Influence of Llama, Horse, and Foot Traffic on Soil Erosion From Established Recreation Trails in Western Montana

by

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Various types of recreational trail users impact hiking trails uniquely and cause different levels of trail degradation. The purpose of this study was to assess the relative physical impacts of llamas used as packstock on recreational trails. Horse, llama, and hiker traffic were simulated on 56 separate plots of a 300-meter-long segment of existing trail at Lubrecht Experimental Forest. Llama, horse, and hiker traffic, at intensities of 250 and 1,000 passes, were applied along with a no traffic control plot for a total of 7 treatments per block. Traffic was applied to separate plots on 4 blocks of wet, and 4 blocks of dry trail conditions in a randomized complete block design.

Simulated rainfall was applied to each plot after traffic treatments in order to asses erosion potential as sediment yield in runoff. Other dependent variables measured were bulk density and soil roughness. Soil moisture, slope, and rainfall intensity were recorded as independent variables in order to evaluate the extent to which they were held constant by the experimental design. Analysis of variance with multiple comparisons was used to compare treatment means. Correlation coefficients were calculated to determine the influence of bulk density, surface roughness, and the independent variables on sediment yield.

Horses consistently made more sediment available for erosion from trails than the llama, hiker, or no traffic plots when analyzed across wet and dry trail plots, and high and low intensity traffic plots. Trail traffic did not increase soil compaction on wet trails. All dry trail traffic treatments, except the low level of hiker traffic, resulted in significant decreases in bulk density compared to the control. Decreased bulk density correlated with increased sediment yield. Significantly rougher trail surfaces were measured for horse traffic compared to hiker and llama traffic, and this correlated significantly with higher sediment yields. For the variables of sediment yield, bulk density, and surface roughness, llamas had impacts similar to hikers and significantly less than horses. Trail managers may want to consider managing llamas used as packstock independently of restrictions placed on horses.

PREFACE

Many thanks are due to those who made this project a success. The Aldo Leopold Wilderness Research Institute, agreement # INT/ALWRI-95030-RJVA for funding and Dr. David Cole for his valuable research experience and advice. My graduate committee members: Steve Siebert, Fletcher Brown, Wayne Friemund, and Tom DeLuca for their direction and timely review of drafts. A special thanks to Tom DeLuca for extra assistance with field work far above and beyond the responsibilities of an academic advisor.

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

Figures

Tables

-CHAPTER ONE-
INTRODUCTION

Problem Background

Soil erosion rates on recreational hiking trails may be accelerated depending on the type of trail traffic. Accelerated erosion causes aesthetic, economic, and ecological impacts to recreation trails that receive high levels of use. Trails that receive less use but are highly susceptible to impact are also of concern. Horse traffic has the most impact on trails among hikers, motorcycles, bicycles and horses (Wilson and Seney, 1994; Weaver and Dale, 1978). However, little is known about the affects on soil erosion rates of alternative types of packstock defined by McClaran and Cole (1993) as any animal other than a horse, mule, or burro. To address our lack of knowledge regarding llama impacts on hiking trails, the results reported in this study compare the relative impacts of llama, horse, and hiker traffic on established hiking trails.

Although trail compaction and erosion directly impact only a small portion of the whole landscape, indirect impacts can cause serious problems on a larger scale (Hammit and Cole, 1987). Indirect impacts of trail erosion in riparian areas include interception of subsurface flow, channelization of runoff, increased overland flow, and increased sedimentation of streams (Bratton et al., 1979; McClaran and Cole, 1993). Indirect impacts are particularly important in sensitive environments such as riparian areas, alpine meadows, or on steep slopes. Alpine meadows have sensitive vegetation and easily eroded soils where erosional down cutting of trails may lead to water table lowering by effectively creating a drainage ditch (Summer, 1986; Dotzenko et al., 1967; Ketchledge 1970). Water table lowering or direct trampling can in turn lead to long term modification of plant communities (Summer, 1980; Kuss, 1983).

Economic and aesthetic considerations add to the importance of minimizing trail impacts. Cole (1991) points to the large amount of money spent each year for trail maintenance and relocation in wilderness areas as a reason to minimize user impacts. As one of the more obvious marks of human use on wilderness and other natural areas, severely degraded trails may also diminish the visitor experience (Helgath, 1975). Clearly both social and environmental concerns call for minimizing the impact of trail users.

Trail systems are important in recreation management beyond the actual physical impacts that occur to them. Trail systems allow access to large areas and many campsites which may require special management. Trailheads and the trails that allow access are the first and most powerful way to influence the management of recreation or wilderness areas. Whether a trail is physically damaged is only one of many considerations when deciding how to manage different trail users in a given area. The results of this study should be considered along with information about the social interactions of different types of trail users (Blahna, 1995) and with information about campsite and off-trail vegetation impacts now being studied.

Previous trail and wilderness impact research has evaluated only horse traffic to represent packstock, ignoring alternative types of packstock. Presently, few distinctions are made between different types of packstock for management on public lands (David Cole, Pers. Comm 1995). Llama users frequently report frustration when obeying management restrictions designed for horses. Many believe that llamas have little impact on trails (Harmon, 1989; Markham, 1990; Blahna, 1995). This belief has lead to the suggestion that llamas used as packstock should be allowed greater leeway in trail use than horses (Blahna, 1995). However, there is a lack of quantitative information available to justify or guide management. The impacts of llamas on trails should be quantified to insure protection of trail systems and fair treatment of different types of stock users.

Objectives

In order to compare the relative impacts of llamas, horses, and hikers on established recreation trails, the objectives of this study were to:

1) Measure erosion potential as sediment yield from runoff in simulated rain storms following llama, horse, and hiker traffic treatments on alternating segments of the same trail.

2) Measure soil compaction as bulk density after traffic treatments.

3) Measure soil surface roughness after traffic treatments.

4) Measure soil infiltration rate at time of rainfall simulation.

5) Evaluate the relative impacts of llama, horse, and hiker traffic on wet and dry trails, and at high and low traffic intensities.

Literature Review

Recreational Traffic

The concept of carrying capacity in recreation is under debate (Manning, 1986), and may not be a viable application for established recreation trails. However, established trails represent a well defined system where the physical impacts of individual users can theoretically be quantified. For these systems, there is some relevance to the suggestion by Weaver and Dale (1978), that the carrying capacity for hiking trails should be calculated based on the reciprocal of the damage caused by each user type. This suggestion elicits a variety of emotional and environmental arguments that cannot be easily balanced by trail managers.

There is both scientific and anecdotal evidence to suggest that trail location and construction is more important in determining trail conditions than the type of use that it receives (Summer, 1980; Summer, 1986; Helgath, 1975; Cole, 1991). The importance of location and construction is apparent in the variety of conditions found when traveling any section of a given trail. An individual trail receives the same type and level of use throughout it's length, however it displays a wide range of physical conditions. Despite available information about the proper location of hiking trails, many trails traverse sensitive areas and may require special management of trail users.

There have been few controlled experiments that directly compare soil impacts by different user types. The relative extent of soil compaction and erosion appears to vary among different types of trail uses including bicycle, motorcycle, foot, and horse traffic (Weaver and Dale, 1978; Wilson and Seney, 1994). Among these, horse traffic appears to cause the greatest increase in soil compaction and erosion potential. Weaver and Dale (1978) found that hikers always had the least impact on vegetation, trail width, trail depth, and bulk density when forming new trails, and that horses and motorcycles had increased levels of impact. Foot traffic has been found to generally make more sediment available for transport than wheeled traffic, with horse traffic causing the only significant increase in sediment yield relative to other types of trail users (Wilson and Seney, 1994).

In a multiple year survey of trail impacts under natural conditions, Summer (1980) was unable to detect differences in erosion rates between trails used by horses and those not used by horses. This survey evaluated natural trail conditions and use patterns, but the conclusions are limited by the wide variation in environmental conditions and lack of scientific control. Summer (1986) later recommended that horse trails in particular be restricted under some conditions to less sensitive land forms and soil types in spite of her earlier findings. The application of such restrictions is of particular interest to those who use alternative types of packstock and might face the same restrictions. This raises the question of whether restrictions placed on horses should be applied to all types of packstock.

Llamas as Packstock

Alternative packstock are primarily goats and llamas and currently make up about five percent of all packstock use (McClaran and Cole, 1993). Llamas may have limited cumulative impact on our trail systems (Blahna et al., 1995), but it is important to have some measurement of a llama's erosion potential from a management perspective, especially as llama use increases. The use of llamas as packstock has increased greatly in the last fifteen years and Harmon (1989) estimates that the number of llamas in the United States will increase from 22,000 in 1989 to 150,000 by the year 2000. Although not all llamas are used as packstock, their increased popularity has meant an increase in backcountry use by llamas and further emphasizes the need for information about llama impacts on established trails (McClaran and Cole 1993; Blahna et al., 1995).

Proponents for llama use as packstock have suggested that llamas have little impact on trails relative to other types of packstock (Harmon, 1989; Markham, 1990; Harmon and Rubin, 1992; Blahna et al., 1995). Advertisements may be found in magazines published by llama organizations or on the "World Wide Web" computer network that claim llamas have less impact on hiking trails than would the average hiker. To date however, there is no experimental evidence concerning llama impacts on existing hiking trails, only anecdotal observations, mostly by llama users themselves.

Blahna et al. (1995) conducted trail head opinion surveys in and around Yellowstone National Park asking all trail users to evaluate any impacts of llamas that they had observed. Results showed that llamas were perceived to have less impact on the environment than horses. These results do not provide complete information for management decisions because they rely on human perception and may have been biased by the low frequency of llama encounters among those surveyed. The evidence of Blahna et al. (1995) is most useful as a gauge of the social acceptability of llama's on trails and should be considered along with experimental measurement of a llama's erosion potential on trails.

