PHYSIOGRAPHIC COMPONENTS OF TRAIL EROSION

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

August 2000

APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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"Supposing a tree fell down, Pooh, when we were underneath it?"

"Supposing it didn't", said Pooh after careful thought.

Piglet was comforted by this, and in a little while they were knocking and ringing very cheerfully at Owl's door.

The Te of Piglet
by Benjamin Hoff

ACKNOWLEDGMENTS

I would most like to thank Andrew Marcus for his significant assistance in the preparation of this thesis. I also appreciate the input and assistance of the two other members of my committee, Jon Wraith and Kathy Hansen. John Wilson gets credit for proposing the project. Heidi M. Graham-Godwin gets credit for her patience and support throughout the extended period of preparation of this work.

I would also like to acknowledge the Colorado Outward Bound School for both the help and hindrance they provided. Without their willingness to employ me, I could not have afforded to complete my coursework and research. Without their willingness to employ me, I might have finished this much sooner.

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ABSTRACT

No previous study has sought to discriminate between soil erosion and soil compaction when explaining the “missing” cross-sectional areas of incised trails, assuming instead that erosion was the dominant process. Separating the two processes of erosion and compaction is critical to understanding the relationship between physiographic variables and the structure of trails.

The purposes of this project are to estimate the relative effects of compaction and erosion on trail cross sectional area along the New World Gulch Trail, Montana, and to better understand the relationship between erosion, compaction, local topography, vegetation, soil bulk density, and soil texture. The following hypotheses were addressed: 1) adjusting the incised cross sectional area of a trail, by removing the effects of soil compaction, will increase the amount of variance in erosion explained by collected physiographic variables; and 2) inclusion of soil bulk density and soil texture as physiographic variables will increase the amount of variance in cross-sectional area explained along the trail.

The goals of this study required the collection of field data, analysis of soil samples, and statistical analysis of data. Soil samples and other field measurements were collected over several months during the summer and fall of 1994. Some of the topographic information used in the statistical analysis originated in Urie's (1994) study of recreational trails.

The determination of trail slope as one of the primary components of trail incision is consistent with previous studies. Soil water content is the second most significant independent variable when the percentage of particle sizes are not considered. Percent vegetative cover is also significant in the stepwise regression, although it is not significantly correlated to cross-sectional area.

The most significant variable added to those already studied was soil bulk density. When individual variables were regressed against the measured cross-sectional area, off-trail soil bulk density accounted for the second greatest amount of variance ($r^2 = 0.12$) after trail slope ($r^2 = 0.35$). The ratio of on-trail soil bulk density to off-trail soil bulk density, which could be considered a measure of compaction, accounted for even more variance ($r^2 = 0.18$) than soil bulk density.

CHAPTER ONE

INTRODUCTION

A 1975 survey of wilderness managers indicated that trail deterioration and erosion were major backcountry concerns (Godin and Leonard, 1979). Since that time, the use and abuse of mountain trails has increased, forcing managers to expend more resources to maintain, rebuild and relocate trails (Cole, 1991). With ever increasing numbers of hikers, cross-country skiers, mountain bikers, and horse riders using trails, land managers need to be more knowledgeable and conscientious about the placement, maintenance and management of trails.

The goal of backcountry management is to maintain a healthy and sustainable recreational and natural resource (U.S. Department of Agriculture, 1981). Brooks *et al.* (1991) state that where erosion is concerned, best management practices (BMP's) are well known for agriculture, forestry, and road construction activities. Research on erosion in backcountry areas that could lead to the development of appropriate BMP's, however, is scarce.

In particular, no previous study has sought to discriminate between soil erosion and soil compaction when explaining the "missing" cross-sectional areas of incised trails, assuming instead that erosion was the dominant process (Urie, 1994). The greater the amount of soil compaction at a given location along a trail, the deeper the trail incision and the greater the amount of error in the measurement of erosion. Separating the two processes of erosion and compaction is critical to understanding the relationship between physiographic variables and the structure of trails. Being able to more clearly recognize and distinguish between the effects that various physiographic factors have on trail erosion and compaction will facilitate defining BMP’s for trail location and remediation.

The purposes of this project are to estimate the relative effects of compaction and erosion on trail cross sectional area along the New World Gulch Trail, Montana, and to better understand the relationship between erosion, compaction, local topography, vegetation, soil bulk density, and soil texture. While compaction has been measured and observed to be an important component contributing to trail erosion, it has not been evaluated as a possible cause for the “missing” trail cross-sectional area commonly used to quantify the amount of erosion from a given point. Similarly, aside from the "Leave No Trace" principal of traveling cross country on durable surfaces to minimize erosion, the bulk density of pre-trampled soils has been overlooked as a significant control on erosion. The results should assist forest and park managers in evaluating the appropriate location for planned and future trails.

The following hypotheses will be addressed: 1) adjusting the incised cross sectional area of a trail, by removing the effects of soil compaction, will increase the amount of variance in erosion explained by collected physiographic variables; and 2) inclusion of soil bulk density and soil texture as physiographic variables will increase the amount of variance in cross-sectional area explained along the trail.

Literature Review

Much has been written about human impacts on wilderness recreation areas. People seek wilderness to commune with the untouched wild, so their wilderness experiences are easily affected by relatively minor impacts. Recreational misuse or abuse of wilderness areas thus destroys this conceptual resource, as well as placing significant strains on the actual natural resources. Vogler and Butler (1996), for example, state that when path erosion rates exceed an adjacent streams ability to transport the increased sediment influx, stream clogging and diversion can occur. Similarly, Hardin (1992) notes that significant water quality degradation can occur due to increased loads from trail erosion.

The topic of recreational degradation of wilderness has been one of concern since at least 1933, when Bob Marshall noted the impacts of excessive use at campsites and the need for user education programs (Lucas, 1987). Since that time, there has been an ever increasing number of wilderness users (Lucas and Stankey, 1989) and access to many areas is now restricted. At the same time, most users are willing to accept the restrictions with few complaints (Lucas, 1983). The acceptance of restrictions is frequently the result of impact studies that show that wilderness areas are suffering in some ways under the increased pressure of use.

The increasing degradation of wilderness recreation resources is primarily restricted to trails (Godin and Leonard, 1979), other frequent use corridors such as saddles between popular drainages, and near or within established campsites. Much of the research done on the impacts of recreational use prior to 1990 had focused on backpacker impacts on soils and vegetation at campsites (*e.g.*, Price, 1985; Cole, 1989; Cordell *et al.*, 1990) and was descriptive in nature (Cole 1986). More recent quantitative studies document the influence of variables such as use, vegetation density and fragility, and topographical variables on the amount of degradation at wilderness campsites (*e.g.*

Cole, 1992; Steele, 1998). In recent years, a large portion of the literature regarding recreational impacts has also focused on trail erosion.

Trail Erosion

Soil erosion primarily occurs when soil particles are entrained by wind or water and transported to another location. Most erosion research has focused on agricultural areas, particularly since the Oklahoma dustbowl in the 1930’s (Wischmeier, 1970; Wischmeier and Smith, 1978; Dutch *et al*., 1998), although increasing resources have been devoted to trail erosion studies since the late 1970's (McQuaid-Cook, 1978; Summer, 1980; Quinn *et al.*, 1980; Fish *et al.*, 1981; Cole, 1983; Bayfield, 1985; Tinsley and Fish, 1985; Bayfield, 1986; Summer, 1986; Lance *et al.*, 1989; Cole, 1991; Seney, 1991; Urie, 1994; Wilson and Seney, 1994).

At its' most basic level, water erosion is often the result of the overland flow caused when water inputs exceed the soil’s infiltration rate (Quinn *et al.*, 1980; Harden, 1992; Oyarzun, 1995). Much research has shown that climate, soil properties, and topography are the three primary factors effecting erosion rates (Martz, 1992). McQuaid-Cook (1978), Cole (1983), Wilson and Seney (1994), and Vogler and Butler (1996) have also shown that user type and intensity of use are also key controls of erosion on trails.

Climate primarily influences erosion rates through the frequency, timing and intensity of precipitation. The force generated by the impact of raindrops is capable of displacing sediment up to a meter or more (Brooks *et al.*, 1991). Beyond simple displacement, long-term precipitation events may exceed soil infiltration rates, which leads to overland flow and entrainment of dislodged sediment. Additionally, infiltration rates are more likely to be exceeded if the soil water content is already near field capacity due to either frequent or recent precipitation or snowmelt.

Soil properties effecting erosion potential include texture, partially defined by the rock fragment and clay content, and organic matter content. Rocks are more resistant to erosion and transportation by water than individual soil particles. As the rock fragment content of the soil increases, the overall resistance to water erosion also increases (Davis and Shovic, 1996). The presence of clay in the soil generally results in decreased hydraulic conductivity relative to coarser soils. Reduced conductivity, combined with some clays' tendency to swell when moistened, diminishes the amount of time required for a given precipitation event to exceed the soils' infiltration rate. Once the infiltration rate is exceeded, ponding, possibly followed by overland flow, begins and loose sediment or particles detached by rainfall may become entrained and transported by the flow.

Increased soil organic matter content has the reverse effect from clay. As organic matter content increases, total porosity generally increases (Kay and Angers, 2000). Soil organic content has also been shown to mitigate soil compaction and reduce soil erodibility by increasing aggregate stability (Kay and Angers, 2000). The spaces created by root growth and spreading allow surface moisture easier access to the subsoil system, thus enhancing infiltration (Marshall, *et al.*, 1996). Additionally, once a rain event has concluded, plant transpiration removes the moisture within the root zone more rapidly.

Along with the climate and soil properties, the shape of the landscape, or topography, also influences the rate and amount of erosion. Martz (1992) showed that about 40% of the variability in rain splash erosion could be explained by slope position. Wischmeier and Smith (1978) indicated the importance of topography in the soil erosion process by including the slope-length factor in the Universal Soil Loss Equation. In her 1994 study, Urie identified slope as one of the primary factors influencing trail erosion. All other things being equal, as slope increases so does the velocity and resulting kinetic energy of overland flow, which increases the ability of runoff to entrain sediment.

Harden (1992) bridged the gap between agricultural erosion studies and trail erosion studies in her work evaluating the feasibility and ability of agriculturally based erosion models to include erosion from roads and foot trails. She found that roads and trails are the most active runoff generators in inhabited mountain landscapes. The effectiveness of trails in initiating downslope soil erosion depended on the potential for path spillage, which is the transport of sediment beyond the confines of the trail, and downslope surface vulnerability, which is the presence of disturbed and degraded soils that are predisposed to transport.

The type and amount of use have been identified as important controls on the amount of trail erosion (McQuaid-Cook, 1978; Summer, 1980; Cole, 1983; Vogler and Butler, 1996; Seney, 1991), although studies have been hampered by the scarcity of data on users in back country areas (Krumpe and Lucas; Daigle, *et al.*, 1994). More people tracking over the same land reduce the vegetative cover and increase disturbance to the soil surface. Different user types, such as hikers, bikers and horses, all may eliminate vegetation and disturb soil particles, but each produces different amounts and rates of soil erosion on trails. Wilson and Seney (1994) found that different user types caused differing amounts of soil displacement depending on whether they were ascending or descending a trail. Generally, horses caused the most soil displacement when descending trails, followed in quantity by hikers and mountain bikers. Mountain bikers produced the most soil displacement when ascending trails, followed by hikers and horses.

Soil Compaction and Bulk Density

Soil compaction may result when pressure is applied to soils. Compaction increases the soil's bulk density and decreases its porosity, which in turn reduces the infiltration rate, influences plant root propagation, and increases the potential for overland flow (McQuaid-Cook, 1978; Quinn *et al.*, 1980; Vogler and Butler, 1996). Compaction often occurs in soils under intensive agriculture, grazing, and forestry. Animals, machinery and the dragging of fallen logs can exert pressures up to 100 kPa (Marshall *et al.*, 1996).

McQuaid-Cook (1978) found that the type of terrain, user type, soil type, soil water content, and intensity of use were the primary factors controlling soil compaction and the resulting trail "incision". Incision occurs because soil compaction reduces soil volume and therefore depresses the elevation of pathways and trails. Incised trails, with their low permeability, act as intermittent stream channels, funneling water during precipitation and melt events (McQuaid-Cook, 1978; Quinn *et al.*, 1980; Harden, 1992; Oyarzun, 1995; Vogler and Butler, 1996). This funneling can increase the velocity and subsequently the erosive power of water.

According to Vogler and Butler (1996), paths on level ground at their University campus were more susceptible to compaction than they were to water erosion. Their assertion is based on previous research by others (Liddle, 1975; Bratton *et al.*, 1979; Coleman, 1981; Morgan and Kuss, 1986; Garland, 1990; Ferris *et al.*, 1993; Wilson and

Seney, 1994) showing the effects of trampling on trail soil, and they suggest that soil bulk density data on paths and in adjacent untrampled areas be collected to evaluate differences in compaction. They observed a weak correlation between depth of path incision and slope, though they ascribed the relationship more to the user types than specific terrain attributes. They found that the steeper paths were located next to stairways and used almost exclusively by bicyclists.

In their laboratory based experiments, Quinn *et al.* (1980) found that the maximum compressive load occurs as a hiker's heel places pressure on a small contact area of the ground. In keeping with their findings regarding the compressive effects of the heel, Quinn *et al.* viewed the shearing action associated with toe action at the end of each step, and loss of vegetation, as the major controls on soil detachment.

CHAPTER 2

STUDY AREA

The study area consists of the New World Gulch and Bozeman Creek Trails in Southwest Montana (Figure 1). The two trails have a combined length of approximately 13 km and an elevation change of approximately 400 meters (Figure 2).

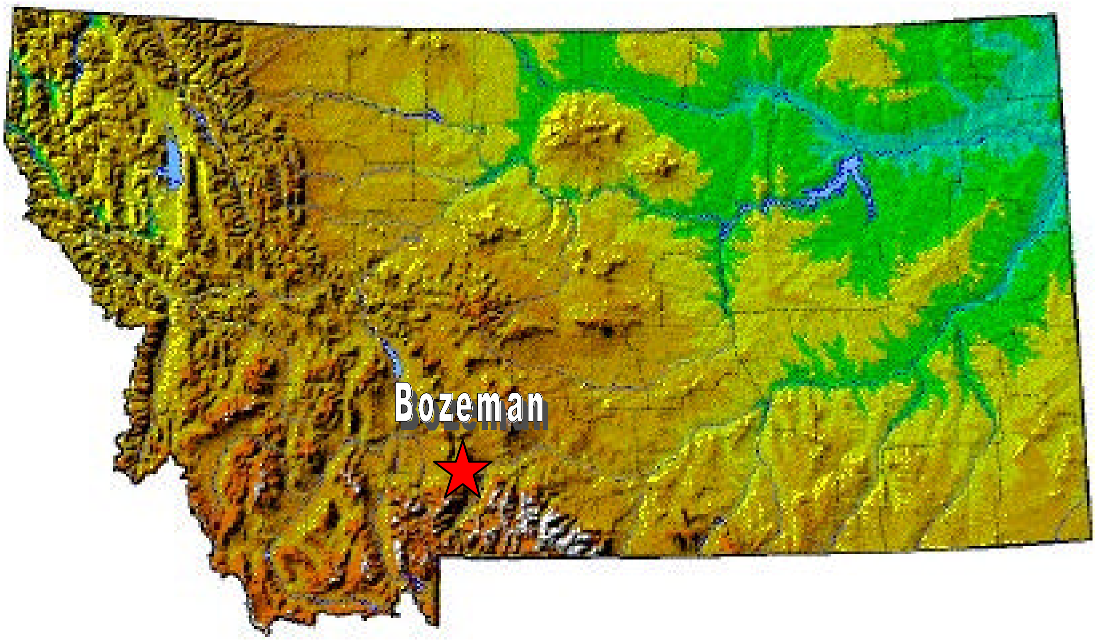


Figure 1: General location of study area near Bozeman, Montana. Trails are in the Northeastern corner of the Gallatin Mountain Range.

