	10.076	11.875	40.34	1.00	0.58	2.601	0.112	0.034
9	1	47	7.723	8.884	40.34	1.00	1.29	4.560	0.087	0.020
10	1	84	3.514	3.641	40.34	1.00	0.23	0.938	0.101	0.014
11	1	48	6.958	7.926	40.34	1.00	0.23	1.030	0.111	0.017
13	1	63	13.780	14.051	40.34	1.00	1.17	2.225	0.047	0.033
14	1	76	9.091	9.537	40.34	1.00	0.18	0.629	0.086	0.026
Mean		102.5	8.70	10.55	40.34	1.00	0.62	2.104	0.090	0.020
Median		69.5	8.70	10.71	40.34	1.00	0.31	1.252	0.094	0.017
Max		478	13.78	15.58	40.34	1.00	1.96	6.365	0.125	0.034
Min		41	3.38	3.64	40.34	1.00	0.11	0.167	0.014	0.011
					Low Use Trails					
2	3	198	4.126	6.901	40.34	1.00	0.13	0.05	0.01	0.01
4	1	330	1.547	2.847	40.34	0.45	0.69	0.10	0.01	0.01
4	2	150	3.489	5.269	40.34	1.00	0.75	0.24	0.01	0.01
4	3	84	1.626	2.935	40.34	0.45	0.63	0.01	0.00	0.00
5	1	59	3.688	4.991	40.34	1.00	1.42	0.47	0.01	0.00
5	2	154	3.094	4.333	40.34	1.00	0.75	0.17	0.01	0.02
6	1	142	8.732	11.320	40.34	1.00	0.66	0.47	0.02	0.02
Mean		159.6	3.76	5.51	40.34	0.84	0.72	0.216	0.008	0.011
Median		150.0	3.49	4.99	40.34	1.00	0.69	0.169	0.008	0.010
Max		330	8.73	11.32	40.34	1.00	1.42	0.470	0.018	0.022
Min		59	1.55	2.85	40.34	0.45	0.13	0.012	0.001	0.000

Table 3-4 Relationships between erodibility, sediment load, organic matter content, soil water content for trail use categories. Product moment indicates linear associations, while rank order indicates non-linear relationship between variables. Bold indicates non-linear relationships ($p<0.05$).

Variables	*Type*	*N*	*Spearman rank order r*	*P*	*Pearson product moment r*	*P*	*Relationship (*see graphs)*
Erodibility and Organic Content	All trails	19	**-0.577**	**0.009**	**-0.526**	**0.021**	Exponential decay
	High use	12	0.231	0.456	0.050	0.877	None determined
	Low use	7	**-0.929**	**<0.001**	**-0.813**	**0.026**	Linear (low power)
Erodibility and SWC	All trails	19	**-0.539**	**0.017**	**-0.397**	**0.092**	Exponential decay
	High use	12	-0.007	0.974	0.044	0.893	None determined
	Low use	7	**-0.893**	**<0.001**	**-0.741**	**0.057**	Linear (low power)
Total Sediment and Total Runoff	All trails	19	**0.754**	**<0.001**	**0.564**	**0.012**	Possibly exponential
	High use	12	0.455	0.130	0.359	0.251	None determined
	Low use	7	0.500	0.217	0.697	0.082	Weak Linear
Total Sediment and Peak Discharge	All trails	19	**0.749**	**<0.001**	**0.628**	**0.004**	Possibly exponential
	High use	12	0.531	0.071	0.497	0.100	Weak linear
	Low use	7	0.500	0.217	0.635	0.125	Weak linear
Organic Content and Total Runoff	All trails	19	-0.386	0.100	-0.528	0.020	None determined
	High use	12	0.406	0.181	0.573	0.052	None determined
	Low use	7	**-0.857**	**0.006**	**-0.575**	**0.177**	Weak Linear
Organic Content and Peak Discharge	All trails	19	-0.428	0.066	-0.630	0.004	Inverse 3rd
	High use	12	0.210	0.498	0.404	0.192	None determined
	Low use	7	-0.893	<0.001	-0.829	0.021	Strong Linear
SWC and Total Runoff	All trails	19	-0.302	0.205	-0.349	0.143	None determined
	High use	12	0.406	0.181	0.593	0.042	Weak Linear
	Low use	7	**-0.964**	**<0.001**	**-0.510**	**0.242**	Exponential decay
SWC and Peak Discharge	All trails	19	-0.370	0.116	-0.502	0.029	Weak Linear
	High use	12	0.218	0.484	0.313	0.322	None determined
	Low use	7	**-0.964**	**<0.001**	**-0.775**	**0.041**	Exponential decay

Table 3-5 Relationships between sediment load (t ha^{-1}) with trail characteristics and runoff variables for trail use categories. Bold indicates relationships with $\alpha < 0.1$.

Variable	*Type*	*d f*	*Adjusted r^2*	*P value*	*Equation*
Percent Slope of Plot	All trails	18	**0.339**	**0.005**	Y= 0.142x -0.822
	High use	11	**0.842**	**<0.001**	Y= 0.207x -0.978
	Low use	6	0.259	0.139	Y= 0.0188x -0.110
Percent Organic Content	All trails	18	0.059	0.163	Y= -0.0451x +1.789
	High use	11	0.000	0.919	Y= -0.0742x +2.318
	Low use	6	0.135	0.223	Y= -0.00539x +0.312
Percent Soil Water Content	All trails	18	0.037	0.212	Y= -0.0354x +1.906
	High use	11	0.000	0.497	Y= -0.0912x +2.954
	Low use	6	0.141	0.218	Y= -0.00445x +0.314
Percent Sand on Plot	All trails	18	0.000	0.495	Y= 0.0151x +0.577
	High use	11	0.000	0.492	Y= -0.0353x +4.277
	Low use	6	0.049	0.304	Y= 0.00333x +0.0680
Percent Silt on Plot	All trails	18	0.000	0.550	Y= -0.0190x +1.964
	High use	11	0.000	0.833	Y= 0.0131x +1.759
	Low use	6	0.088	0.264	Y= -0.00513x +0.392
Percent Clay on Plot	All trails	18	0.000	0.486	Y= -0.0403x +2.031
	High use	11	**0.214**	**0.074**	Y= 0.281x -1.291
	Low use	6	0.000	0.473	Y= -0.00694x +0.363
Total Runoff	All trails	18	**0.278**	**0.012**	Y= 263.246x -0.403
	High use	11	0.042	0.251	Y= 213.795x +0.243
	Low use	6	**0.382**	**0.082**	Y= 54.324x +0.0115
Peak Runoff	All trails	18	**0.358**	**0.004**	Y= 265127.603x -0.785
	High use	11	0.172	0.100	Y= 270947.483x -0.668
	Low use	6	0.284	0.125	Y= 39957.519x +0.0191
Time to Runoff	All trails	18	**0.171**	**0.045**	Y= -0.00738x +2.320
	High use	11	0.116	0.149	Y= -0.00698x +2.819
	Low use	6	0.000	0.367	Y= -0.000863x +0.353

Table 3-6 Relationships between erodibility with trail characteristics and runoff responses from the rainfall experiment for trail use categories. Bold indicates relationships with $\alpha < 0.06$.

Variable	*Type*	*d f*	*Adjusted r^2*	*P value*	*Equation*
Percent Slope of Plot	All trails	18	0.003	0.320	Y= -0.00151x +0.0834
	High use	11	0.000	0.478	Y= -0.000855x +0.102
	Low use	6	0.000	0.739	Y= -0.000127x +0.0106
Percent Organic Content	All trails	18	**0.230**	**0.020**	Y= -0.00192x +0.0758
	High use	11	0.000	0.877	Y= 0.00191x +0.0840
	Low use	6	**0.593**	**0.026**	Y= -0.000222x +0.0124
Percent Soil Water Content	All trails	18	0.108	0.093	Y= -0.00126x +0.0774
	High use	11	0.000	0.893	Y= 0.000306x +0.0866
	Low use	6	**0.459**	**0.057**	Y= -0.000166x +0.0121
Percent Sand on Plot	All trails	18	**0.180**	**0.040**	Y= 0.00115x -0.00372
	High use	11	0.000	0.390	Y= 0.000737x +0.0442
	Low use	6	0.314	0.111	Y= 0.000128x +0.00272
Percent Silt on Plot	All trails	18	0.080	0.130	Y= -0.00125x +0.0963
	High use	11	0.000	0.424	Y= -0.000820x +0.111
	Low use	6	0.354	0.093	Y= -0.000190x +0.0149
Percent Clay on Plot	All trails	18	**0.300**	**0.010**	Y= -0.00372x +0.117
	High use	11	0.000	0.546	Y= -0.00172x +0.110
	Low use	6	0.124	0.232	Y= -0.000294x +0.0147
Total Runoff	All trails	18	**0.358**	**0.004**	Y= 7.899x +0.00527
	High use	11	0.000	0.625	Y= 1.574x +0.0758
	Low use	6	**0.759**	**0.007**	Y= 1.867x +0.00138
Peak Runoff	All trails	18	**0.300**	**0.009**	Y= 6629.323x +0.00478
	High use	11	0.000	0.845	Y= 581.140x +0.0836
	Low use	6	**0.878**	**0.001**	Y= 1596.690x +0.000544
Time to Runoff	All trails	18	**0.231**	**0.02**	Y= -0.000224x +0.0873
	High use	11	**0.433**	**0.012**	Y=-0.000184x +0.108
	Low use	6	0.000	0.712	Y= 0.00000980x +0.0068

Figure 3-1 Location of rainfall simulation plots near Coleman, AB in the Municipality of Crowsnest Pass. Triangles are the locations of sites on trails later considered as high OHV use intensity, circles indicate low OHV use intensity.

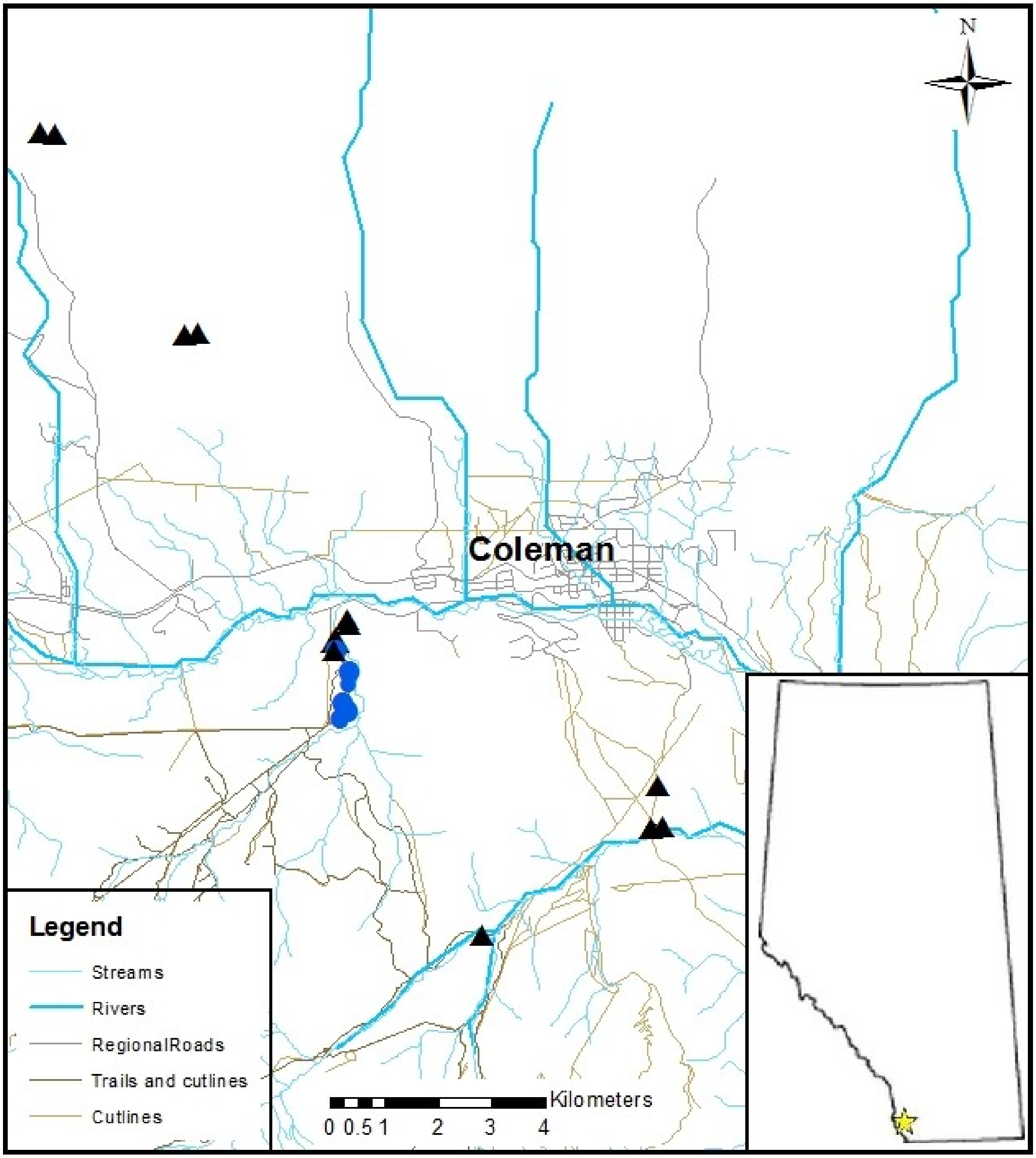


Figure 3-2 Typical example of OHV trail used in rainfall simulations.

Figure 3-2 Photo showing rainfall simulator and runoff plot set up including wind screen. Note: rainfall simulator hidden from view by screen.

Figure 3-3 Diagram of rainfall simulator.

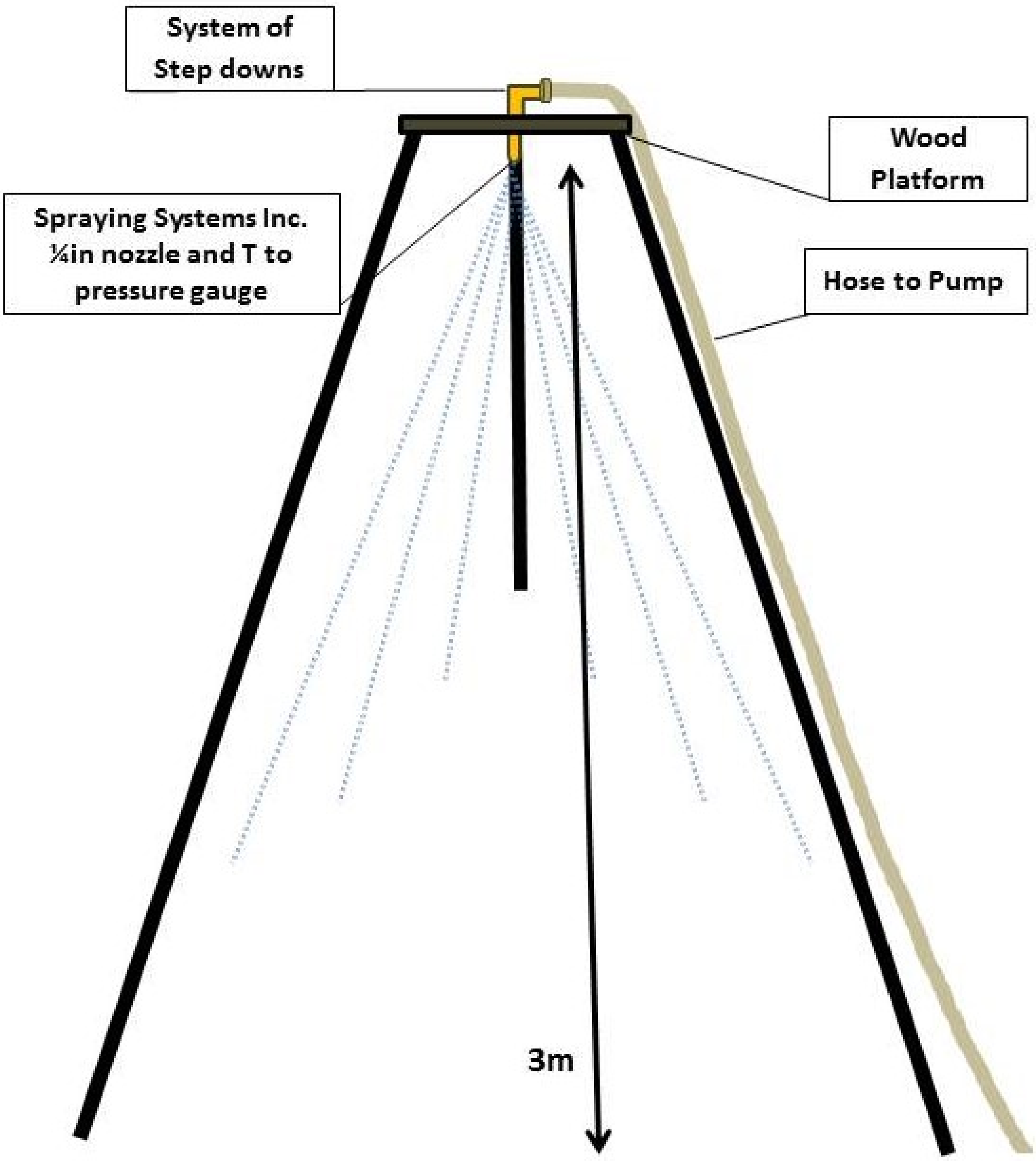


Figure 3-4 Photo of oil filled Petri dish showing drop size distribution after Eigle and Moore (1983). Scale at bottom shows 2 mm increments.