Harmon (1989) offers sound reasons why llamas might have less impact than horses on hiking trails, including: (1) Llama's have a relatively low average weight of 160 to 180 kg (350 to 400 pounds) as compared to an average of 450 kg (1,000 pounds) for horses; (2) The llama's soft, padded foot may also cause less soil disturbance in comparison to the hoof or metal shoe of a horse; (3) The manner in which a llama carefully and deliberately places its foot (Harmon, 1989). Unlike horses and other ungulates, the llama is a pacer, meaning that both feet on a side move in the same direction at the same time. This motion, combined with the careful, deliberate placement of their feet, may be the result of llama evolution in the steep mountainous terrain of the South American Andes. The foot placement of a llama is in sharp contrast to the scuffing, digging motion observed when a horse places its hoof (Harmon, 1989). Based on the study of the mechanical forces applied by the human foot, differences in walking motions might be expected to influence the amount of sediment made available for transport from a hiking trail (Quinn et al., 1980).

Llamas generally can be packed with 20 to 25 percent of their body weight, but for short trips may pack as much as a third of their body weight (Markham, 1990). For the llama of average size, this means an average packing weight of 75 to 90 pounds up to a maximum of 120 pounds. This is considerably less weight than the 250 to 300 pounds a horse may typically carry, however llamas and horses generally carry a comparable percentage of their body weights (Markham, 1990).

Site Characteristics Affected By Recreational Trail Traffic

Erosion

Soil erosion is defined as the detachment and entrainment of soil particles and is clearly the major impact of trail use. Sediment yield is the primary variable of interest in this study. It is an accepted means of quantifying erosion potential (Lal, 1988), and can be measured when soil particles are suspended and transported. Sediment yield from trails is influenced by rainfall intensity, slope, and soil characteristics. The type and intensity of recreational trail traffic influences sediment yield most directly through soil compaction, detachment of soil particles, and changes in the roughness of surface soils (Quinn et al., 1980; Wilson and Seney, 1994).

Erosivity

Erosivity is defined as the force driving soil detachment and transport processes (Lal, 1988). Erosivity is the influence of raindrop impact, and not a measure of soil characteristics or the impacts caused by various trail users. Detachment and transport forces are a function of rain drop size, velocity, and intensity. Transport capacity increases with greater amounts of overland flow and is largely determined by rainfall intensity and infiltration rate which is, itself, a function of surface roughness, surface sealing, steepness and length of slope (Lal, 1988).

Erosivity is influenced by rainfall intensity, which is a measure of water volume to fall as rain over a period of time and thus is simply a rate. Intensity is not a measure of the amount of kinetic energy with which individual raindrops strike a surface. Kinetic energy is determined by drop size and velocity.

Rainfall simulators mimic natural rainfall characteristics with varying degrees of accuracy. Although it is difficult to reproduce realistic rainfall conditions (Young, 1979), rainfall simulation has the advantages of controlled timing and replicable rainstorm events. Lack of overland flow on small simulation plots is one of the limitations of rainfall simulation for erosion studies. Because rainfall simulation causes little cumulative overland flow, plots for this study will be analogous to a section of trail just below a water bar where overland flow is funneled off of the trail.

Overland flow is channelized on hiking trails which increases volume and kinetic energy available for sediment transport. Because the focus of this study is on how different trail users make sediment available for detachment, subsequent transport is of secondary concern. Transport is influenced less by trail user type, and more by rainfall intensity, steepness and length of slope, placement of water bars, and other trail conditions. These generalizations are supported by Wilson and Seney's (1994) findings that sediment yield from hiking trails is detachment limited rather than transport limited.

Soil Characteristics

To corpare relative impacts of different trail user types, it is important to control non-dependent variables for minimal variation. Soils respond differently to recreational traffic based on the soil physical characteristics (Helgath, 1975; Bratton et al., 1978; Summer, 1986; Wilson and Seney, 1994), thus study results may vary with soil type. By holding trail characteristics constant, a study should allow for comparison of the relative impacts of different user types on established hiking trails with some degree of general applicability.

Soil characteristics that influence resistance to erosion include: soil texture, organic matter content, degree of aggregation, pH, antecedent moisture level, bulk density, and porosity (Wischmeier and Mannering, 1969). Among these factors, Gabriels and Moldenhauer (1978) concluded that texture and aggregate stability influenced sediment yield to the greatest extent. Particle size distribution is a major determinant of a soil's aggregate stability, soils high in clay are more cohesive. Although clay soils are generally well aggregated, they are not always the most resistant to erosion because of poor drainage. Organic matter content is a primary determinant of aggregate stability, but established hiking trails are expected to have lost surface horizons along with most of their organic matter (Wilson and Seney, 1994). Because of this, organic matter content is expected to be low with little variability on individual trail plots and not an important variable for established trails.

Soils that exhibit the greatest resistance to soil erosion have a fairly even mix of sand, silt, clay, and coarse fragments (Nimlos, 1986) allowing good soil aggregation and drainage, thus minimizing overland flow. These generalizations are supported by agricultural research findings that soils high in silt, while low in clay and organic matter are the most easily eroded by water and wind (Wischmeier and Mannering, 1969). Erodibility decreases in the following order: silt > silt loam > sandy-loam > loamy sand > sandy clay loam > loam > clay loam (Bryan, 1969). These terms are defined by the U.S.D.A. Soil Survey (1994).

Degree of soil aggregation is a primary determinant of a trail's susceptibility to erosion. Although the overall effect of trail use is soil compaction, individual trail users disaggregate the surface soils, rendering sediment easier to dislodge and more readily available for transport (Quinn et al., 1980). Water-stable aggregate particles and solid particles of equal size will behave similarly in response to raindrop impact and overland flow (Farmer and Van Haveren, 1971). Trail users that cause a greater disaggregation of the soil surface and reduction of the average aggregate size will tend to make more sediment available for erosion.

Soil Compaction

Compaction reduces soil porosity, and in particular reduces the amount of macro-pore volume which in turn reduces infiltration rates (Kuss, 1983). Reduced infiltration increases overland flow and kinetic energy available to enhance sediment transport. A soils resistance to compaction or strength is determined by particle size distribution, texture, and organic matter content. Soils with a mixed particle size distribution fill voids within the soil most efficiently and are the most easily compacted soils (Lull, 1959). Organic matter acts as a cushion and reduces compaction of forest soils (Johnson and Bescheta, 1980).

However, organic matter is not expected to have a significant influence on established hiking trails which have already lost most organic matter from surface horizons (Wilson and Seney, 1994).

The degree of compaction that occurs on a trail is strongly influenced by soil moisture content at the time of traffic. Moisture in the soil lubricates soil particles. This reduces sheer strength, a measure of a soils resistance to compaction. Compaction does not increase linearly with soil moisture content, because as soils approach field capacity (saturation) they behave more like liquids which do not compact (Lull, 1959). Generally the soil moisture content of maximum compactability lies at a point about mid-way between field capacity and wilting point, but is variable with soil characteristics (Lull, 1959).

For a given soil type, compaction is a function of the magnitude of and manner in which force is applied (Quinn, 1980). Forces applied to a soil have two components: (1) the force per unit area (usually measured in pounds per square inch, or PSI) and (2) the amount of vibration or motion with which the force is applied. Force per area can be measured by dividing mass by the surface area over which the force is applied. Average standing pressures range from 25 to 40 PSI for a horse and between 6 and 13 PSI for humans (Lull, 1959). Harmon (1989) measured the force exerted by a llama foot at 9.1 PSI, but he also reported 12.7 PSI for a horse, which is lower than measurements of others.

The motion with which a force is applied is more difficult to measure but is a function of compressive and sheer forces. Compressive force depends not only on the mass of the trail user but also depends on the velocity with which a foot strikes or pushes off from a surface. Vibrational forces increase the compaction of soil particles over stationary forces and also influence soil sheering which will reduce soil strength and increase soil erodibility (Lull, 1959). There are two peaks in the amount of force applied by the single step of a hiking boot: the striking of the heel and pushing off with the toe (Quinn et al., 1980). The heel strike tends to have a compressive effect whereas the toe push has a sheering or loosening effect. The maximum force applied by a horse or llama hoof or foot might also be much greater than the force per area of the stationary animal because of impact and sheering motions. Any scuffing or movement of the foot while in contact with the trail would also influence soil compaction and aggregation (Quinn, 1980). Quantifying differences in the walking motions of each trail user type is beyond the scope of this study, but is an important factor that should be observed and considered as a possible cause for differences in trail impacts.

Since established hiking trails are already well compacted, additional traffic may not result in a measurable increase in compaction. This follows from the principal that less dense, more porous soil has greater opportunity for compaction (Lull, 1959). Changes in compaction on existing hiking trails have not been accurately measured because techniques available to measure soil compaction lack sensitivity (Summer, 1980; Wilson and Seney, 1994). Based on the conflicting processes discussed and the difficulty of measurement, the effect of additional traffic on compaction of established hiking trails is not clear.

Surface Roughness

It is important to measure surface roughness after traffic application as an explanatory variable for differences in sediment yield. The roughness of the soil surface influences the volume and kinetic energy of overland flow and sediment yield (Ruttiman et al., 1995). Studies from agricultural fields show that in the absence of vegetation, rougher surfaces have a small-scale ponding effect which slows down overland flow, increases infiltration, and traps sediment (Dixon, 1995). It is possible that a trail user causing greater trail roughness will leave the surface in a condition that will trap sediment in small depressions.

Slope

One of the most important factors determining the amount of erosion on a hiking trail is the steepness and length of slope (Bratton et al., 1979). The slope of a trail greatly determines the ratio of infiltration to runoff and the resulting amount of water available for sediment transport. Not only do steeper slopes yield a greater volume of runoff, they also cause this overland flow of water to have greater kinetic energy which increases sediment transport capacity (Satterlund, 1972).

The slope of a trail also alters the magnitude of and manner in which force is applied by different user types. Quinn et al. (1980) found that hikers exert greater sheer forces when climbing steeper slopes and greater compressive forces when descending steeper slopes. The relative magnitude of forces applied also vary by user type according to up- or down-slope travel; Weaver and Dale (1978) found that horses and hikers caused greater damage when descending, and wheeled vehicles caused greater damage when climbing. Clearly, constant slopes among plots will be extremely important in allowing comparison of horse, llama, and hiker influences on soil erosion.

