



Erosional impact of hikers, horses, off-road bicycles, and motorcycles on mountain trails
by Joseph Paul Seney

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Earth Sciences

Montana State University

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Abstract:

Little is known about the erosional impacts of hikers, horses, motorcycles and off-road bicycles on mountain trails. The purpose of this investigation was to determine the relative impacts of different trail uses with respect to water runoff and sediment yield. A total of 108 sample plots were examined on existing trails in or near the Gallatin National Forest of southwestern Montana. A modified Meeuwig drip-type rainfall simulator was used to reproduce natural rainstorm events. Treatments of 100 passes were applied to each of the sample plots. This approach meant that 24 sample plots were established for each treatment type (hiking, horseback riding, motorcycling, bicycling) in addition to 12 sample plots for the control or null hypothesis case to represent two soil texture groupings (clay and sandy clay or loam and sandy loam), two antecedent soil moisture classes (dry and prewetted), and two slope gradients (0-6 percent and 8-21 percent), and three replications.

The results of this study demonstrate the interaction of topographic, soil, and geomorphic variables and the difficulty of understanding natural processes on existing trails. None of the hypothesized relationships between water runoff and slope, soil texture, antecedent soil moisture, trail roughness, and soil resistance were statistically significant. However, the multiple regression results for sediment yield were statistically significant. Five independent variables or cross-products explained 42% of the variability in sediment yield when soil texture was used as a series of indicator variables. The addition of a trail user as a second series of indicator variables explained an additional 28% of the variability in sediment yield. Ten variables combined to explain 70% of the variability in sediment yield with simple or combined variables incorporating soil texture (37%), slope (35%), user treatment (35%), and accounting for the largest contributions. The use of multiple comparison tests clarify the roles of the different trail users and in particular showed that horses and hikers (hooves and feet) made more sediment available than wheels (motorcycles and off-road bicycles). This effect was most pronounced on prewetted trails.

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A thesis submitted in partial fulfillment
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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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ABSTRACT

Little is known about the erosional impacts of hikers, horses, motorcycles and off-road bicycles on mountain trails. The purpose of this investigation was to determine the relative impacts of different trail uses with respect to water runoff and sediment yield. A total of 108 sample plots were examined on existing trails in or near the Gallatin National Forest of southwestern Montana. A modified Meeuwig drip-type rainfall simulator was used to reproduce natural rainstorm events. Treatments of 100 passes were applied to each of the sample plots. This approach meant that 24 sample plots were established for each treatment type (hiking, horseback riding, motorcycling, bicycling) in addition to 12 sample plots for the control or null hypothesis case to represent two soil texture groupings (clay and sandy clay or loam and sandy loam), two antecedent soil moisture classes (dry and prewetted), and two slope gradients (0-6 percent and 8-21 percent), and three replications.

The results of this study demonstrate the interaction of topographic, soil, and geomorphic variables and the difficulty of understanding natural processes on existing trails. None of the hypothesized relationships between water runoff and slope, soil texture, antecedent soil moisture, trail roughness, and soil resistance were statistically significant. However, the multiple regression results for sediment yield were statistically significant. Five independent variables or cross-products explained 42% of the variability in sediment yield when soil texture was used as a series of indicator variables. The addition of a trail user as a second series of indicator variables explained an additional 28% of the variability in sediment yield. Ten variables combined to explain 70% of the variability in sediment yield with simple or combined variables incorporating soil texture (37%), slope (35%), user treatment (35%), and accounting for the largest contributions. The use of multiple comparison tests clarify the roles of the different trail users and in particular showed that horses and hikers (hooves and feet) made more sediment available than wheels (motorcycles and off-road bicycles). This effect was most pronounced on prewetted trails.