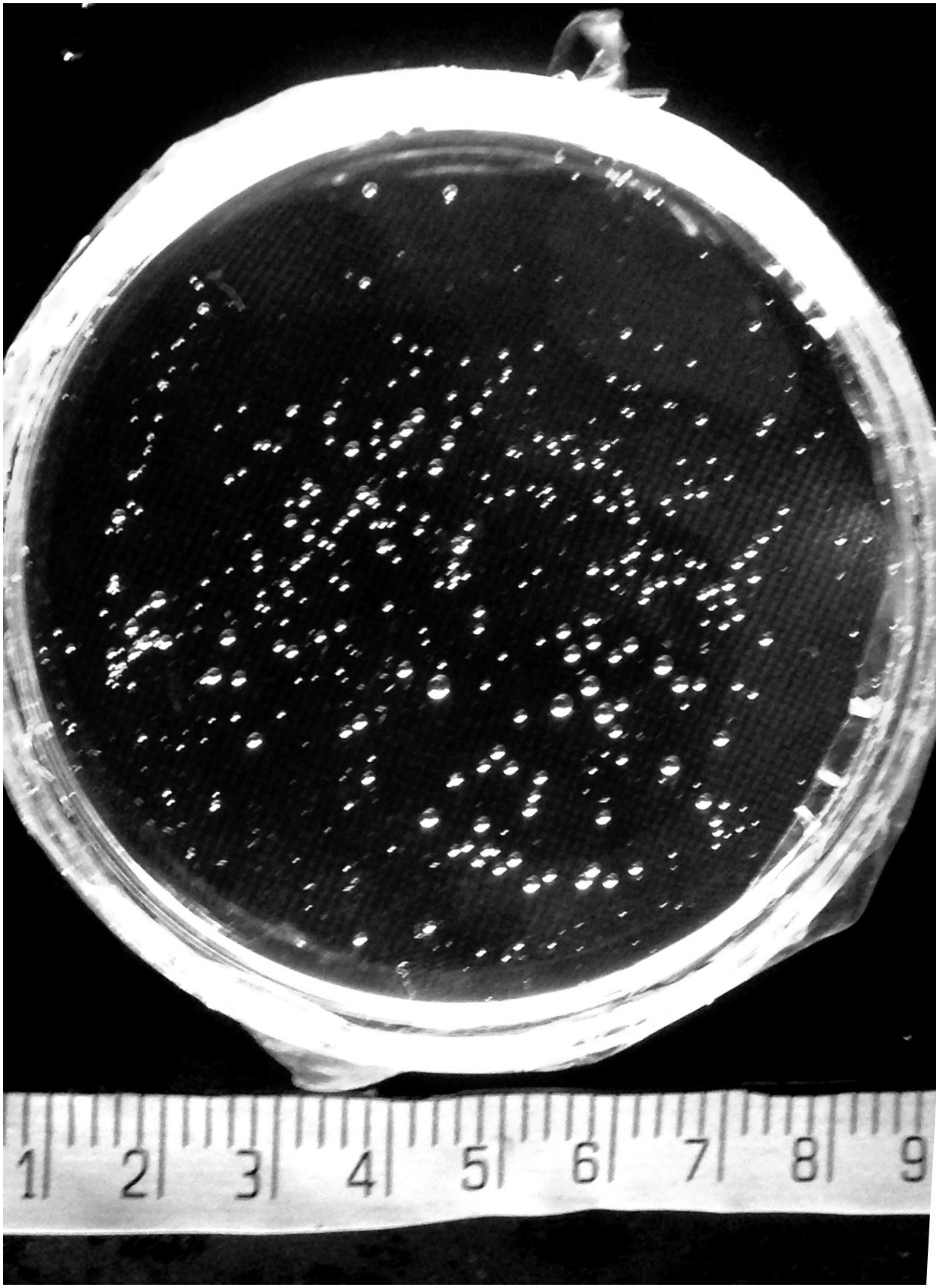
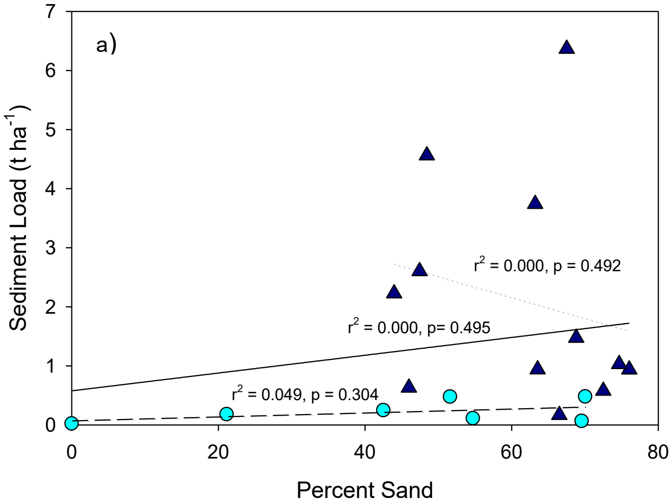
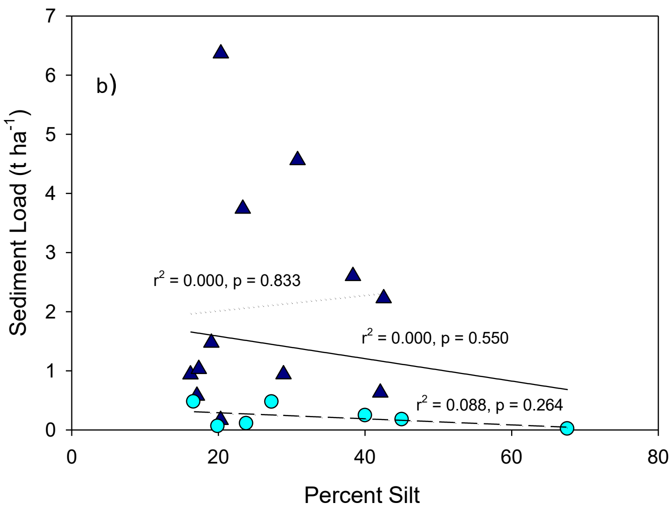


Figure 3-5 Runoff plot frame and sediment collection pan with outlet and rain shield.

Figure 3-6 Relationship between sediment load with soil texture - a) % sand, b) % silt, and c) % clay from runoff plots. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails.





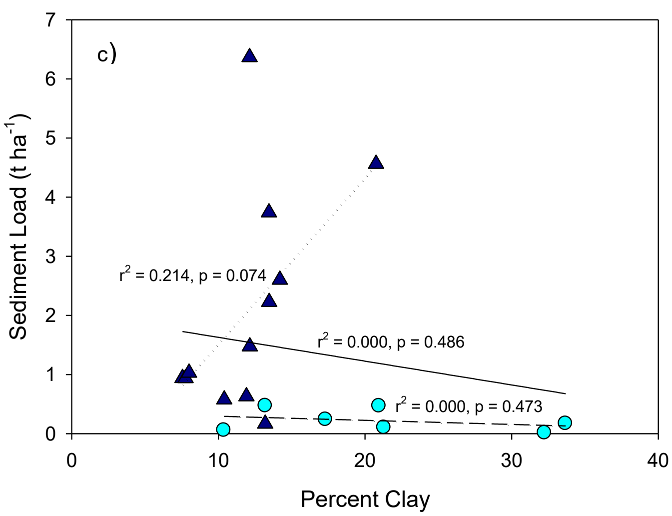


Figure 3-7 Relationship between sediment load with a) plot slope, b) organic matter content, and c) soil water content from runoff plots. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed =low-use trails.

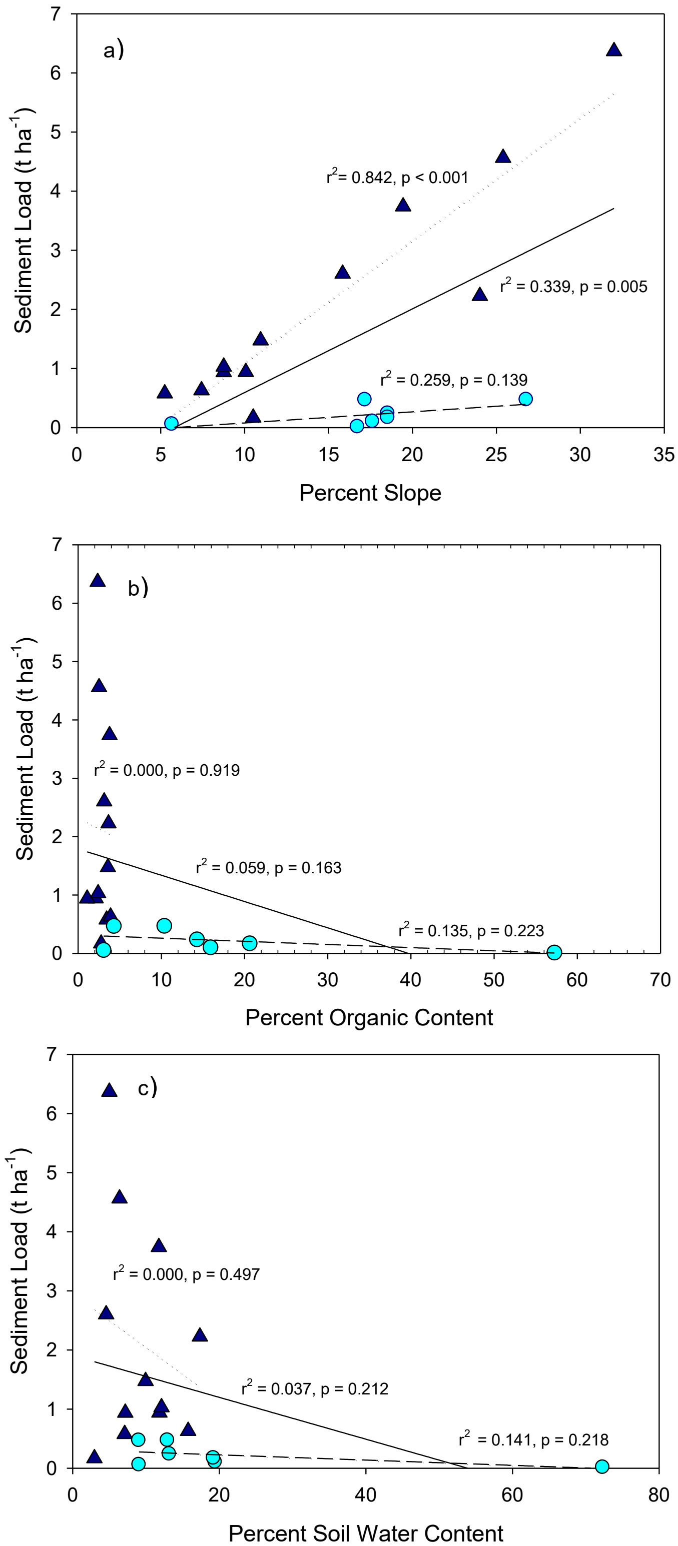
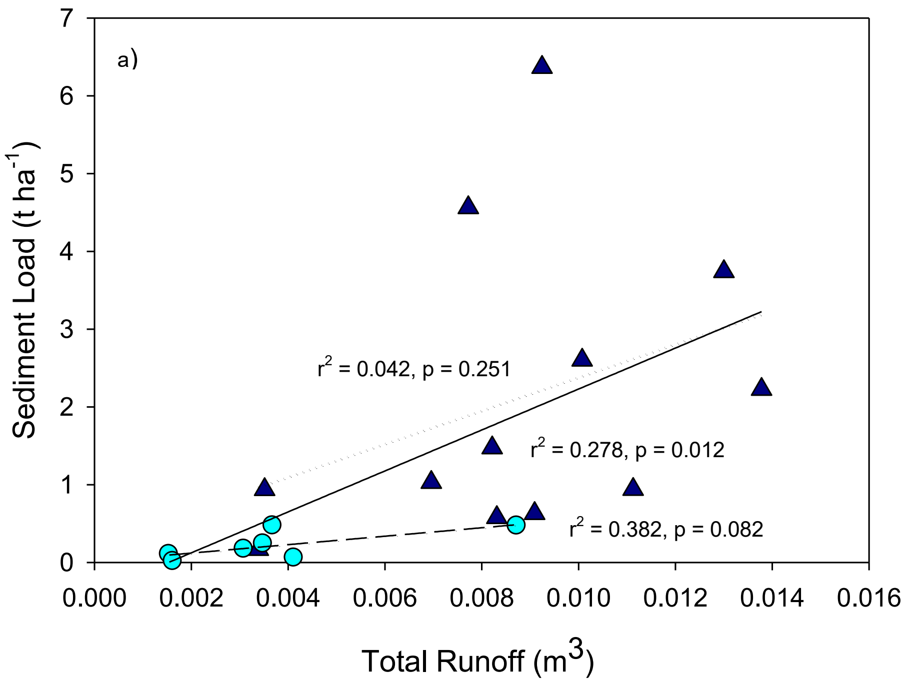


Figure 3-8 Relationship between sediment load with a) total runoff, and b) peak runoff from runoff plots. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high use trails, and dashed = low-use trails.



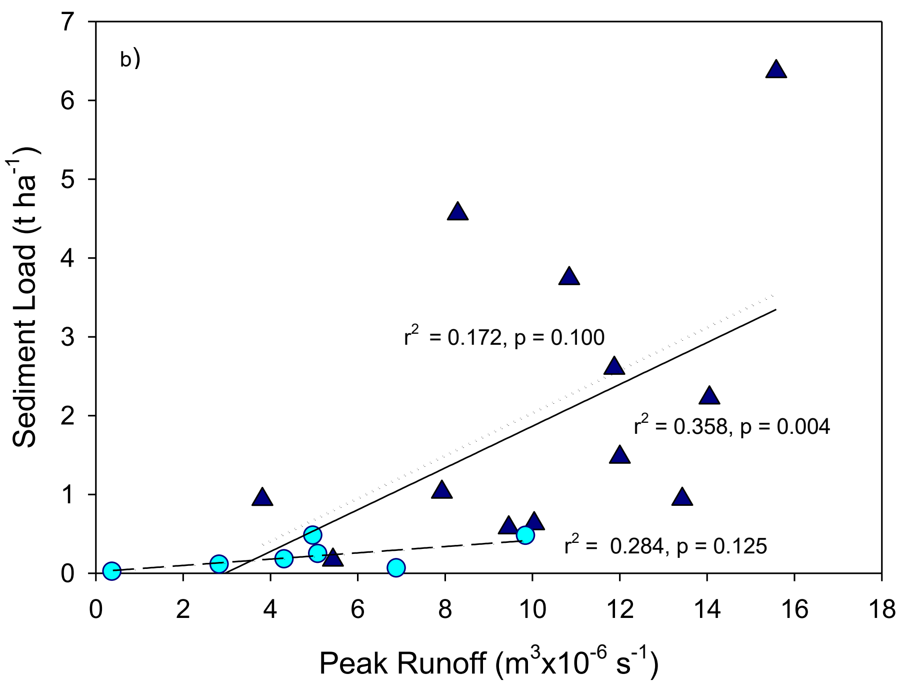


Figure 3-9 Relationship between erodibility with a) plot slope, b) organic matter content, and c) soil water content from runoff plots. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails.

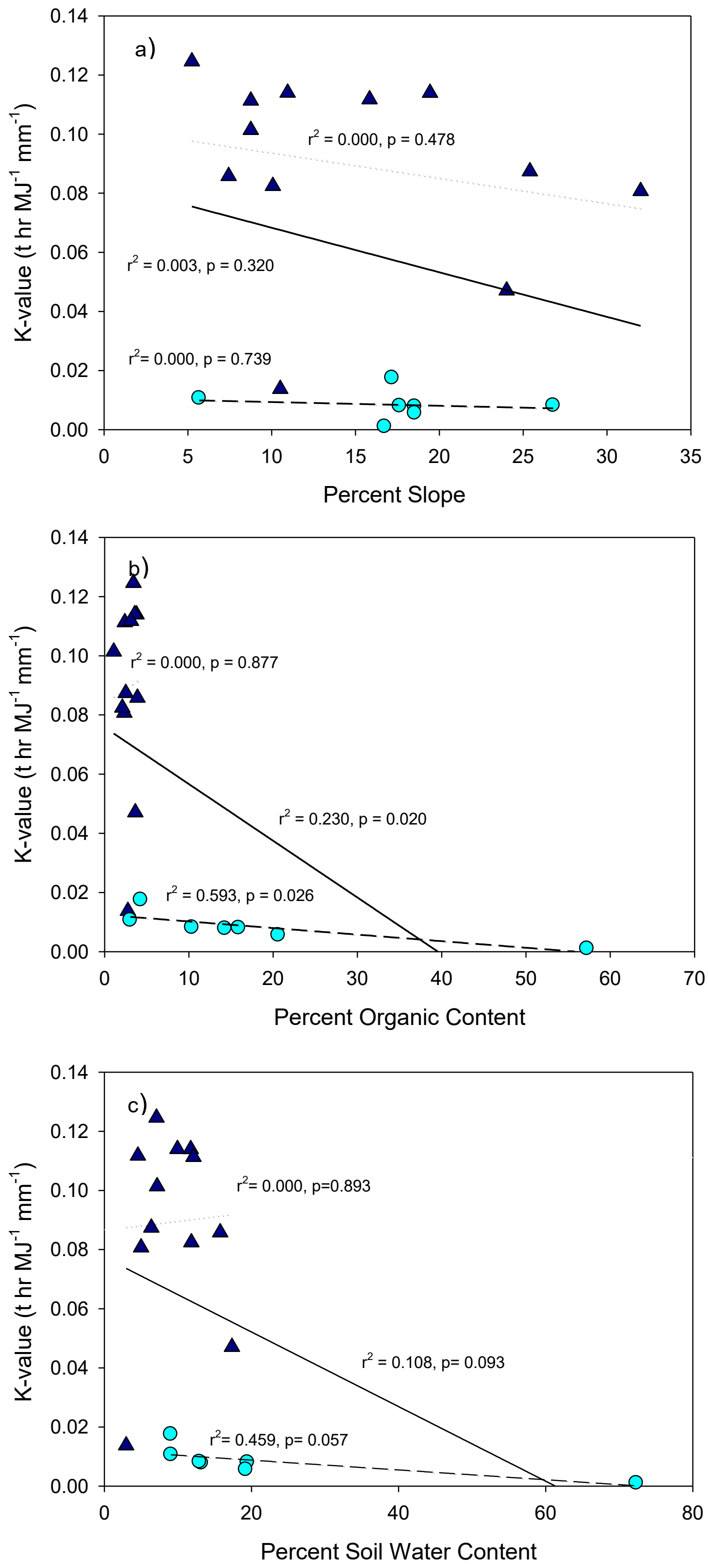


Figure 3-10 Relationship between measured K with soil texture - a) % sand, b) % silt, and c) % clay from runoff plots. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails.