Hypotheses

The primary hypothesis of this study is that llamas, horses, and hikers do not impact established recreational trails to the same extent. To test this hypothesis, impacts measured as sediment yield (g), bulk density (g/cc), surface roughness (cm), and infiltration (ml), were tested with 95% confidence for differences among means as follows:

-H_1: Trail users have equal impacts.

If H_1 rejected,

-H_2: Impact varies between llamas, horses, and hikers.

-H_3: Impact varies by traffic level.

-H_4: Impact varies on wet and dry trails.

-CHAPTER TWO-
METHODS

Location of Study

The study was conducted at the University of Montana's Lubrecht Experimental Forest near Greenough, Montana (T.13N., R.14W., section 7). The trail segment was selected based on attributes of consistent slope and soil characteristics as well as ease of closing the trail to visitor use. The most important factor in a study comparing different trail users is that all trail plots have the same historical use and start with a common condition.

A 300-meter long segment of trail, mapped as the "D Loop" of Lubrecht's cross country ski trail system (appendix A) was closed to all traffic immediately following snow melt. The portion of the trail system selected has been used by a wide variety of users in the past including foot, horse, bicycle, motorcycle, and vehicle traffic, and thus has two parallel tracks. This arrangement allowed traffic simulation on both tracks and reduced the overall length of trail needed for the study, minimizing the amount of variability in slope and soil characteristics.

The disadvantage of selecting a trail segment with historic use by vehicular traffic was considered. The trail segment selected for this study receives few vehicle passes each year (Hank Goetz Lubrecht Forest Administrator, Personal Communication). Freeze/thaw action in the surface horizons of soils acts to loosen and reduce compaction each winter (Johnson and Bescheta, 1980). Closing the trail at the time of snowmelt prevented any vehicle traffic from occurring during the 1995 season and took full advantage of the winter's freeze/thaw activity.

The section of trail selected is located on a Winkler gravelly loam; a loamy-skeletal, mixed, frigid, Udic Ustochrept (Nimlos, 1986). The parent material for this soil type is belt colluvium, metamorphosed Precambrian sedimentary rock. The need to compare different user types on a consistent soil, and the importance of maximizing replication, precluded the use of more than one soil type. The Winkler soil series has a low compactibility rating and moderate road limitations (Nimlos, 1986). In consideration of these ratings, low slope steepness, and the gravelly-loam classification, this soil provided an intermediate to high level of resistance to soil compaction and erosion.

The width of the trail ranges from 2 to 3 meters and has little entrenchment. The elevation is 1,250 meters (4,100 feet) and the trail has an east aspect. The average slope of the trail segment is six percent with little variability. Based on samples from the control plots, the pre-treatment bulk density of the trail's surface 5 cm is 1.5 g/cc. It is located in a *Pseudotsuga menziesii/Arctostaphylos uva-ursi* habitat type (Pfister et al., 1977). The canopy is thin enough and the trail wide enough so that most of the trail does not have tree canopy directly above it. Similar elevations at Lubrecht receive approximately 46 cm (18 inches) of precipitation annually, about 40 percent of which falls as snow (Nimlos, 1986).

Site Characterization

Several soil pits were excavated on the trail and five meters off of the trail to describe the soil profile and ground truth existing soil map units. Precipitation was monitored with a Tru-Chek brand rain gauge during the weeks prior to and during traffic application. The slope of each individual rainfall simulation plot was measured by laying a 12-inch-long board along the trail surface and then measuring the slope of this board with the clinometer on a Suunto MC-1D professional compass.

Plot Layout

Plots were arranged in a randomized complete block design to control for possible gradients in slope or soil characteristics along the trail segment. There were 8 blocks total, 4 wet trail and 4 dry trail blocks. Because of differences in equipment and timing necessary for wet and dry trail blocks, wet and dry blocks were grouped and not randomly interspersed (Figure 1). However, all 8 blocks were located on a consistent slope and soil type with all treatments randomly distributed within blocks.

Each block contained seven treatments: 1,000 horse passes, 250 horse passes, 1,000 llama passes, 250 llama passes, 1,000 hiker passes, 250 hiker passes, and a control with no traffic (Figure 1). Each plot was one meter wide and three meters long with a three-meter-long buffer zone between plots for turning, this allowed animals and hikers to reach a normal stride upon entering the plot. Areas of notable existing erosion, gullies, or deposition along the trail were avoided when locating plots.

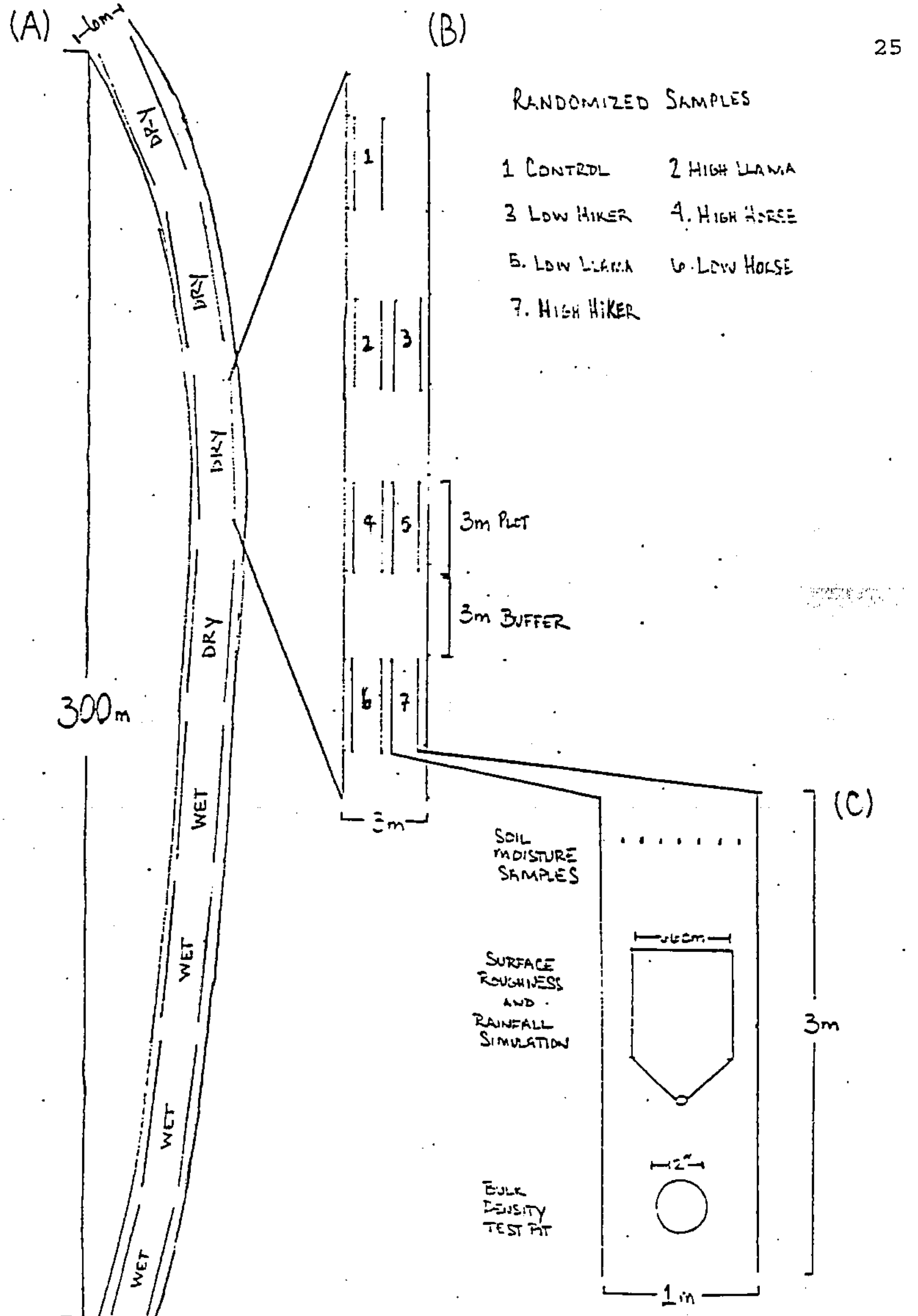

Figure 1- Full view of trail section (A), randomized block layout (B), and sample arrangement within traffic plot (C).

Application of Trail Traffic

Trail traffic was applied and data collected during June and July of 1995. The month of June was selected for the wet trail simulations, because it is normally the wettest month of the summer at Lubrecht. Wet trail traffic applications and data collection were completed between June 19 and June 24. July was selected for dry traffic applications because of the normally dry weather patterns at Lubrecht during that month. Dry traffic treatments were applied between July 18 and July 25. Less than one cm of rain fell during this time period, and traffic application was suspended for 24 hours following the rain to allow the trail to dry sufficiently.

Wet Trail Treatments

To create wet trail conditions, plots and buffer zones received one centimeter of water per unit area applied by a gas powered pump through a low pressure, fine spray nozzle. Immediately after each plot was wet, seven composite soil moisture samples were taken across the plot to a depth of five cm, stored in a sealed container, and later dried in an oven at 110° Celsius. Percent soil moisture was determined on a gravimetric basis (Klute, 1986). Water holding capacity was determined by the method of Harding and Ross (1964).

Traffic application began immediately following soil moisture sampling. Different traffic treatments required variable amounts of time, so rainfall simulation was delayed a minimum of two hours after initial trail wetting, for all treatments and the control plot. This was done to equalize soil moisture conditions at the time of rainfall simulation.

Several rain storms complicated traffic application during the week of wet traffic simulation. Although natural rainfall maintains soil moisture, better control of soil moisture conditions would have been achieved using only a system for wetting the trail and avoiding periods of natural rainfall. Traffic application was suspended and plots covered with plastic tarps during natural rainstorms to prevent additional trail wetting and loss of sediment.