The New World Gulch and Bozeman Creek trails were chosen for this study because the sites had been previously sampled by Urie (1994), and could be positively identified by relocating the site markers. Urie's sites were used because topographic and soils data had been previously collected and entered into a GIS for these locations. Only 67 of Uries 130 sites could be relocated with precision that was adequate for this study (Figure 3). The Urie sites which were relocated were 1 - 6, 8 - 18, 21 - 30, 34,

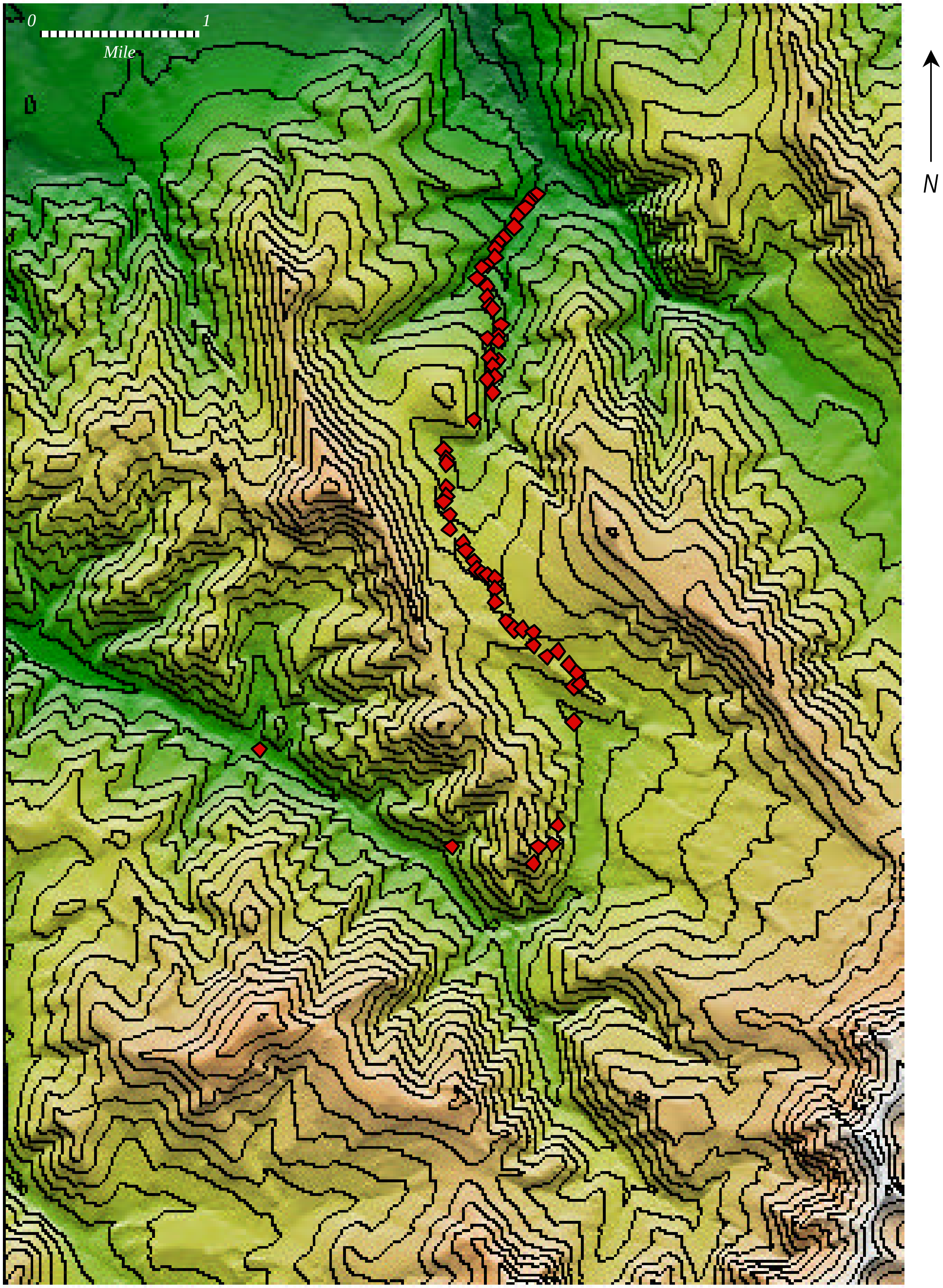


Figure 2: Study area map with approximate location of sample sites. 60 m contour interval.

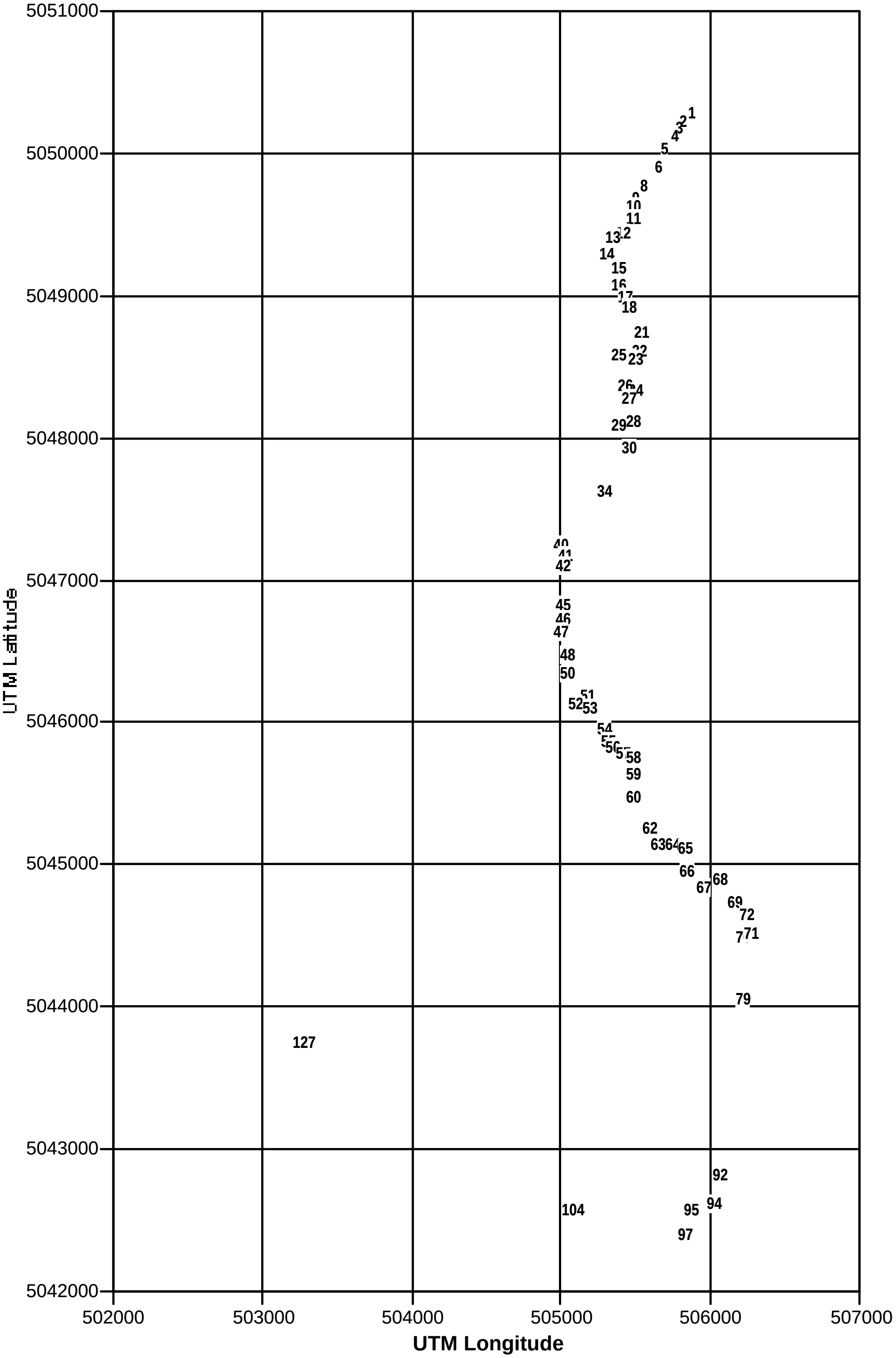


Figure 3: Relative location of sample sites along New World Gulch and Bozeman Creek Trails.

40 - 42, 45 - 48, 50 - 60, 62 - 72, and 79 found along the New World Gulch trail, with sites 92, 94 and 95, 97, 104, 113 and 114, and 127 found along the Bozeman Creek trail (Figures 2 and 3).

While both trails experience multiple use, Bozeman Creek Trail tends to have more mountain bike use than the New World Gulch Trail, which supports greater hiker, horse rider, and occasional motorcycle use. The New World Gulch Trail also experiences more winter use by cross-country skiers and occasional snowmobilers than the Bozeman Creek Trail, which is steeper and narrower in its headwaters areas. Sections of the trail vary significantly in width, depth and the number of braids (Figures 5, 6, and 7). Use of non-government motorized vehicles is prohibited in the Gallatin National Forest portion of the study area.

The general topography of the study area consists of ridges with steep stream-cut valleys and broad, sloping benches (Figure 4). The geology of the study area consists of sedimentary rocks (shales, mudstone, siltstone and sandstone) underlaying the New World Gulch Trail, transitioning to bands of limestone, dolemite, and more shales along the upper reaches of the Bozeman Creek Trail (Roberts, 1964). Trail slopes range from 0.5 degrees to 18.5 degrees with an average slope of 5.9 degrees. Side slopes adjacent to the trail range from 0 degrees to 24 degrees, with the average being 8.5 degrees. The soil types and rock fragment content at the sample sites are described in Table 1 (Davis and Shovic, 1996).

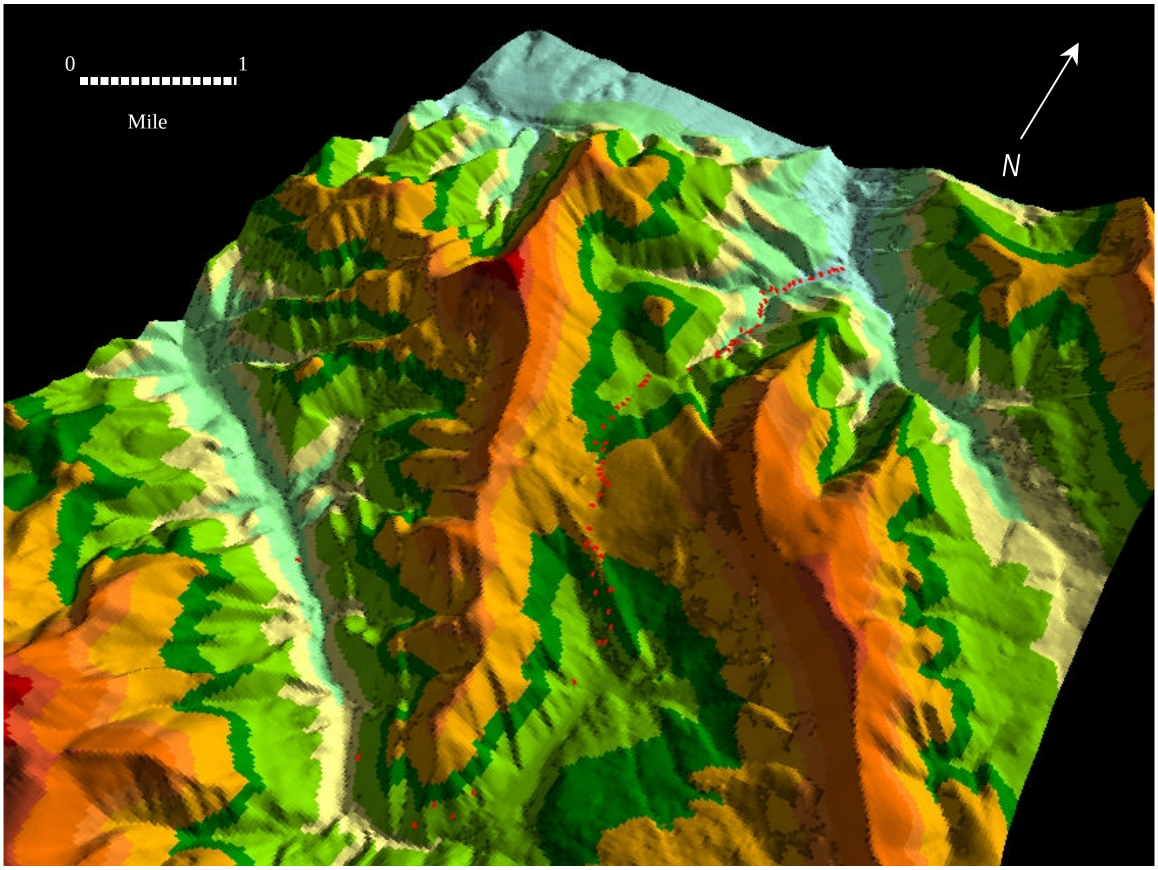


Figure 4: Topography of New World Gulch / Bozeman Creek trails study area. Red points indicate sample locations. Colors represent elevation change.

Figure 5: Braided trail with moderate incision. (Site #8, July 1994)

Figure 6: Broad trail (~2 m) along relatively steeper slope. (Site #17, July 1994)

Figure 7: Narrow meadow trail with little incision. (Site #58, July 1994)

The study area has a continental climate. Late June through August comprise the summer months with an average temperature of 16^0 C and little rainfall. July receives an average of 3.4 cm of precipitation, and August receives an average of 3.8 cm of precipitation. Autumn typically extends to November and is generally cool and dry. Precipitation from November through April generally falls as snow. Spring is marked by continued cool and wet weather with the greatest amount of annual precipitation occurring during May, with a normal monthly accumulation of 8.1 cm, and June, with a normal accumulation of 7.3 cm (NOAA, 1993). Snow can occur during any month of the year in this area, particularly at higher elevations.

The New World Gulch Trail originates in a mountain meadow habitat dominated by lodgepole pine (*Pinus contorta* Dougl. ex Loud.) with Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and Englemann

Site	Soil Subgroup	Description	Rock Fragment
-26	Mixed Glossic Cryoboralf	- Different survey from remainder of	20 to 40%
27-	Typic Cryochrept – Typic Cryoboralf complex	NA - Different survey from remainder of table.	5 to 15%
34-40	Mollic Cryoboralf – Typic Cryoboralf complex, steep	Medium textured surface layer and an accumulation of clay in the subsoil. Soil properties are not obviously associated with landscape features. Parent material – interbedded sandstone and shale.	35 to 50%
41-42	Cryaquolls and Cryaquent, flood plains	Medium textured surface layer which, in places, occasionally floods during spring snowmelt. Properties vary depending on age of alluvial deposits.	5 to 10%
45-63	Typic Cryoboralf – Mollic Cryoboralf complex	Medium textured surface layer with subsoil accumulations of clay. Parent material – interbedded sandstone and shale.	0 to 50%
64-68	Mollic Cryoboralf – Typic Cryoboralf complex, steep	Medium textured surface layer and an accumulation of clay in the subsoil. Soil properties are not obviously associated with landscape features. Parent material – interbedded sandstone and shale.	35 to 50%
69-72	Typic Cryoboralf – Argic Cryoborolls association	Medium textured surface layer and an accumulation of clay in the subsoil. Soil properties vary depending on the vegetation. Parent material – interbedded sandstone and shale.	10 to 20%
79	Typic Cryoboralfs – Typic Cryochrepts – Rock outcrop complex, calcareous substratum	Medium textured surface layer. Soil properties vary depend on topography. Soils on benches or in saddles have an accumulation of clay in the subsoil, where ridge soils do not. Parent material – limestone and shale	35 to 50%
92-97	Typic Calciborolls – Rock outcrop – Typic Ustochrepts complex, limestone substratum, steep	Medium textured or moderately fine textured surface layer. Properties vary according to soil aspect. Parent material – limestone.	35 to 50%
104	Typic Cryoboralf – Typic Cryochrepts – Rock outcrop complex, calcareous substratum	Medium textured surface layer. Soil properties vary depend on topography. Soils on benches or in saddles have an accumulation of clay in the subsoil, where ridge soils do not. Parent material – limestone and shale	35 to 50%
127	Typic Cryoboralfs and Argic Cryoboroll association	Medium textured surface layer and an accumulation of clay in the subsoil. Soil properties vary depending on the vegetation. Parent material – interbedded sandstone and shale.	10 to 20%

Table 1: Soil subgroups and characteristics at study sites (Davis and Shovic, 1996).

spruce (*Picea engelmanii* Parry ex Engelm.). Grouse whortleberry (*Vaccinium scoparium* Leiberg ex Cov.), blue huckleberry (*Vaccinium globulare* Rydb.), and twinflower (*Linnaea borealis* L.) make up the bulk of the understory vegetation. Meadows are populated by mat shrubs such as blue huckleberry (*Vaccinium globulare* Rydb.), bearded wheatgrass (*Agropyron caninum* Link), twinflower, bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Love), mountain brome (*Bromus carinatus* Hook. and Arn.) and Idaho fescue (*Festuca idahoensis* Elmer). Overstory vegetation on the Bozeman Creek Trail consists primarily of less densely distributed Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) with bluebunch wheatgrass and Idaho fescue populating the understory (Seney, 1991).

CHAPTER THREE

METHODS

The goals of this study required the collection of field data, laboratory analysis of soil samples, and statistical analysis of data. Soil samples and other field measurements were collected over several months during the summer and fall of 1994. In addition, some of the topographic information used in the statistical analysis originated in Urie's (1994) study of recreational trails.

Urie's (1994) examination of the relationship between landscape variables and trail condition concluded that the variables that she collected explained roughly 50% of the variation in cross-sectional area. Cross-sectional area was defined by taking a transect at each sample site and measuring the: 1) width of the disturbed zone between two fixed points on either edge of the trail, and 2) the depth of the trail across this width at 10 cm intervals (Urie, 1994). In order to further explain the variation, I examined variables that had not been examined in Urie's study: soil bulk density, estimated degree of compaction, slope intersection angles, adjusted trail azimuth, and soil particle size distribution.

Soil bulk density measurements were made on and off the trail to document the undisturbed and disturbed soil bulk densities needed to estimate the amount of compaction that had occurred. Considering the compaction effect on the cross-sectional area of the trail also provides a more accurate measure of the erosion along the trail, which was the primary emphasis of Urie's (1994) study.

The difference between the azimuth of the trail and the aspect of the dominant regional slope was determined at each site. This measurement provided information on whether the angle of interception of overland flow from the regional slope influenced trail erosion (Bratton *et al.*, 1979). The aspect data used by Urie was adjusted to represent angular deviations from a North - South base line. This adjustment to Urie's data was designed to eliminate the use of Urie's aspect units in the regression analysis. Particle size distribution was determined for approximately 1/3 of the samples and recorded as percentages of the total sample mass to negate the effect of the variation in mass from sample to sample.