CHAPTER ONE

INTRODUCTION

Scope and Purpose

The tremendous increase in outdoor recreation during the past two decades has created crowded conditions and intensified environmental impact in nature reserves, national forests and parks, and state and municipal recreation centers (McQuaid-Cook, 1978; Cole, 1989). A 1975 survey of land managers reported substantial erosion on mountain trails during the previous decade (Godin and Leonard, 1979). The erosion was attributed to dramatic increases in horse and foot travel on trails not designed to accommodate higher volumes of traffic. The National Park Service (1975) predicted that soil compaction and erosion caused by foot and horse traffic on trails would contribute the most environmental damage to trail systems in the future; however, trail use during the past ten years has grown to include off-road bicycles and motorcycles as well as horse and foot traffic. Off-road bicyclists in many cases use the same trails as hikers, horses and motorcycles, so that this additional use compounds erosional concerns and user conflicts. Intensive use of recreation areas may cause irreversible damage to trails in a short period of time as increased use reduces plant growth, destroys ground cover, and increases runoff and soil erosion (Dotzenko

et al., 1967).

Today's land managers need to assess the carrying capacities of their trail systems as they struggle to accommodate the increased numbers of users and still maintain high quality recreational experiences. The increased use and popularity of off-road bicycles during the past ten years has increased user conflicts and erosional concerns among land managers and environmental organizations (Douglas, Shovic, pers. comm., 1989). The development of pertinent studies to assess trail user impacts and conflicts will help land managers develop policies to regulate off-road bicycling and other trail uses. The results of studies comparing different trail users will allow land managers to evaluate the trail impacts of all users and differentiate the emotional and environmental arguments that are presently invoked to support and/or challenge one or more of these uses.

This study assesses the erosional impacts of hikers, horses, motorcycles, and off-road bicycles on two existing mountain trails. The study had three objectives as follows: 1) quantify the individual and combined relationships between water runoff and selected topographic and soil variables; 2) quantify the individual and combined relationships between sediment yield and selected hydrologic, topographic, and soil variables; and 3) quantify the relative impacts of different trail uses on water runoff and sediment yield.

Quantifying Trail Impacts

The durability of recreational sites is influenced by the physical and human site characteristics. Climate, terrain attributes, and soil

properties determine the physical site characteristics. The critical human site characteristics are more complicated. For example, the type and volume of use reflect the distance of the recreational site from population centers and the perceived intrinsic qualities of the site, so that sites adjacent to large population centers often experience greater levels of use. Heavy use often leads to increased user conflicts, erosional concerns, and a decrease in the perceived intrinsic qualities of recreational sites. The ability of recreational sites to tolerate recreational use is partially dependent on intensity and type of use. When the intensity of use exceeds some threshold value related to some perceived or actual human or physical site characteristic, land managers may limit the types and quantity of use or they may alter and repair recreational sites to better withstand higher intensities of use. For example, a few trails located in Yosemite National Park, California have been paved or graveled to reduce trail erosion caused by heavy use.

The choice and location of recreational sites, site construction methods, and types and intensities of use affect the quality and durability of these sites. Trail systems are necessary to provide access to recreational sites; however, the quality of a recreational experience is inevitably reduced as trail use and trail degradation increase. Past trail studies have focused on foot, horse, and motorcycle traffic. Most studies have examined the relationship between trail location, methods of trail construction, and type and frequency of use with vegetation and/or soil impacts (e.g., Bates, 1935; Dotzenko et al., 1967; Ketchledge and Leonard, 1970; Dawson et al., 1974; Helgath,

1975; Bryan, 1977; Weaver and Dale, 1978; Bratton et al., 1979; Leonard and Plumley, 1978; Summer, 1980, 1986; Coleman, 1981; Fish et al., 1981; Kuss and Morgan, 1980; Jubenville and O'Sullivan, 1987; Kuss, 1987). Other studies have attempted to model recreation-induced soil erosion effects or the physical carrying capacity of natural areas by utilizing the Universal Soil Loss Equation (e.g., Kuss and Morgan, 1980, 1984).