Procedures for Wet and Dry Trail Segments

With the exception of wetting the trail, sampling and treatment were the same for both wet and dry traffic treatments (Table 1). Traffic was applied continuously on plots until the specified number of passes were accumulated. Equal numbers of uphill and downhill passes were made on each plot. Horses and llamas were led in such a way that the person leading the animals stayed out of the plots. Because of differences in the amount of weight carried and variations in back country use patterns for llamas, horses, and hikers, trail users did not carry packs in this study. This allowed for an objective one-to-one comparison of the three types of trail users, although it did not simulate the impact of loaded animals and hikers. Any manure from the animals was removed from the trail before further traffic application to avoid influences on sediment yield or soil structure.

Table 1- List of tasks performed at each traffic simulation plot.

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1) Wet plot and buffer zone (pre-wet trail treatments only).
2) Take seven composite soil moisture samples.
3) Apply traffic continuously until 250 or 1,000 passes reached.
4) Measure soil surface roughness.
5) Measure bulk density.
6) Apply simulated rainstorm and collect sediment.
7) Measure slope of rainfall plot.

Hikers wore non-lug sole hiking boots and weighed between 55 and 75 Kg. Two hundred and fifty hiker passes required about 20 minutes to apply and 1,000 hiker passes took a little over one hour. Two horses with cleated shoes were used that weighed around 500 and 400 Kg each. Two hundred and fifty horse passes could be applied in about two hours and 1,000 horse passes were usually completed in six hours. Two llamas weighing 160 and 190 Kg were used, however the majority of llama traffic was applied by the 160 kg pound llama. Llama toe nails were trimmed prior to traffic application. Llamas generally took about one-third less time than horses for traffic application, primarily because they could be turned more quickly in the buffer zone.

Measurement of Dependent Variables

Surface Roughness

Surface roughness was measured by fitting a length of thin, flexible, cotton crochet thread to the surface of the trail over a 70 cm linear distance. The length of this thread was then measured, after fitting to the specified length of trail to determine the additional length in excess of 70 cm due to the uneven surface. A sampling frame (Figure 2) was used to guide the measurement which was repeated over a grid three times parallel to the direction of traffic and three times perpendicular to traffic. The six values were averaged for each plot. This method was adapted from Beckman and Smith (1974) where the concept of measuring the trace of the surface of a soil ped was used to measure it's circumference.

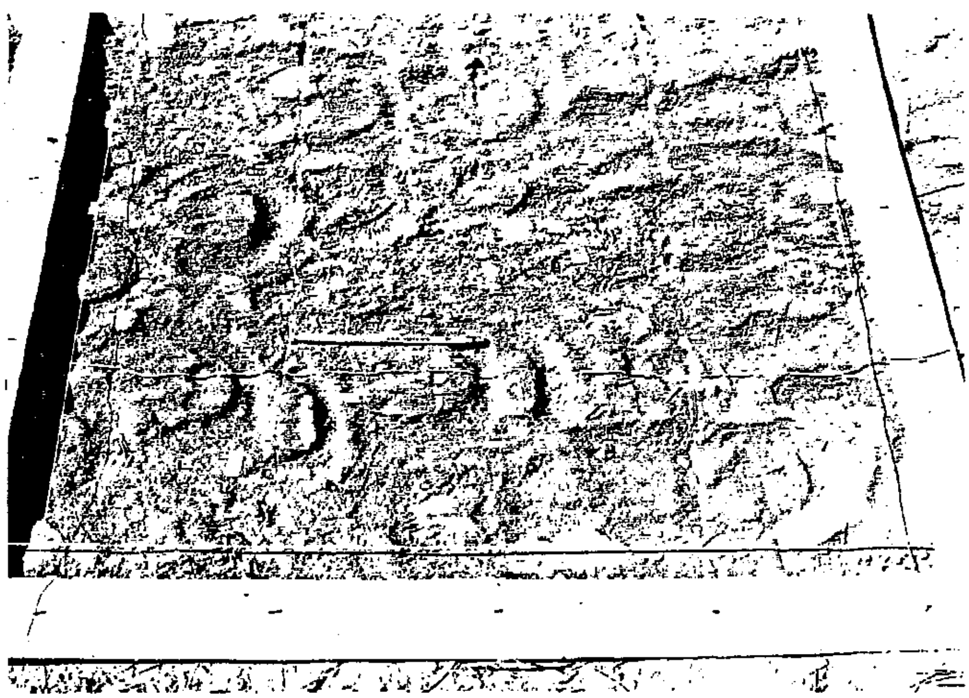

Figure 2- Photograph of sampling frame and method used for measuring surface roughness.

Bulk Density

Bulk density was measured by an excavation and volume measurement method (Klute, 1986). A 12 cm diameter hole was dug to a depth of five cm with a spoon. A template was used to guide the shape of the excavation. All soil materials removed from the hole were saved and dried to constant weight at 110° Celsius to determine the dry mass of the material removed from the hole. The volume of the hole was determined by filling it back to surface level with a measured volume of washed quartz sand which passed a # 20 (0.841 mm) soil sieve and was retained by a # 60 (0.250 mm) sieve. Bulk density was calculated in g/cc by dividing the mass of soil excavated by the volume of soil removed (or sand added).

To determine the influence of coarse fragments and large pieces of organic matter on bulk density, coarse fragments and organic matter > 2 mm diameter were removed from the samples. This was done by passing the fine materials through a # 10 (2.001 mm) sieve. The volume of coarse materials removed was determined by water displacement in a 500 ml graduated cylinder. Fine materials were reweighed and bulk density values recalculated without the volume or mass of coarse materials.

Rainfall Simulation

The use of rainfall simulation for soil erosion studies offers the advantage (over natural rainfall and sediment collection) of controlled timing and application of a replicable rainfall event to all study plots. Drop size, height of drop fall (which determines velocity), and rate of rainfall are the three most important characteristics to consider in the design of a rainfall simulator. Drop size and velocity determine the kinetic energy (KE) of drop impact. This relationship is expressed by the equation $KE=1/2MV^2$ (Gifford, 1979) where M=mass and V=velocity. This equation is useful in comparing the kinetic energy of simulated rainfall events to that of natural rainfall events through the ratio $[(MsVs^2)/(MnVn^2)]$ (Gifford, 1979). This allows the percentage of natural rainfall KE to be calculated for a rainfall simulator of given drop size and fall height. Achieving realistic rainfall intensity (rate of rain fall over time) and kinetic energy are major limitations of rainfall simulation (Young, 1979), as most rainfall simulators range from 25 to a maximum of 75 percent of natural kinetic energy.

Most rainfall simulation studies use intensities of about

12 cm/hr which is far in excess of normal rainfall rates (Wischmeier and Mannering, 1969; Bryan, 1969; Johnson and Bescheta, 1980; Quinn et al., 1980; Quansah, 1981; Wilson and Seney, 1994). High intensity is necessary for two reasons, to produce adequate runoff to make up for limited overland flow, and to simulate the high intensity rainfall events that usually cause the greatest erosion.

Hourly precipitation data are available for Ovando, Montana, a station at the same elevation, but 32 km to the north-east of the study site. Between 1973 and 1994, the maximum hourly precipitation rate recorded for a single rainfall event during the months of June or July was 6.1 cm/hr for a 15-minute interval and 5.6 cm/hr for a 30-minute interval (NOAA, 1971-1994). To be consistent with previous research and to insure generation of adequate volumes of runoff, a 12 cm/hr simulated rainstorm event was applied to all plots for a 15 minute period.

Simulated rainfall was produced with a modified Meeuwig drip-type rainfall simulator (Figure 3). This simulator produces a drop size of 2.8 mm, with a KE roughly one third that of natural rain when suspended from a drop height of 1.5 meters, (Meeuwig, 1971). In an effort to increase the

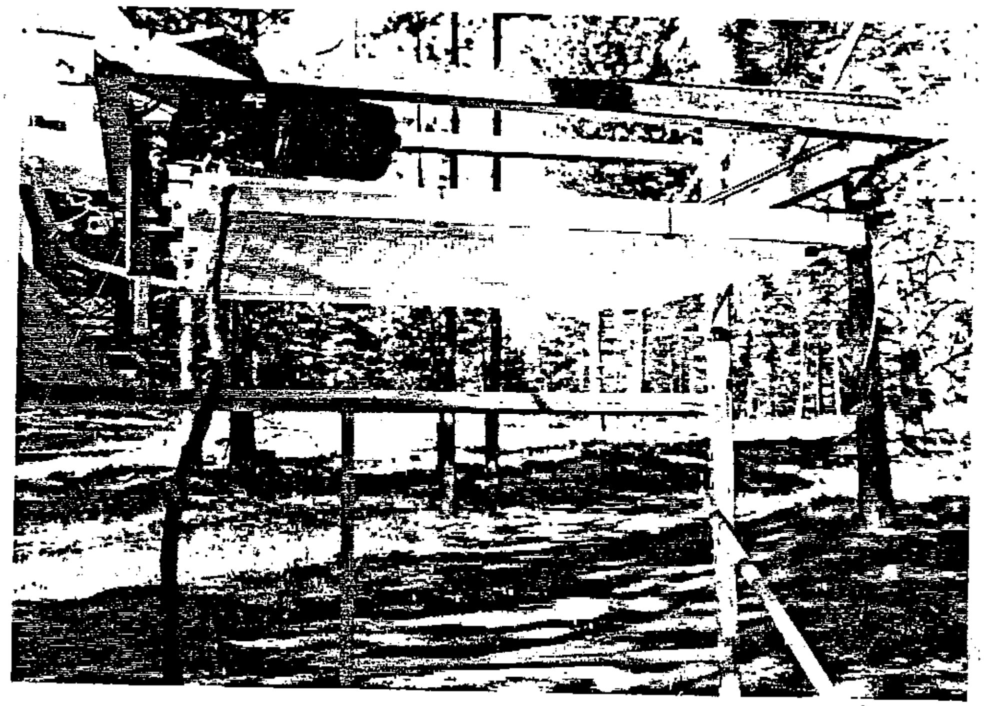

Figure 3- Photograph of Meeuwig drip-type rainfall simulator.

rainstorm KE for this experiment, drop fall height was increased from 1.5 to 2 meters, this still produced a KE less than half that of natural rainstorms.