Data Acquisition

Pilot Study, Sampling Strategy and Soil Data

Field work began with the relocation and/or reestablishment of as many as possible of the 130 study sites originally established by Urie (1994). Ultimately, with the assistance of Urie, 67 of the sites were relocated. Seven of those sites (12, 29, 59, 79, 104, and 127), representing the extremes of the cross-sectional area "missing" from the trail, along with three others (1, 11, and 21) were used as pilot study sites to establish the optimum sampling strategy.

At each of the ten pilot study sites, the sampling strategy consisted of taking twelve 5.2 cm diameter by 5.2 cm deep (approximately 111 cm^3) cores. Four of the cores were taken along the center and parallel to the trail. Four cores were taken one meter from the edge of either side of the trail (two core samples each side), and four cores were taken two meters from the edges of the trail (two core samples each side) in order to capture trends in variability between soil bulk densities and to determine the appropriate sampling strategy needed to collect a representative sample.

The metal coring cylinders were driven into the soil until the top of the tube was even with the surface (Figure 8). To minimize the sampling error due to dislocation of soils during the coring process, wood block buffers were placed between the hammer driver and the top of the core. Soil cores that were noticeably disturbed during the coring process were discarded.

Even cores that were not noticeably disturbed may have had their *in situ* bulk densities compromised by the coring process (Black, 1965; Page-Dumroese *et al*., 1999). In some cases, the brittle nature of the dry compacted soils on the trail may have resulted in a slight under representation of that soil's true bulk density due to "delaminating" between soil layers caused by vibration. On the other hand, particularly soft or compressible soils may have been slightly compacted in the coring process, thereby increasing the bulk density. Care was taken to minimize such effects.

Pilot study core samples along the sides of the trail frequently included vegetative litter. The inclusion of litter reduced the measured bulk densities of the "off trail" samples, thereby confounding estimates of compaction. All sites sampled after the pilot study phase were therefore clipped of vegetation and cleared of the litter to the uppermost surface of the mineral soil (Figure 9).

Pebbles in the soil influenced the compactability of the soil, so they were included in the calculations of the bulk densities. However, where pebbles constituted in excess of about one third of the volume of the core, that core was discarded and another taken due to the possible misrepresentation of that sample to the surrounding soil. One of the pilot

Figure 8: Core sampler in center of trail.

Figure 9: Core off trail with vegetation clipped.

study sites, #102, was unusable for the entire project because it consisted of a large boulder with only a veneer of soil, making coring impossible.

Once the core samples were extracted, they were placed in paper sacks in a shaded pack for transport to the lab where they were weighed on the day of collection. Later, the samples were dried in an oven for 24 hours at 110^0 C. The dry samples were then reweighed and the soil bulk density (ρ_b) calculated by dividing the oven dry weight (m_s) by the total core volume (V_t).

The results of the pilot study, as discussed in the results section, indicated that collecting one core in the center of the trail and one core one meter from each trail edge would represent the range of bulk densities on and off the trail at each site. This was done for the remaining study sites. All other soil sample collection and laboratory analysis techniques established during the pilot study were maintained.

Particle size distributions were measured using the sieve method (Marshall *et al.*, 1996). Seven sieve sizes were used, resulting in the following sieved particle size classes: < 0.063 mm, 0.063 - 0.125 mm, 0.125 - 0.25 mm, 0.25 - 0.5 mm, 0.5 - 1 mm, 1 - 2 mm, and > 2 mm. Each sample was sieved for ten minutes. Particle size classes were weighed and converted to a percentage of the total sample weight. Moving the lab while the researcher was gone resulted in the loss of some samples, so only a portion of the sites have particle size results.

Physiographic Data

Topography as well as bulk density can contribute to trail erosion and changes in cross-sectional area. Data was therefore collected on the trail aspect and the dominant slope aspect at each site. It was assumed that as the difference between the trail azimuth and slope aspects increase, trail erosion might decrease due to the trail acting increasingly like a sediment trap rather than a channel (Bratton *et al*., 1979). There may be some discrepancy between the slope aspect measured for this study and that reported by Urie (1994) due to the fact that Urie's values were derived from a Digital Elevation Model (DEM), while those for this work were measured directly.

In addition to the soil bulk density, soil type, and aspect data collected by this author, Urie (1994) collected data at each site on trail slope, soil water content, and vegetative cover. Soil water content was measured three times (June ,1993; July, 1992; September, 1992) with a Tektronic time domain reflectometry (TDR) tester for the top 20 cm of the soil profile along the trail. The mean of the measurements at each site was used in the analysis of the data (Urie, 1994). Urie also used the Topographic Analysis Programs for Environmental Sciences - Grid version (TAPES - G) program coupled with a Geographic Information System (GIS) and Digital Elevation Model (DEM) to generate data on regional slope, profile curvature, plan curvature, trail aspect, elevation, and specific catchment area.

Analysis

Statistical Tests

A t-test was used to determine if bulk densities on and off of the trail were significantly different. A correlation matrix established association among variables and suggested whether variables could be included together in a multiple regression. Scatterplots for the measured and adjusted cross-sectional trail areas were developed for all variables. Those scatterplots were used to identify any nonlinear and/or threshold relationships between variables. Multiple regression analysis was the primary statistical tool used to establish the degree to which variations in erosion and compaction at each site were controlled by different driving variables.

Soil Compaction & Erosion

Equation (1) was used to calculate the depth of trail incision due to compaction (Δd) occurring at each site, where ρ_{bcen} is the bulk density at the center of the trail, ρ_{boff} is the mean soil bulk density off the trail at each site, and d_c is the depth of the soil in which compaction occurred. The bulk density samples (Table 3) from the 64 reestablished sites were entered into eq. (1) to estimate the potential magnitudes of the cross-sectional erosion and compaction at each site. The trail incision due to compaction was calculated by subtracting the adjusted cross-sectional area from the measured area.

$$\Delta d = d_c\left(\frac{\rho_{boff}}{\rho_{bcen}} - 1\right) \qquad (1)$$

Equation (1) assumes that the on trail bulk density was the same as the off trail bulk density before compaction. The "soil expansion" equation was first used with the depth of the core sample (5.2 cm) to determine the minimum difference between the measured and adjusted cross-sectional areas. The 5.2 cm depth was used as a minimum (conservative) estimate because it was the depth of the soil core sample, and because visual observation suggested that compaction occurred to at least this depth.

Through visual inspection during the coring process, it was apparent that compaction occurred below the 5.2 cm depth at many sites. To estimate the potential maximum effect of soil compaction, eq. (1) was used again assuming a uniform compaction depth of 25 cm.

CHAPTER FOUR

RESULTS

This chapter summarizes the data, reports on the results of the pilot study, and examines the relation of cross-sectional area to soil bulk density, compaction and topographic variables. To isolate the significant variables, correlation matrices were developed for both the cross-sectional and adjusted cross-sectional areas. Scatter plots were used to verify the strength of relationships and to inspect for nonlinear relationships. Finally, multiple stepwise regressions were used to assess the amount of variability in the measured and adjusted cross-sectional areas that could be explained by measured and derived variables.

Pilot Study Data

Bulk density samples from the pilot study (Table 2) were evaluated to determine the most efficient sampling strategy for documenting any differences between on and off trail bulk densities. A t–test showed significant differences in bulk density at the 0.05 level between the combined samples taken on and off the trail. It also showed that there was no significant difference between the samples taken 1 meter off the trail versus those taken 2 meters off the trail. Additionally, all samples taken on the trail at a site were found to be statistically similar in bulk density (Table 3).

	Left 2m (g/cm^3)	**Left 1m** (g/cm^3)	**Center** (g/cm^3)		**Right 1m** (g/cm^3)	**Right 2m** (g/cm^3)
Site #1	1.13	1.02	1.65	1.61	1.11	1.05
	1.33	1.20	1.74	1.50	1.35	1.11
Site #11	0.95	1.02	1.62	1.62	0.78	0.71
	0.85	0.83	1.52	1.69	0.93	0.71
Site #12	1.43	1.13	1.76	1.64	1.31	NA^1
	1.05	1.17	1.69	1.85	1.39	NA^1
Site #21	1.07	1.03	1.82	1.82	0.79	0.75
	1.25	0.85	1.69	1.71	0.61	0.83
Site #29	0.62	0.32	1.64	1.23	0.55	0.45
	0.84	0.91	1.65	1.48	0.57	1.01
Site #59	1.14	0.89	1.58	1.71	1.27	1.17
	1.06	1.10	1.67	1.69	1.26	1.40
Site #79	1.31	1.38	1.55	1.50	1.07	0.99
	1.43	1.38	1.48	1.38	1.20	1.00
Site# 102	NA^2	NA^2	1.54	NA^2	NA^2	NA^2
	NA^2	NA^2	NA^2	NA^2	NA^2	NA^2
Site #104	1.03	1.03	1.25	NA^3	1.31	1.22
	1.13	0.97	1.25	1.13	0.95	0.93
Site #127	1.05	1.31	1.65	1.73	1.16	1.08
	1.14	1.32	1.65	1.44	1.17	1.10

Table 2: Bulk density of pilot study samples. (^{1} - 2m right of trail was a stream, ^{2} - Site was on top of predominantly exposed rock, ^{3} - Incomplete sample).

	Bulk Density (g/cm^3)		
	Trail Center	1m from edge	2m from edge
Mean	1.59	1.16	1.05
Standard Dev.	0.17	0.21	0.18
Range	0.60	0.70	0.51

Table 3: Summary statistics for pilot study.

Data

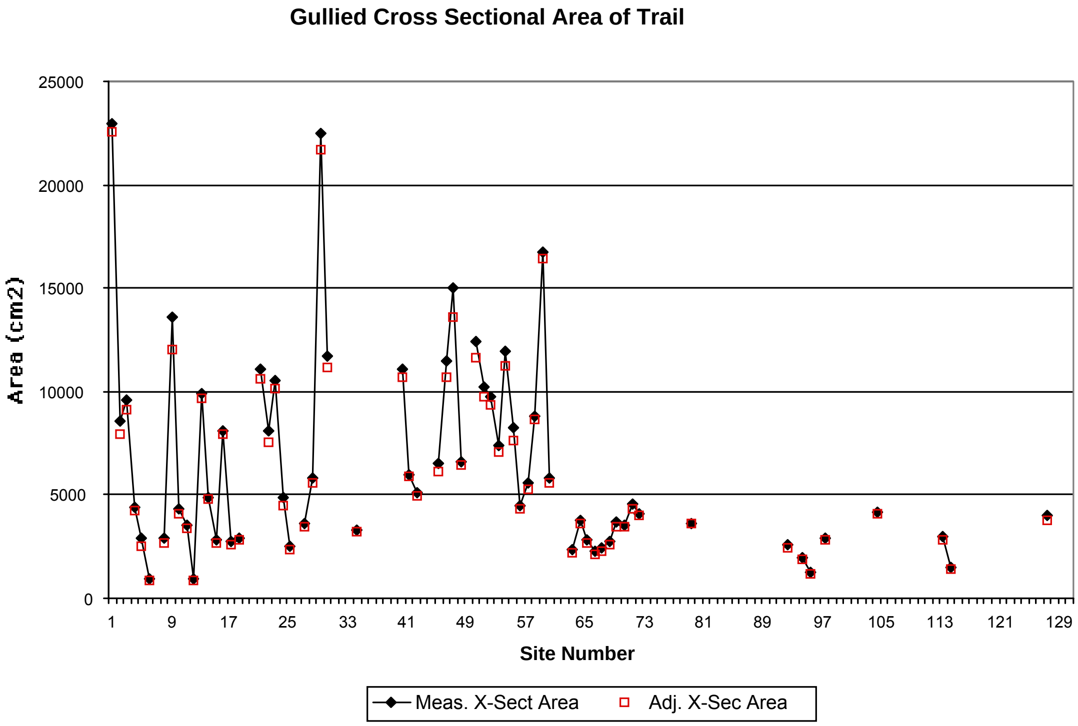
Soil bulk density data for each site and the differences in measured and adjusted cross-sectional areas between the 5.2 cm and 25 cm depth of compaction measurements are shown in Table 4. As expected, the amount of the incised trail area attributable to erosion decreases when the depth of compaction is assumed to extend beyond the 5.2 cm depth to 25 cm in depth (Figure 10).

Soil particle size distribution data, shown in Table 5, was measured for each sieve size by mass. The mass of soil that did not pass each sieve size was then converted to a percentage of the total mass of the sample.

Analysis

Descriptive Analysis

Scatter plots were developed to observe the relationships between the measured cross-sectional area and the off trail soil bulk density (Figure 11) and the ratio of the on and off trail soil bulk densities (ρ_{bcen}/ρ_{boff}) (Figure 12). Using the measured cross-sectional area of the trail and the adjusted cross-sectional area derived using the soil expansion equation, scatter plots were developed to compare the relationships between the measured and adjusted cross-sectional areas to the other significant variables as defined by the correlation matrices (Figures 13 - 27). These figures were further used to determine if non-linear relationships existed, and if there might be thresholds.



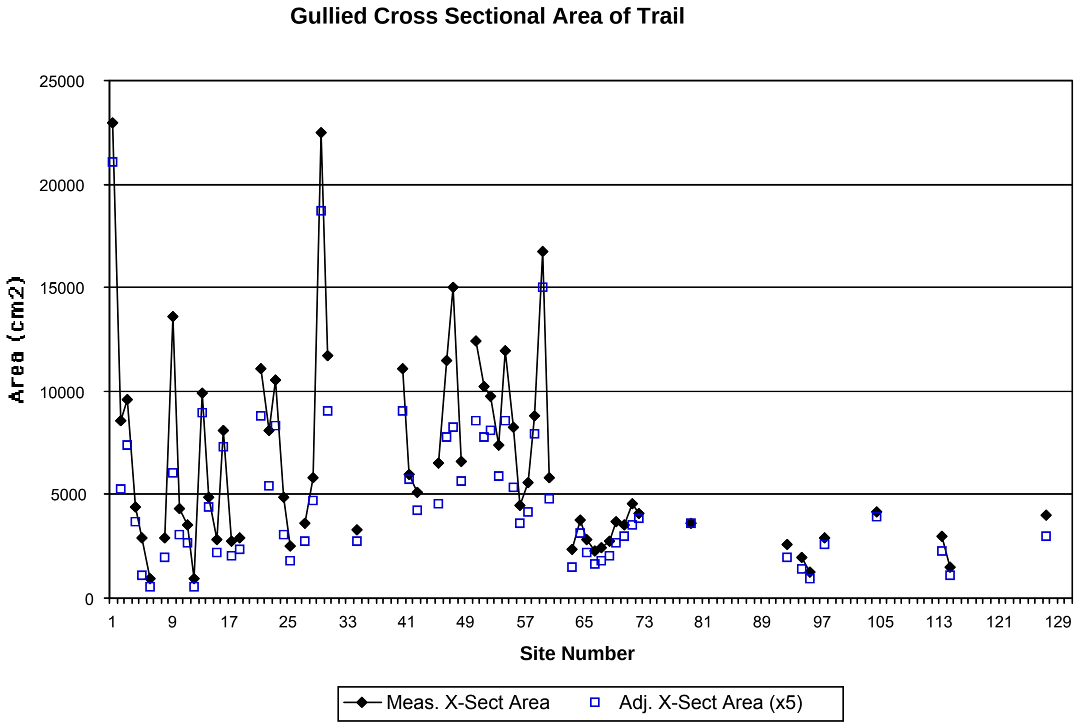


Figure 10: The adjusted area derived using the 5.2 cm (above) and 25 cm depths (below) in Equation (1).

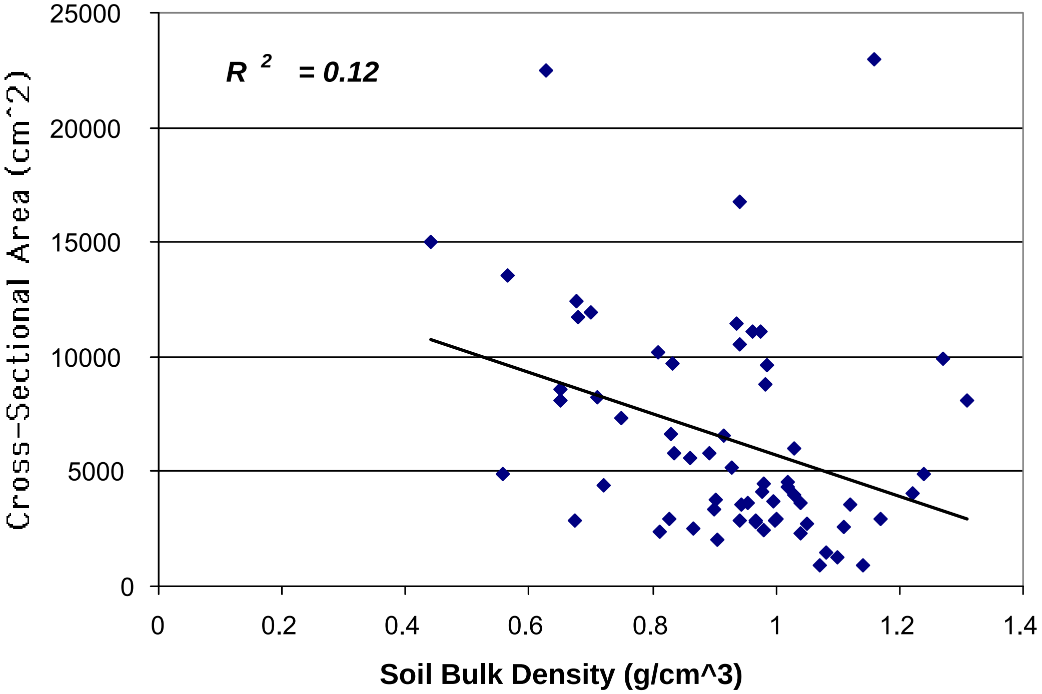


Figure 11: Measured cross-sectional area *vs*. off-trail soil bulk density.