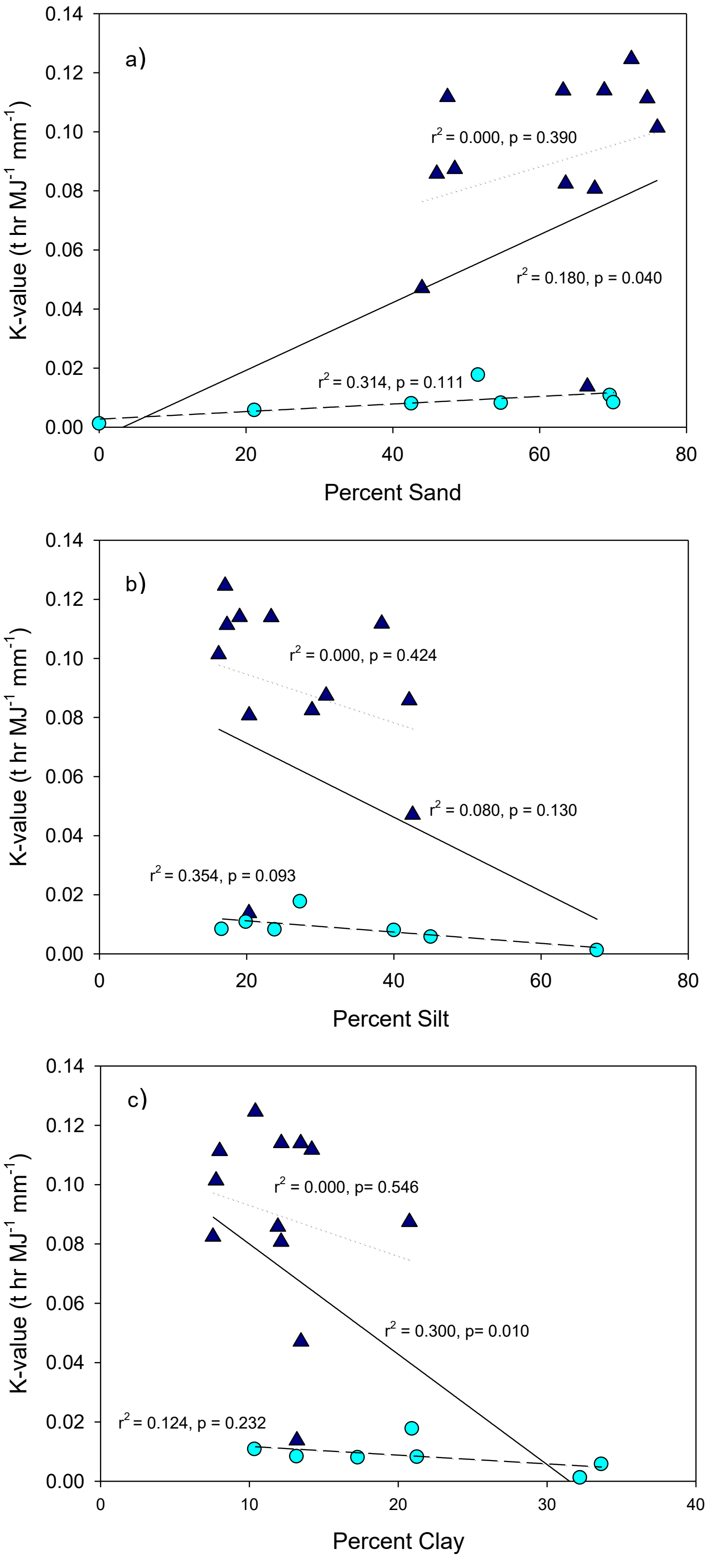


Figure 3-11 Relationship between measured K with a) total runoff, and b) peak runoff from runoff plots. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails.

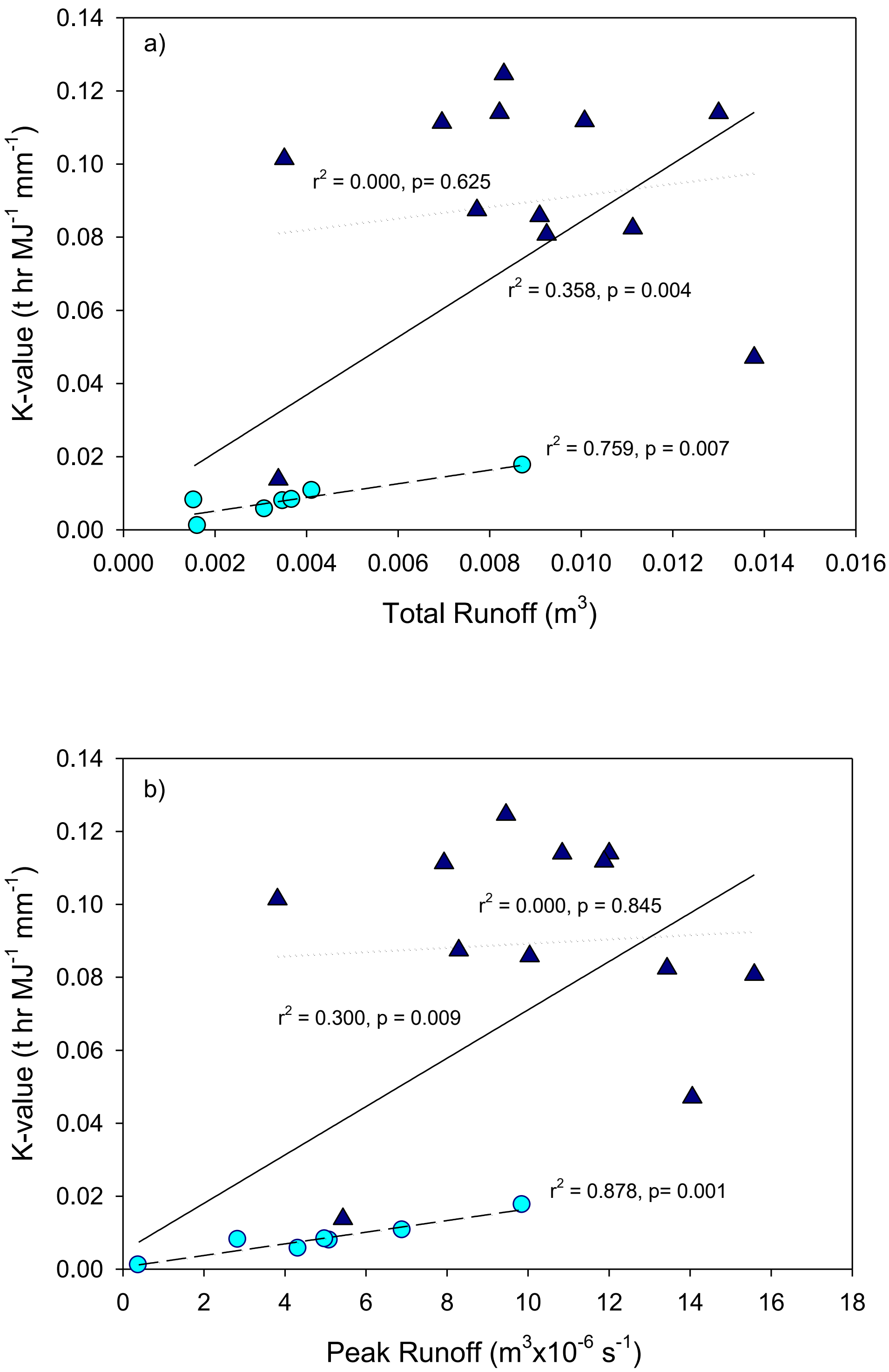


Figure 3-12 Distribution of predicted and measured K across all trails (pooled), low-use, and high-use trails. Horizontal lines indicate median, upper/lower box boundaries indicate 25th and 75th percentiles, whiskers indicate 5th and 95th percentiles, dots indicate outliers.

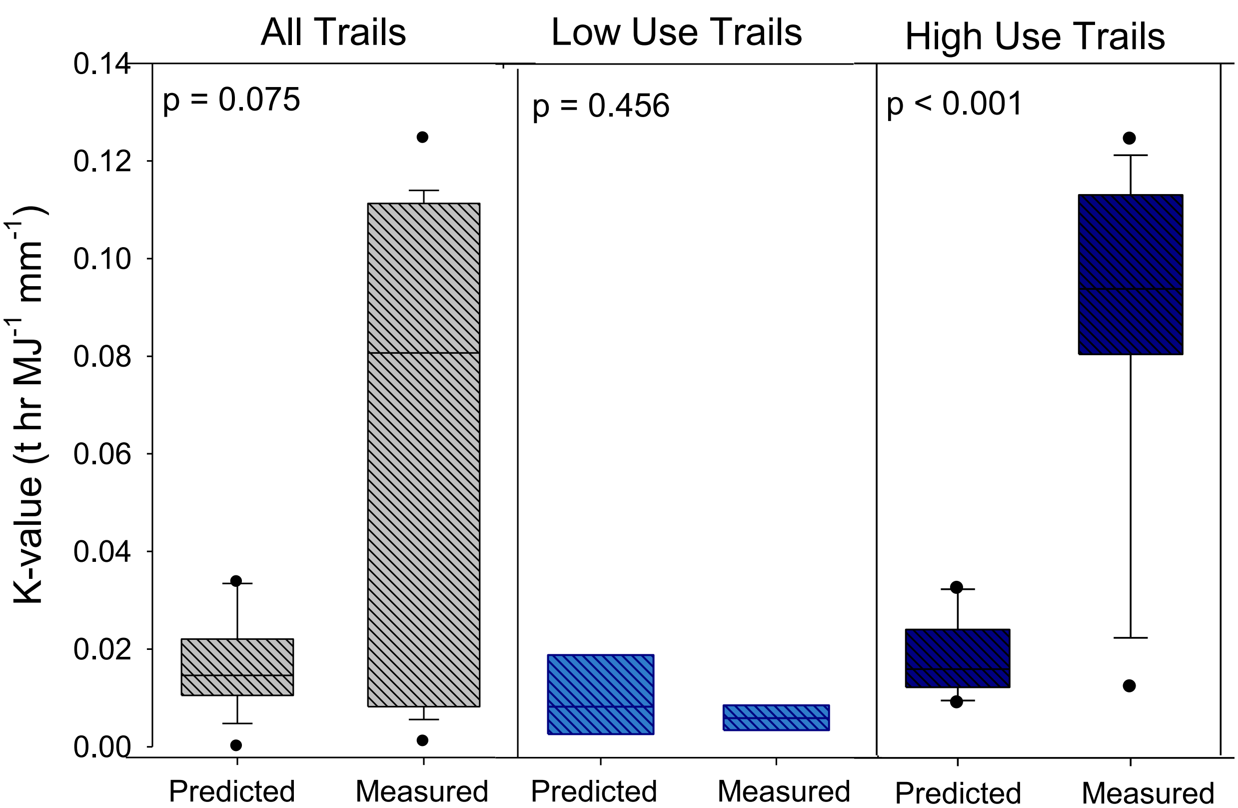
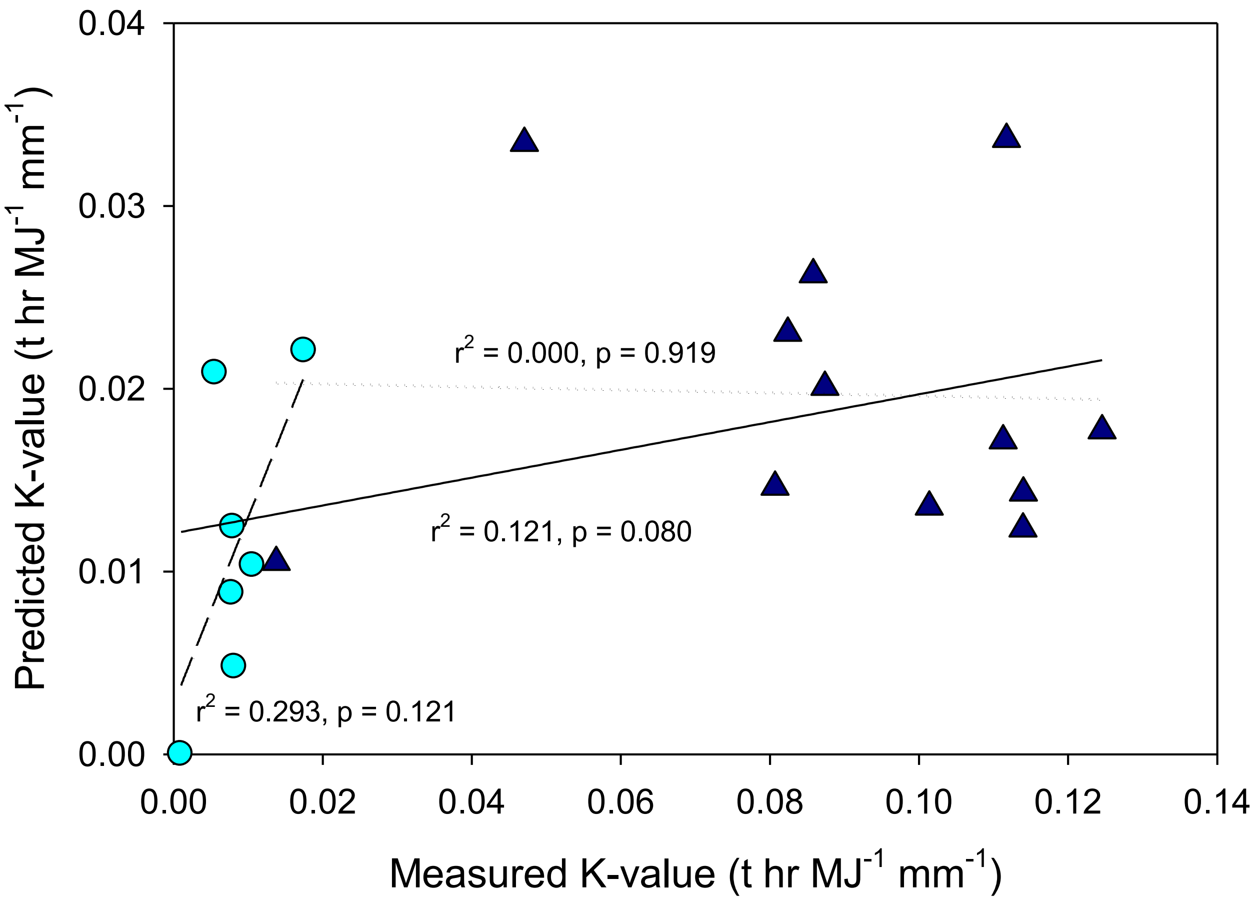


Figure 3-13 Relationship between measured and predicted K. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails.



Chapter 4 Natural Rainfall Observations

4.1 Introduction

Given the popularity of OHV use in the Southern Rockies of Alberta there is an increasing need to understand the potential effects of OHV use in environmentally sensitive areas. Recreational use of OHV trails may present a risk to streams through their potential to deliver sediment during runoff events. Management of OHV trail networks partially relies on the ability to assess potential risks to aquatic life and downstream users from erosion, as related to trail use. Erosion models are a cost effective and efficient way for predicting sediment inputs to streams which could be useful in identifying problem areas for potential mitigation measures. However, there has been no assessment or validation of erosion prediction models for OHV trail use in the Alberta Rocky Mountains region.

Several erosion prediction models have been developed for use on linear features such as roads; the Water Erosion Prediction Project (WEPP) and Geomorphic Road Analysis and Inventory Package (GRAIP) are two such model systems, however, evaluation of these tools in Alberta has only been recently undertaken for resource roads. Both models can be used to scale smaller area or road specific erosion up to a watershed level (United States Department of Agriculture, 1995; Rocky Mountain Research Station Air Water and Aquatic Environments Program, 2018).While these procedures use regionally available spatial GIS and database information, model predictions are often based on generalized estimates of erodibility (K) based on soil texture for which data with sufficient spatial resolution is difficult to obtain. Moreover, it is unclear if such procedures can be applied to OHV trail networks because of lack of information on erodibility of trail surfaces that have been modified by OHV traffic. The most widely used model for erosion prediction is the Universal Soil Loss Equation (USLE), established from decades of soil erosion research following the dust bowl era in the United States. Chapter 2 outlines history, development, and application of USLE in soil loss prediction. The USLE was suggested by Wischmeier and Smith in Agricultural Handbook #537 to be an acceptable tool for predicting erosion from construction sites (Wischmeier & Smith, 1978). It appears in the revised version (RUSLE) in numerous engineering applications including Alberta Transportation's Erosion Control Manual (Alberta Transportation , 2011). The use of USLE for predicting erosion has been widely validated for agricultural plots around the world, which has supported broad application of the USLE in agricultural settings (Barnette & Dooley, 1972; Nolan, et al., 1997; Hamed, et al., 2002). However, the precision of the USLE in other landscape settings, at larger scales, and in areas outside of the United States has not been as extensively validated (Wang, et al., 2013; Saygin, et al., 2018). It is unclear if the primary USLE parameters such as erodibility (K) and erosivity (R) represent key erosional processes with sufficient resolution to adequately predict erosion observed in field experiments (Bryan, 2000; Sheridan, et al., 2000). More specifically, the suggestion that the USLE can be used for predicting erosion across variable land use remain unclear given the simplified assumptions in the USLE regarding interactions between infiltration, sheet erosion, and shear stress (Bryan & Poesen, 1989; Bryan, 2000).