Sediment Collection

Each rainfall simulation was applied over a 66x66 cm plot (Figure 4) and all runoff funneled into storage containers for transport. Total volume of runoff collected was measured and subtracted from the amount of water applied to the plot in order to determine infiltration. Runoff samples were allowed

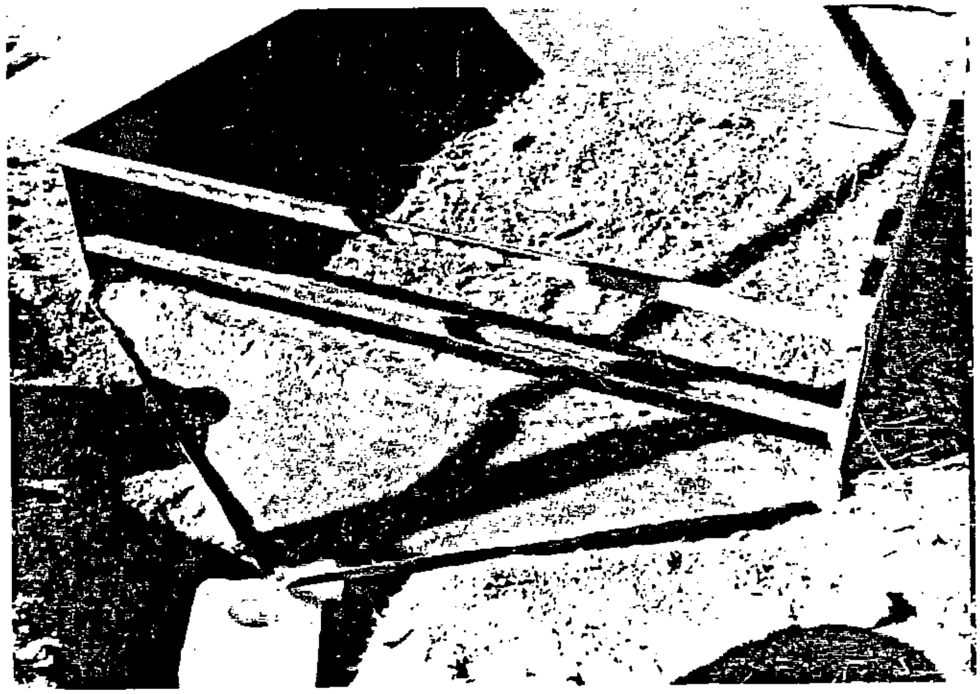

Figure 4- Photograph of runoff collection system over which rainfall simulation occurred.

to settle for at least one day, most of the water was siphoned off the top, and the remaining sediment dried to constant weight. The total mass in grams of sediment collected from each rainfall simulation plot was used as a measure of the relative erosion potential of different trail user types.

Statistical Methods

The analysis of variance (ANOVA) procedure of SPSS was used to test the significance of user type, level of traffic, and their interactions for the dependent variables, sediment yield, bulk density, and surface roughness. In order to determine the validity of combining the wet and dry blocks as an 8 block data set for comparison of user type with increased sample size, the interaction between user type and trail moisture was also tested in a 3 way ANOVA of user type, level of traffic, and wet or dry trail. Because wet and dry blocks were not randomized, differences between wet and dry trails were tested using paired t-tests instead of ANOVA. Bartlett's test (Zar, 1984) was used to evaluate the degree to which the data met the assumption of homogeneity of variance required by ANOVA. Data did not require any type of transformations.

Scheffe's multiple comparison procedure may be used for uneven sample sizes and allows for all possible pair-wise comparisons while controlling for the experiment-wise error rate (Kleinbaum et al., 1988). This means that the probability for a single, type-one error (finding a significant difference in means when one really does not exist) is held at $p<0.05$ among all possible comparisons for this data set. Holding the experiment-wise error probability at 0.05 reduces each comparison P value to a very small value (<<0.01). The result is a conservative comparison process, and, for sediment yield data with inherently high variation

(Dixon, 1995), a high risk of a type II error.

For sediment yield, correlation coefficients and probability values were calculated for slope, soil moisture, and rainfall intensity. This gives an indication of how the controlled dependent variables influenced sediment yield. Correlation coefficients were also calculated between sediment yield and the dependent variables bulk density and surface roughness to determine the extent to which these factors explained variability in sediment yield.

-CHAPTER THREE-
RESULTS

Sediment Yield

Sediment yield means ranged from 31 g for the wet control plots to a maximum of 304 g for the dry high traffic level horse plots. There are distinct patterns in means by user type and level of traffic with the horse trail treatment plots producing more sediment than other trail users, and higher levels of traffic producing more sediment than lower levels for all user types (Figure 5). It is also important to note that with the exception of the low hiker plots, dry trail traffic produced more sediment than wet trail traffic. Statistical analysis focused on these trends to determine which were significant.

Different types of trail users have similar patterns in sediment yield means at high and low traffic levels, and on wet and dry trails (Figure 5). A 3-way ANOVA (Table 2) was used to test the validity of a one-way ANOVA with traffic level and trail moisture condition averaged by user type. The arrangment of blocks in the experimental design (Figure 1)

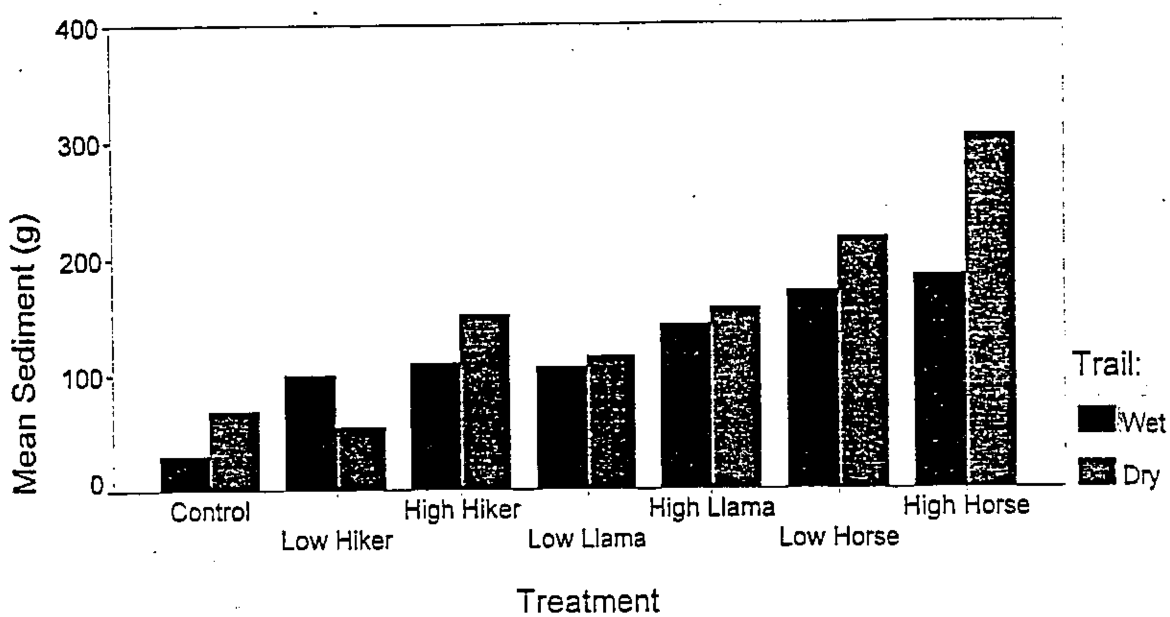

Figure 5- Sediment yield means grouped by user type and traffic level for wet and dry trails.

does not allow for ANOVA with regard to trail moisture condition. However, the insignificant tests for interaction of trail moisture condition with both user type and level (Table 2), allows for multiple comparisons of user type averaged across all 8 blocks (Table 3). User type and level of traffic were fully randomized across these 8 blocks.

Table 2- Three-way ANOVA for wet and dry trail plot sediment yield, control excluded to allow comparison of levels.

Factor	D.F.	F	P
User (Llama, Horse, Hiker)	2	9.156	0.001
Level (250 or 1,000 passes)	1	4.244	0.047
Trail (Wet or Dry)	1	1.824	0.185
2- Way Interactions			
User * Level	2	0.038	0.963
User * Trail	2	1.300	0.285
Level * Trail	2	1.454	0.236
3-Way Interactions			
User * Level * Trail	2	0.303	0.740

Sediment yield was averaged across trail moisture condition and traffic level for one-way ANOVA and multiple comparisons of trail user type (Table 3). Horse traffic plots produced significantly more sediment than either llama, hiker, or no traffic plots with 95 percent confidence. Llama traffic plots produced sediment yields similar to hiker plots and significantly lower than horse plots. Hiker and llama traffic plots produced greater sediment yield means compared to the no traffic plots, but these differences were not significant at alpha=0.05 (Table 3).

Table 3- Multiple comparisons for sediment yield by user type for a one way ANOVA with user type means averaged across level of traffic and trail moisture condition.

User Type	# of Samples	Sediment Yield (g)	Group
No Traffic	8	50	A
Hiker	16	104	A
Llama	16	130	A
Horse	16	219	B

Note: Means with the same letter are not significantly different at alpha=0.05 using Scheffe's multiple comparison procedure.

Averaging the high and low level traffic plots for each user results in a smaller sample size for control plots. Scheffe's multiple comparison procedure allows comparison of uneven sample sizes. The comparison of trail users in Table 3 is the most useful way to look at different trail users for two reasons, it produces the maximum possible sample size, and it evaluates the different trail users over multiple soil moisture conditions and traffic levels. This range of conditions is appropriate because trail traffic normally occurs over a range of moisture conditions and suggests that these results are not limited to a single condition. The results can thus be applied to the relative erosion potential of llamas, horses, and hikers beyond the experimental design.