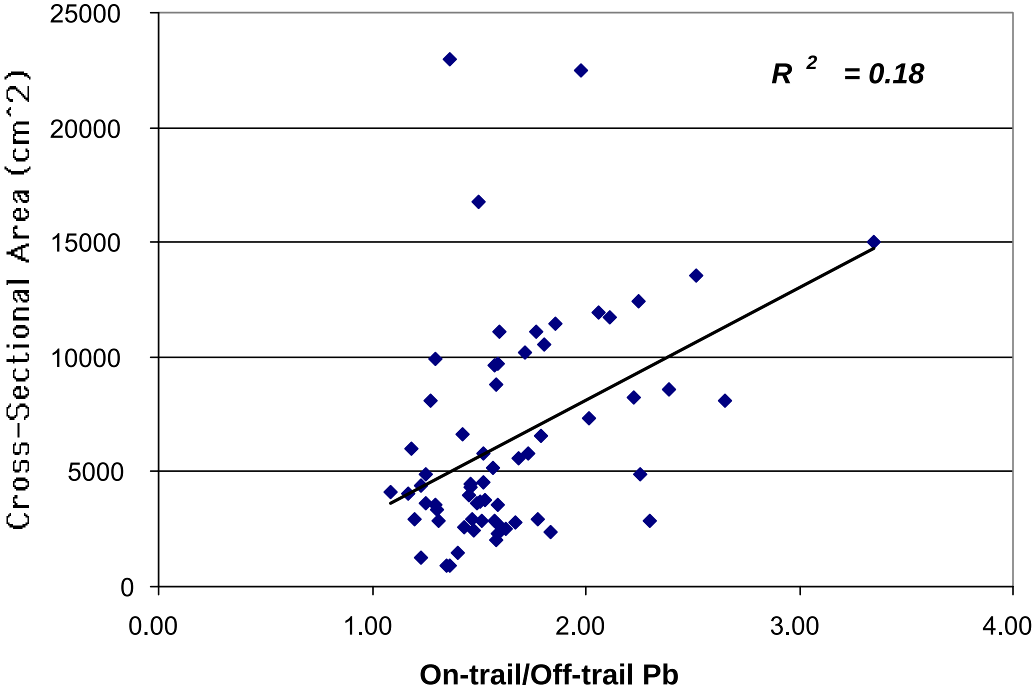


Figure 12: Measured cross-sectional area *vs.* ratio of on-trail and off-trail soil bulk density.

Stake #	Off trail ρ_b (gcm^3)	Center trail ρ_b (gcm^3)	Off trail ρ_b (gcm^3)	Avg Off trail ρ_b (gcm^3)	X-Sect Area (cm^2)	X-Sect Area adj to 5.2 cm (cm^2)	X-Sect Area adj to 25 cm (cm^2)
1	1.1	1.58	1.22	1.16	22942	22560	21101
2	0.459	1.56	0.845	0.652	8600	7904	5253
3	1.14	1.55	0.824	0.984	9618	9149	7363
4	0.865	0.887	0.579	0.722	4414	4259	3670
5	0.83	1.55	0.516	0.673	2893	2525	1125
6	0.988	1.46	1.16	1.07	909	827	515
8	1.04	1.51	0.956	0.999	2870	2687	1990
9	0.318	1.42	0.811	0.564	13562	11995	6027
10	0.945	1.49	1.1	1.02	4342	4083	3096
11	0.967	1.5	0.922	0.944	3573	3392	2702
12	1.04	1.54	1.24	1.14	937	851	521
13	1.44	1.65	1.09	1.27	9884	9688	8940
14	1.28	1.55	1.2	1.24	4857	4760	4392
15	0.888	1.48	0.996	0.942	2841	2701	2169
16	1.43	1.67	1.18	1.31	8112	7951	7336
17	0.971	1.61	0.961	0.966	2761	2615	2061
18	1.18	1.47	0.822	1	2921	2798	2330
21	0.937	1.72	1.01	0.975	11073	10593	8767
22	0.63	1.73	0.674	0.652	8122	7565	5443
23	0.875	1.7	1.01	0.942	10567	10110	8371
24	0.755	1.26	0.361	0.558	4893	4516	3082
25	0.818	1.41	0.915	0.866	2538	2388	1815
27	1.02	1.42	0.888	0.954	3606	3425	2736
28	0.847	1.27	0.82	0.834	5780	5559	4716
29	0.743	1.24	0.51	0.627	22483	21702	18726
30	0.564	1.43	0.791	0.678	11733	11167	9012
34	1.06	1.17	0.739	0.899	3335	3210	2733
40	0.972	1.53	0.95	0.961	11107	10676	9034

Table 4 (continued next page)

Stake #	Off trail ρ_b (gcm^3)	Center trail ρ_b (gcm^3)	Off trail ρ_b (gcm^3)	Avg Off trail ρ_b (gcm^3)	X-Sect Area (cm^2)	X-Sect Area adj to 5.2 cm (cm^2)	X-Sect Area adj to 25 cm (cm^2)
41	1.01	1.22	1.06	1.03	5975	5922	5722
42	0.965	1.45	0.89	0.927	5144	4960	4260
45	1.05	1.64	0.781	0.915	6558	6144	4569
46	0.783	1.74	1.09	0.935	11447	10689	7804
47	0.567	1.48	0.316	0.442	14992	13588	8241
48	0.752	1.18	0.906	0.829	6622	6421	5655
50	0.786	1.52	0.568	0.677	12428	11626	8573
51	0.883	1.39	0.733	0.809	10216	9714	7802
52	0.817	1.32	0.85	0.833	9736	9391	8076
53	0.717	1.51	0.778	0.748	7352	7053	5914
54	0.711	1.44	0.686	0.699	11948	11247	8577
55	0.783	1.58	0.638	0.71	8232	7625	5314
56	1.11	1.43	0.85	0.979	4471	4299	3643
57	0.716	1.45	1.01	0.861	5577	5277	4135
58	1.19	1.55	0.772	0.983	8801	8630	7978
59	0.868	1.41	1.01	0.941	16767	16406	15029
60	0.892	1.54	0.89	0.891	5806	5598	4805
63	0.868	1.49	0.756	0.812	2369	2187	1493
64	0.975	1.38	0.832	0.903	3755	3627	3141
65	0.855	1.27	1.08	0.967	2830	2706	2234
66	1.04	1.65	1.05	1.04	2272	2145	1662
67	1.04	1.45	0.923	0.981	2433	2300	1794
68	0.947	1.67	1.16	1.05	2733	2596	2074
69	1.06	1.5	0.927	0.995	3668	3467	2700
70	1	1.45	1.23	1.12	3538	3431	3026
71	0.898	1.55	1.14	1.02	4569	4350	3518
72	1.21	1.43	1.23	1.22	4075	4021	3814
79	1.18	1.3	0.901	1.04	3610	3610	3610

Table 4 (continued next page)

Stake #	Off trail ρ_b (gcm^3)	Center trail ρ_b (gcm^3)	Off trail ρ_b (gcm^3)	Avg Off trail ρ_b (gcm^3)	X-Sect Area (cm^2)	X-Sect Area adj to 5.2 cm (cm^2)	X-Sect Area adj to 25 cm (cm^2)
92	1.16	1.59	1.07	1.11	2606	2476	1980
94	0.769	1.43	1.04	0.904	1999	1879	1424
95	1.05	1.35	1.15	1.1	1232	1176	963
97	1.27	1.4	1.07	1.17	2902	2830	2557
104	0.943	1.06	1.01	0.978	4150	4109	3955
113	0.813	1.47	0.843	0.828	2966	2818	2256
114	1.04	1.51	1.12	1.08	1497	1413	1091
127	1.07	1.5	0.984	1.03	3981	3777	3002

Table 4: A-Pb and C-Pb are soil bulk density one meter from the edge of the incised trail. B-Pb is the soil bulk density in the incised trail center. X-Sect Area is the measured cross-sectional area. X-Sect Area adj. To 5.2 cm is the adjusted cross-sectional area derived with Equation 1, using 5.2 cm as the depth of compaction. X-Sect Area adj to 25 cm is the adjusted cross-sectional area derived with Equation 1 using a depth of compaction of 25 cm.

Stake #	> 2 mm (gm)	1-2 mm (gm)	0.5-1 mm (gm)	0.25-0.5 mm (gm)	0.125-0.25 mm (gm)	0.063-0.125 mm (gm)	< .063 mm (gm)
1	0.71	0.13	0.05	0.03	0.02	0.02	0.03
2	0.67	0.18	0.06	0.03	0.02	0.02	0.03
4	0.30	0.21	0.13	0.10	0.06	0.05	0.14
6	0.31	0.22	0.17	0.04	0.12	0.07	0.06
9	0.49	0.21	0.10	0.07	0.05	0.03	0.06
10	0.57	0.15	0.08	0.07	0.05	0.03	0.06
11	0.33	0.27	0.15	0.09	0.05	0.04	0.08
25	0.09	0.15	0.23	0.22	0.14	0.08	0.09
27	0.48	0.25	0.09	0.06	0.05	0.03	0.04
30	0.40	0.24	0.15	0.10	0.05	0.03	0.04
34	0.46	0.20	0.11	0.08	0.06	0.04	0.04
41	0.23	0.10	0.10	0.12	0.18	0.09	0.18
46	0.37	0.23	0.09	0.06	0.06	0.06	0.12
47	0.42	0.19	0.11	0.08	0.07	0.05	0.08
50	0.64	0.16	0.07	0.04	0.03	0.02	0.03
53	0.40	0.19	0.10	0.07	0.06	0.06	0.11
54	0.44	0.19	0.08	0.05	0.05	0.06	0.13
55	0.56	0.19	0.07	0.04	0.03	0.03	0.07
57	0.46	0.16	0.07	0.05	0.04	0.06	0.17
60	0.28	0.25	0.05	0.09	0.06	0.08	0.20
63	0.37	0.23	0.11	0.07	0.06	0.06	0.10
65	0.39	0.13	0.10	0.09	0.08	0.08	0.14
66	0.31	0.14	0.10	0.10	0.13	0.13	0.10
69	0.52	0.02	0.16	0.10	0.08	0.05	0.07
71	0.42	0.19	0.09	0.08	0.12	0.05	0.04
94	0.32	0.12	0.06	0.08	0.13	0.13	0.15
114	0.58	0.20	0.12	0.05	0.02	0.01	0.02

Table 5: Soil particle size class distribution by weight for off trail soil core samples.

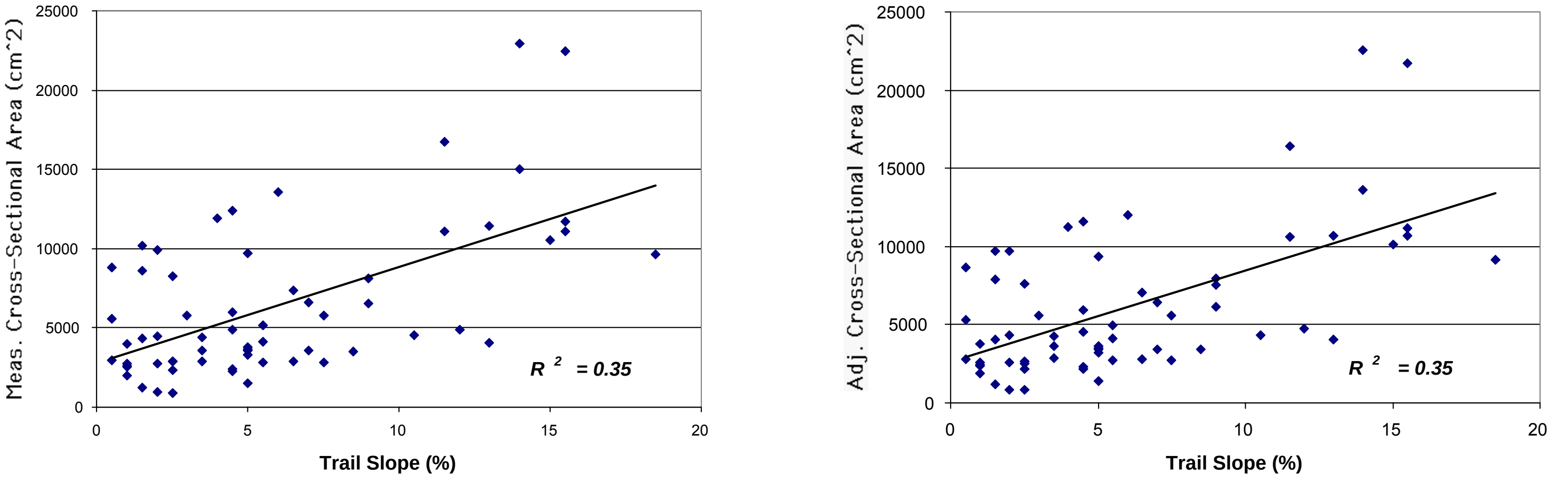


Figure 13: Measured and adjusted cross-sections *vs.* trail slope.

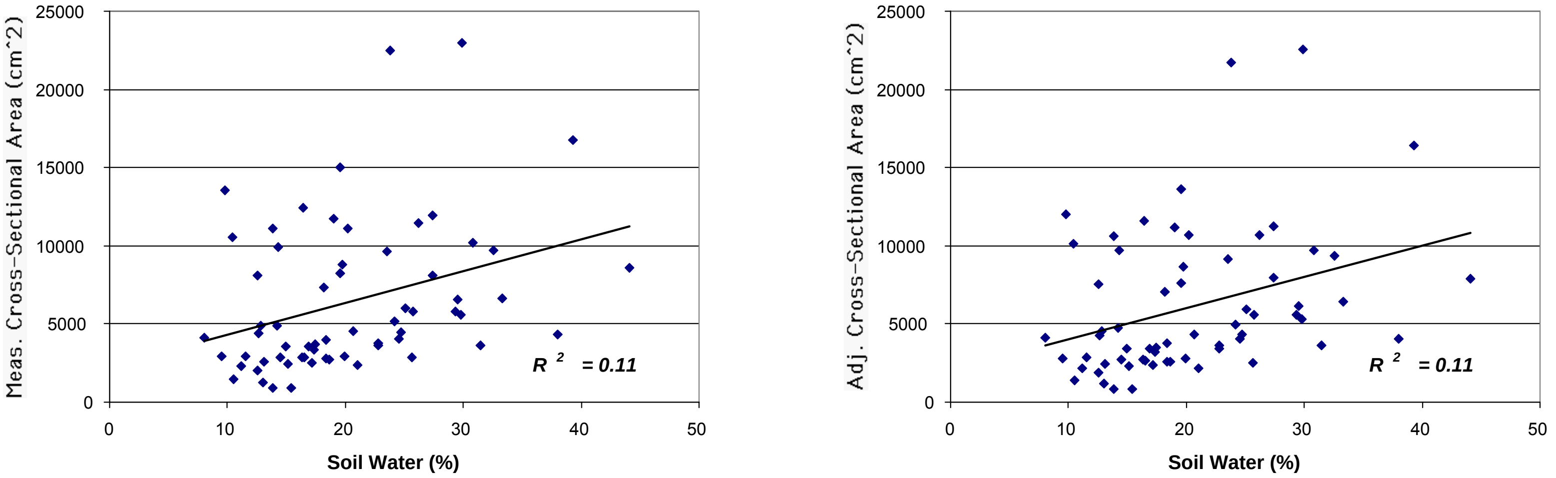


Figure 14: Measured and adjusted cross-sections *vs.* soil water.

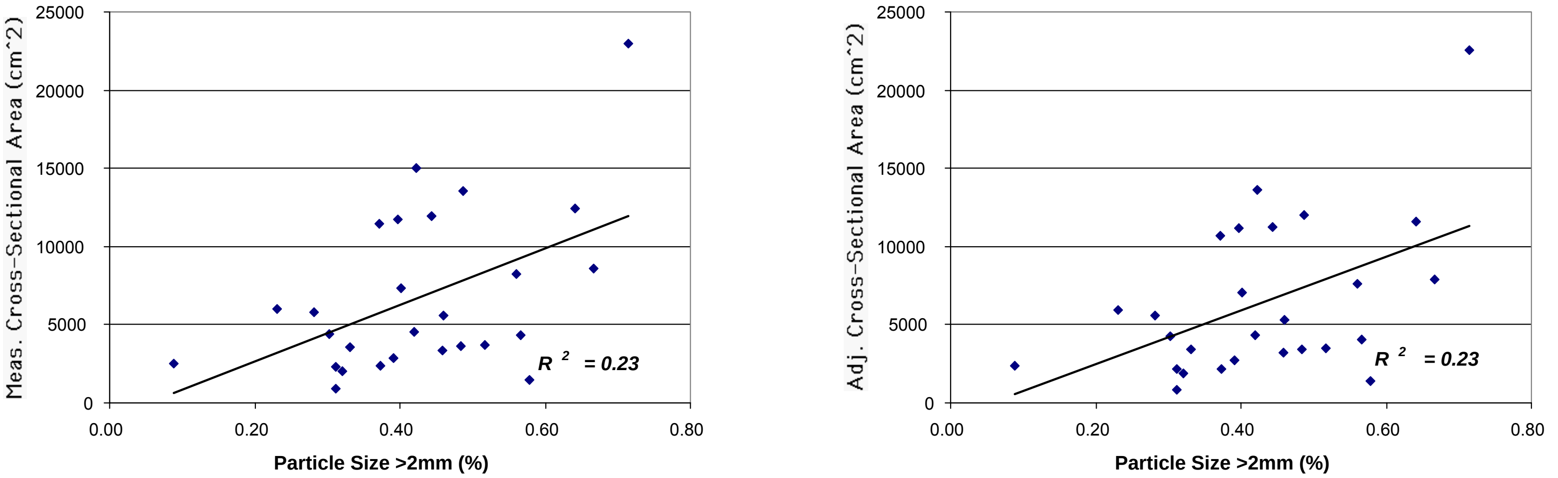


Figure 15: Measured and adjusted cross-sections *vs.* percent particle size greater than 2mm.