For example, the use of the USLE for erosion prediction on undeveloped roads is far less well established. In particular, high variability of key erosion parameters such as erodibility (K), runoff and sediment yield have been reported across road erosion studies between small plots and large plots and/or between simulated and natural rainfall events on roads. Ziegler et al. (2000) compared sediment concentration from rainfall simulation and natural events and concluded that while higher sediment concentrations are typically observed from more heavily used roads, major challenges exist in comparing erosion studies across varying spatial scales and erosion measurement methods. Sheridan et al. (2006, 2008) found low accuracy of erosion prediction using different measures of erodibility (K) and model variants of USLE. These same authors reported high variation and inconsistent results between erosion studies using natural rainfall and rainfall simulation. Furthermore, variation in roads traffic intensity, road treatments and maintenance regimes among studies (Reid & Dunne, 1984; Bilby, et al., 1989; Ziegler & Giambellucca, 1998; Luce & Black, 2001; Lane & Sheridan, 2002) makes it exceedingly difficult to draw parallels from undeveloped roads to infer erosion or major controls on erosion for OHV trails.

While the very few studies specific to OHV use have shown increased erosion and erodibility on highly trafficked trails/roads in comparison to both decommissioned roads and undisturbed forest soils (Sosa-Perez & MacDonald, 2017; Meadows, et al., 2008) the decommissioned roads evaluated in these studies are not representative of undeveloped OHV trails typical in Alberta's

Rocky Mountain region. Furthermore, only one study (to my knowledge) has attempted to validate erosion models (WEPP and SEDMODL2) on OHV trails concluding that neither were accurate at predicting sediment loss from OHV trails and roads in the Upper South Platte River Watershed (Welsh, 2008).

The limited research on erosion from both undeveloped roads and OHV recreational trails suggests that considerable additional research is needed to better understand factors controlling erosion from OHV trails prior to potential application of erosion models for the prediction of erosion from trail networks as management tools. In particular, a) it is unclear if the factors controlling erosion from OHV trails at the small plot scale (Chapter 3) provide meaningful insights into erosion and sediment production at larger scales characteristic of actual OHV trails or trail networks, and b) if insights into erosion processes and factors controlling erosion from OHV trails from controlled rainfall simulation studies are reasonably representative of actual erosion produced from natural rainfall.

Accordingly, the broad objectives of this study were to determine erodibility, runoff, and sediment generation from larger OHV trail sections under natural rainfall conditions in Alberta's Southern Rockies and explore the variation in both sediment production and erodibility (K) as a function of physical trail characteristics and trail use intensity. The specific objective of this study included a) characterizing the variation in sediment generation and erodibility (K) under natural rainfall conditions across precipitation events of variable magnitude and intensity among trails of contrasting physical characteristics (slope, organic matter content, trail surface stoniness and canopy cover) and trail use intensity, and b) evaluating the similarities and differences in sediment generation and erodibility (K) measured from rainfall simulation studies (Chapter 3) with those produced by naturally occurring rainfall.

4.2 Methods

4.2.1 Study Area

This research was conducted in Southern Alberta on recreational trails in the Crowsnest Pass region (49°37N, 114°40W). This region receives heavy OHV use from spring through late fall from recreational users in Alberta and elsewhere. A more complete description of the study area, topography, and climate is presented in Chapter 3.

4.2.2 Study Design

This study employed the use of large, variable-sized erosion plots to measure sediment production from OHV trails of variable trail physical characteristics (slope, organic matter content, trail surface stoniness and canopy cover) from late spring to early fall 2014. Erosion plots were selected on an existing network of OHV trails in the Star Creek and North York Creek watersheds south of Coleman, Alberta (Figure 4-1) both because of their variable trail use intensity and pre-existing climate data availability. Within the population of potential trail sections, plot selection criteria included trail sections where runoff would be largely constrained to the trail (avoiding side-slopes) and the length of the trail section receiving precipitation and producing runoff could be clearly defined (i.e. trail segments with a small topographic high and low that would receive and discharge runoff). Potentially suitable trail segments were randomly situated across the two watersheds. Trails located in North York Creek (1540-1640 m. elevation) were situated along a 3.8 km loop of heavily used recreational trails. Trails located in Star Creek (1425-1540 m. elevation) appeared to receive less use than those in North York Creek.

Sediment diversions and silt fences were constructed on each plot to divert and capture the sediment loss over from June 13 until September 28, 2014. Sediment was collected, weighed, and sampled across 16 different trail sections with a total length of about 20 kilometers and 39 total observations. While OHV traffic intensity was not initially considered as a factor for assessment, preliminary analysis of the data from rainfall simulation (Chapter 3) indicated trail use intensity, as shown by the presence or absence of litter/grass cover on trails, was a strong factor governing variation in erosion response and was thus included as a factor in these studies. In this particular research several trail physical characteristics; trail width, canopy cover, and organic content, are characteristics related trail use intensity.

4.2.2.1 Sediment Diversions and Traps

At the bottom of each trail segment (plot), V-notch trenches were excavated across the trail at a 30 degree angle from the trail edge to divert runoff off of the trail into a collection trap, with the highest section of the trench on the outer edge of trail opposite the collection fence (see figure 4-2, and 4-3). Trenches were supported with 8 x 2 in. wooden beams to prevent filling of the trench caused by OHV traffic. Lumber was reinforced with 2 ft. long pieces of rebar. Nilex™ geotextile silt fencing material was used to line the trench and held in place using 8 in. framing nails and plastic washers (figure 4-3).

Off-trail sediment traps consisting of semi-circular silt fences (30-50 cm high supported by vertical posts) were excavated and lined with overlapping Nilex, and anchored to the ground with large nails. The surface and trail margins were similarly lined with overlapping Nilex. Trail margins (front) and sides adjacent to the trail contoured to form a lip to reduce overflow and spillage prior to Nilex installation. The only flow path into the trap was via the diversion trench or contribution area upslope of the diversion.

Sediment was collected from traps after every significant storm or after several smaller storms over several days. During drier periods in 2014, it was possible to leave traps up to a month prior to sampling. For sediment collection, a temporary weighing station consisting of a large tripod was erected at each site to enable weighing wet sediment shoveled into sturdy 19 L pails (capable of holding ~ 20-25 kg). All sediment/water slurry in each trap was weighed as follows; pails were sequentially pre-weighed using a high capacity hanging scale, filled with sediment from the trap, wet weight was determined for 3 consecutive measurements and the mean weight was recorded, sediment was discarded off trail prior to pre-weighing and filling the next bucket. This was repeated until all sediment from the trap was removed. Three subsamples of representative wet sediment were collected during sediment measurements for later determination of water content to enable correcting total sediment wet weight to equivalent dry sediment weight. Subsamples were stored in airtight containers stored in coolers (later frozen), and then processed in the lab for determination of soil moisture content and final dry weight.

4.2.2.2 Trail Physical Characteristics

Key physical characteristics (width, length, slope, stoniness, % overhead canopy cover, and presence of rutting) were measured on trail segments draining into each trap at the beginning of the season during plot installation. Trail physical characteristics were measured across 5 transects (top, 75-, 50-, and 25% of the total trail sediment length, and at the bottom above the diversion trench) where each transect spanned the full trail width. Long or branched trails had more transects. Trail segment lengths were measured using a tape measure, or using GIS with GPS points collected where significant trail segment length and branching of trail sections occurred. Width was measured at each transect with a tape measure. For trails composed of rut areas, the total edge to edge width was measured and the width of central vegetated strip was subtracted from total width. Width was averaged over the entire plot length. Trail slope was measured using a level at each transect. Slopes were averaged over the entire plot length. Percent overhead canopy cover and percent stoniness were visually assessed at each transect and averaged for the plot.

4.2.3 Sample and Statistical Analysis

4.2.3.1 Subsample/Sample Preparation and Analysis

4.2.3.1.1 Percent Organic Matter

Organic matter content (OM) of oven dried samples from water content analyses samples was determined through loss on ignition of a 5-mg oven dry sub-sample (Klute, Arnold (Ed.), 1986).

4.2.3.1.2 Total Precipitation

Precipitation (P) from each measurement period was measured using the Southern Rockies Watershed Project (SRWP) rain gauge networks in Star and North York Creeks. For each sediment trap/trail segment, the P from the nearest gauge was used, and total P occurring between the time of plot installation and each subsequent sediment collection date was matched to total sediment mass from each collection date.

4.2.3.1.3 Maximum Peak 30 Minute Rainfall Intensity (I_{30})

Maximum peak 30 min. rainfall intensity (I_{30} mm hr^{-1}) was calculated a) to establish R needed for the USLE erosion estimates (see Chapter 2), and b) to explore relationships between sediment production and peak storm I_{30}. Rolling 30 minute total rainfall was calculated from 10 min. time step P data to identify the peak I_{30} for each storm occurring over the season.

4.2.3.2 USLE Parameters

4.2.3.2.1 Slope-length (LS) Factor

The LS parameter used in USLE was calculated from trail segment total length and mean slope as detailed above using equation 2-8 (Chapter 2), (Wischmeier & Smith, 1978; Flanagan, et al., 1995; Stone & Hilborn, 2015).

4.2.3.2.2 Cover-management Factor (C)

Cover-management factor for each trail segment was calculated as the mean of visual estimates for each of the 5 transects for both canopy cover, ground cover, and percent stoniness at each site based on tabular values given in RUSLEFAC (Flanagan, et al., 1995) .

4.2.3.2.3 Erosivity (R)

Erosivity (R, MJ mm ha^{-1} hr^{-1}) was determined for all storms occurring at each plot using equation 2-4 (Chapter 2). This resulted in inclusion of a broader range of naturally occurring storm P energy than the controlled P used in rainfall simulation plots (Chapter 3).

4.2.3.2.4 Sediment Load (A)

The three subsamples collected during sediment sampling of each trap were used to correct field measured total wet sediment mass to equivalent dry mass. Subsamples were thawed to measure wet weight. Samples were dried at approximately 108 ^{o}C until they reached a steady weight (up to 7 days in some cases) and re-weighed (dry weight). Soil water content (gravimetric) was determined using Equation 3-1 (Chapter 3) and average of the soil water content from all three samples was used to estimate the total dry weight of the sediment collected from each sediment trap.

Equation 3-1

Soil water content (%) = (wet weight- dry weight)/dry weight *100

Equation 4-1

Dry weight = (100-soil water content (%)/100) * wet weight

4.2.3.2.5 Erodibility (K)

Erodibility (K) was calculated from sediment load from each plot by re-arranging the parameters in USLE (Equation 3-2, Chapter 3 below).

Equation 3-2 K= A/(R*C*LS)

where,

A = total sediment produced from runoff (t ha^{-1})

R = rainfall erosivity factor (MJ mm ha^{-1} hr^{-1})

LS = slope length factor

C = cover factor

Erodibility was calculated for each rainfall event occurring on all plots; however, erodibility estimated from individual rainfall events was extremely variable and unrelated to any of the trail physical characteristics. Similar findings from previous studies suggest that mean seasonal erodibility (rather than K from individual events) is a more reliable reflection of inherent erodibility of soils (Wischmeier & Smith, 1978; Renard, et al., 1991). Accordingly, total seasonal erodibility was estimated from total (summed) season R and A from each plot.

4.2.3.3 Statistical Analysis

During the initial exploratory analysis of Chapter 3, it became apparent that two distinct patterns of runoff and erosion generation were present across OHV trails in the study (see 3.2.4.2). In keeping with methods of Chapter 3, organic matter content was likewise considered as a proxy indicator of OHV traffic intensity in this study. Trails were partitioned into low-use and high-use trail categories as a factor in analysis. Analysis of both trail characteristics and runoff/erosion parameters was done for both a) all plots pooled, and b) trails partitioned by use category.

Furthermore, because of the highly variable erodibility estimates from analysis of individual rainfall events (see 4.2.3.2.5), relationships between precipitation and erosion variables were explored for both shorter-term event-based observations and seasonal means or totals for each erosion plot.

Variables from plots on high-use trails and pooled (all) trails were not normally distributed, whereas variables from low-use plots were normally distributed based on Shapiro-Wilk normality tests. Erodibility (K) between high-use and low-use plots was compared using non-parametric Wilcoxon-Mann-Whitney rank sum tests using a confidence interval of 95%. The relationships between trail characteristics with sediment production and erodibility were explored using linear regression to evaluate factors regulating erosion.

In order to compare the rate of erosion across experiments all sediment production values were expressed as sediment per unit P. Erodibility from the rainfall simulation experiment (Chapter 3) and sediment per unit P were compared to the large plot observations of total seasonal K from this study (see 4.2.3.2.5) using linear regression. The relationship between trail OM% and slope with total sediment production per unit P was explored using Kruskal Wallace, One way Anova on Ranks followed by Dunn's method for multiple comparisons then verified using and Wilcoxon-Mann-Whitney Rank Sum tests, all at confidence intervals of 95%.

4.3 Results

A total of 39 observations were collected for per cleaning/event-based data and a total of 16 diversion sites were used for seasonal analysis. Of the original 19 diversion sites and 51 cleanings, 3 sites and 5 samples were omitted due to problems with diverting trail erosion into sediment traps (site design), and 7 samples from dependable sites were omitted due to overflow from the diversion or trap.

4.3.1 Trail Characteristics

Consistent with observations from Chapter 3, trail characteristics were both variable and moderately or strongly related to the variability in organic matter content (OM) as a function of trail use intensity. Mean trail slope was 15.0% (7.82 -24.5%), and roughly equally variable across all trails (Table 4-1). Mean trail stoniness was 43.7% (16.6-70.0%, Table 4-1) across all trails. Mean organic matter content (OM) of low-use trails was 20.4% (7.71-53.1%) compared to 3.46% (2.19-5.09%) on high-use trails ($p = 0.02$, Table 4-1). Variance in OM% among trail use categories was also associated with variability in trail width ($p = 0.004$) and percent canopy cover ($p = 0.04$, Table 4-1). Each of these characteristics is representative of trail use intensity; as trail use increases, more trail area is compacted, vegetation is unable to grow, and trails become wider. On low-use trails, leaf and branch litter increases OM. Trail width was most strongly associated with OM% for the pooled data ($r^2 = 0.679$, $p < 0.001$) though moderate to weaker relationships were still evident within each trail use categories (Table 4-1, and Table 4-2). Mean trail width for low-use and high-use trails were 1.74m and 3.01m respectively. Canopy cover was weakly related to OM across all trails (r^2=0.380, p=0.007). Mean canopy cover of low-use trails was 30.2% (0-51%) and 8.56% (0-37%) for high-use trails (Table 4-1).

4.3.2 Precipitation and Peak I_{30}

Precipitation varied over the season and between events/plot cleanings. Trail runoff diversions in Star Creek (mostly low-use trails) were installed prior to those in North York (high-use trails) which was factor in the variation in precipitation observed across each trail use category ($p <$ 0001, Table 4-3 and 4-4). Mean total precipitation for events on low-use trails was 107 mm (30.0-188 mm) and 68.5mm (35.6-146 mm) for high-use trails (Table 4-3). Mean precipitation over the entire season was 275 mm (266-294 mm) and 160 mm (79.5-267 mm), for low-use and high-use trails respectively (Table 4-4).

Maximum peak intensity (I_{30}) was not variable across trail use intensity categories for neither individual events nor across the full season. Mean I_{30} of P events for all trails (pooled) was 15.1 mm/hr (4.57-38.1 mm hr^{-1}, Table 4-3). Mean I_{30} for the full season was 22.57 mm hr^{-1} for all data (10.7-38.1 mm hr^{-1}, Table 4-4).

4.3.3 Sediment Production

Sediment production was highly dependent upon precipitation-generated runoff among differing trail use categories. High-use trails received both lower individual event P and total seasonal P yet generated much greater mean sediment (11.19 and 26.11 t ha^{-1} , Table 4-3) compared to low-use trails (1.16 and 2.89 t ha^{-1}) for both individual event-based and total seasonal erosion measures respectively (Table 4-3 , Table 4-4). Total P and maximum peak intensity were the strongest predictors of sediment generation for high-use trails for the event based data (r^2=0.689 and 0.632 respectively, Table 4-5). For pooled and low-use trails the strongest predictors of sediment generation were related to trail characteristics associated with intensity of use and/or moderating effects on erosion, for example canopy cover (Table 4-5).

High-use trails generated 12.8 times greater sediment per unit precipitation for event based data compared to low-use trails. The mean sediment production per unit of precipitation across events for low-use trails was 0.011 t ha^{-1} mm^{-1} (0-0.038 t ha^{-1} mm^{-1}) compared to 0.140 t ha^{-1} mm^{-1} (0.025-0.306 t ha^{-1} mm^{-1}) for high-use trails ($p<0.001$, Table 4-3). Variation in sediment production over the entire season was also strongly associated with difference in trail use. Over the season, sediment produced per unit of precipitation was 15 times greater on high-use trails as compared to low-use trails (Table 4-4). Mean sediment production per unit precipitation was 0.011 t ha^{-1} mm^{-1} (0.00-0.024 t ha^{-1} mm^{-1}) for low-use trails and 0.166 t ha^{-1} mm^{-1} (0.093-0.296 t ha^{-1} mm^{-1}) for high-use trails.