Alteration of the biotic environment due to trampling and subsequent trail development can be related to the resilience of an ecosystem and its carrying capacity. Burden and Randerson (1972) define carrying capacity as "the maximum intensity of use an area will continue to support under a particular management regime without inducing a permanent change in the biotic environment". Carrying capacity is a function of the physical and biological factors that influence the erosion potential of recreation sites (Kuss and Morgan, 1984).

The pressure exerted per unit area of ground per unit time integrates the effect of weight, size of impact area, length of impact and frequency of use, and may indicate recreational user impacts and rates of trail degradation (Burden and Randerson, 1972). However, information about location of frequency use is seldom available and many researchers have resorted to physical and biological variables to estimate carrying capacity and recreational impacts.

Klock and McColley (1978), for example, suggested four site factors that determine the durability of recreational sites: trafficability, depth, drainage, and erodibility. Trafficability was defined as the capacity of a soil to bear a moving load. This factor is highly

dependent on the strength of the soil which, in turn, is influenced by the texture, structure, and permeability. Soil resistance also varies with soil moisture levels through time (Lull, 1959). Travel over wet soils often increases compaction and, in turn, reduces porosity, particularly the volume of macropores (Cole, 1987). This tends to reduce water-holding capacity in fine-textured soils and increase it in coarse-textured soils. Coarse-textured soils (i.e., coarse sands) tend to resist erosion because the particles are not easily detached or moved; however, the soils are structurally unstable and trail width is easily increased. In contrast, fine-textured soils (i.e., silt and clays) are highly erodible and easy to detach and move (Cole, 1987).

Depth was defined by Klock and McColley (1978) as the amount of unconsolidated soil material above bedrock. This factor is related to the durability of recreational sites because it affects the moisture and nutrient pools available for plant growth. Hence, shallow soils are more sensitive to vegetation disturbance and more susceptible to erosion and/or trail widening once the soil is exposed.

Drainage was defined by Klock and McColley (1978) as the propensity of the soil within an area to retain groundwater. This factor is related to the durability of recreational sites because the vegetation species found in poorly drained areas usually suffer more from disturbance than the vegetation species found in well-drained areas. Trails located on poorly drained soils are usually deeper and display greater roughness than trails located on well-drained sites (Weaver and Dale, 1978).

Erodibility was defined by Klock and McColley (1978) as the

resistance of a soil to displacement by the action of wind or water. Highly erodible soils are less likely to withstand a given level of use and therefore are less durable than less erodible soils. Generally, soils with good aggregation and intermediate texture (sandy loams to loams) appear to be least erosive while silty-clay, clay, or fine-textured soils are most susceptible to wind and water erosion (Meeuwig, 1971b; Klock and McColley, 1978; Leonard and Plumley, 1978). However, other factors affect rates of wind and/or water erosion as well. Farmer and Van Haveren (1971), for example, showed that 90 percent of the variability in soil erosion was due to variations in rainfall intensity and slope gradient in their study of mountain soils in Utah and Idaho. Slope gradient and soil loss are positively correlated (Wischmeier and Smith, 1978) and steeper slopes often experience increased trail degradation (Leonard and Plumley, 1978).

Many studies have examined the impacts of foot, horse, and motorcycle recreation uses on vegetation along trails without examining the carrying capacity of recreational trails (Bates, 1935; Bayfield, 1971; Chappell et al., 1971; Burden and Randerson, 1972; Liddle and Moore, 1973; Dale and Weaver, 1974; Liddle, 1975; Liddle and Greig-Smith, 1975; Cole, 1978; Weaver and Dale, 1978; Summer, 1980). Removal of vegetation can increase direct precipitation and solar intensity along trails which, in turn, alters trailside microclimate and plant composition (Cole, 1978). Trampling or removal of vegetation is generally the first consequence of planned and unplanned trail formation (Quinn and Morgan, 1980).