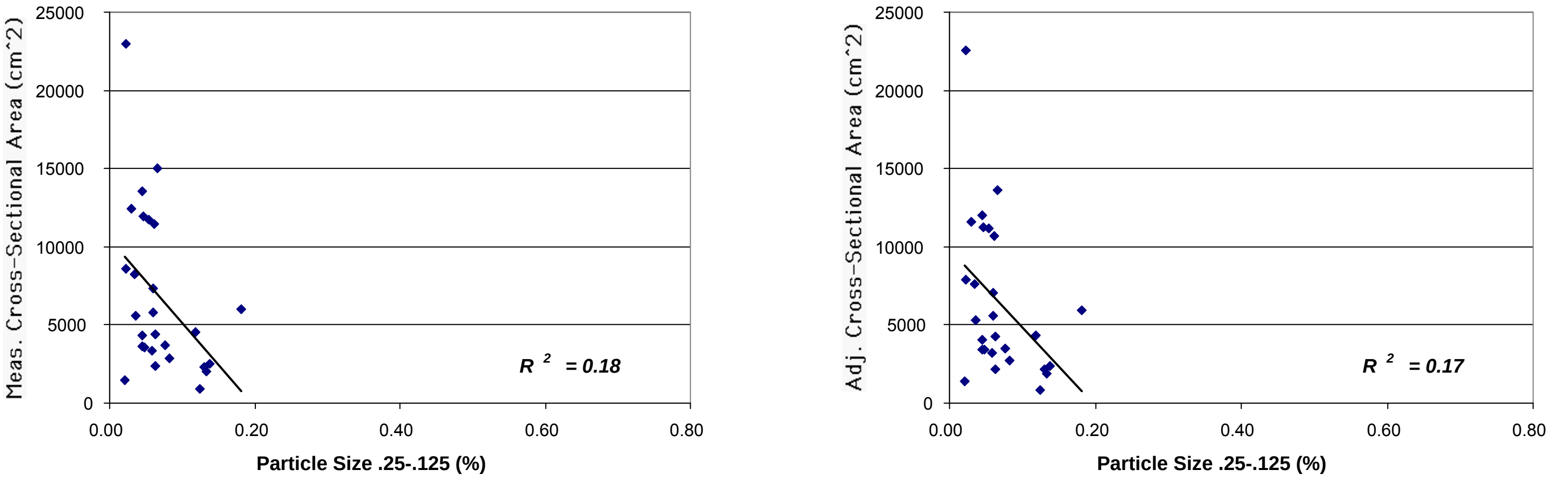


Figure 16: Measured and adjusted cross-sections *vs.* percent particle size 0.25 - 0.125 mm.

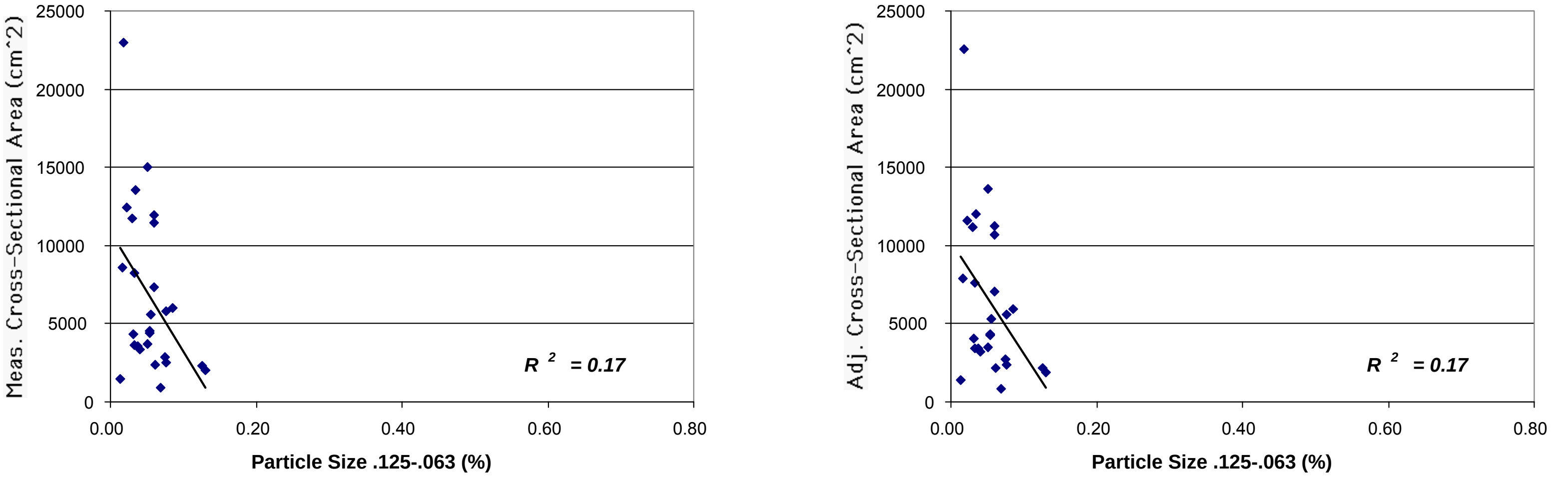


Figure 17: Measured and adjusted cross-sections *vs.* percent particle size 0.125 - 0.065 mm.

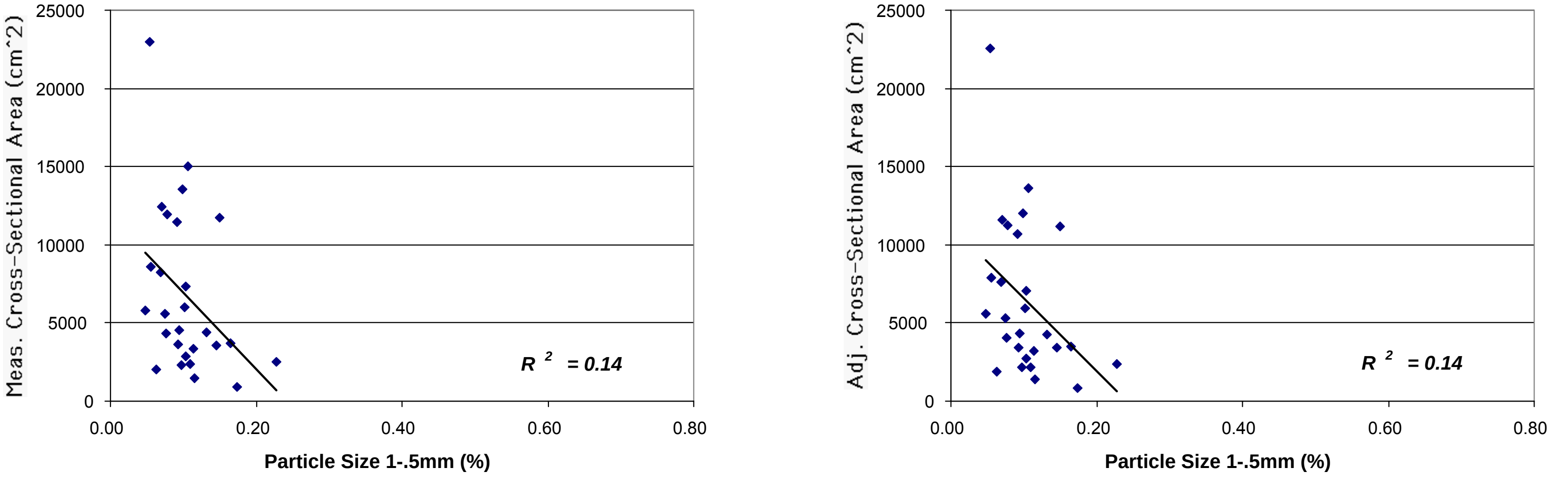


Figure 18: Measured and adjusted cross-sections *vs.* percent particle size 1.0 - 0.5 mm.

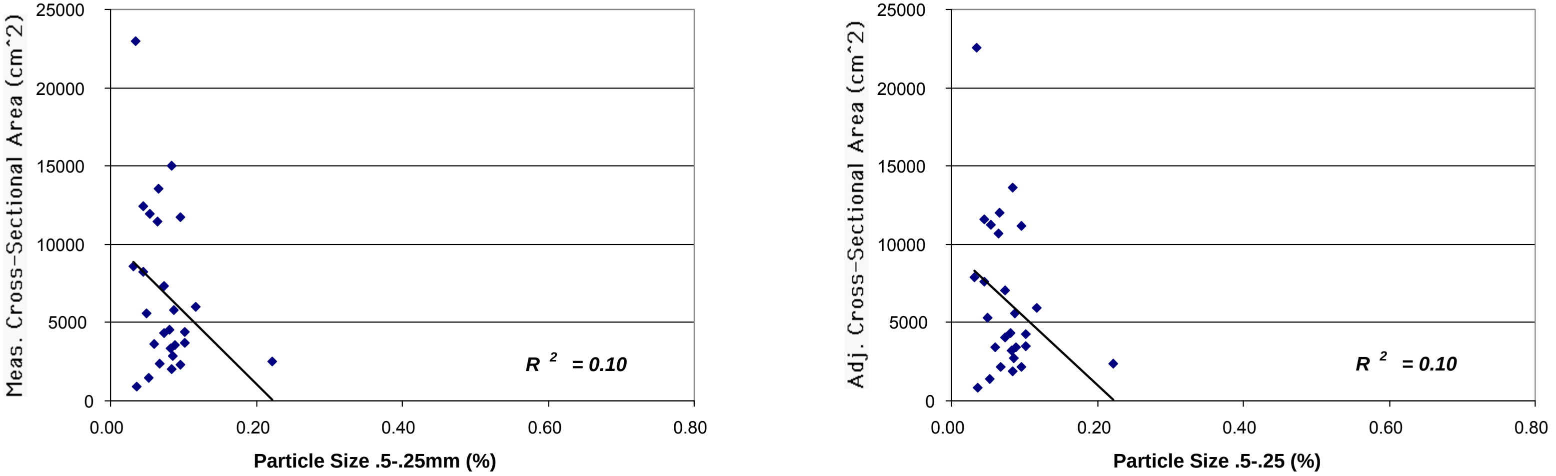


Figure 19: Measured and adjusted cross-sections *vs.* percent particle size 0.5 - 0.25 mm.

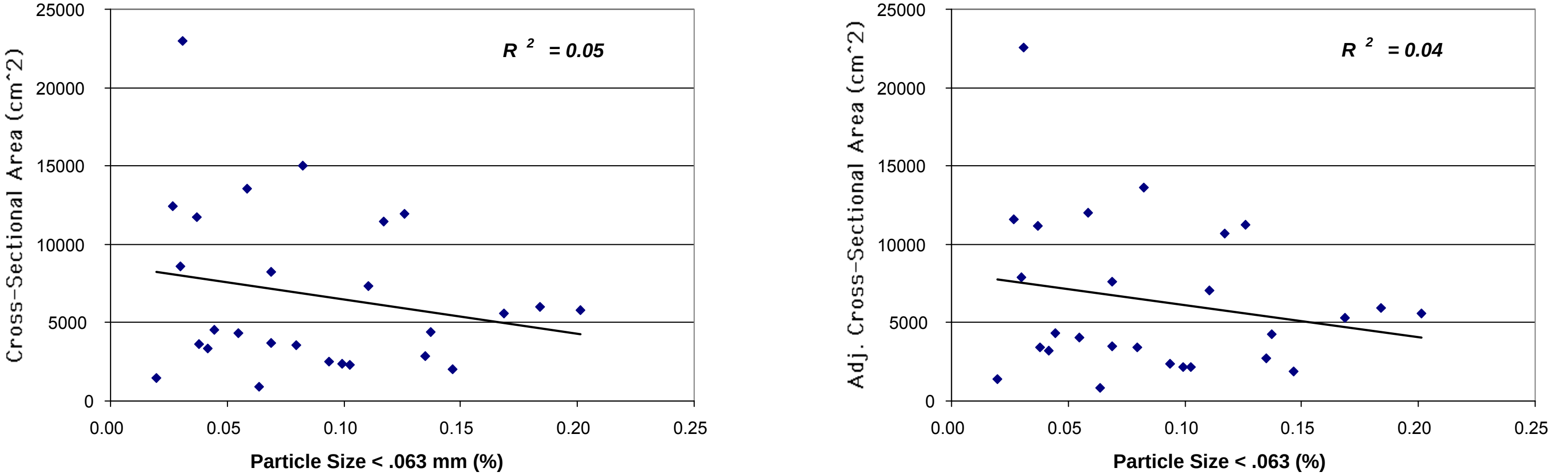


Figure 20: Measured and adjusted cross-sections *vs.* percent particle size less than 0.063 mm.

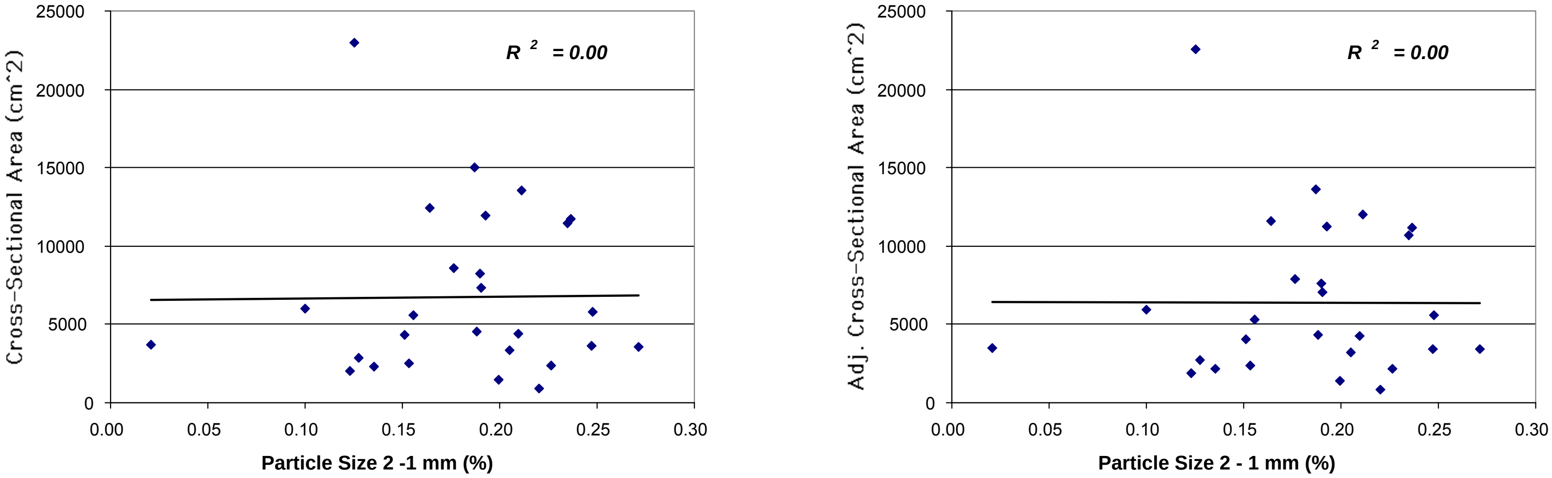


Figure 21: Measured and adjusted cross-sections *vs.* percent particle size 2 mm - 1 mm.

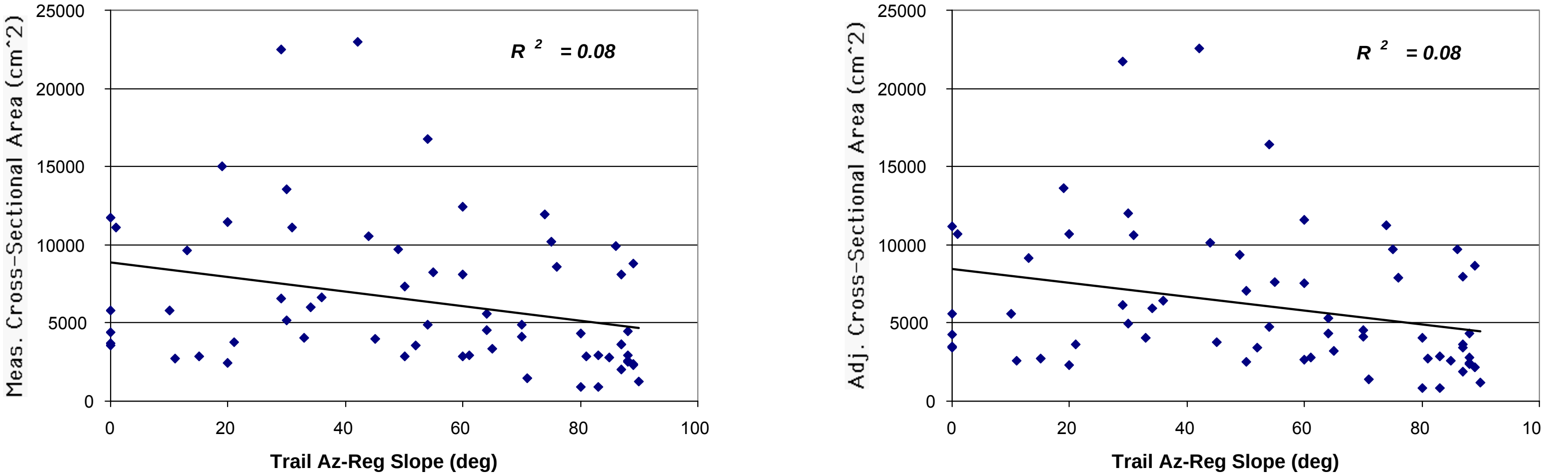


Figure 22: Measured and adjusted cross-sections *vs.* angle of trail intercept.