No linear relationships were evident between sediment production and event precipitation (mm) across all trails (pooled data) whereas relationships somewhat stronger within trail categories. Sediment production was strongly associated with event P on high-use trails ($r^2 = 0.689$, $p < 0.001$) whereas low-use trails showed only a weak positive relationship to event precipitation ($r^2 = 0.125$, $p = 0.076$, Figure 4-4a). A 3.8 km loop of sediment traps on the North York trail system (all high-use trails) all showed strong positive relationships between sediment production with P, regardless of variability in trail characteristics such as slope (r^2= 0.867, $p<0.001$ (Figure 4-4b). While a significant negative relationship between the amount of sediment generated over the entire season and seasonal P was evident, this was likely an artifact of low-use trails receiving more precipitation but generating less sediment compared to high-use trails receiving less precipitation but generating more sediment (Figure 4-4c), rather than a functionally meaningful finding.

Sediment production in response to peak rainfall intensity (I_{30}) for each event was also significant but weak (r^2 = 0.220, p=0.002) across all trails (pooled data). However, relationships between sediment production and peak I_{30} were on stronger high-use trails (r^2= 0.632, p<0.001, Figure 4-5a) and weak low-use trails (r^2 of 0.265, p= 0.014, Figure 4-5a) to event I_{30}.

Trail characteristics affecting the production of sediment were those that showed strong associations with OM%, trail width, and canopy cover, which in turn were all associated with trail use intensity. Sediment production over the season for all trails (pooled) was most strongly related to trail width (r^2=0.379, p= 0.007, Table 4-5, Figure 4-5b) and OM% (r^2=0.300, p=0.016, Figure 4-6a). Low-use trails showed a moderate negative relationship with percent canopy cover (r^2=0.680, p=0.014, Figure 4-6b), and strong positive relationship stoniness of the trail (r^2=0.771, p=0.006, Figure 4-6c). Sediment production from high-use trails was not related to any of the trail physical characteristics, responding only to variation in total P and peak I_{30} for only the per event data.

4.3.4 Erodibility (K)

Variation in measured erodibility (K) was likewise associated with variation in trail use. Erodibility of high-use trails was 9.8 times greater than that of low-use trails (medians, p=0.001, Figure 4-7a). Mean erodibility for low-use trails was 0.005 t hr MJ^{-1} mm^{-1} (0.00-0.014 t hr MJ^{-1} mm^{-1}) and 0.038 t hr MJ^{-1} mm^{-1} (0.017-0.062 t hr MJ^{-1} mm^{-1}) for high-use trails. Despite high variation in erodibility across all trails (pooled), moderately strong relationships between K and both seasonal precipitation (r^2=0.327, p=0.012, Table 4-6) and maximum I_{30} (r^2=0.411, p=0.004, Table 4-6) were evident.

Significant relationships between seasonal erodibility and trail characteristics were similar but stronger than those observed for sediment production. The erodibility of all trails (pooled) had a moderate positive relationships with trail width (r^2= 0.524, p<0.001, Figure 4-7b), and weak negative relationship to OM% (r^2 =0.362, p=0.008, Figure 4-8a). Low-use trails had a moderate negative relationship with canopy cover ($r^{2\,=}$ 0.691, p=0.013, Figure 4-8b) and moderate positive relationship to trail stoniness (r^2 = 0.681, p=0.014, Figure 4-8c). These relationships were likely due to the co-variance of greater erosion created by trail use intensity, as amounts of canopy cover and stoniness are included in the cover factor and should have had less impact on erodibility (K). No variation of erodibility on high-use trails in response to variation in trail characteristics was observed (Figures 4-7c and 4-8a-c).

4.3.5 Comparisons across Experiments

4.3.5.1 Sediment Production

Both sediment production normalized per unit P for low-use and high-use trails, and the relationships between erosion and many trail physical characteristics were broadly consistent across rainfall simulation studies (Chapter 3) and the present study with natural rainfall (Figure 4-9). Sediment production from high-use trails was consistently greater than from low-use trails across both studies ($p<0.05$). Furthermore, while median sediment production observed from the rainfall simulation study was 52% and 22% greater than observed in the present natural rainfall study for low-use and high-use trails, respectively, the distribution and range of sediment production observed from both low-use and high-use trails did not differ among these two studies ($p>0.05$).

Despite differences in characteristics of precipitation produced by rainfall simulation and naturally occurring rainfall, the relationship between P normalized sediment production and several important trail characteristics such as trail slope was remarkably similar across studies (Figure 4-9b). Linear regression of sediment generated per unit P with plot slope was similar across studies for both high-use ($r^2 = 0.618$, $p<0.001$) and low-use trails (r^2 of 0.336, $p=0.018$, Figure 4-9b) though the range of trail slopes measured in the rainfall simulation plots was greater, likely due to short plot lengths.

4.3.5.2 Measured Erodibility

Erodibility showed similar general consistency across studies, though greater variation occurred in the high-use trail rainfall simulation plots than in all others. Erodibility was consistently greater from high-use compared to low-use trails in both studies ($p<0.05$, Figure 4-10a). However, while the distribution of K in low-use trails did not vary between the rainfall simulation and natural rainfall studies ($p=0.291$), median K of high-use trails was ~2.6 times greater from rainfall simulation compared to natural rainfall in the present study ($p=0.003$ from Wilcoxon-Mann-Whitney Rank Sum test).

However, despite this difference in K estimates across studies, the relationships between K and key trail physical characteristics such as OM% was also strongly similar. Low-use and high-use trails showed two clearly differing relationships between K with OM% where K was negatively related to OM% in low-use ($r^2 = 0.413$, $p = 0.008$). While parallel linear relationships where not evident in high-use trails ($r^2 = 0.006$, $p = 0.304$), this was the result of very low OM% with a very small range of variation (Figure 4-10b). The consistent finding of two differing response populations from low-use and high-use trails across both studies strongly supports the assumption of a proxy relationship between trail use and OM content.

4.4 Discussion

The principal aim of this research was to characterize erosion from OHV trails in Alberta's Rocky Mountain region from natural rainfall events and to explore variation in sediment production and erodibility (K) as a response to trail characteristics and trail use intensity. More specifically, to evaluate sediment production and erodibility (K) on OHV trails of variable physical characteristics and trail use intensity, and to compare these to the results of smaller scale rainfall simulation experiments of Chapter 3.

The primary driver of erosion is precipitation-generated runoff, in this study, significant variation in runoff and sediment generation was demonstrated on OHV trails as a result of trail use intensity. Trails receiving greater use generated between 12.8 and 16 times (means) more sediment per unit of natural rainfall than trails receiving lower use; this was comparable to approximately 10 times greater sediment for rainfall simulation experiments (Chapter 3). This finding is broadly consistent with erosion studies on undeveloped roads (Bilby, et al., 1989; Reid & Dunne, 1984; Luce & Black, 1999). Similar 5-10 fold increases in sediment production from roads or footpaths with greater traffic were reported by Sheridan et al. (2006, 2008) and Ziegler, et al., (2000). For high-use trails in the present study the greatest predictor of sediment generation was the amount of precipitation produced by each rainfall event followed by maximum peak intensity (I_{30}) of an event. In addition to traffic related variation in sediment production per unit precipitation, the strongest predictor of sediment generation for all natural rainfall plots (pooled) was the width of the trail, a direct physical measurement of the trail's use rate. For low-use trails the greatest predictors were trail stoniness (positive) and canopy cover (negative). Both trail width and canopy cover were found to have a relationships to organic matter content of the plot supporting the notion that OM appears to be a good proxy measure for trail use intensity.

The simple relationship between precipitation and sediment generation, observed for high-use plots, was not present for all plots in this experiment, but precipitation and runoff importance is likely also the underlying factor for low-use trails as well. Surface roughness, infiltration, and organic materials impede erosion and the entrainment of eroded sediment (Ziegler & Giambellucca, 1998; Croke, et al., 1999; Bryan, 2000). However, there was also a moderate negative relationship between sediment production with canopy cover for low-use trails in the natural rainfall observations. Similar to effects of surface roughness, erosive energy of a storm is reduced as raindrops are intercepted by canopy cover, for low-use trails this relationship was significant ($r^2 = 0.680$, $p=0.014$). The cover-management factor is an important variable in the USLE and may be under represented as an important parameter in this data (Wischmeier & Smith, 1978). Several of the high-use trails (those in North York) in this study did not have any appreciable canopy cover, however if trails with 0% canopy cover were removed from the analysis (Figure 4-6b), a similar relationship could exist for the high-use trails. This may indicate the potential importance of rainfall canopy interception in reducing erosive power. Rainfall simulation generated 2.1 and 2.6 times more sediment than natural observation on low-use and high-use trail plots, respectively. Some additional erosive power from rainfall simulation plots could be due to the fact that there is no interception of rainfall energy from canopy cover. Low-use trail natural rainfall plots had canopy cover whereas low-use rainfall simulation plots did not. Given the lack of statistical difference in these groups, additional modifying factors abating erosion were likely surface roughness and infiltration. Studies of pavement movement and wash out from roads show that it is unlikely for sediment to flow very far across forested landscapes even under high intensity simulated storms (Heede, 1984; Croke, et al., 1999). Rainfall simulations on vegetated grass plots by Pan and Shangguan showed reduced erosion by up to 90% with as little as 35% coverage (2006). Likewise, Nolan et al. showed that plots with zero tillage, allowing vegetation regrowth, had a low erosion response to even a high intensity storm (1997).

As precipitation and peak intensity of a storm increase, the total amount of sediment generated by that storm increases. Erosive energy produced by rainfall is expressed in erosion models as the runoff discharge from the plot or a combination of intensity-rainfall depth in a single factor such as R. Many researchers suggest that simple models disregard dynamic characteristics of the energy-erosion relationship (Mathier, et al., 1989; Bryan, 2000; Saygin, et al., 2018). However, relationships between rainfall and erosion from high-use trails in our study area indicate that dynamic models may not be necessary for erosion prediction. These trails were well compacted with what appears to be a moderate amount of surface or subsurface sealing. Indeed, a simple empirical linear relationship between sediment production and event precipitation was the strongest predictor of total erosion/sediment production (r^2=0.867, p<0.001), particularly for the North York trail system's 3.8 km loop of trails. There is significant consistency in the characteristics of these trails; they have common use rates, similar particle size distribution - ranging from clay-loam to sandy loam and are relatively close to each other making climactic conditions similar. Furthermore, despite large variation in plot lengths (3-100+ m) and slopes (7.82-24.47%), neither of these characteristics –vital in many erosion models, had an effect on the sediment generated from them, contrary to the rainfall simulation results of Chapter 3. However, recall that on rainfall simulation plots, the amount of precipitation and the intensity of the precipitation were consistent. For those plots, the strongest predictor of sediment generation on high-use trails was trail slope. Findings regarding the effect of slope on sediment loss from both studies are consistent with each other when the amount of sediment generated from the plots is normalized to per unit of rainfall (Figure 4-9b).

Traffic was also the main factor responsible for variance in measured erodibility (K) of the trails in this research. The erodibility of the high-use trails was about 9.8 times higher than that of low-use trails. This is higher than has been found in other studies with only 3-4 times greater erodibilities for more highly used roads (Sheridan, et al., 2006; Meadows, et al., 2008). There are however, not many studies on erodibility of road and trail surfaces to which comparisons can be made. This variation was likewise seen across experiments with statistically significant differences found between the high-use natural rainfall and rainfall simulation erodibilities ($p<0.001$). Median erodibility for rainfall simulation was approximately 2.6 times higher than that of natural rainfall. There was no significant difference in comparisons of erodibility across low-use natural rainfall and rainfall simulations, despite the rainfall simulation median being 2.1 times higher. In contrast, Sheridan et al. (2008) showed underestimation of erosion from rainfall simulated erodibility estimates from plots of 2 m length. The explanation for this may be, as in the comparison of sediment generated per unit of precipitation, due to the higher slopes over shorter plot lengths of the rainfall simulation experiment. Erodibility functions are meant to remove slope as a factor, however, over such a short distance the USLE slope factor may not be effective at reducing slope effects. Significant variation in effectiveness of slope length factors has been demonstrated (Bryan & Poesen, 1989; Sheridan, et al., 2003). Erodibility values were not initially generated on slopes higher than 20%, Wischmeier & Smith stated in Handbook #537 that predicting erosion on slopes this steep should be done with caution (1978). Attempting to predict total erosion from high-use plots using the USLE erodibility values, even those from this rainfall simulation experiment, could significantly underestimate the amount of erosion that is likely to occur under natural conditions.

Significant relationships for the measured erodibility (K) of all plots (pooled) to physical trail characteristics were found for trail width and OM, two characteristics appearing to be proxies for use rate. OM% is known to decrease erodibility for some soils but the response of soils above 4% in OM has generally not been considered in modelling (Wischmeier & Mannering, 1969). However, linear regression of erodibility and OM% across all both studies here showed remarkable consistency, further supporting the use of OM as an indication of trail use intensity.

Erodibility on low-use trails had similarly strong relationships to canopy cover and trail stoniness as observed with sediment production. This was surprising as both are elements in the cover factor of USLE which should have removed their influence on variation in K. The effect of both of these characteristics is greater than expected and could account for the slightly lower erodibility values (Wischmeier & Smith, 1978). The interception of raindrops, by canopy cover, dissipates erosive energy, thereby decreasing erosive power of the storm. This same effect is thought to occur in ground cover which in our study was referred to as trail stoniness. Cover-management factor represents areas less susceptible to erosive energy of raindrops and shear energy (Wischmeier & Smith, 1978). However, this does not appear to have as great an effect on erodibility or erosion on the low-use trails in our study area. OHV trails are not generally maintained with gravel or grading, they are more often native soiled surfaces as such the effect of traffic may outweigh any abatement that natural trail stoniness provides against erosion.

4.5 Conclusion

Trail use intensity was the most important factor governing sediment generation and erodibility for all trails and plots in this study. High-use trails had strong linear relationships to precipitation and runoff, while multiple factors appeared to interact to regulate erosion on low-use trails likely due to modifying effects of characteristics like infiltration, interception and organic litter. Despite some variability in sediment production between rainfall simulation and natural rainfall erosion studies, generally similar patterns of sediment production were observed among these studies. However, somewhat stronger variation among studies was evident for erodibility, particularly for high-use OHV trails.

The forgoing suggests that greater resolution in the determination of K is likely needed if models such as USLE are to be considered as management tools for the prediction of erosion to help manage OHV trail networks. A much better understanding of the factors governing erodibility is required to enable reasonable accuracy in model predictions.

4.6 Literature Cited

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Table 4-1 Plot and trail characteristics.

Site	Plot	Slope (%)	Width (m)	OM (%)	Canopy (%)	Stoniness (%)
			High Use trails			
Lower Star	6	12.83	2.62	4.35	37.00	48.00
Fire Guard	1	15.44	2.80	2.59	0.00	51.30
Fire Guard	2	7.82	3.20	2.20	0.00	47.50
Fire Guard	3	9.75	3.30	2.85	0.00	16.60
Fire Guard	4	11.90	3.10	3.78	0.00	23.70
North York M	1	20.80	3.40	2.19	20.00	50.00
North York M	2	24.47	2.87	4.45	10.00	50.00
North York M	3	21.48	2.80	5.09	10.00	56.25
North York U	1	17.16	3.00	3.68	0.00	44.70
Mean		15.74	3.01	3.46	8.56	43.12
Median		15.44	3.00	3.68	0.00	48.00
Max		24.47	3.40	5.09	37.00	56.25
Min		7.82	2.62	2.19	0.00	16.60
			Low Use trails			
Lower Star	2	11.43	2.15	15.86	7.50	62.00
Lower Star	3	17.63	2.44	14.22	49.40	30.28
Lower Star	4	9.84	1.48	21.62	51.00	29.50
Lower Star	5	13.04	2.88	7.71	15.00	60.00
Upper Star	1	9.75	0.68	53.13	48.75	21.25
Upper Star	3	17.49	1.17	11.59	0.00	70.00
Upper Star	4	19.66	1.36	18.30	40.00	37.50
Mean		14.12	1.74	20.35	30.24	44.36
Median		13.04	1.48	15.86	40.00	37.50
Max		19.66	2.88	53.13	51.00	70.00
Min		9.75	0.68	7.71	0.00	21.25
			All trails (pooled)			
Mean		15.03	2.45	10.85	18.04	43.66
Median		14.24	2.80	4.77	10.00	47.75
Max		24.47	3.40	53.13	51.00	70.00
Min		7.82	0.68	2.19	0.00	16.60

Table 4-2 Relationships between percent organic matter content and plot characteristics, sediment production, and measured K. Bold indicates relationships with $\alpha < 0.1$.

Variable	Type	Df	Adjusted r^2	P Value
Percent Stoniness	All trails	15	0.0624	0.179
	High use	8	0.00	0.627
	Low use	6	0.347	0.096
Percent Canopy Cover	All trails	15	**0.380**	**0.007**
	High use	8	0.00	0.418
	Low use	6	0.135	0.223
Trail Width	All trails	15	**0.679**	**<0.001**
	High use	8	**0.414**	**0.036**
	Low use	6	**0.398**	**0.076**
Sediment Load	All trails	15	**0.300**	**0.016**
	High use	8	0.113	0.198
	Low use	6	**0.445**	**0.061**
Measured Erodibility (K)	All trails	15	**0.362**	**0.008**
	High use	8	0.00	0.560
	Low use	6	0.144	0.216

Table 4-3 Event precipitation, sediment load, and erodibility from study trails.