By the time vegetation wear is noticed the critical period in which

accelerated erosion occurs has already passed (Quinn and Morgan, 1980). Water runoff is expected to increase in the early stages of trampling because infiltration is decreased due to increased density (compaction) of the soil (Quinn and Morgan, 1980; Cole, 1987; Kuss, 1987). Most studies show that trampling increases the bulk density of the soil which, in turn, changes soil porosity, moisture content, aeration, and the availability of soil nutrients (Baver, 1933; Liddle and Greig-Smith, 1975; Weaver and Dale, 1978; Kuss, 1983).

Once vegetation is removed erosion is the primary problem, especially where trails channel water which is not diverted from the tread (Cole, 1987). Trails located parallel to the slope channel water down the trail and increase erosion when compared to trails oriented perpendicular to the slope (Bratton, et al, 1979). Potential erosion is influenced by the position of the trail with respect to the top or bottom of a slope in addition to the gradient of the slope along and across the trail. Summer (1986), for example, examined trails in Rocky Mountain National Park in northcentral Colorado and suggested trails located below the crest of a hillslope will erode at a higher rate than trails located on other segments of the slope. The erosion potential increases exponentially as the slope gradient exceeds 12 to 13 percent (Coleman, 1981). Slope gradient is closely associated with type of landform (Helgath, 1975). Bratton et al. (1979), for example, inventoried trail degradation in Great Smokey Mountain National Park of eastern Tennessee and western North Carolina, and found that the slope of the trail was the most important factor in explaining rates of trail deterioration.

The results from other studies indicate that soil factors also influence trail degradation. Bryan (1977), for example, examined mountain hiking trails in Grovelsjon, Sweden and related the severity of degradation to soil resistance. Soil resistance was estimated from several soil properties, including aggregate stability, soil texture, and quantity of coarse fragments embedded in or on the trail. He thought that particle aggregation initially increases up to a threshold determined by the soil shearing strength when pressure is exerted on soil. Aggregation declined and soil erodibility and soil loss increased once this threshold was reached. The loose materials in or on the trail tend to counteract soil compaction and increase resistance during the early stages of trail degradation. However, coarse fragments promote erosion by increasing the turbulence and erosive capacity of trail runoff when trail use continues because loose materials saltate along the trail corradng the trail bed and undermining trail sides (Bryan, 1977).

In contrast to the previous group of studies which focused on natural processes and controls, a smaller group (Ketchledge and Leonard, 1970; Dale and Weaver, 1974; Helgath, 1975; Weaver and Dale, 1978; Bratton, 1979; Burde and Renfro, 1986) has examined the relationships between topographic and soil variables and the impacts of foot, horse, and motorcycle traffic on trails. These studies show that different trail uses result in different trail erosion rates, probably because different users exert different impacts per unit area (Lull, 1959). The impact per unit area combines the weight of the user and size of the impact area or "foot print" of the user. Weaver and Dale (1978), for

example, found that horse use caused more pronounced increases in trail width, depth, litter, and soil compaction than hiking and motorcycling. Horse traffic applies the greatest impact (force) per unit area among hikers, horseback riders, off-road bicyclists, and motorcyclists.

Weaver and Dale (1978) also compared motorcycle erosion with horse and foot erosion and found that motorcycles moving uphill established a narrow rut which served as a funnel and increased the velocity and sediment transport capacity of trail runoff. The development of a linear channel was the direct result of the imprint of the tire and the torque applied by the motorcyclist which, in turn, led to increased erosion. However, motorcycles moving downhill, when torque is not needed, did not greatly affect the rate of trail degradation. In contrast to motorcyclists, hikers and horses do not rely on the same forces to decelerate. Hikers and horses tend to loosen soil when descending a steep trail; hence, greater forces were applied when decelerating and moving down a steep trail. Shear stresses are increased and compressional stresses are reduced on steeper slopes which increases the quantities of loose sediment available for transport (Quinn and Morgan, 1980). Weaver and Dale (1978) suggested motorcycles ascend gentle slopes and descend steep slopes and hikers and horses ascend steep slopes and descend gentle slopes to minimize erosional impacts.