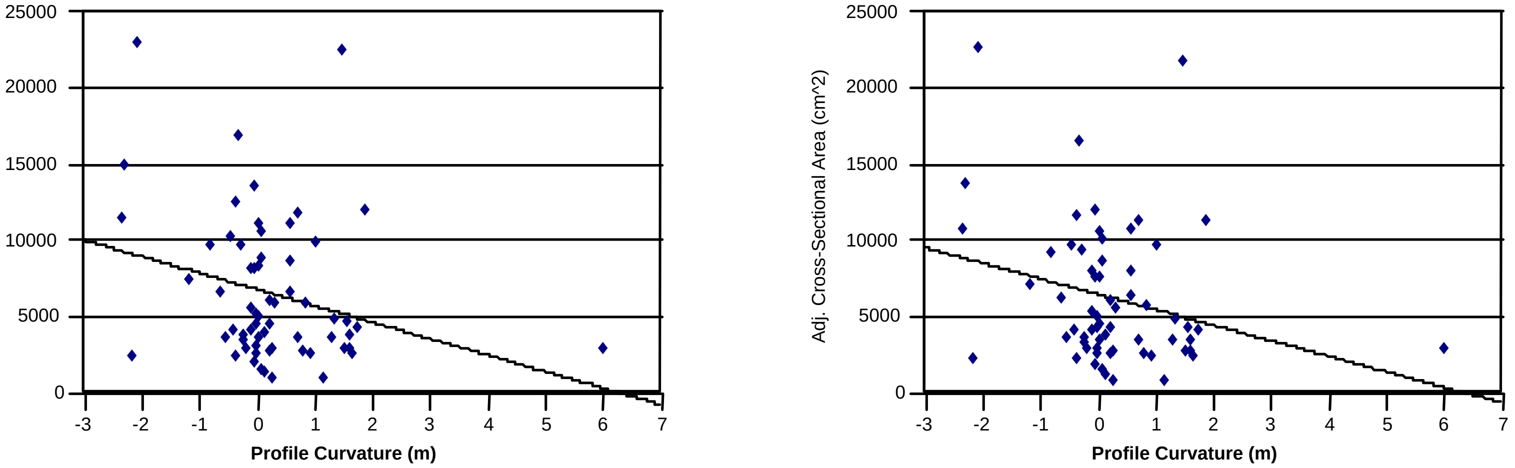


Figure 23: Measured and adjusted (to 5.2 cm depth of compaction) cross-sections *vs.* profile curvature.

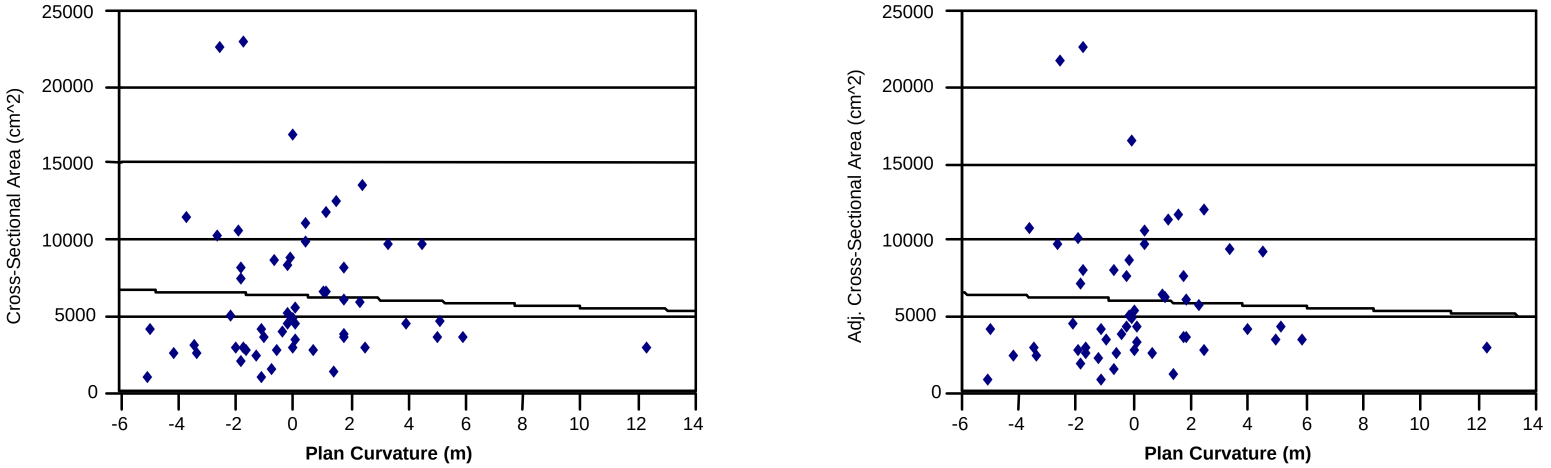


Figure 24: Measured and adjusted (to 5.2 cm depth of compaction) cross-sections *vs.* plan curvature.

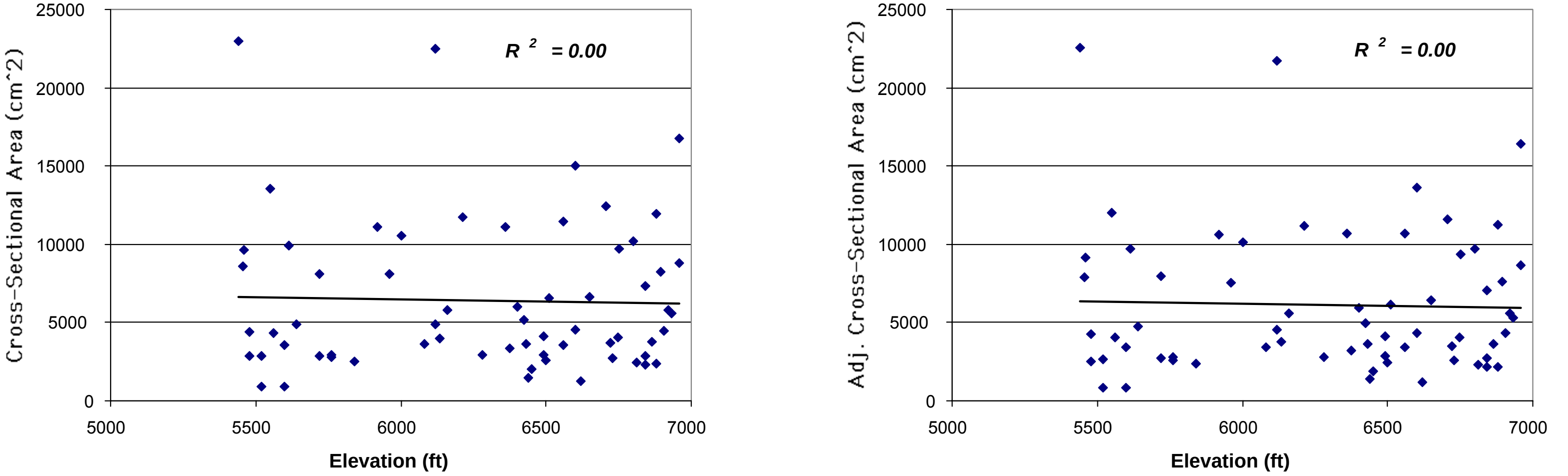


Figure 25: Measured and adjusted cross-sections *vs.* elevation.

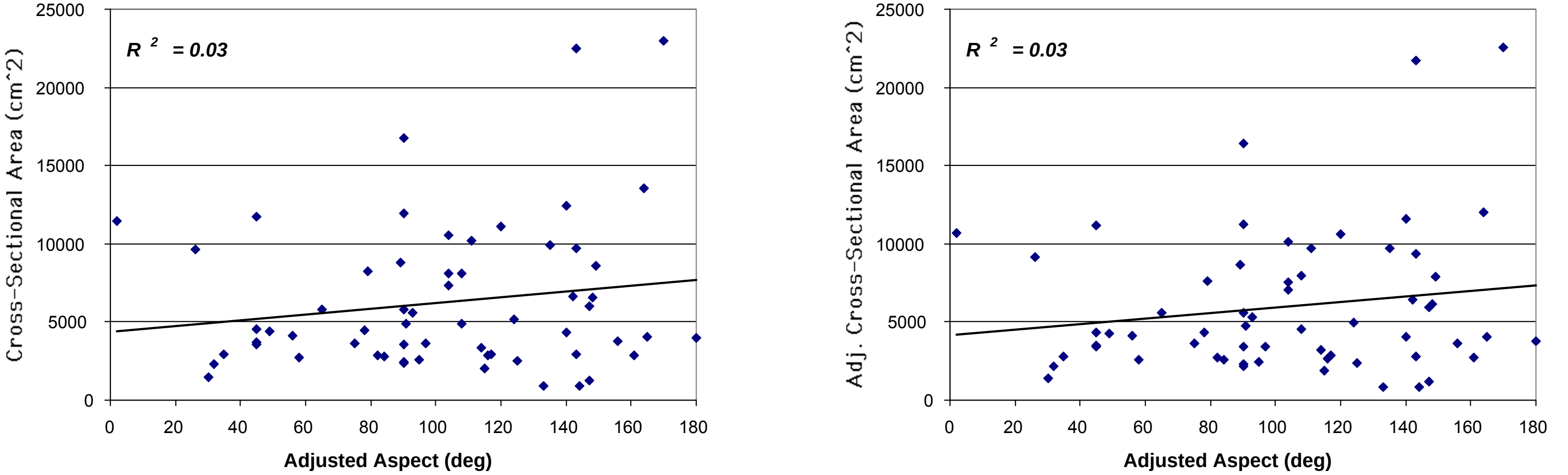


Figure 26: Measured and adjusted cross-sections *vs.* adjusted aspect.

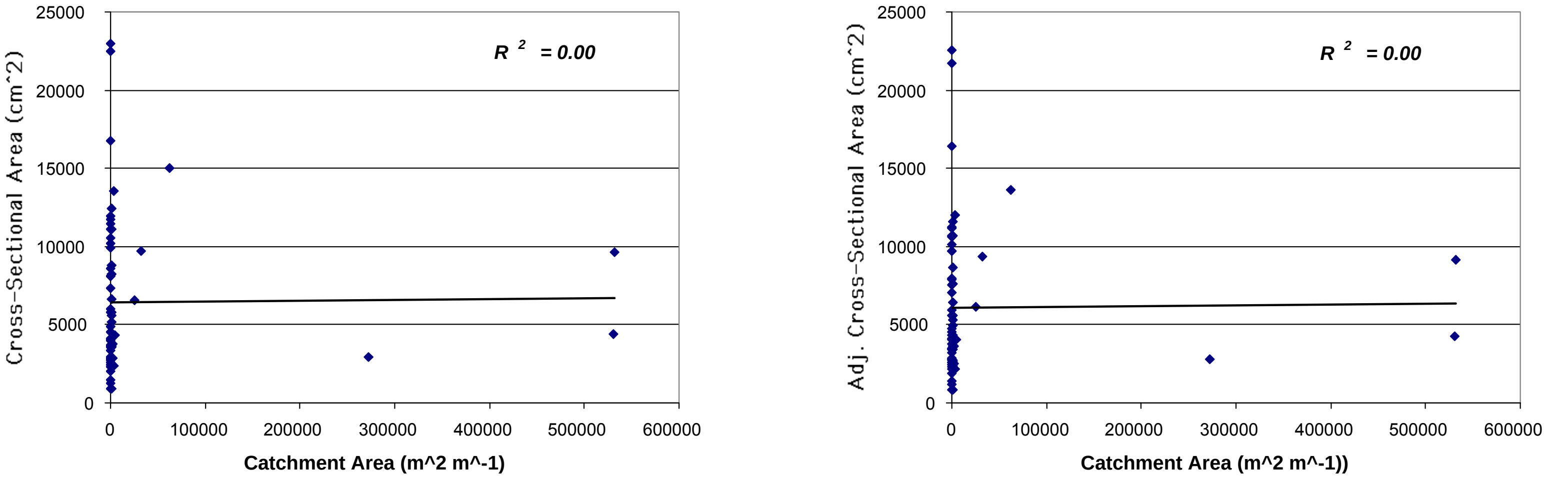


Figure 27: Measured and adjusted cross-sections *vs.* catchment area.

Correlation Analysis

Correlation matrices were used to evaluate relationships between the measured physiographic variables and the measured trail cross-sectional area (Table 6), the cross-sectional areas adjusted with the 5.2 cm depth bulk density (Table 7), and the cross-sectional area adjusted with the 25 cm depth bulk density (Table 8). Additionally, these correlation matrices were used to look for statistically significant relationships between physiographic variables, in order to avoid collinearity in subsequent multiple regression analysis.

The adjusted cross-sectional areas are derived from eq. (1) and are therefore a function of the difference between the on-trail and off-trail soil bulk densities. Because the adjusted cross-section measurements are derived from the measured soil bulk densities, it is inappropriate to include those measurements in correlation or regression equations with adjusted cross-section as the dependant variable.

Significant relationships between the measured and adjusted cross-sectional areas and the other variables were consistent (Tables 6, 7 and 8). Significant relationships exist between cross-sectional areas and trail slope, soil water content, profile curvature (except when the depth of compaction is adjusted to 25 cm), the trail intercept angle, and five of the seven particle size classes.

Multiple Regression Analysis

The issue of collinearity exists primarily among the particle size variables, as would be expected given that each size variable is expressed as a percentage (a necessity due to the variation in sample bulk densities). The other notable variables displaying

Pearson Product-Moment Correlation (r)

	Cross-sect area	Trail Slope	Soil Water	% Cover	Reg. Slope	Profile Curvature	Plan Curvature	Adj Aspect	Elevation	Catch Area	Trail Az - Reg Slope	Part. Size > 2 mm	Part. Size 1-2 mm	Part. Size 0.5-1 mm	Part. Size 0.25-0.5 mm	Part. Size .125-.25 mm	Part. Size .063-.125 mm	Part. Size .063 mm
Cross-section	1.000																	
Trail Slope	**.592**	1.000																
Soil Water	**.336**	.065	1.000															
% Cover	.083	-.046	**.357**	1.000														
Reg. Slope	-.242	-.101	**-.407**	-.200	1.000													
Profile Curvature.	**-.268**	-.175	-.049	-.066	-.122	1.000												
Plan Curvature	-.044	.080	0.145	-.046	-.220	**0.537**	1.000											
Adj Aspect	.164	-.181	0.138	**0.362**	-.015	-.069	-.245	1.000										
Elevation	-.032	-.129	0.104	-.048	-.060	-.213	-.021	-.151	1.000									
Catch Area	.011	.207	-.041	-.028	-.207	0.106	**0.329**	**-.336**	**-.309**	1.000								
Trail Az.-Reg. Sl	**-.290**	-.511	-.053	.017	.245	.067	-.169	0.105	-.104	-.230	1.000							
Part. > 2 mm	**.482**	.156	**.356**	.017	.038	-.125	.209	.195	-.106	-.181	0.038	1.000						
Part. 2 mm	.016	.181	-.020	.001	-.084	-.122	**-.282**	-.219	-.160	.110	.056	-.121	1.000					
Part. 1 mm	**-.378**	.006	**-.458**	-.188	-.092	**.268**	-.108	-.133	**-.259**	.132	-.052	**-.537**	.003	1.000				
Part. 0.5 mm	**-.346**	-.089	**-.291**	-.133	-.080	**.292**	-.024	-.092	-.026	.130	-.107	**-.762**	-.197	**.674**	1.000			
Part. 0.25 mm	**-.431**	-.148	**-.283**	.044	.158	.112	.019	.029	.087	-.046	.125	**-.748**	-.361	.371	**.628**	1.000		
Part. 0.125 mm	**-.413**	**-.273**	**-.252**	-.015	.194	-.074	-.183	-.091	**.349**	-.032	.137	**-.718**	-.292	.065	**.443**	**.777**	1.000	
Part. 0.063 mm	-.208	**-.301**	.041	.182	-.161	.047	-.045	-.088	**.401**	.199	-.241	**-.608**	-.109	-.157	.288	**.395**	**.689**	1.000

Table 6: Correlation matrix for measured cross-sectional area (X-Sect Area) and physiographic variables. Figures in **bold** are significant at 0.05.