Site	Plot	Precipitation (mm)	I_{30} (mm hr^{-1})	Sediment Load (t ha^{-1})	K (t hr MJ^{-1} mm^{-1})	Sed/Unit P (t $ha^{-1}mm^{-1}$)
			High Use trails			
Fire Guard	1	43.43	10.16	6.01	0.0223	0.1385
Fire Guard	1	36.07	7.11	3.24	0.0173	0.0898
Fire Guard	2	43.43	10.16	3.94	0.0424	0.0906
Fire Guard	2	36.07	7.11	2.60	0.0403	0.0721
Fire Guard	2	84.07	24.38	15.73	0.0373	0.1871
Fire Guard	3	62.23	10.16	4.59	0.1001	0.0738
Fire Guard	3	84.07	24.38	12.25	0.0879	0.1457
Fire Guard	4	62.23	10.16	3.76	0.0362	0.0605
Fire Guard	4	84.07	24.38	14.48	0.0459	0.1722
North York M	1	36.32	7.11	1.87	0.0321	0.0516
North York M	1	110.74	24.38	27.46	0.0664	0.2479
North York M	2	50.80	10.16	15.55	0.0795	0.3061
North York M	2	36.07	7.11	2.60	0.0192	0.0722
North York M	2	84.07	24.38	20.60	0.0232	0.2450
North York M	3	50.80	10.16	9.69	0.0547	0.1907
North York M	3	36.07	7.11	0.90	0.0073	0.0249
North York M	3	84.07	24.38	21.59	0.0269	0.2568
North York U	1	146.30	24.38	43.33	0.0256	0.2961
Lower Star	6	92.96	11.68	3.55	0.0186	0.0382
Lower Star	6	35.62	4.57	1.74	0.2987	0.0488
Lower Star	6	138.18	20.32	19.55	0.0630	0.1415
Mean		68.46	14.47	11.19	0.0545	0.1405
Median		62.23	10.16	6.01	0.0373	0.1385
Max		146.30	24.38	43.33	0.2987	0.3061
Min		35.62	4.57	0.90	0.0073	0.0249
			Low Use trails			
Lower Star	2	92.96	11.68	0.90	0.0091	0.0097
Lower Star	2	173.79	20.32	2.70	0.0165	0.0155
Lower Star	3	92.96	11.68	0.72	0.0020	0.0078
Lower Star	3	173.79	20.32	2.14	0.0036	0.0123
Lower Star	4	101.09	11.68	0.32	0.0024	0.0032
Lower Star	4	62.54	9.14	0.41	0.0113	0.0066
Lower Star	4	111.25	20.32	0.57	0.0033	0.0051
Upper Star	1	106.68	11.68	0.00	0.0000	0.0000
Upper Star	1	187.76	20.32	0.05	0.0002	0.0003
Upper Star	4	98.04	11.68	0.06	0.0001	0.0006
Upper Star	4	60.51	9.14	1.30	0.0110	0.0215
Upper Star	4	107.70	20.32	0.56	0.0009	0.0052
Lower Star	5	104.39	12.19	0.55	0.0022	0.0053
Lower Star	5	35.62	18.29	0.85	0.0083	0.0238
Lower Star	5	138.18	38.10	3.04	0.0061	0.0220
Upper Star	3	109.98	11.68	1.14	0.0043	0.0104
Upper Star	3	30.03	4.57	0.32	0.0944	0.0105
Upper Star	3	138.18	20.32	5.18	0.0129	0.0375
Mean		106.97	15.75	1.16	0.0105	0.0110
Median		105.53	11.94	0.65	0.0040	0.0087
Max		187.76	38.10	5.18	0.0944	0.0375
Min		30.03	4.57	0.00	0.0000	0.0000
			All trails (pooled)			
Mean		86.23	15.06	6.55	0.0034	0.0810
Median		84.07	11.68	2.60	0.0186	0.0382
Max		187.76	38.10	43.33	0.2990	0.3060
Min		30.03	4.57	0.00	0.0000	0.0000

Table 4-4 Seasonal precipitation, runoff, sediment load, and erodibility from study trails.

Site	Plot	Precipitation (mm)	I_{30} (mm hr^{-1})	Sediment Load (t ha^{-1})	K (t hr MJ^{-1} mm^{-1})	Sed/Unit P (t ha^{-1}mm^{-1})
			High Use trails			
Lower Star	6	266.75	20.32	24.83	0.04900	0.093
Fire Guard	1	79.50	10.16	9.25	0.01730	0.116
Fire Guard	2	163.57	24.38	22.27	0.03670	0.136
Fire Guard	3	146.30	24.38	16.84	0.04290	0.115
Fire Guard	4	146.30	24.38	18.24	0.04350	0.125
North York M	1	147.06	24.38	29.33	0.06220	0.199
North York M	2	170.94	24.38	38.76	0.03180	0.227
North York M	3	170.94	24.38	32.17	0.02920	0.188
North York U	1	146.30	24.38	43.33	0.02560	0.296
Mean		159.74	22.35	26.11	0.03758	0.166
Median		147.06	24.38	24.83	0.03670	0.136
Max		266.75	24.38	43.33	0.06220	0.296
Min		79.50	10.16	9.25	0.01730	0.093
			Low Use trails			
Lower Star	2	266.75	20.32	3.60	0.01370	0.014
Lower Star	3	266.75	20.32	2.86	0.00300	0.011
Lower Star	4	274.88	20.32	1.30	0.00381	0.005
Lower Star	5	278.18	38.10	3.85	0.00604	0.014
Upper Star	1	294.44	20.32	0.05	0.00024	0.000
Upper Star	3	278.18	20.32	6.63	0.00994	0.024
Upper Star	4	266.24	20.32	1.92	0.00166	0.007
Mean		275.06	22.86	2.89	0.00548	0.011
Median		274.88	20.32	2.86	0.00381	0.011
Max		294.44	38.10	6.63	0.01370	0.024
Min		266.24	20.32	0.05	0.00024	0.000
			All trails (pooled)			
Mean		210.19	22.57	15.95	0.02400	0.098
Median		218.59	22.35	13.05	0.02145	0.104
Max		294.44	38.10	43.33	0.06220	0.296
Min		79.50	10.16	0.05	0.00024	0.000

Table 4-5 Relationships between total sediment (t/ha) generated and plot and characteristics across trail use categories for seasonal data from the natural rainfall observations of summer 2014. Maximum peak intensity values are count data as such care should be taken in the interpretation of their significance.

Variable	**Type**	**d f**	**Adjusted r^2**	**P value**	**Equation**
Percent Slope of Plot	All trails	15	0.146	0.080	Y= +1.306x-3.684
	High use	8	0.306	0.071	Y= +1.202x 7.199
	Low use	6	0.0436	0.310	Y= +0.234x -0.411
Trail Width	All trails	15	**0.379**	**0.007**	Y= +11.110x -11.290
	High use	8	0.00	0.814	Y= -3.853x +37.711
	Low use	6	0.00	0.505	Y= +0.832x +1.445
Percent Organic Content	All trails	15	**0.300**	**0.016**	Y= -0.655x +23.060
	High use	8	0.113	0.198	Y=+4.895x +9.156
	Low use	6	**0.445**	**0.061**	Y= -0.103x +4.977
Percent Canopy Cover	All trails	15	0.161	0.069	Y= -0.333x +21.959
	High use	8	0.00	0.638	Y= +0.156x +24.781
	Low use	6	**0.680**	**0.014**	Y= -0.0825x +5.383
Percent Stoniness	All trails	15	0.00	0.540	Y= +0.152x +9.313
	High use	8	0.0264	0.306	Y= +0.311x +12.714
	Low use	6	**0.771**	**0.006**	Y= +0.0992x -1.514
Total Precipitation	All trails	15	**0.337**	**0.011**	Y= -0.128x +42.914
	High use	8	0.00	0.396	Y= +0.0726x +14.515
	Low use	6	0.00	0.527	Y= -0.0610x +19.662
Maximum Peak I_{30}	All trails	15	**0.549**	**0.001**	Y= -3.386x +134.643
	High use	8	0.00	0.911	Y= -0.236x +33.830
	Low use	6	-	-	Y=

Table 4-6 Relationships between erodibility values (K) and plot and characteristics across trail use categories for seasonal data from the natural rainfall observations of summer 2014. Maximum peak intensity values are count data as such care should be taken in the interpretation of their significance.

Variable	Type	d f	Adjusted r^2	P value	Equation
Percent Slope of Plot	All trails	15	0.00	0.739	Y= +0.000354x +0.0182
	High use	8	0.00	0.783	Y= -0.000256x +0.0416
	Low use	6	0.00	0.891	Y= -0.0000756x +0.00656
Trail Width	All trails	15	**0.524**	**<0.001**	Y= +0.0172x -0.0187
	High use	8	0.141	0.172	Y= +0.0259x -0.0403
	Low use	6	0.00	0.486	Y= +0.00197x +0.00206
Percent Organic Content	All trails	15	**0.362**	**0.008**	Y= 0.0339 -0.000955x
	High use	8	0	0.560	Y=0.0476 -0.00288x
	Low use	6	0.144	0.216	Y= 0.00896 -0.000170x
Percent Canopy Cover	All trails	15	0.126	0.097	Y= 0.0310 -0.000415x
	High use	8	0.215	0.117	Y= 0.0325 +0.000590x
	Low use	6	**0.691**	**0.013**	Y= 0.0112 -0.000189x
Percent Stoniness	All trails	15	0.00	0.967	Y= -0.0000138x +0.0241
	High use	8	0.00	0.511	Y= -0.000253x +0.0485
	Low use	6	**0.681**	**0.014**	Y= +0.000215x -0.00405
Total Precipitation	All trails	15	**0.327**	**0.012**	Y= -0.000171x +0.0595
	High use	8	0.0942	0.218	Y= +0.000127x +0.0174
	Low use	6	0.0	0.452	Y= -0.000163x +0.0505
Maximum Peak I_{30}	All trails	15	**0.411**	**0.004**	Y= -0.00414x +0.169
	High use	8	0	0.405	Y= +0.00211x -0.0314
	Low use	6	-	-	Y= -

Table 4-7 Comparison of sediment load, erodibility, and sediment generated per unit of precipitation across experiments.

	Sediment Load ($t\ ha^{-1}$)	K ($t\ hr\ MJ^{-1}\ mm^{-1}$)	Sed/Unit P ($t\ ha^{-1} mm^{-1}$)
	All High Use		
Mean	12.39	0.067	0.232
Median	4.56	0.062	0.137
Max	43.33	0.125	0.849
Min	0.17	0.014	0.022
	All Low Use		
Mean	1.55	0.007	0.020
Median	0.47	0.007	0.013
Max	6.63	0.018	0.063
Min	0.01	0.000	0.000

Figure 4-1 Location of natural rainfall observation and rainfall simulation plots near sites outside of Coleman, AB in the Municipality of Crowsnest Pass. Triangular points are the locations of those sites on trails considered as high intensity of use. Dark blue triangles are rainfall simulation experiment of summer 2015. Traingles with a red outline are natural rainfall observations from the summer of 2014. Circles are the locations of trails considered as low intensity of use. Blue circles are rainfall simualtion experiment from the summer of 2015. Black circles with blue crosshairs are natural rainfall observations from the summer of 2014.

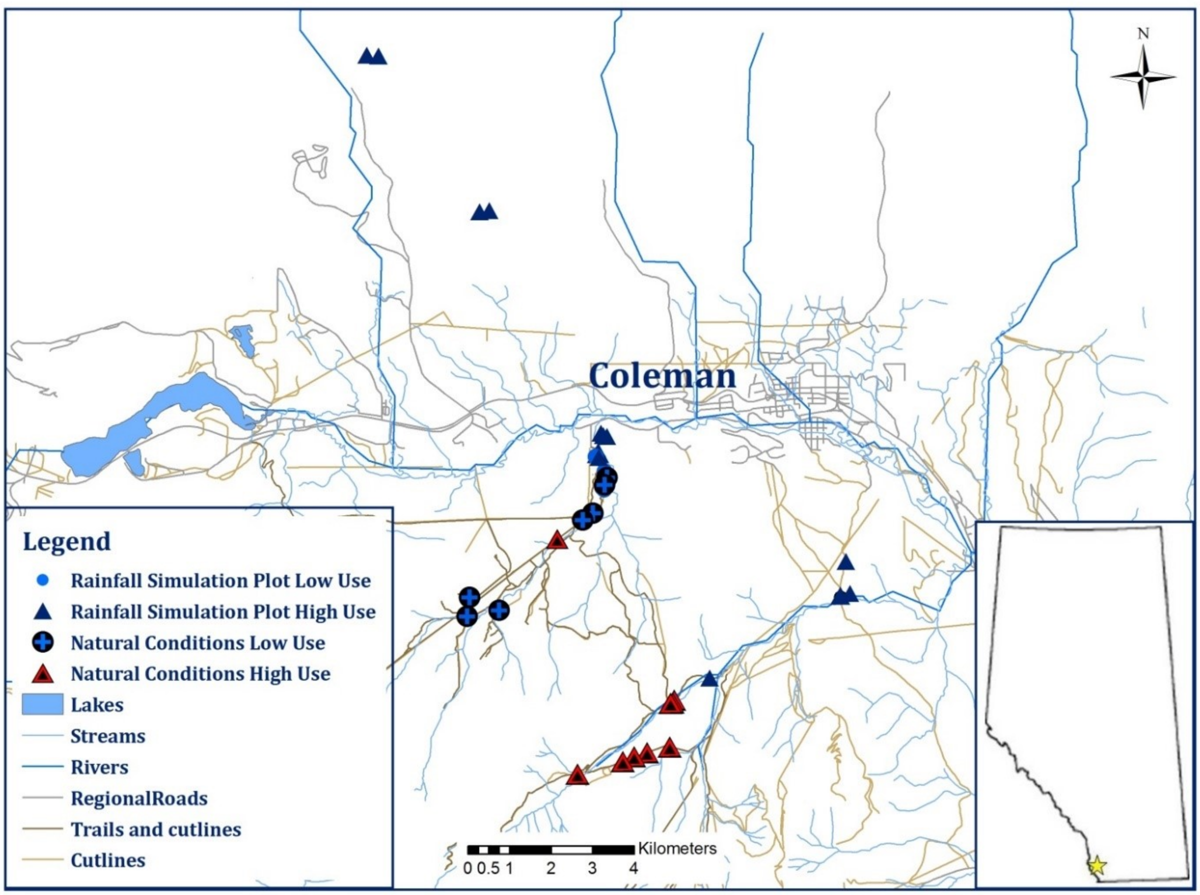

Figure 4-2 Example of natural rainfall observation plot for summer 2014. Site Fire Guard 1 is shown at time of installation in top picture and after rainfall event in bottom picture.

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Figure 4-3 Close-up example of natural rainfall observation plot for summer 2014. Site Fire Guard 1 is shown during rainfall event.

Figure 4-4 Relationship between sediment load and precipitation (mm) for a) all events, b) North York site events, and c) seasonal precipitation amounts. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails

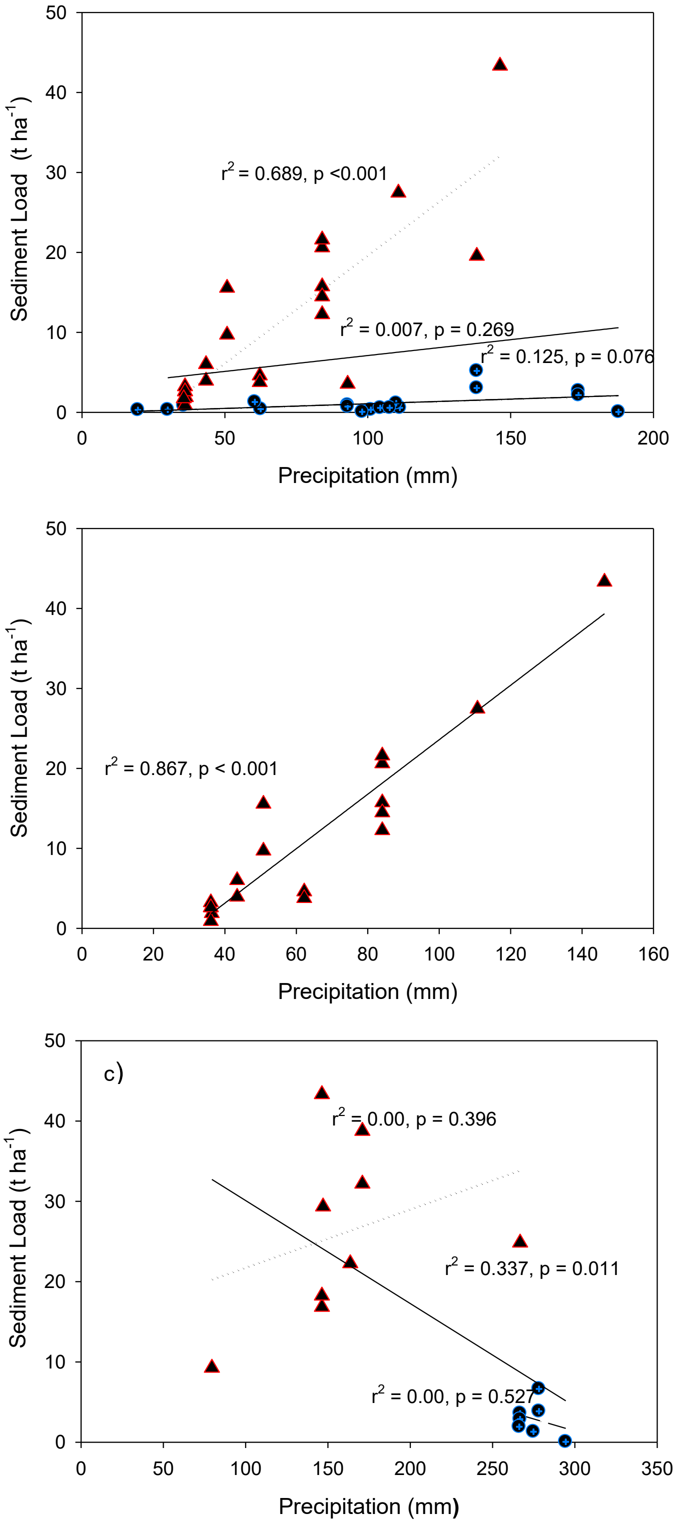
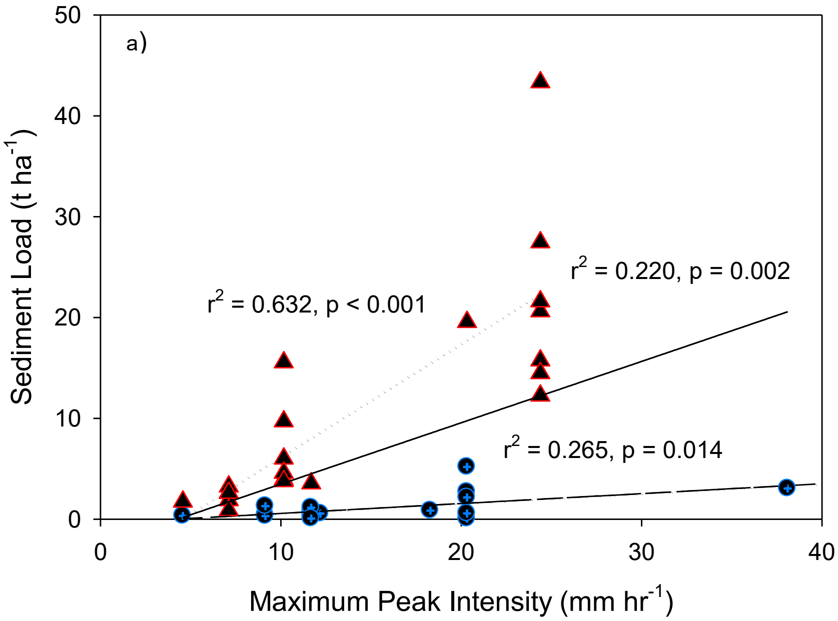


Figure 4-5 Relationship between sediment load with a) maximum peak intensity (I_{30}) and b) trail width,. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails.