If wet and dry trail conditions are separated, the data show that horse traffic plots yielded sediment in excess of control plots (alpha=0.05). This suggests as does the combined analysis, that under either wet or dry conditions, horse traffic has the greatest impact on soil erosion potential.

Bulk Density

The excavation method was a sufficiently accurate and sensitive technique for measuring bulk density differences on established trails. The mean bulk density for no traffic plots on wet trails was 1.49 g/cc and 1.50 g/cc on dry trails. Coefficients of variation were impressively low for bulk density means, averaging 10% with a maximum of 17%. By comparison, sediment yield coefficients of variation ranged from 20% to 80%. Low coefficients of variation indicate that different traffic treatments had very consistent effects on bulk density.

Table 4 shows a similar 3-way ANOVA for bulk density as was displayed for sediment yield. Trail user type was not significant P=0.285 for this model. As mentioned in the preceding sediment yield section, a paired t-test is the appropriate method of comparing dry and wet trail conditions

Table 4- Three-way ANOVA for wet and dry trail plot bulk density, control excluded to allow comparison of levels.

Factor	D.F.	F	P
User (Llama, Horse, Hiker)	2	1.302	0.285
Level (250 or 1,000 passes)	1	0.137	0.713
Trail (Wet or Dry)	1	47.795	0.000
2- Way Interactions			
User * Level	2	0.159	0.853
User * Trail	2	1.415	0.256
Level * Trail	2	3.300	0.078
3-Way Interactions			
User * Level * Trail	2	1.539	0.228

in this experimental design. However, the highly significant effect of trail moisture condition and the pattern of bulk density for dry trails shown in Figure 6, suggest that user type and level should be evaluated in two-way ANOVA's for wet and dry trail plots separately.

Interaction between user type and level of use was not significant, thus means for traffic levels and user types may be averaged to maximize sample sizes in multiple comparisons. Wet trail traffic produced no significant differences in bulk density for llama, horse, hiker, and no traffic plots. For dry trail traffic, user type and level of use were significant

(Table 5). Llama, horse, and hiker traffic plots all had lower bulk density means (alpha=0.05) after traffic compared to the control plots, but did not differ significantly depending on type of traffic (Table 6). When the no traffic plot mean is included for a one-way ANOVA of traffic level, level does not have a significant influence on bulk density.

Table 5- ANOVA for bulk density on dry trail treatment plots, control excluded to test for interaction of user type and traffic level.

Factor	D.F.	F	P
User Type (llama, horse, hiker)	2	5.516	0.014
Traffic level (1,000, 250)	1	6.124	0.024
User Type * Traffic Level	2	1.723	0.207

Table 6- Multiple comparisons among bulk density means for a one-way ANOVA with user type for dry trail treatments.

User Type	# of plots	Bulk Density (g/cc)	Group
No Traffic	4	1.50	A
Hiker	8	1.28	B
Llama	8	1.28	B
Horse	8	1.12	B

Note: Means with the same letter are not significantly different at alpha level=0.05 using Scheffe's multiple comparison procedure.

To determine the extent to which bulk density changes influenced sediment yield, correlation coefficients were calculated for wet and dry plots separately. Correlation between bulk density and sediment yield was not significant (alpha=0.05) on wet trails. A negative correlation (R^2= -.5864) between bulk density and sediment yield was highly significant $p<0.001$. Lower bulk densities caused increased sediment yields on dry trails and this pattern appears to be closely related to trail user type (Figure 6).

Surface Roughness

Surface roughness was significantly influenced by trail user type as shown by a 3-way ANOVA (Table 7). Lack of interactions in this 3-way ANOVA again allowed averaging user type by traffic level and trail moisture condition as was done for sediment yield multiple comparisons. The 3-way ANOVA shows that surface roughness did not vary between high and low levels of trail traffic.

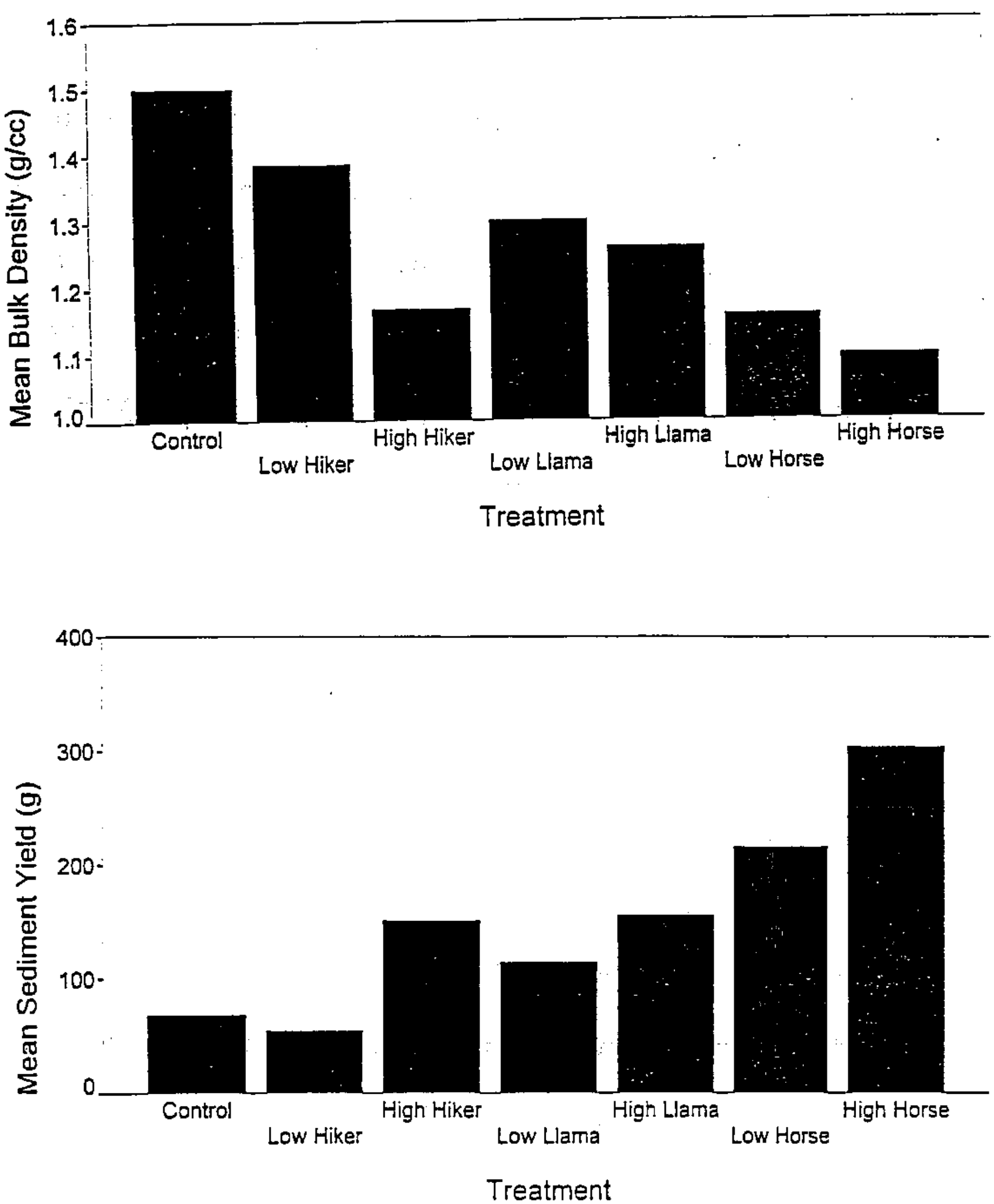

Figure 6- Trends in dry trail bulk density and surface sediment yield means by treatment, sediment yield increases as bulk density decreases.

Table 7- Three-way ANOVA for wet and dry trail plot surface roughness, control excluded to allow comparison of traffic levels.

Factor	**D.F.**	**F**	**P**
User (Llama, Horse, Hiker)	2	20.002	0.000
Level (250 or 1,000 passes)	1	2.151	0.151
Trail (Wet or Dry)	1	0.008	0.930
2- Way Interactions			
User * Level	2	0.211	0.810
User * Trail	2	2.132	0.133
Level * Trail	2	1.000	0.324
3-Way Interactions			
User * Level * Trail	2	1.083	0.349

Table 8 shows multiple comparisons of surface roughness by user type averaged across traffic level and trail moisture condition. Horse traffic plots had significantly greater surface roughness than both llama and hiker traffic. It is important to note that relative to the no traffic treatment, differences were due as much to a reduction in surface roughness by hikers and llamas as an increase in roughness by horses.

Table 8- Multiple comparisons among bulk density means by user type averaged across wet and dry trails, and high and low traffic intensities.

User Type	**# of plots**	**Roughness (cm)**	**Group**
Hiker	16	73.8	A
Llama	16	74.8	A
No Traffic	8	75.4	A B
Horse	16	76.7	B

Note: Means with the same letter are not significantly different at alpha level 0.05 using Scheffe's multiple comparison procedure.

Because there were no significant interactions of user type, traffic level, and trail moisture condition, wet and dry trail plots were combined for calculation of correlation coefficients. Trails with greater surface roughness were significantly correlated with an increase in sediment yield (.2373, p=0.039, n=58).

Infiltration

Measurement errors for infiltration during simulated rainstorms made this data unusable. Thus, significant differences by treatment in bulk density and surface roughness could not be linked to changes in infiltration and runoff from the trail. Treatment induced differences in infiltration may not exist and would be difficult to measure on established trails due to the insensitivity of methods available.

Based on observations made during field work, it does not appear likely that different infiltration rates are induced by different t·pes of trail users on existing trails. Variation in the amount of runoff from each plot was minimal and did not appear to cause different levels of sediment yield by trail user type.