Pearson Product-Moment Correlation (r)

	Adj. Cross-sect area	Trail Slope	Soil Water	% Cover	Reg. Slope	Profile Curvature	Plan Curvature	Adj Aspect	Elevation	Catchment Area	Trail Az-Reg Slope	Part. Size > 2 mm	Part. Size 1-2 mm	Part. Size 0.5-1 mm	Part. Size 0.25-.5 mm	Part. Size .125-.25 mm	Part. Size .063-.125 mm	Part. Size .063 mm
Adj. Cross-sect	1.000																	
Trail Slope	**.594**	1.000																
Soil Water	**.344**	.065	1.000															
% Cover	.092	-.046	**.357**	1.000														
Reg. Slope	-.237	-.101	**-.407**	-.200	1.000													
Profile Curvature	**-.264**	-.175	-.049	-.066	-.122	1.000												
Plan Curvature.	-.047	0.080	0.145	-.046	-.220	**.537**	1.000											
Adj Aspect	.164	-.181	.138	**.362**	-.015	-.069	-.245	1.000										
Elevation	-.029	-.129	.104	-.048	-.060	-.213	-.021	-.151	1.000									
Catchment Area	.010	.207	-.041	-.028	-.207	.106	**.329**	**-.336**	**-.309**	1.000								
Trail az.-Reg Slop	**-.286**	-.511	-.053	.017	.245	.067	-.169	.105	-.104	-.230	1.000							
Part. > 2 mm	**.481**	.156	**.356**	.017	.038	-.125	.209	.195	-.106	-.181	.038	1.000						
Part. 2 mm	.004	.181	-.020	.001	-.084	-.122	**-.282**	-.219	-.160	.110	.056	-.121	1.000					
Part. 1 mm	**-.382**	.006	**-.458**	-.188	-.092	**.268**	-.108	-.133	**-.259**	.132	-.052	**-.537**	.003	1.000				
Part. 0.5 mm	**-.344**	-.089	**-.291**	-.133	-.080	**.292**	-.024	-.092	-.026	.130	-.107	**-.762**	-.197	**.674**	1.000			
Part. 0.25 mm	**-.426**	-.148	**-.283**	.044	.158	.112	.019	.029	.087	-.046	.125	**-.748**	-.361	.371	**.628**	1.000		
Part. 0.125 mm	**-.407**	**-.273**	**-.252**	-.015	.194	-.074	-.183	-.091	**.349**	-.032	.137	**-.718**	-.292	.065	**.443**	**.777**	1.000	
Part. 0.063 mm	-.202	-.301	.041	.182	-.161	.047	-.045	-.088	**.401**	.199	-.241	**-.608**	-.109	-.157	.288	**.395**	**.689**	1.000

Table 7: Correlation matrix for the adjusted cross-sectional area assuming a compaction depth of 5.2 cm (Adj. X-Sect) and physiographic variables. Figures in **bold** are significant at 0.05.

Pearson Product-Moment Correlation (r)

	Adj. Cross-sect area	Trail Slope	Soil Water	% Cover	Reg. Slope	Profile Curvature	Plan Curvature	Adj Aspect	Elevation	Catchment Area	Trail Az-Reg Slope	Part. Size > 2 mm	Part. Size 1-2 mm	Part. Size 0.5-1 mm	Part. Size 0.25-.5 mm	Part. Size .125-.25 mm	Part. Size .063-.125 mm	Part. Size .063 mm
Adj. Cross-sect	1.000																	
Trail Slope	**0.589**	1.000																
Soil Water	**0.367**	0.065	1.000															
% Cover	0.131	-.046	**0.357**	1.000														
Reg. Slope	-.208	-.101	**-.407**	-.200	1.000													
Profile Curvature	-.237	-.175	-.049	-.066	-.122	1.000												
Plan Curvature.	-.062	0.080	0.145	-.046	-.220	**0.537**	1.000											
Adj Aspect	0.158	-.181	0.138	**0.362**	-.015	-.069	-.245	1.000										
Elevation	-.015	-.129	0.104	-.048	-.060	-.213	-.021	-.151	1.000									
Catchment Area	0.006	0.207	-.041	-.028	-.207	0.106	**0.329**	**-.336**	**-.309**	1.000								
Trail az.-Reg Slop	**-.256**	**-.511**	-.053	0.017	0.245	0.067	-.169	0.105	-.104	-.230	1.000							
Part. > 2 mm	**0.458**	0.156	**0.356**	0.017	0.038	-.125	0.209	0.195	-.106	-.181	0.038	1.000						
Part. 2 mm	-.056	0.181	-.020	0.001	-.084	-.122	**-.282**	-.219	-.160	0.110	0.056	-.121	1.000					
Part. 1 mm	**-.385**	0.006	**-.458**	-.188	-.092	**0.268**	-.108	-.133	**-.259**	0.132	-.052	**-.537**	0.003	1.000				
Part. 0.5 mm	**-.318**	-.089	**-.291**	-.133	-.080	**0.292**	-.024	-.092	-.026	0.130	-.107	**-.762**	-.197	**0.674**	1.000			
Part. 0.25 mm	**-.379**	-.148	**-.283**	0.044	0.158	0.112	0.019	0.029	0.087	-.046	0.125	**-.748**	-.361	0.371	**0.628**	1.000		
Part. 0.125 mm	**-.361**	**-.273**	**-.252**	-.015	0.194	-.074	-.183	-.091	**0.349**	-.032	0.137	**-.718**	-.292	0.065	**0.443**	**0.777**	1.000	
Part. 0.063 mm	-.166	**-.301**	0.041	0.182	-.161	0.047	-.045	-.088	**0.401**	0.199	-.241	**-.608**	-.109	-.157	0.288	**0.395**	**0.689**	1.000

Table 8: Correlation matrix for the adjusted cross-sectional area assuming a compaction depth of 25 cm (Adj. X-Sect - x5) and physiographic variables. Figures in **bold** are significant at 0.05.

possible collinearity are the soil water, which correlated strongly with vegetative cover, regional slope, and five of the seven particle size classes), and catchment area which correlated moderately with plan curvature, the adjusted aspect, and elevation.

Single variable regression analyses were conducted to evaluate the amount of variability in the measured cross-sectional area explained by the off-trail soil bulk density and the ratio of the on-trail and off-trail soil bulk densities. Off-trail soil bulk density accounted for 11.6% of the variability in the measured cross-sectional area of the trail (Table 9). The ratio of the on and off-trail soil bulk densities accounted for 17.5% of the variability in the measured cross-sectional area (Table 10).

Variables included in the stepwise multiple regression were added based on a correlation matrix of the variables' residuals. The first variable added, trail slope, had the highest computed residual. Once this variable was added to the stepwise regression, it was removed from the matrix and new residuals were recomputed. The new variable with the highest computed residual was added next, and so on until the significance of the variable being added to the regression exceeded the 0.05 level.

Initial stepwise regression did not include particle size distribution which reduced the sample size from 61 to 27. The significant variables (trail slope, soil water content, and the adjusted aspect) accounted for 43% of the variability in the measured cross-sectional area when soil particle size was not included. Those same variables remained significant in the regression of the cross-sectional area adjusted with the 5.2 cm depth of compaction and the 25 cm depth of compaction, accounting for 44% and 46% of the variability respectively (Table 11).

When particle size distribution was included in the stepwise multiple regression, the three variables which account for the most variation (60.0%) in the measured cross-sectional area of the entrenched trail were trail slope, the percentage of soil particles greater than 2 mm in size, and the percent of understory vegetative cover. A stepwise regression with the cross-sectional area adjusted to the 5.2 cm depth bulk density indicates that slightly more of the variation found (61.8%) in the trail incision can be explained by the same variables. The explained varience increases to 64.7% using the same three independent variables and an assumed depth of compaction of 25 cm (Table 12). None of the additional variables added to the regression proved to be significant at the 0.05 level.

Dependent variable is: **Measured Cross-sectional Area**
R squared = **11.6%**
62 degrees of freedom

Variable	***Coefficient***	***s.e. of Coeff***	***t-ratio***	***prob***
Constant	14729.7	2969	4.96	≤ 0.0001
Off-trail avg Pb	-8995.49	3153	-2.85	0.0059

Table 9: Regression for measured cross-sectional area and off-trail soil bulk density.

Dependent variable is: **Measured Cross-sectional Area**
R squared = **17.5%**
62 degrees of freedom

Variable	***Coefficient***	***s.e. of Coeff***	***t-ratio***	***prob***
Constant	-1637.17	2283	-0.717	0.4759
Pb Ratio	4885.83	1345	3.63	0.0006

Table 10: Regression for measured cross-sectional area and ratio of on-trail and off-trail soil bulk densities (ρ_{bcen}/ρ_{boff})

Dependent variable is: **Measured Cross-sectional Area**

R squared (adjusted) = **43.2%**

57 degrees of freedom

Variable	*Coefficient*	*s.e. of Coeff*	*Partial r^2*	*prob*
Constant	-3248.38	1728		0.0652
Trail Slope	605.139	104.9	0.34	≤ 0.0001
Soil Water	165.965	57.82	0.08	0.0057
Adj Aspect	25.8327	11.29	0.01	0.0258

Dependent variable is: **Adjusted Cross-sectional Area (depth of compaction 5.2 cm)**

R squared (adjusted) = **44.1%**

57 degrees of freedom

Variable	*Coefficient*	*s.e. of Coeff*	*Partial r^2*	*prob*
Constant	-3260.05	1650		0.0530
Trail Slope	586.377	100.2	0.34	≤ 0.0001
Soil Water	163.178	55.21	0.09	0.0045
Adj Aspect	24.8069	10.77	0.01	0.0250

Dependent variable is: **Adjusted Cross-sectional Area (depth of compaction 25 cm)**

R squared (adjusted) = **46.0%**

57 degrees of freedom

Variable	*Coefficient*	*s.e. of Coeff*	*Partial r^2*	*prob*
Constant	-3302.87	1412		0.0228
Trail Slope	514.914	85.71	0.34	≤ 0.0001
Soil Water	152.515	47.24	0.10	0.0021
Adj Aspect	20.8964	9.221	0.02	0.0272

Table 11: Regression matrix for adjusted cross-sectional areas with physiographic variables (except particle size distribution) significant at .05 level.

Dependent variable is: **Measured Cross-sectional Area**

R squared (adjusted) = 60.0%

23 degrees of freedom

Variable	*Coefficient*	*s.e. of Coeff*	*Partial r^2*	*prob*
Constant	-9274.02	3170		0.0076
Trail Slope	688.606	153.9	0.34	0.0002
> 2 mm	14421.5	4665	0.17	0.0052
% Cover	96.1386	37.71	0.09	0.0179

Dependent variable is: **Adjusted Cross-sectional Area (depth of compaction 5.2 cm)**

R squared (adjusted) = 61.8%

23 degrees of freedom

Variable	*Coefficient*	*s.e. of Coeff*	*Partial r^2*	*prob*
Constant	-9190.76	2939		0.0047
Trail Slope	657.554	142.7	0.34	0.0001
> 2 mm	13642.2	4325	0.17	0.0044
% Cover	96.6204	34.96	0.11	0.0111

Dependent variable is: **Adjusted Cross-sectional Area (depth of compaction 25 cm)**

R squared (adjusted) = **64.7%**

23 degrees of freedom

Variable	*Coefficient*	*s.e. of Coeff*	*Partial r^2*	*prob*
Constant	-8871.78	2350		0.0010
Trail Slope	539.288	114.1	0.34	≤ 0.0001
> 2 mm	10671.4	3459	0.14	0.0052
% Cover	98.4463	27.96	0.17	0.0018

Table 12: Regression matrix for adjusted cross-sectional areas with physiographic variables significant at .05 level.

CHAPTER FIVE

DISCUSSION

Urie (1994) stated that the significant variables associated with trail cross-sectional area along the New World Gulch and Bozeman Creek trails were trail slope, soil water content, and regional slope. Those variables accounted for 50% of the variability in trail cross-sectional area. Urie proposed that additional variables not measured in her study, in particular the failure to account for the contribution of soil compaction to the system, may have accounted for portions of the unexplained variance. The following sections evaluate the role of these additional variables proposed by Urie, discusses general controls on trail incision and the utility of including compaction, presents management implications of these findings, and outlines some potential avenues for future research.

Variables Controlling Trail Incision

The role of trail slope as one of the primary physiographic determinant of trail incision (Tables 11 and 12) is consistent with previous studies (Bratton *et al*., 1979; Urie, 1994; Leung and Marion, 1996). As local trail slope increases, downslope gravitational forces increase the likelihood of overland flow of water deposited by precipitation events, and the dislocation and transport of sediment by water or user disturbance. Sediment transported from inclines will lead to trail incision at that site, and deposition elsewhere.

The soil particle size class distributions as reported in the results (Table 5) are biased because a significant portion of those particles reported as greater than 2 mm are aggregates of smaller particles. Including the weight of the aggregated particles with the finer particle size classes may suggest an explanation for the role of soil particle size that is more consistent with previous studies. The correlation matrices indicate that fine particles of <1 mm are inversely related to the measured or adjusted cross-sectional areas (without the inclusion of the aggregated particles). This indicates that increases in the percentage of < 1 mm soil classes are associated with decreases in the amount of trail incision. This is inconsistent with the other findings of this work (Figure 11) showing that increases in soil bulk density, associated with greater percentages of larger particle size classes, are associated with decreases in trail incision. However, increasing the percentage of fine soil particles (by breaking up the aggregated material) and the associated increase in total pore space, which decreases the soil bulk density, might reverse the inverse relationships displayed in Figures 15-21. The general decreases in the correlation values of the fine particle size classes from the measured to the adjusted cross-sectional areas (Tables 6, 7, and 8) also suggest that soils with more fines are more sensitive to compaction than they are to erosion.

Soil water content is the second most significant independent variable when the percentage of particle sizes are not considered in the regression equation (Table 11). This is consistent with the significant correlation between soil water content and the particle size classes. Soil water holding capacity is partially a function of particle size distribution, so when particle size distribution is absent from the equation, soil water content, dependant as it is on the size and availability of pore spaces, replaces it as a significant variable in the regression.

Percent vegetative cover is significant in the stepwise regression (Table 12), although it is not significantly correlated to cross-sectional area (Tables 6, 7, and 8). However, the percent of vegetative cover is significantly correlated with soil water and the adjusted aspect. When included in the regression with the particle size distribution data, it is conceivable that the vegetation data, which is related to both soil moisture and aspect, acts to represent both of those variables in the regression.

One goal of this study was to include additional physiographic variables not considered in Urie's (1994) study to explain a greater amount of the variance in cross-sectional areas along the trail. The most significant variable added to those already studied was soil bulk density. Users are frequently advised to hike and camp on durable or resistant surfaces to minimize impact in less traveled and untrailed areas (LNT, 2000), the belief being that soils with greater bulk density are more resistant to mechanical stress and should therefore be more resistant to disturbance, erosion and incision.

When individual variables were regressed against the measured cross-sectional area, off-trail soil bulk density accounted for the second greatest amount of variance ($r^2 = 0.12$) (Table 9) after trail slope ($r^2 = 0.35$). The ratio of on-trail soil bulk density to off-trail soil bulk density (ρ_{bcen}/ρ_{boff}), which could be considered a measure of compaction, accounted for even more variance ($r^2 = 0.18$) than soil bulk density. This would indicate that compaction, or the difference between the on-trail and off-trail soil bulk densities at a given site, explains a significant portion of the variability in trail incision. Unfortunately, it was inappropriate to use soil bulk density and the ratio of soil bulk densities in a regression model with the adjusted cross section, because the method for defining the adjustment was based on the same bulk density variables, automatically producing high r^2 values.

Urie speculated that a second variable untested by her, the orientation of the trail relative to the regional slope orientation, could improve the explanation of the regression model. Bratton *et al.* (1979) determined that the slope alignment angle was significant in intercepting or channeling water and sediment and influenced user-related trail widening. The negative correlation of slope alignment angle with cross-sectional area (Tables 6, 7, 8) does indicate that as the difference between the trail azimuth and regional slope orientation increases, trail incision decreases. This variable had a r^2 value of 0.08 when regressed individually against both the measured and adjusted cross-sections, but it failed to be a significant factor when entered in the stepwise regression model.

One other variable, soil type, was considered for inclusion in the evaluation of physiographic factors influencing incision. The use of soil *k* values (or erosivity factor used in the Universal Soil Loss Equation) might have offered a way to include soil type as an indicator variable in the regression equation. However, just as Urie found that inaccuracies in coregistering sample sites and geologic unit boundaries hindered the use of geology as an indicator variable, inaccurate coregistration of sample sites with soil map units also hindered the use of this variable in the multiple regression equation. The use of different scales and soil map units by National Forest soil surveys and state soil surveys also made the use of this variable problematic.

The Role of Soil Compaction

Identifying the effective depth of soil compacted along the trail should lead to a more accurate understanding of the relationship between various physiographic variables and erosion. Defining the effective depth of the soil compacted was problematic for two reasons. First, it was necessary to assume that the difference between the soil bulk densities was due to compaction, although this is probably a reasonable assumption. Second, defining the depth to which soils in a natural system can be compacted seems to have been a topic so far overlooked. Soil physicists have spent time looking at the effects of soil compaction on crop growth, the depth to which stress can be transmitted through a column of soil (Das, 1997; Horn and Baumgartl, 2000), and increases in soil bulk density (Marshall *et al*., 1996; Larson *et al*., 1980), likewise geotechnical engineers have studied structure settlement in soils (Maugeri *et al*., 1998) and the effects of compaction on soil and fill strength. Little information is available, however, on the depth to which various soil types are compacted due to walking in a natural system. Without knowing how deep a given soil can be compacted and the variations in compaction through the soil column, actual changes in depth due to compaction can not be accurately estimated. While it might have been possible to define an estimate of the depth to which given soils have been compacted based on existing soil bulk density versus compaction curves and consideration of other variables influential in the soil compaction process, such efforts were beyond the scope of this study.