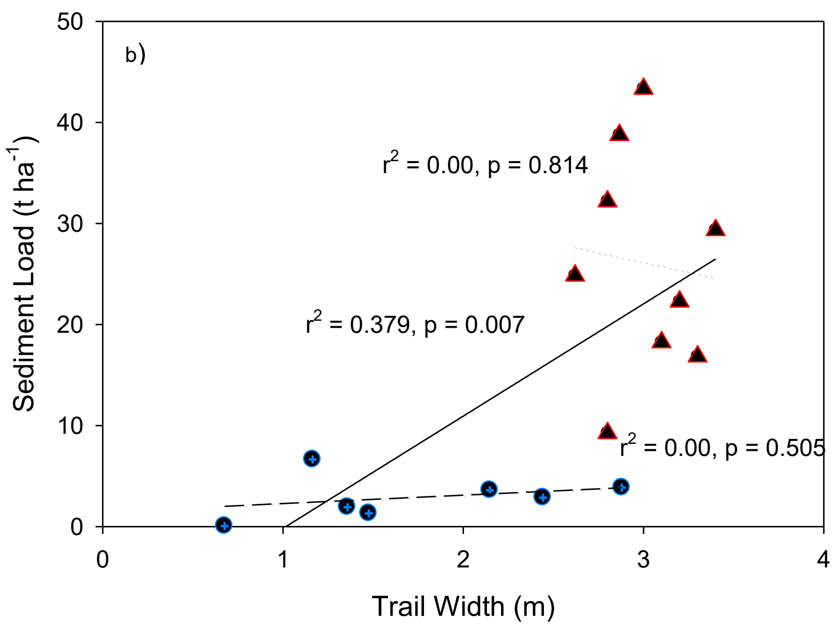


Figure 4-6 Relationship between sediment load with a) OM%, b) canopy cover, and c) trail stoniness. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails.

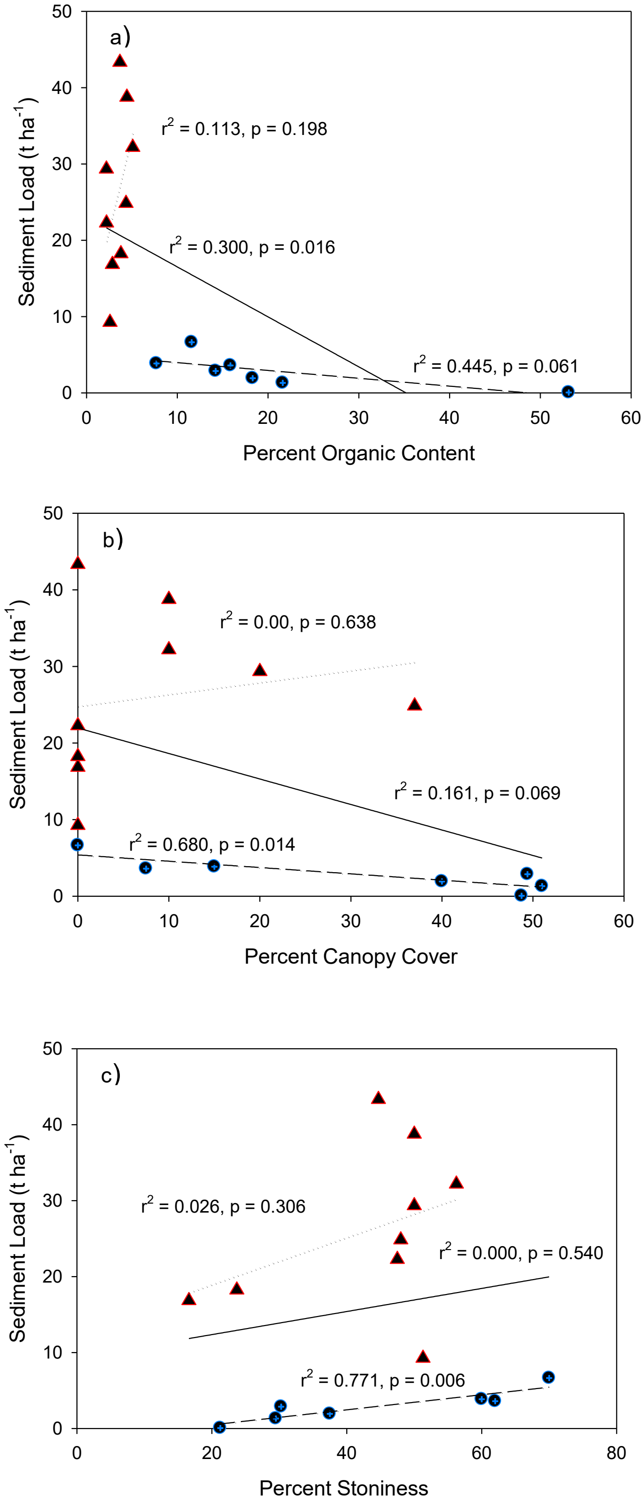
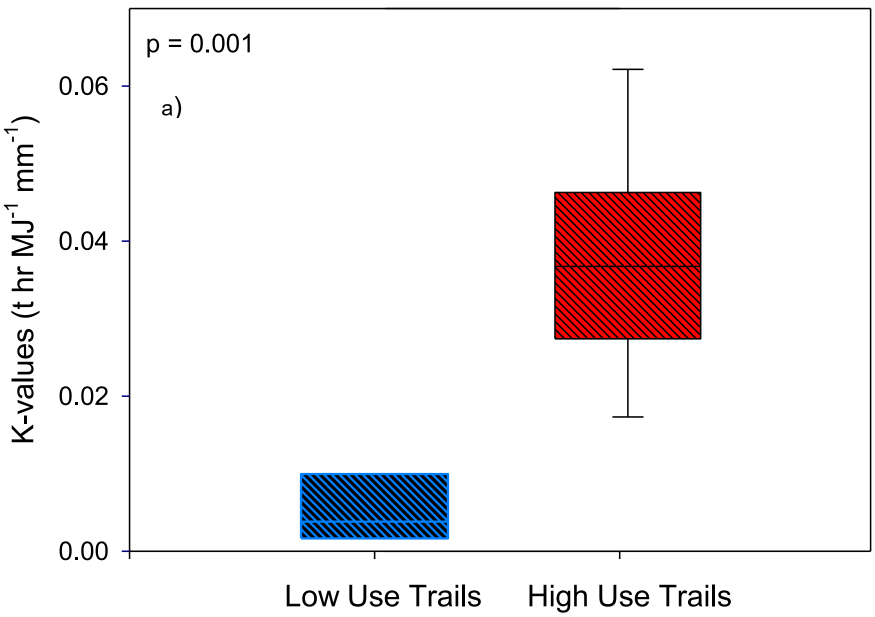


Figure 4-7 Relationship of measured K for a) distribution of K across low-use, and high-use trails, horizontal lines indicate median, upper/lower box boundaries indicate 25th and 75th percentiles, whiskers indicate 5th and 95th percentiles, dots indicate outliers, and b) pot width. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails



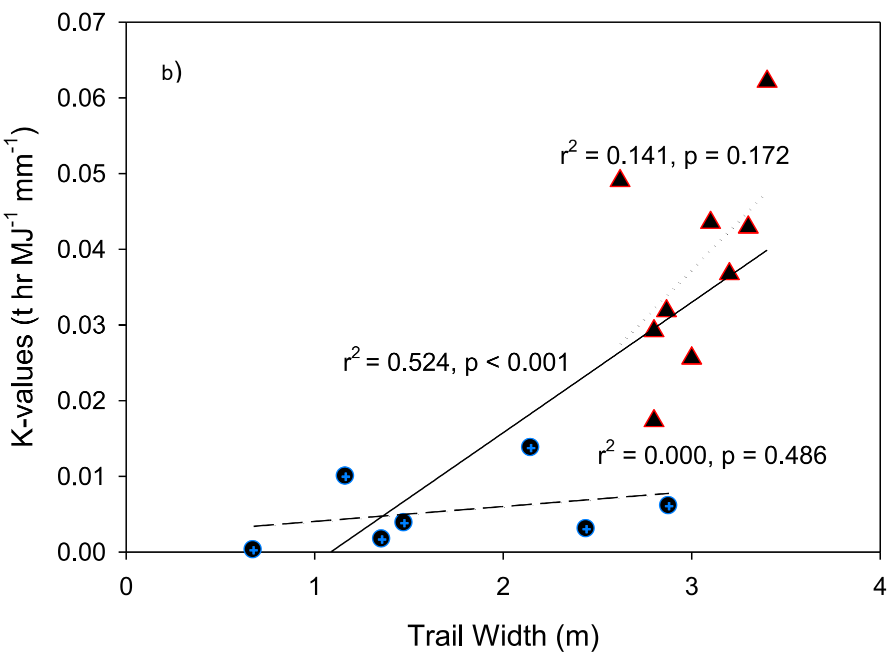


Figure 4-8 Relationship between measured K with a) organic matter content) canopy cover and c) trail stoniness from runoff plots. Triangles indicate high-use trails, circles indicate low-use trails. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails

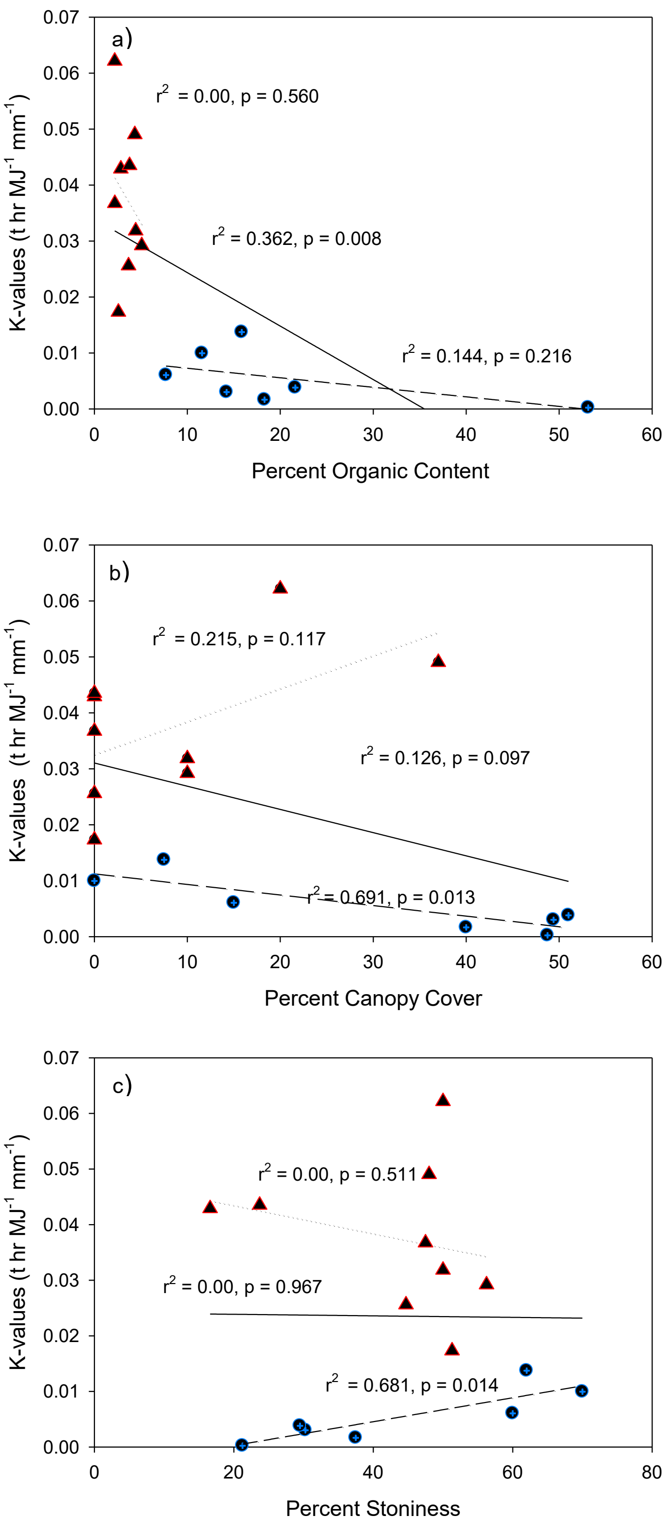
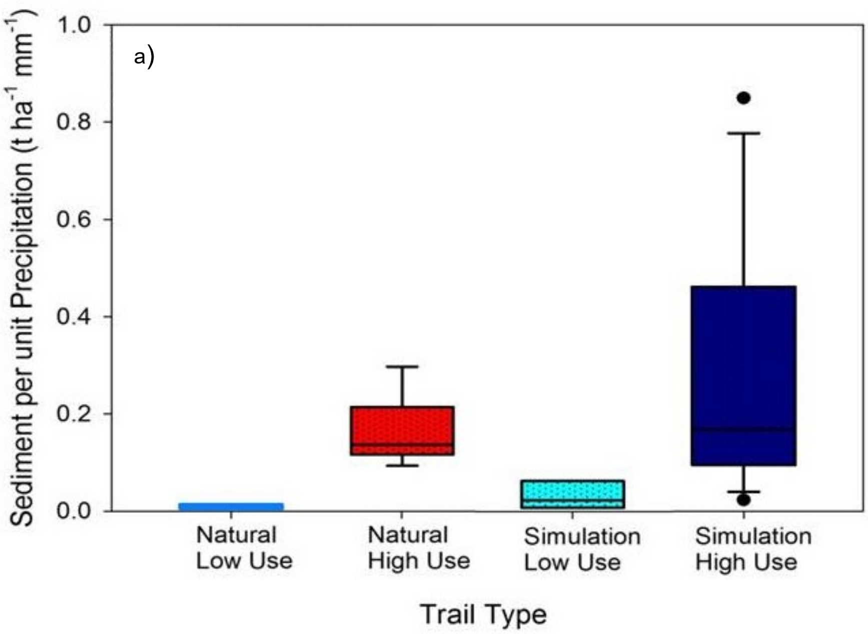


Figure 4-9 Comparisons of sediment per unit precipitation for a) distribution of sediment across all experiments for; low-use and high-use trails, horizontal lines indicate median, upper/lower box boundaries indicate 25th and 75th percentiles, whiskers indicate 5th and 95th percentiles, dots indicate outliers, and b) pot slope across experiments. Triangles indicate high-use trails, dark blue triangles for simulations and outlined red for natural rainfall; circles indicate low-use trails, light blue circles for simulations medium blue cross hairs for natural rainfall. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails



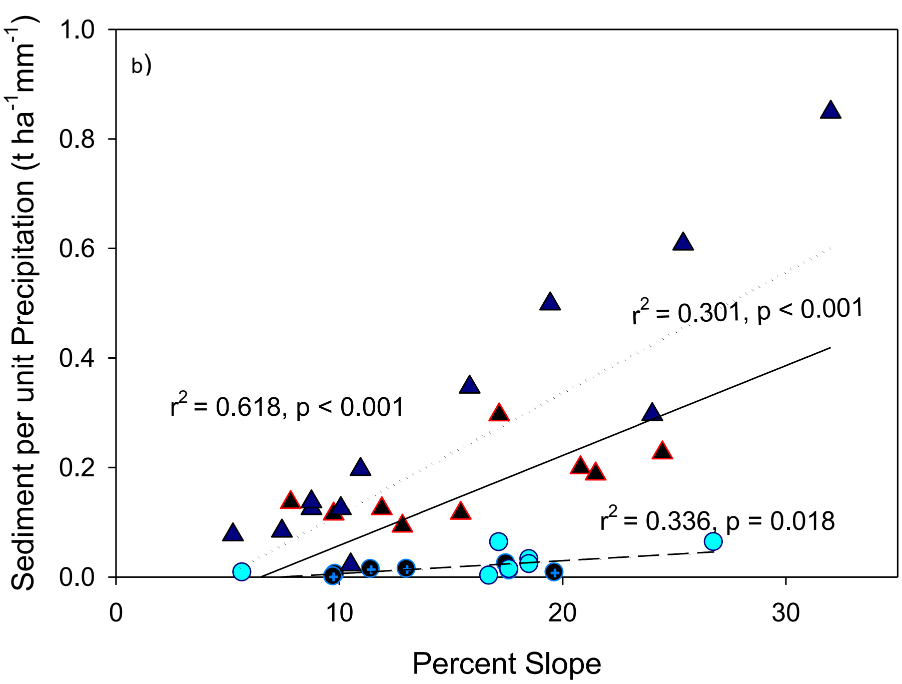
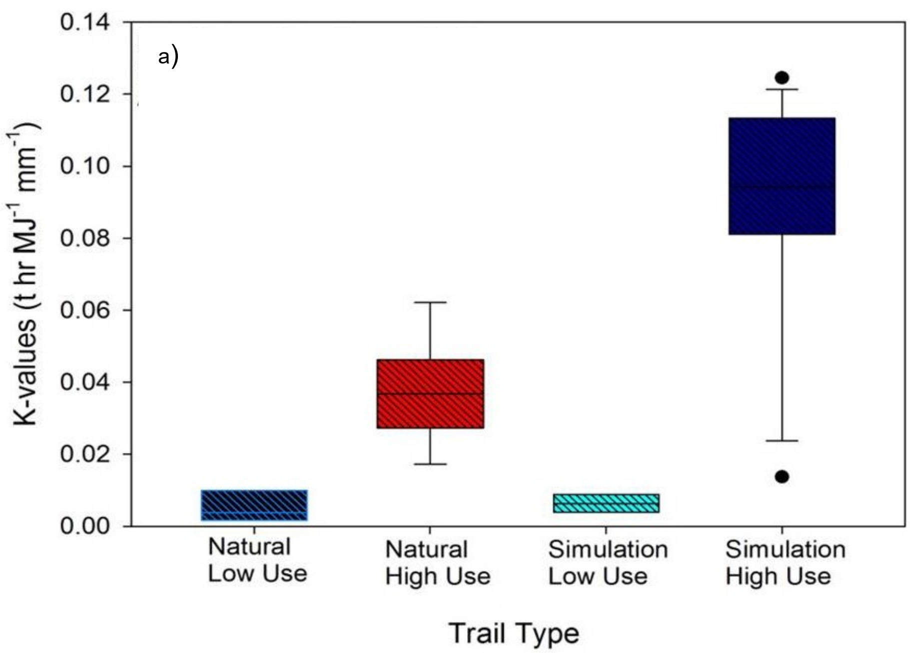
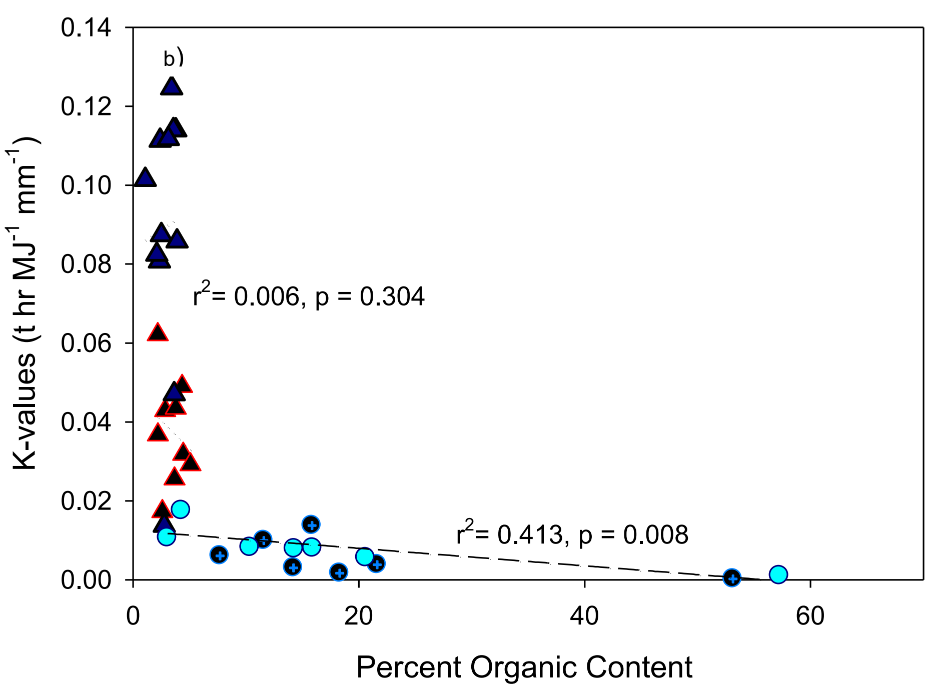


Figure 4-10 Comparisons of K for a) distribution of K across all experiments for; low-use, and high-use trails, horizontal lines indicate median, upper/lower box boundaries indicate 25th and 75th percentiles, whiskers indicate 5th and 95th percentiles, dots indicate outliers, and b) organic matter content across experiments. Triangles indicate high-use trails, dark blue triangles for simulations and outlined red for natural rainfall; circles indicate low-use trails, light blue circles for simulations medium blue cross hairs for natural rainfall. Lines indicate regression lines; solid = all plots (pooled), dotted = high-use trails, and dashed = low-use trails





Chapter 5 Synthesis

Undeveloped trails for OHV use are an important potential source of sediment to sensitive areas and the ability to manage trails to limit erosion requires improved understanding of the dominant factors driving erosion from these trails. The broad goals of this research were to improve this understanding with the purpose to help develop tools to predict how much, and under what conditions significant amounts of erosion will occur. This research is intended to support management of OHV trails in Alberta and to pinpoint where more research is needed. Accordingly, the broad objectives of this research were to a) determine total erosion and erodibility (K) from off highway vehicle (OHV) trails in Alberta's Rocky Mountain region and b) explore if the USLE could be used to predict trail erosion to enable management of OHV trail networks to minimize potential impacts of OHV use on sediment loading into regional streams.

5.1 Evaluation of Erosion from Rainfall Simulations

The objectives of the study outlined in Chapter 3 were to a) characterize runoff, total erosion, and erodibility (K) using rainfall simulation on trails of contrasting physical characteristics (slope, soil texture, water content), and organic matter content/trail use intensity, b) explore the relative sensitivity of total erosion and sediment production to variation in trail physical characteristics and trail use intensity, and c) evaluate the accuracy of commonly used approaches for predicting K using generalized nomograph approaches based on soil properties against actual field measured K.

It is particularly noteworthy that exceedingly little prior research had been conducted on erosion from OHV trails anywhere worldwide and despite considerable recent provincial public and government focus on this issue, no research (to my knowledge) has been done in Alberta's eastern slopes region.

The results of the rainfall simulation experiment showed that while runoff, erodibility (K) of trail surfaces, and amount of sediment generated from large but commonly occurring high intensity rainstorms was somewhat greater from steeper trails, trail surface characteristics such as soil texture or antecedent moisture content did not exert strong control over runoff, K, or total erosion. In contrast, intensity of trail use as reflected in organic matter content of trail surfaces, had a large effect on runoff and erosion with much greater runoff, erodibility, and sediment production from high-use compared to low-use trails. Furthermore, while trail physical characteristics such as trail slope had no effect on erosion from low-use intensity trails with high organic matter content, trail slope was an important controlling factor on high-use trails with higher slopes promoting; less infiltration, faster time to runoff, greater runoff, and therefore more erosion. Low-use trails with greater organic matter on trail surfaces had greater infiltration, and surface roughness leading to the reduction of erosion regardless of the slope of the plot.

While physical trail properties associated with intensity of OHV use such as bulk density (Db) are not likely possible to characterize because sampling fixed soil volumes needed to measure Db is generally not possible on stony trail surfaces, organic matter content was shown to serve as a useful proxy indicator of trail use intensity. Trails with higher organic content showed greater resilience to rainfall energy and had higher resistance to erosive forces. For the trails in this study, organic matter content greater than four to five percent (by mass) showed notable thresholds of decreased runoff, rates of erosion, and lower erodibility.

While erodibility was directly measured in this study, typical use of models to predict erosion requires estimates of inherent erodibility (K) which are usually estimated from soil properties (texture, organic matter content, soil structure, and permeability). However, results of this study showed that such estimates are generally inaccurate and would lead to errors in the prediction of erosion from models in which they might be used. In particular, while estimates of K from soil properties where close to measured K on low-use trails, they significantly underestimated K and erosion on high-use trails. Highly used trails in this study had erodibility values 5.6 times greater than erodibility predicted using commonly used approaches based on soil properties. Traffic intensity appears to be an important underlying factor affecting both erosion and the predictability of total erosion on these trails. This has important implications for use of generalized erosion models to predict and manage soil loss from these trails including a specific need to better understand and represent the impact of trail use intensity in model predictions.

Prediction using erosion models requires confidence that the parameters of those models are accurate and that the models provide reasonable estimates of erosion in the target region. While the USLE is a commonly used tool in agricultural, construction and engineering applications, this study showed that it would likely underestimate the erosion that could be occurring from highly travelled OHV trails. Evaluating the underlying reasons for this finding will help to develop alternate approaches or models for use in managing trail systems.

Over all the results of this study show that, for recreational trails in Alberta's Southern Rockies, USLE does not adequately represent the effect of traffic or trail use intensity as a key factor in affecting erosion on OHV trails. Rainfall simulations showed that usage rates, evidenced by organic matter content, affect runoff pathways through; compaction and reduction of infiltration on high-use trails, and surface roughness, and increased infiltration on low-use trails. In addition, it is unclear how OHV use affects the availability of sediment on trails, what the legacy and continued effect of compaction on trails that were formerly used for larger vehicles is, and how the energy from OHV use can be represented in prediction models. It is necessary to have greater understanding of these unknowns in order to accurately predict sediment loss from OHV trails.

5.2 Evaluation of Erosion from Natural Rainfall Observations

The objectives of this study were to a) characterize total erosion and erodibility (K) under natural rainfall conditions among trails of contrasting physical characteristics (slope, trail surface stoniness and canopy cover) and organic matter content/trail use intensity, b) explore the sensitivity of total erosion and sediment production from both shorter term or individual rainfall events and broader seasonal averages in response to variation in trail physical characteristics and trail use intensity, and c) evaluate the accuracy of rainfall simulated measures of erodibility (K) and total sediment generation against those from natural rainfall observations

Confidence in the ability to predict erosion from OHV trails can help managers to make appropriate decisions regarding the environmental risks of recreational trail use. However, a practical limitation in the use of erosion modelling approaches for management purposes requires relatively simple but accurate techniques to estimate key model parameters. A broad goal of this study was to explore the potential suitability of a simple, but well used model such as the USLE for prediction of erosion from OHV trails in Southwest Alberta where OHV use and concerns over potential impacts to water resources are high. The overall high-level conclusions from this study were similar to those of Chapter 3 that the USLE did not accurately predict erosion from all OHV trails in this region. However, the research also showed that empirical relationships between precipitation and trail erosion may serve as simpler, regionally specific alternatives to models such as the USLE.

This study explored total sediment generation and erodibility from both shorter term or discrete rainfall events and over the entire summer season. As with the previous study conducted using controlled rainfall simulation, naturally occurring rainstorms in the region produced much greater erosion from high use compared to low-use intensity trails. Direct (width) and proxy (organic content and canopy cover) measures of trail use intensity had the most significant effects on erodibility and sediment generation rates. While erodibility (K) from natural rainfall events did not vary as strongly among use categories as was observed in the rainfall simulation experiments, the erodibility of high-use trails was 9.8 times greater than those of low-use trails.

The results from the low-use trails in Star Creek showed that the lower erosion occurring from these trails was associated with significant canopy cover, higher organic matter content, and greater infiltration rates that likely buffered the energy transfer from raindrop impact required to dislodge and carry sediment from these trails. For these low-use trails the USLE could predict the amount of erosion occurring. As was found in the previous study, organic matter content above four to five percent was found to be a characteristic of low-use trails that was strongly associated with apparent thresholds for lower erosion and erodibility (K). As in the previous study, results for high-use trails showed that the USLE would under predict the amount of erosion occurring, but also showed that that erosion was strongly proportional to total precipitation the trail receives. Sediment generation per unit area from the 3.8km loop on the North York trail system showed a strong linear relationship ($r^2=0.87$, $p<0.001$) to individual storm event P. While such empirical relationships would be regionally specific, this finding suggests more accurate predictions may be possible through such relationships than may be possible using erosion models such as the USLE.

The results of both the rainfall simulation study (Chapter 3) and observations of erosion from natural rainfall (Chapter 4) showed strong consistency in the finding of trail use intensity as a strong factor controlling erosion from OHV trails from a weight of evidence perspective. While this is broadly consistent with general findings from two other studies that explored trail use intensity (Meadows et al., 2008; Sosa-Perez and McDonald, 2017), pooled data from both studies in the present research show much greater increases in sediment generation per unit precipitation (high-use trails roughly 10 times higher than low-use trails) than suggested by these previous studies. Greater OHV traffic probably acts to compact sediments, reducing infiltration, and makes sediment available to be carried away by rainfall. Thus, less rainfall energy is required to move sediment from the high-use trails than what is required to move sediment from the low-use trails. There was no significant difference in erodibility of low-use trails among the two studies nor was any meaningful difference found between the predicted and measured erodibility of low-use trails. Thus, the USLE could be used to predict erosion from low-use trails in this region.

However, some notable differences in results of studies from Chapters 3 and 4 were also evident. In particular, erodibilities (K) estimated from the rainfall simulation study (Chapter 3) were on average 2.6 times greater for high-use trails and 2.1 times greater for low-use trails than those estimated from natural rainfall events (Chapter 4). The reasons for these contrary estimates are not clear (see section 5.4)

5.3 Management Implications

There are several important implications for management of OHV trails arising from this work. Firstly, OHV trails subject to higher use produce more runoff and are more susceptible to erosion. Broad objectives for limiting erosion from OHV trail networks should likely include some best management practices (BMPs) for erosion control. Monitoring and maintenance (if needed) of BMPs to ensure their efficacy in controlling erosion would be important components of such strategies. Secondly, trail slope was found to be an important factor governing sediment production from high-use trails in both studies. This suggests that BMPs to control both runoff and erosion may be particularly important on trail segments with greater slope in existing trail networks. Thirdly, use of erosion models such as the USLE or models that employ a similar foundation (i.e. use of erodibility) do not accurately predict the erosion from a broad range of OHV trails spanning low-use and high-use trails this study area. Models that do not take into account the significant difference in the response of sediment generation from this range of trail use intensities cannot likely be used to accurately predict erosion. If low-use trails and high-use trails could be differentiated from each other using proxy measures such as organic content, canopy cover, or trail width, it may be possible to use different models for accurate prediction, but the USLE was clearly not able to predict erosion from high-use trails in this study. Mangers could use a model like the USLE for low-use trail systems. However, total storm precipitation (mm) served as strong predictor of total sediment generated on high-use trails in the North York trail system. Similar empirical relationships could be developed between precipitation and erosion in other regions. Another crude alternative approach to modeling erosion could be based on the finding of high-use trails having 10 times greater erosion than low-use trails; this could be used as a coefficient to roughly estimate the sediment generation from trails in the study area. It is however suggested that further study be undertaken before attempting to model sediment generation from trails in this study region.

5.4 Future Research

This study showed that trail use intensity directly affects the underlying conditions that drive erosion processes and that the sensitivity of erosion to trail use intensity was far greater in this region than suggested by other researchers (Meadows et al., 2008; Sosa-Perez and McDonald, 2017). Further research needs to be conducted on OHV trails to confirm if similar patterns are evident in other regions of Alberta where sedimentary or glacial parent materials might promote greater sensitivity to traffic effects on erosion. Before confidence in prediction of erosion can be achieved it is necessary to address the following uncertainties. Traffic related magnification of erosion on roads has been demonstrated in many studies having results similar to the conclusion in this study, that traffic or rate of use increases erosion from linear features like roads and trails. The substantial range of variation in results from other studies indicates that it would be prudent to conduct more research with regard to the effect of traffic on erosion from OHV trails.

5.5 Scaling up of Rainfall Simulation

The erodibility values and sediment production from rainfall simulation was 2.6 and 2.1 times higher than that observed from erosion resulting from natural rainfall. This is contrary to the accepted notion that rainfall simulation results underrepresent erosion and need to be “scaled up”. Scaling up is thought to be necessary to account for the lower energy of simulated rain in compared natural rainstorms, and the idea that longer slopes have higher sediment yield per unit land base (Wischmeier & Smith, 1978; Nolan, et al., 1997).There are many reasons that simulated rainfall could generate higher volumes of sediment. The characteristics of OHV trails and the study area were in a different physiographic setting than is typical for most rainfall simulation research that is often conducted on agricultural plots with less slope. Slope was found to be an important factor on high-use trails and this may indicate an important relationship between erosion from short plots and slope. This could be of significant concern where there are short slope lengths that are connected to water sources as the implication that greater rates of erosion occur on longer slopes would lead models to underestimate the amount of sediment entering stream systems from short slopes. Bryan (2000) suggested that erosion was consistent on plots of length of 2.39m and those of 7.18m but did not stay consistent beyond 17m. An investigation of how erosion rates change over short slopes in the study area should be explored to ensure accuracy of erosion modeling parameters.

Furthermore, the 2.6 and 2.1-fold relative difference in erodibility estimated from rainfall simulation and natural rainfall studies (Chapters 3 and 4) was remarkably consistent. Simulated rainfall was chosen to represent a large, but representative storm for the study area (approximately 1.9-year return interval storm). The drop size of the simulated rain was tested using the Eigle and Moore oil drop method and found to have drop sizes consistent with lower intensity storms evenly distributed across a petri dish (Eigel & Moore, 1983). The nozzle was placed at least 3 m above the ground to ensure that most drops had enough fall distance to reach terminal velocity. A substantial wind block was used to ensure that wind could not disrupt the consistent fall of simulated rain. All attempts were made to restrict confounding variables that could increase or decrease the amount of energy imparted to the trail through rainfall simulation. The reason for this consistent difference is not clear.

Organic content and other descriptive characteristics of low use

Organic matter content was used as a proxy for trail use intensity in this research because other soil measures such as bulk density could not be sampled. Use of other allied measures of trail use intensity such as penetration resistance (measured with penetrometer) or other proxy measures could be investigated to enable better representing this factor in future OHV trail erosion research.

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