Wet and Dry Trail Comparisons

As previously mentioned, ANOVA cannot be used for multiple comparisons of wet and dry trails, because wet and dry trail blocks were grouped, not randomly mixed. However, paired t-tests may be used to see if individual trail users had significantly different effects on wet trails compared to dry trails for sediment yield, bulk density, and surface roughness. Means by user treatment were not significantly different between wet and dry trails for sediment yield. However mean sediment yields were consistently higher on dry trails than wet trails with the exception of the low intensity hiker traffic treatment (Figure 4). Bulk density means were lower (alpha=0.05) for dry trails than wet trails. This represents a loosening effect on dry trails rather than a compaction effect on wet trails. Surface roughness means were not different between wet and dry trails, which supports observations made in the field.

-CHAPTER 4-
DISCUSSION

Sediment Yield

The total weight of sediment in the runoff from rainfall simulation plots was used as a measure of erosion potential. This measurement is useful in quantifying the relative effects of llamas, horses, and hikers on trail surfaces in terms of the ease with which sediment may be detached and transported a short distance. Erosion potential may be related to sediment loss from trails occurring under natural conditions, but is not intended to be a generic measure of environmental impact. Interpretation of the results are limited to direct comparisons among user types and the control in order to determine whether differences exist by type of trail user.

Horse traffic made more sediment available for erosion than either llama or hiker traffic. These findings are similar to those of Wilson and Seney (1994), who found that horse traffic produced greater sediment yields than hikers, bicycles, or motorcycles. Previous studies on the physical impacts of packstock on trails have focused on horses as the sole representative of all packstock. The result is that all packstock, including llamas, are often restricted on steep slopes, wet soils, and otherwise sensitive trails. This study clearly shows that llama traffic produced levels of sediment yield similar to hiker and no traffic plots. Thus, llama traffic does not impact established hiking trails in the same way that horse traffic does and may not require the same management restrictions as those applied to horses.

Previous soil erosion research on trails and agricultural lands has demonstrated the difficulty of identifying the contributions of the many variables influencing sediment yield (Schmid, 1988; Wilson and Seney, 1994; Ruttimann, 1995;). Given the amount of variability expected even under controlled conditions, it is particularly notable that trail user impacts were measured as sediment yield for this study.

Sediment yield means increased as bulk density means decreased (Figure 5), suggesting that loosening and disaggregation of soil aggregates made sediment more easily detached and transported. The high sediment yield means for horse traffic plots under dry conditions may be best explained by: (1) extent of soil disaggregation (a pulverizing effect); and (2) the depth to which this disaggregation occurred. Smaller particles can be more easily transported by moving water (Wischmeier and Mannering, 1969). Further investigation of this effect might include an attempt to measure the particle and aggregate size distribution of the trail surface following traffic to compare how different types of trail users disaggregate the soil surface.

Depth of soil loosening and disaggregation as a result of trail traffic may also influence sediment yield. Although depth of loosening was not measured, horse traffic appeared to loosen the surface soil to a greater depth (3 to 4 cm) than either llama, or hiker traffic (1 to 2 cm). If it is assumed that soil erosion from established hiking trails is detachment limited rather than water transport limited (Wilson and Seney, 1994), then disturbance to a greater depth would mean more sediment is available for transport.

A marked decrease in the amount of sediment carried in runoff was observed toward the end of most 15 minute simulated rainfall applications. This suggests that most available sediment was removed by the rainfall, and that the amount of sediment collected was dependent on differences in sediment made available by different trails users. It is clear that sediment yields from horse traffic plots were greater than hiker or llama traffic plots, regardless of complicated interactions among trail surface conditions.

Bulk Density

Recreational traffic is often associated with increased soil compaction, measured as bulk density. Several studies show that recreational use of previously unused trails or campsites does, in fact, cause compaction (Weaver and Dale, 1978; Summer, 1980; Kuss, 1983). However, studies of soil compaction on existing trails have not found increased compaction due to additional traffic (Summer, 1980; Wilson and Seney, 1994). These authors suggested the lack of compaction might be due to the insensitivity of measurement equipment.

Wet and dry trail bulk density measurements for this study provide further evidence that traffic on existing trails may not cause additional compaction. The finding of no significant compaction on wet trails by any type of trail user may have several explanations. Further compaction to established hiking trails may require more use than the 250 or 1,000 passes applied for this study. A second explanation is that little additional compaction occurs on established trails, or that compaction occurs at greater depths or to expanding areas along the sides of trails which were not measured.

The only significant change in compaction by trail traffic was a loosening effect of traffic on dry trails relative to control plots. This is similar to the loosening effect of foot traffic found by Quinn et al. (1980), and was readily observed during field work. Although hiking trails are certairly compacted relative to the surrounding soils (Weaver and Dale, 1978), soil compaction does not appear to be a significant effect of additional trail traffic on established hiking trails.

On dry trails, reduced compaction measured as bulk density was correlated with increased sediment yield. It appears that a traffic induced reduction in bulk density is one of the most important mechanisms by which soil erosion is accelerated on established hiking trails. For existing trails, bulk density may be more useful as a measure of disaggregation or loosening than as a measure of compaction. The connection between bulk density, disaggregation, dry trails and the observed increase in sediment yield over wet trails is worth further investigation. In particular, measurement of bulk density should focus on the relative depth below trail surface of disaggregation caused by different trail users.

Trail Surface Roughness

Hiker and llama traffic plots had significantly less surface roughness than horse traffic plots, but none of the user types caused significantly different surface roughness than the control plot which fell in the middle of the distribution of means. Differences in trail roughness were the result of both a smoothing effect by hikers and llamas, combined with an increase in roughness for horses. Hikers and llamas had a smoothing effect primarily because they flattened or removed from the trail any surface organic debris that caused roughness on the no traffic plots.

The effect of surface roughness on sediment yield from hiking trails is uncertain. Agricultural theory suggests that rough soil surfaces reduce sediment yields by creating small reservoirs that trap sediment (Ruttimann, 1995). However, increased trail roughness is generally regarded as a negative impact of trail traffic (Helgath, 1975; Wilson and Seney, 1994). Trail roughness might, in theory, have two opposing effects. Churned up, rough trail surfaces might increase the amount of sediment available for detachment, but small pools of runoff created by foot or hoof prints in the trail might act as settling ponds that catch sediment. The trail smoothing that was measured for llama and hiker traffic might lead to a higher volume and velocity of overland flow that could have greater erosive power.

The significant positive correlation between surface roughness and sediment yield found after llama, hiker, and no traffic treatments, suggests that increased surface roughness may in fact be a measure of negative impact on established hiking trails in terms of sediment yield. It is possible that increased roughness is actually caused by loosened soils and reduced compaction after traffic, and in that way only indirectly correlated with increased sediment yield. Measuring surface roughness after rainfall as well as before, might help determine whether surface roughness influences sediment yield from hiking trails. Any change in surface roughness due to hoof or foot prints appeared to be washed smooth after simulated rainfall, most notably on dry plots but to a lesser extent on wet plots. This suggests that surface roughness did not have a sediment trapping effect on overland flow.

The technique used to measure surface roughness effectively measured small differences. However, even wet trail plots did not appear to reach the level of roughness commonly observed on wet sections of heavily trafficked trails. Greater differences in surface roughness might have been observed if traffic were applied under conditions of greater soil moisture. On the gravely silt-loam used in this study, the 20 to 30% gravimetric soil moisture measured on wet trails represents about 50% of the soils water holding capacity (Harding and Ross, 1964). This represents a moderate level of soil moisture, for this soil type.

The observed sensitivity of this surface roughness measurement technique (Figure 2), suggests that it might be effectively applied to future erosion studies. Most attempts to measure surface roughness on recreational trails use a series of measurements of the depth of trail incision relative to a line strung perpendicular across the top of the trail (Cole, 1991). When several of these measurements are taken along a line across the trail, they are useful for calculating the cross-sectional area of the soil which has been eroded from the trail. This cross-sectional measurement is useful as a long-term evaluation of the amount of soil lost. However this method is insensitive to small traffic induced changes in surface roughness such as foot or hoof prints.

Wilson and Seney (1994) used a variation on the depth of incision method where pins are dropped through a board and the variation in depth to soil contact gives a relative measure of surface roughness. This technique did not yield significant results when used to compare surface roughness caused by different types of trail users. Different types of trail users may cause only small differences in surface roughness (especially on dry trails) not detectable with the limited number of points measured by the pins. Fitting a string to the trail surface eliminates the problem of sampling only a limited number of points across the trail, because it effectively measures all points along that line.

Traffic Intensity

Wilson and Seney (1994) found that hiker traffic plots did not have significantly increased sediment yields relative to control plots. However the experiment used only 100 passes of traffic for each plot and the authors suggested that this might not have reached a minimum threshold for significant impact. The traffic levels of 250 and 1,000 passes used in this study still did not cause a significant increase in sediment yield for hiker traffic over no traffic plots. Visual observations during field work suggest that a level of

200 to 500 passes caused the most noticeable changes in trail surface conditions, and that further traffic up to 1,000 passes caused little additional change. There is little reason to believe that application of a greater number of passes would have changed the results for this soil type.

In a study of newly constructed hiking trails, Kuss (1983) found significant differences in sediment yield from plots treated with 600 hiker passes and 2,400 hiker passes. Weaver and Dale (1978) found that bulk density and trail widening on new trails increased with additional traffic. Both of these studies were conducted on previously unused trails. For established trails, there is no evidence that erosion potential, bulk density, and surface roughness vary with level of use beyond the establishment of some minimum impact. This supports the notion that amount of use is not a primary determinant of trail impacts on existing trails. Any study of user impacts on established trails might allocate valuable treatment time most efficiently by studying a single traffic intensity level of somewhere around 500 passes.