The amount of estimated trail incision can vary significantly when the compacted soil is "expanded" to provide more accurate estimates of erosion at each site. The depth of the soil compaction determines how much resulting incision estimates will vary. As the depth of the compacted soil increases, the relative amount of incision due to erosion decreases. Removing the effects of compaction on trail incision increased the amount of variance in cross-sectional area explained by the collected physiographic variables (Tables 11 and 12) from 43.2% to 46% when particle size was not included, and from 60% to 64.7% when particle size data is included (Tables 11 and 12). Regardless of whether or not particle size was included, increasing the estimated depth of the compacted soil, did not change which controls were significantly related to trail incision.

Management Implications

Land managers at all levels find themselves in the quandary of being asked to do more with ever diminishing resources. While the total amount of erosion from trails could be considered negligible at lanscape scales, trail erosion and subsequent sedimentation and degradation of those local habitats is a management problem. Additionally, of increasing concern over the past two decades has been the perceptions of the users of these managed parcels of land. Due to their need to maximize their management options with minimum resources, it will be a great benefit to be able to isolate the major contributing variables to trail erosion and incision. From there, managers can determine how and where to focus control efforts.

This research suggests where managers can locate new trails or relocate existing trails to minimize trail incision. Trail slope is the most critical physiographic variable to control in any trail construction or restoration project. Minimizing trail slope should be the clear priority for managers trying to mitigate trail erosion and disturbance. In areas of comperable slope, soil bulk densityis an important secondary control. Soils with the highest bulk densities will tend to erode less readily. Finally, locating trails in areas with vigorous and resilient vegetation, where soil structures tend to be more consolidated with better infiltration and less direct exposure to rainfall, seems to be the third most significant variable to consider. None of these variables, however, exhibit clear thresholds that need to be considered when evaluating potential trail locations.

DEM, soil and vegetation coverages coupled with a GIS might minimize the effort and error involved in siting trails, but these tools can be expensive and the data hard to locate or expensive to develop. Ferguson (1998) also found that GIS user-assisted trail design methods were both less effective in minimizing potential disturbances and more costly than more traditional "office oriented" trail design techniques. Similar results could be realized with a topographic map to initially site trail options, followed by bulk density and particle size disribution sampling to help define the options with the least impact.

It is possible that a weighted average rating system could be developed using the significant controls on trail erosion: trail slope, soil bulk density, particle size distribution and percent vegetative cover. Using those controls in proportion to the amount of variability in erosion that they account for (Tables 9 and 12) could provide a general erosion potential index. Before such a system was universally applied, duplicate studies in other climates and regions should be conducted to see if the controls and/or ratios of the controls need to adjusted for localities in a manner similar to the adjustment of constants in the USLE.

Trails are generally designed to get users from one location to other locations where a resource or attraction exists. Given that the locations of one or more of these points are fixed, the possibilities for minimizing the impact of any trail due to its design are not unlimited. Land managers, who presumably have made the decision to make a location more accessible through construction or relocation of a trail, are inevitably constrained by the landscape on which the trail will be placed. Keeping in mind that the actions of land managers are also usually constrained by the availability of time and resources (both human and equipment) the following course of action when siting trails to minimize compaction and erosion is proposed.

The process should start by identifying the realistic corridors where a trail could be located, or relocated, to achieve the objective of providing access to the specific feature or point(s) of interest. Areas where soil erosion and the resulting sedimentation would be the most harmful, such as those immediately adjacent to streams and other aquatic or sensitive habitats, should be eliminated. Areas along the proposed travel corridor where the slope of the proposed trail can be minimized can be identified with a topographic map. Using soil maps, the manager can next identify the soils along the low slope corridors with the greatest resistance based on soil texture. The spatial resolution of soil maps will probably be insufficient for identifying site specific soil properties, particularly on or near soil map unit boundaries. The manager should therefor identify those areas where the clear definition of soil properties along the predetermined corridors may be questionable. Selective soil bulk density sampling in these areas, requiring minimal time and effort, should then be used to isolate the site specific location of the proposed trail.

Further Research

Up to 64.7 percent of the variability in trail erosion along the New World Gulch / Bozeman Creek trail system can be ascribed to trail slope, soil bulk density, proportions of fine soil particle sizes, and percent vegetative cover. It may be possible to increase the explanation by incorporating user types and numbers, or by continuing to look at additional physiographic and climatic variables.

To better quantify the role of soil compaction on the amount of incision along a trail, further studies should be initiated to evaluate the rate and maximum depth of soil compaction in a natural environment. To do this successfully would require paired soil testing (compressed and control samples) on varied soil types.

Further exploration into the role of understory vegetative cover should be conducted. While it proved to be a significant variable in the regression equations including soil particle size classes, its exact role in the moderation of the trail incision process is unclear. The possibility that percent vegetative cover is an indicator of combinations of other variables (soil water content, slope aspect, organic content, *etc*.) warrants study for definition.

The more obvious physiographic variables to look at would include soil type (*k* factors, rock fragment content, texture) and geology. If this approach were to be pursued, the optimum study site would need to have complete and consistent soil and geologic surveys available at a resolution fine enough to differentiate categories along the length of the trail. Additionally, one would need to consider how nominal soil or geologic classes could be incorporated into multivariate statistical analysis.

In this study, some of the climate effects have been accounted for through surrogate data such as soil wetness and percent vegetative cover. What has not been adequately accounted for are the effects of snow deposition, accumulation and melt patterns on trail erosion. Traditionally, snow has been considered insignificant as far as erosion processes are concerned, primarily because snow melt regimes rarely exceed infiltration rates in undisturbed forest soils (Hart and Loomis, 1982). Multi-use, multi-season trails, however, may have defined circumstances that make snowmelt one of the more significant variables involved in the trail erosion process.

Specifically, it has been shown that winter use trails may have up to 1.3 to 2.3 times the snow water equivalent of the adjacent snow covered terrain (Hogan, 1972; Kattelmann, 1985). This is due to compaction of snow along the trail, which creates surface variations leading to wind eddy deposition of more snow along the trail, followed by more compaction of the snow along the trail. It has further been demonstrated that compacted snow has a different melt regime than undisturbed snow, so that it tends to melt later but more quickly (Grady, 1982; Kattelmann, 1986). The result is that there is more snow water equivalent being released over a shorter amount of time in a confined trail which has significantly lower infiltration rates. This may likely increase the amount of overland flow within the trail, which increases the erosion potential. With this in mind, another possible area of research into the factors influencing trail erosion might involve the collection of snow water equivalent measurements, snowmelt, and infiltration rates for insertion into the regression analysis.

REFERENCES CITED

Bayfield, N.G. 1985. The effects of extended use on mountain footpaths in Britian. In: The ecological impacts of outdoor recreation on mountain areas in Europe and North America. Recreational Ecologic Resource Group Report No. 9. Wye, UK: Wye College, Department of Horticulture, Recreation Ecology Research Group: 100-111.

Bayfield, N.G. 1986. Penetration of the Cairngorm Mountains, Scotland, by vehicle tracks and footpaths: impacts and recovery. In: Lucas, R.C. Proceedings – national wilderness research conference: current research; 1985 July 23-26; Fort Collins, CO. Ogden, UT: U.S. Department of Agriculture, Forest Service, General Technical Report INT-212.

Bratton, S.P., Hickler, M.G., and Graves, J.H. 1979. Trail erosion patterns in Great Smokey Mountains National Park. *Environmental Management*. 3: 431-445.

Brooks, K.N., P.F. Ffolliott, H.M. Gregersen, and J.L. Thames. 1991. *Hydrology and the Management of Watersheds*. Ames, IA: Iowa State University Press.

Cole, D.N. 1983. Assessing and monitoring backcountry trail conditions. Ogden, UT: U.S. Department of Agriculture, Forest Service, Research Paper INT-303.

Cole, D.N. 1986. Resource Impacts Caused by Recreation: A Literature Review. The Presidents Commission on American Outdoors. U.S. Department of Agriculture, Forest Service, Research Paper INT-4901.

Cole, D.N. 1989. Recreation Ecology: What we know, what geographers can contribute. *The Professional Geographer*, 41 (2): 143-148.

Cole, D.N. 1991. Changes on Trails in the Selway-Bitterroot Wilderness, Montana, 1978-1989. Ogden, UT: U.S. Department of Agriculture, Forest Service, Research Paper INT-450.

Cole, D.N. 1992. Modeling Wilderness Campsites: Factors that Influence Amount of Impact. *Environmental Management*, 16 (2): 255-264.

Coleman, R. 1981. Footpath Erosion in the Lake District. *Applied Geography*, 1: 121-131.

Cordell, K.H., J.C. Bergstrom, L.A. Hartman, and D.B.K. English. 1990. An Analysis of the Outdoor Recreation and Wilderness Situation in the United States: 1989-2040. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, General Technical Report RM-189.

Daigle, J.J., A.E. Watson, and G.E Haas, 1994. National Forest Trail Users: Planning for Recreational Opportunities. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. Research Paper NE-665.

Das, B.M. 1997. *Advanced Soil Mechanics*. London: Taylor and Francis Publishers.

Davis, C.E., and H.F. Shovic. 1996. Soil survey of Gallatin National Forest, Montana. U.S. Department of Agriculture, Forest Service and Natural Resources Conservation Service in cooperation with the Montana Agricultural Experiment Station.

Dutch, S.I., J.S. Monroe, and J.M. Moran. 1998. *Earth Science*. Belmont,CA: Wadsworth Publishing Company.

Ferguson, J.Y. 1998. Location and Design of Recreational Trails: Application of GIS Technology. M.S. Thesis. Virginia State University. Blacksburg, VA.

Ferris, T.M.C., Lowther, K.A., and Smith, B.J. 1993. Changes in footpath degredation 1983-1992: A study of the Brandy Pad, Mourne Mountains. *Irish Geography*. 26: 131-140.

Fish, E.B., G.L. Brothers, and R.B. Lewis. 1981. Erosional Impacts of trails in Guadalupe Mountains National Park, Texas. *Landscape Planning*. 8: 387-398.

Garland, G.G. 1990. Technique for assessing erosion risk from mountain footpaths. *Environmental Management*. 14: 793-798.

Godin, V.B. and R.E. Leonard. 1979. Management Problems in designated Wilderness Areas. *Journal of Soil and Water Conservation*, 34 (3): 141-143.

Grady, T.R. 1982. The Effects of Snow Compaction on Water Release and Sediment Yield. M.S. Thesis. Montana State University. Bozeman, MT.

Harden, C.P. 1992. Incorporating roads and footpaths in watershed-scale hydrologic and soil erosion models. *Physical Geography*. 13 (4): 368-385.

Hart, G.E. and S.A. Loomis. 1982. Erosion from Mountain Snowpack Melt. *Journal of Soil and Water Conservation*. Jan-Feb: 55-57.

Hogan, A.W. 1972. Snowmelt Delay by Oversnow Travel. *Water Resources Research.* 8(1): 174-175.

Horn, R. and T. Baumgartl. 2000. Dynamic Properties of Soil. In *Handbook of Soil Science*. Sumner, M.E., ed., Boca Raton, FL: CRC Press.

Kattlemann, R. 1985. Snow Management at Ski Areas: Hydrologic Effects. In *Watershed Management in the Eighties*. Jones, E.B., and T.J. Ward, eds., American Society of Civil Engineers. New York.

Kattlemann, R. 1986. Snow Compaction Effects on Nighttime Freezing. *Proceedings of the Western Snow Conference.* Fort Collins, CO: Colorado State University. 168-171.

Kay, B.D. and D.A. Angers. 2000. Soil Structure. In *Handbook of Soil Science*. Sumner, M.E., ed., New York: CRC Press.

Krumpe, E.E. and R.C. Lucas. Research on Recreation Trails and Trail Users. A Literature Review: The President's Commission on Americans Outdoors. INT 4901, Publication #168.

Lance, A.N., I.D. Baugh, and J.A. Love. 1989. Continued footpath widening in the Cairngorm Mountains, Scotland. *Biological Conservation*. 49: 201-214.

Larson, W.E., S.C. Gupta, and R.A. Useche. 1980. Compression of Agricultural Soils from Eight Soil Orders. Soil Science Society of America Journal. 44: 450-457.

Leave No Trace, Inc. Principles of Leave No Trace. 22 August 2000. <http//www.lnt.org/TeachingLNT/LNTEnglish.html>

Leung, Y. and J.L. Marion. 1996. Trail degradation as influenced by environmental factors. *Journal of Soil and Water Conservation*. 51 (2): 130-136.

Liddle, M.J. 1975. A selective review of the ecological effects of human trampling on natural ecosystems. *Biological Conservation*. 7: 17-36.

Lucas, R.C. 1983. The Role of Regulations in Recreation Management. *Western Wildlands*, 9 (2): 6-10.

Lucas, R.C. 1987. Perspectives on the History of Wilderness Research. In: Proceedings – National Wilderness Research Conference: Issues, State-of-knowledge, Future Directions. Ogden, UT: U.S. Department of Agriculture, Forest Service, General Technical Report INT-220.

Lucas, R.C. and G.H. Stankey. 1989. Shifting Trends in Wilderness Recreation Use. In Alan E. Watson, comp. Outdoor recreation benchmark 1988: proceedings of the national outdoor recreation forum; 1988 January 13-14; Tampa, FL. Gen. Tech. Rep. SE-52, Asheville, NC: US Department of Agriculture, Forest Service, Southeastern Experiment Station. 357-367

Marshall, T.J., J.W. Holmes, and C.W. Rose. 1996. *Soil Physics*. Cambridge, U.K.: Cambridge University Press.

Martz, L.W. 1992. The variation of soil erodibility with slope position in a cultivated Canadian prairie landscape. *Earth Surface Processes and Landforms*. 17: 543-556.

Maugeri, M., F. Castelli, M.R. Massimino, and G. Verona. 1998. Observed and Computed Settlements of Two Shallow Foundations on Sand. *Journal of Geotechnical and Geoenvironmental Engineering*. 124 (7): 595-605.

McQuaid-Cook, J. 1978. Effects of hikers and horses on mountain trails. *Journal of Environmental Management,* 6: 209-212.

Morgan, J.M. and Kuss, F.R. 1986. Soil loss as a measure of carrying capacity in recreational environments. *Environmental Management*. 10(2): 263-270.

National Oceanic and Atmospheric Administration. 1993. *Climatological Data: Montana*. National Oceanic and Atmospheric Administration, Ashville, North Carolina. 96 (5-9).

Oyarzun, C.E. 1995. Land use, hydrological properties, and soil erodibilities in the Bio-Bio River Basin, Central Chile. *Mountain Research and Development*. 15 (4): 331-338.

Page-Dumroese, D.S., M.F. Jurgensen, R.E. Brown, and G.D. Mroz. 1999. Comparison of Methods for Determining Bulk Densities of Rocky Forest Soils. *Soil Science Society of America Journal.* 63 (2): 379-383.

Patric, J.H. 1976. Soil erosion in the eastern forest. *Journal of Forestry*. 74: 671-676.

Price, M.F. 1985. Impacts of Recreational Activities on Alpine Vegetation in Western North America. *Mountain Research and Development*. 5 (3): 263-77.

Quinn, N.W., R.P.C. Morgan, and A.J. Smith. 1980. Simulation of Soil Erosion Induced by Human Trampling. *Journal of Environmental Management*. 10: 155-165.

Roberts, A.E. 1964. Geologic Map of the Mystic Lake Quadrangle, Montana. Washington, D.C.: U.S. Geological Survey, Miscellaneous Geological Investigations, Map I-398.

Seney, J.P. 1991. Erosional impact of hikers, horses, off-road bicycles, and motorcycles on mountain trails. M.S. Thesis. Montana State University. Bozeman, MT

Steele, V.G. 1998. Assessment of Resource Changes in Backcountry Campsites from 1989-1996 in Rocky Mountain National Park, Colorado. M.S. Thesis. Montana State University. Bozeman, MT

Summer, R.M. 1980. Impact of horse traffic on trails in Rocky Mountain National Park. *Journal of Soil and Water Conservation*. 35: 85-87.

Summer, R.M. 1986. Geomorphic impacts of horse traffic on montane landforms. *Journal of Soil and Water Conservation*. 41: 126-128.

Tinsley, B.E., E.B. Fish. 1985. Evaluation of trail erosion in Guadalupe Mountains National Park, Texas. *Lanscape Planning*. 12: 29-47.

Urie, W.A. 1994. Environmental Factors Influencing Recreational Trail Condition. M.S. Thesis. Montana State University. Bozeman, MT

U.S. Department of Agriculture, Forest Service. 1981. *The Northern Region Plan*. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region.

Vogler, J.B., and D.R. Butler. 1996. Pedestrian and bicycle induced path erosion on a university campus. *Physical Geography*. 17 (5): 485-494.

Wilson, J.P. and Seney, J.P. 1994. Erosional Impact of Hikers, Horses, Motorcycles and Off-Road Bicycles on Mountain Trails in Montana. *Mountain Research and Development*. 14: 77-88.

Wischmeier, W.H. 1970. Relation of soil erosion to crop and soil management. *Proceedings for the International Water Erosion Symposium, International Committee for Irrigation Drainage*. 2: 201-220.

Wischmeier, W.H., and D.D. Smith. 1978. *Predicting rainfall erosion losses: A guide to conservation planning*. Washington, D.C.: U.S. Department of Agriculture, Agricultural Handbook No. 537.