The studies referred to above have important implications for this project, even though they do not examine erosion from off-road bicycles nor refer to existing trails in many cases. In particular, they demonstrate the importance of rainfall intensity and slope gradient as

key factors in explaining variation in sediment yield. Soil properties, such as structure, texture, and moisture content determine the resistance to erosion and play secondary roles. The variety of results from past studies exemplify the difficulty of understanding the natural variability of trail degradation. Several studies show trail degradation occurs regardless of specific uses and is more dependent on the geomorphic processes that occur in different landscapes; however, most studies to date have focused on one particular trail use.

The approach of this study was different because an attempt was made to superimpose human impacts on the "natural" factors that influence trail erosion. This approach was needed to evaluate the relative impacts of different trail uses. Few other studies reported in the literature to date have attempted this type of analysis.

Description of Study Area

Two existing trails near Bozeman, Montana were selected as study sites for this project because of ease of access, availability of water from adjacent streams, long consistent sections of trail, and a diversity of slope gradients and soil textures. Both trails, the Emerald Lake trail located 39 km south and the New World Gulch trail located 12 km southeast of Bozeman, Montana (population approximately 30,000) are easily accessible and have experienced all four types of use (foot, horse, motorcycle and off-road bicycle traffic) over the past ten years (Figure 1).

Both study sites were located in or near the Gallatin National Forest, Montana (45°30'N, 111°W) which borders the northern and western