Trail Moisture

Many trail use regulations, particularly for packstock, limit the season of trail use based on the principal that wet soils are more easily compacted and eroded than dry soils (McClaran and Cole, 1993). Wilson and Seney (1994) support this principal, finding that sediment yields from wet trail traffic plo-s were higher than from dry plots. Llama, horse, and hiker traffic consistently produced higher sediment yields on dry traffic plots than on wet plots though not significant at alpha=0.05 (Figure 4). The results of this study apparently contradict this principal, erosion potential was higher on dry trails than wet trails.

Bulk density was significantly reduced on dry trail plots compared to the wet trail plots. These effects may be attributed to the adhesive and cohesive influence of water that act to hold soil particles together until net cohesive forces take over at extremely high water contents (Hanks, 1992). Measurement of different variables such as trail widening or traffic applied to wetter conditions may have resulted in greater wet trail impacts. The finding that dry trails were more severely impacted than wet trails under these conditions should not detract from the importance of managing wet trails, but suggest that substantial impacts occur on dry trails as well.

Wind erosion form dry trails may be a particularly important form of trail erosion based on observations of extremely dusty conditions during horse traffic application. Lal, (1988) describes wind as having considerable importance as an agent in causing soil erosion. Because of the difficulty in measuring wind erosion, accelerated wind erosion has not been studied on recreational trails.

Limitations of This Study

Several limitations need to be considered when applying the results of this study to different trail conditions or management situations. The fact that llamas and hikers did not increase sediment yields relative to control plots for the single set of slope and soil conditions studied, does not mean that these results can be directly applied to other conditions. The relative impacts of llamas, horses, and hikers may apply to a variety of conditions, but can not necessarily be predicted based on these findings. For example, none of the trail users would be expected to cause significant impact on trails over bedrock. However, all three trail users might have significantly different levels of impact to sensitive trails with conditions such as steep slopes, wetland conditions, or high silt soils with poor aggregate stability.

The experiment was not designed to assess trail widening which is an important aspect of trail deterioration and may require evaluation in future studies of llama impacts. Visual observations during field work suggest that llamas do not disturb as wide an area of trails as do horses. Future research should study changes in trail widths of existing hiking trails under extremely wet conditions, over greater trail lengths, and time periods of application. Trail widening research might be combined with a study of campsite impact to further evaluate how llamas compare with horse and hiker traffic.

It is also important to realize that this study looks at only one aspect of trail use, physical impacts on established trails. Trail head management is an important way for wilderness recreation managers to influence the management of much larger areas accessed by those trails. While it is possible to say that llamas do not have greater erosion potential on established trails than hikers, these results should be considered together with the social implications of llama use on trails studied by Blahna et al. (1995), and in conjunction with future studies of llama impacts on campsites.

APPENDIX A

-Fold out map of study site location.

LITERATURE CITED

Beckmann, G.G., Smith, K.J. 1974. Micromorphological changes in surface soils following wetting, drying and trampling. pp 832-45 In: G.K. Rutherford ed. Soil Microscopy, Proceedings of the fourth International Working Meeting on Soil Micromorphology. Limestone Press, Kingston ONT.

Blahna, D.J., K.S. Smith, J.A. Anderson. 1995. Backcountry Llama Packing: Visitor Perceptions of Acceptability and Conflict. Liesure Sciences 17:185-204.

Bratton, S.P., M.G.Hickler, G.H. Graves. 1979. Trail Erosion Patterns in Great Smoky Mountains National Park. Environmental Management 38:119-121.

Bryan, R.B. 1969. The Relative Erodibility of Soils Developed in the Peak District of Derbyshire. Geografiska Annaler 51:145-158.

Cole, D.N. 1991. Changes on Trails in the Selway-Bitterroot Wilderness, Montana, 1978-89. Research Paper INT-450. Ogden, UT: U.S.D.A., Forest Service, Intermountain Research Station. 5p.

Dixon, R.M. 1995. Water Infiltration control at the Soil Surface: Theory and Practice. Journal of Soil and Water Conservation 50:450-453.

Dotzenko, A.D., N.T. Papamichos, D.S Romine. 1967. Effect of Recreational Use on Soil and Moisture Conditions in Rocky Mountain National Park. Journal of Soil and Water Conservation 22:196-197.

Farmer, E.E., B.P. Van Haveren. 1971. Soil Erosion by Overland Flow and Raindrop Splash on Three Mountain Soils. USDA Forest Service. Research Paper INT-100.

Gabriels, D., W.C. Moldenhauer. 1978. Size Distribution of Eroded Material from Simulated Rainfall: Effect Over a Range of Textures. Soil Science Society of America Journal 42:954-958.

Gifford, G.F. 1979. Use of the Rocky Mountain Infiltrometer and a Modular Type Infiltrometer on Rangelands in Utah. In, Proceedings of the Rainfall Simulator Workshop. Tucson, AZ. March 7-9, 1979. USDA-SEA, ARM-W-10: 141-145.

Hammitt, W.E., Cole D.N. 1987. Recreation Use and Resource Impacts. pp 1-25 In: Wildland Recreation, Ecology and Management. John Wiley and Sons. NY. 341 pp.

Hanks, R.J. 1992. Applied Soil Physics: Soil Water and Temperature Applications. (2nd ed.). Springer-Verlag. New York. 176 pp.

Harding, D.E. and D.J. Ross. 1964. Some Factors in Low Temperature Storage influencing the mineralization of Nitrogen in Soils. Journal of Science. Food and Agriculture. 15:829-832.

Harmon, D. 1989. Llama Packing: A Guide for the Low Impact Use of Llama in the Back country. Unpublished Masters Thesis, University of Montana.

Harmon D., A.S. Rubin. 1992. Llamas on the Trail, A Packers Guide. Mountain Press Publishing Company. Missoula, MT. 170 pp.

Helgath, S.F. 1975. Trail Deterioration in the Selway-Bitteroot Wilderness. U.S.D.A Forest Service. Research Note INT-193. Intermountain Forest and Range Experiment Station. Ogden, UT. 15 pp.

Johnson, M.G., R.L. Bescheta. 1980. Logging, Infiltration Capacity, and Surface Erodibility in Western Oregon. Journal of Forestry 78:334-337.

Ketchledge, E.H., R.E. Leonard. 1970. The Impact of Man on the Adirondack High Country. The Conservationist 25: 14-18.

Kleinbaum, D.G., L.L. Kupper,, K.E. Miller. 1988. Applied Regression Analysis and Other Multivariable Methods. PWS Kent Publishing Co. Boston, MA. 718 pp.

Klute, A. 1986. Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods. Soil Science Society of America, Inc. Publisher. Madison WI. 1188 pp.

Kuss, F.R. 1983. Hiking Boot Impacts on Woodland Trails. Journal of Soil and Water Conservation 38:119-121.

Lal, R. 1988. Soil Erosion Research Methods. Soil and Water Conservation Society. Ankeny, IA. 244 pp.

Lull, H.W. 1959. Soil Compaction on Forest and Range Lands. Miscellaneous Publication 768. Washington D.C.: U.S.D.A., Forest Service; 33 pp.

Manning, R.E. 1986. Studies in Outdoor Recreation. O.S.U. Press. Corvallis OR. 166 pp.

Markham, D. 1990. Llamas Are the Ultimate. Snake River Llamas. Idaho Falls, ID. 285 pp.

McClaran, M.P., Cole, D.N. 1993. Packstock in Wilderness: Use, Impacts, Monitoring, and Management. General Technical Report INT-301. Ogden, UT: USDA Forest Service, Intermountain Research Station. 33p.

Meeuwig, R.O. 1971. Soil Stability on High Elevation Rangeland in the Inter-Mountain Area. USDA Forest Service, Research Paper INT-94. Ogden Utah.

Nimlos, T.J. 1986. Soils of Lubrecht Experimental Forest. Miscellaneous Publication No. 44. Montana Forest and Conservation Experiment Station. Missoula Mt. 36 p.

National Oceanic and Atmospheric Administration. 1971-1974. Hourly Precipitation Data / Montana. United States Department of Commerce. Vols. 21-44.

Pfister, R.D., B.L. Kovalchik, S.F. Arno, R.C. Presby. 1977. Forest Habitat Types of Montana. USDA Forest Service General Technical Report INT-34. Ogden, UT.

Quansah, C. 1981. The Effect of Soil Type, Slope, Rain Intensity and Their Interactions on Splash Detachment and Transport. Journal of Soil Science 32:215-224.

Quinn, N.W., Morgan, R.P.C., Smith, A.J. Simulation of soil Erosion Induced by Human trampling. Journal of Environmental Management. 10:155-165.

Ruttimann, M., D. Schaub, V. Prasuhn, W. Ruegg. 1995. Measurement of Runoff and Soil Erosion on Regularly Cultivated Fields in Switzerland - Some Critical Considerations. Catena 25:127-139.

Satterlund, D.R. 1972. Erosion. pp. 172-189 In: Satterlund, D.R. ed. Wildland Watershed Management. Ronal Press, NY.

Schmid, G.L. 1988. A Rainfall Simulator Study of soil Erodibility in the Gallatin National Forest, South-West Montana: Unpublished M.S. Thesis. Department of Plant and Soil Science, Montana State University. Bozeman, MT. 115 pp.

Summer, R.M. 1980. Impacts 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.

United States Department of Agriculture, Soil Survey Staff. 1994. Keys to Soil Taxonomy. Pocahontas Press, Inc. Blacksburg, VA. 524pp.

Weaver, T., Dale D. 1978. Trampling Effects of Hikers, Motorcycles, and Horses in Meadows and Forests. Journal of Applied Ecology 15:451-457.

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

Wischmeier, W.H., J.V. Mannering. 1969. Relation of Soil Properties to It's erodibility. Soil Science Society of America Proceedings 33:131-137.

Young, R.A. 1979. Interpretation of Rainfall Simulator Data. In: Proceedings of the Rainfall Simulator Workshop. Seattle, WA. USDA, Forest Service, ARM-W-10, pp.108-112.

Zar, J.H. 1984. Biostatistical Analysis. Prentice-Hall Inc., Englewood Cliffs, N.J. 718pp.