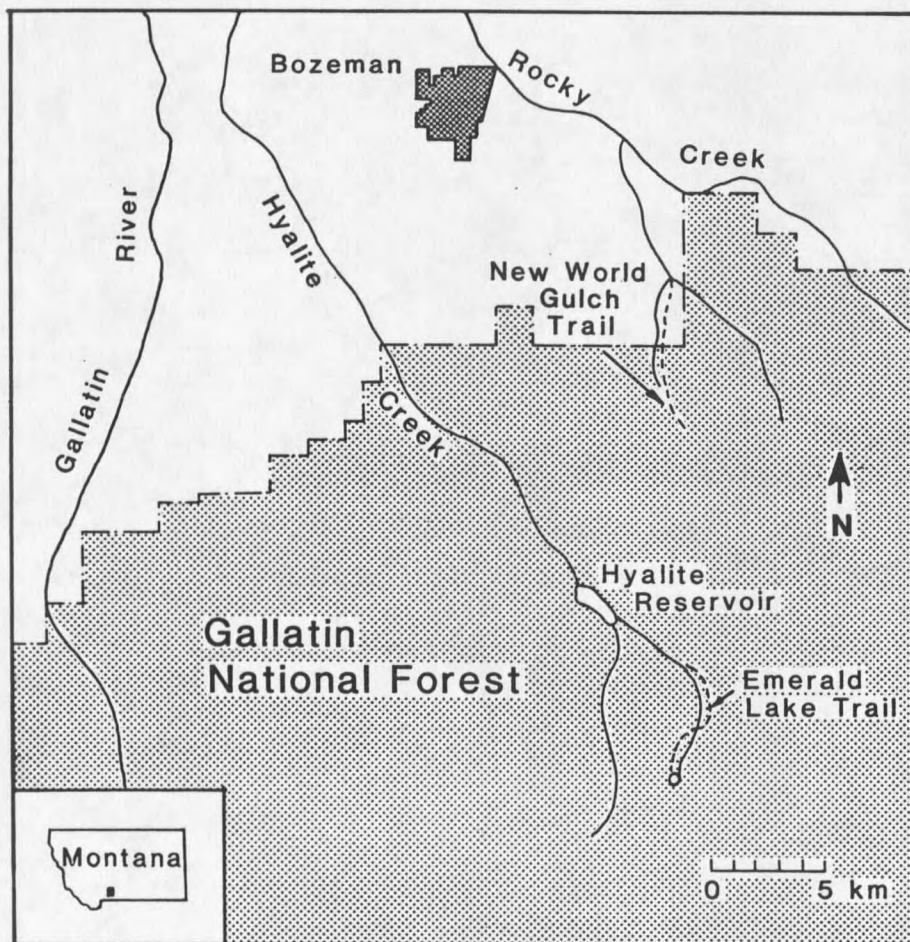


Figure 1. Location of Emerald Lake and New World Gulch trails.

boundaries of Yellowstone National Park. The topography within this forest ranges from forested foothills to rugged rocky alpine peaks. The forests consist mainly of lodgepole pine (*Pinus contorta*) and Douglas fir (*Pseudotsuga menziesii*), with a variety of other species occupying smaller and more specific niches. Approximately 500 km of trails provide recreational opportunities for the four user groups examined in this project. The characteristics of both trails are summarized in Table 1.

The Emerald Lake trail study site was located within the Gallatin National Forest and consisted of a 1.6 km section of trail at an

Table 1. Study site characteristics.

| Characteristics | Emerald Lake Trail | New World Gulch Trail |
|------------------|--------------------|-----------------------|
| Parent material | Glacial till | Sandstone, shale |
| Soil texture | Sandy loam, loam | Clay, sandy clay |
| Elevation | 2000 m | 1600 m |
| Slope (on trail) | 3-17% | 2-21% |
| Aspect | Northeast | North |
| Vegetation | Lodgepole pine | Grasses, Douglas-fir |

approximate elevation of 2000 m. The land surface consists of hummocky, rolling glacial till deposits. The morainal deposits at this study site occupy the bottom of a U-shaped valley. The parent material consists of glacial till deposits of Pleistocene age and are primarily derived from layered, volcanic rock (Davis and Shovic, 1984). These medium-textured deposits contain variable amounts of subrounded rock fragments.

Soils are generally well-drained with medium to moderate textures. Subsoil clay accumulation occurs in some locations. Rock fragments in the lower soil horizons range from 35-50 percent. The soils within the study site are classified as mixed, loamy skeletal, Typic Cryoboralfs (Davis and Shovic, 1984).

A dense lodgepole pine (Pinus contorta) forest surrounds this study site. The understory is composed of a thick groundcover of grouse whortleberry (Vaccinium scoparium), dwarf huckleberry (Vaccinium

caespitosum), and twinflower (Linnaea borealis). The annual precipitation in this area is 65-90 cm and 60 percent falls as snow. Trail accessibility in April and May is limited by the remaining snowpack and saturated surface soils. Peak runoff from the nearby stream usually occurs in late April and early May (Davis and Shovic, 1984).

The New World Gulch trail study site was located on land immediately outside the Gallatin National Forest administered by the State of Montana and consisted of a 0.8 km section of trail at an approximate elevation of 1600 meters. The topography consists of ridges with steep slopes and occasional small valleys or swales (Davis and Shovic, 1984). The locations of ridges and swales are controlled by the underlying bedrock, with the more resistant sandstones and limestones forming ridges and shales and siltstones forming swales and valleys. The bedrock of this area consists of Lower Cretaceous Mowry and Thermopolis shale, Kootenai Formation sandstone and mudstone, and Jurassic Morrison Formation shale, siltstone and mudstone (Roberts, 1964).

Fine- and medium-textured soils have formed in material weathered from thickly bedded sandstones and shales. The soils are classified as mixed, fine loamy Typic Cryoboralfs (Davis and Shovic, 1984). Overall, soils in this area are moderately well-drained with fine and medium textures.

Vegetation surrounding this trail consists predominantly of perennial grasses and some Douglas-fir (Pseudotsuga menziesii). The annual precipitation is similar to the first trail (65-90 cm with 60 percent falling as snow). Trail accessibility between April-May and

October-November is restricted due to saturation of the predominantly clayey soils.

CHAPTER TWO

METHODS

The first two objectives of this research were concerned with the natural variability and geomorphic controls operating on the sections of trails used in the study. The relationships between water runoff and sediment yield, and selected hydrologic, topographic, and soil variables were examined. The third and final objective sought to superimpose human impacts on these geomorphic controls in an attempt to evaluate the relative impacts of different trail uses. This chapter describes the methods used for data collection and analysis.

Study Design and Site Selection

A modified Meeuwig drip-type rainfall simulator was used to reproduce natural rainstorm events and treatments of 100 passes were applied to a total of 108 sample plots on the Emerald Lake and New World Gulch trails. There were 54 sample plots on each of the Emerald Lake and New World Gulch trails consisting of 12 sample plots for each mode of travel (hiking, off-road bicycling, horseback riding, and motorcycling treatment plots) and six sample plots for the control or null treatment case. The twelve sample plots for each mode of travel represented two antecedent soil moisture classes (dry and pre-wetted), two slope gradient classes (0-6 and 8-21 percent), and three

replications for each plot type. The control or null treatment plots combined the two antecedent soil moisture regimes, requiring only six plots.

Sample plot size (66 by 66 cm) was determined by the size of the containment tray that came with the rainfall simulator. Locations of sample plots were determined on reconnaissance hikes along the Emerald Lake and New World Gulch trails in the spring of 1989. Trail sections with uniform slope and soil conditions were selected for study plots, avoiding sections of trail with protruding rocks or roots, where necessary litter and large loose stones were removed from the sample plots before treatments.

Soil Description and Classification

Soil pits were dug adjacent to each trail segment and the Keys to Soil Taxonomy (Soil Survey Staff, 1988) were used to describe and classify the soils. A total of four shallow pits were dug across sections of trail to compare soils on and off the trail.

Field Experiments and Measurements

User treatments were assigned to sample plots based on the availability of the user (hikers, horses, motorcycle and rider, mountain bike and rider), antecedent soil moisture, slope gradient class needed for the particular user (0-6 or 8-21 percent), and daily weather. Afternoon thundershowers reduced the number of experiments conducted on certain days. Four plots were examined on most field days, although six plots were examined on days with good weather and dry treatments.

Data collection consisted of the seven tasks summarized in Table 2. Slope gradient, trail roughness, and soil resistance were measured prior to treatment for each sample plot during Task 1. Slope gradient was measured with a Brunton compass and 3 by 0.6 m board. The 3 m board was placed on the trail and several slope measurements were taken with the Brunton compass on the board to determine the slope gradient along specific sections of trail. Trail roughness or micro-relief was measured using 12 transects marked off at 2.54 cm intervals along each sample plot and a 91.5 cm long, 5 by 10 cm board with 13 evenly spaced slots. A metal ruler was then inserted into each slot moving left to right and a depth measurement was taken for each of the 13 slots (Figure 2). High values represented depressions and low values elevated spots on the trail.

Soil resistance was measured at selected points along transects with a Soiltest, Inc. CN-970 proving ring penetrometer. Hence, soil resistance was treated as a measure of the force required to penetrate to a depth of 2.54 cm. The proving ring penetrometer is a cone type penetrometer which measures the penetration resistance of soils. The instrument consists of a T-handle, 45.7 cm penetration rod, 0.91 m extension, proving ring of 113.4 kg capacity with a dial indicator, and removable cone point (Figure 3).

The cone point used in this study had a base area of 6.34 cm^2 and conical area of 24.69 cm^2 . When the cone is forced into the ground, the proving ring is deformed in proportion to the force applied. This force is thought to represent the shearing resistance of the soil (Liddle and Moore, 1973). The cone penetration was limited to one-half of the area

Table 2. Schedule of data collection activities.

| Task | Summary of data collection activities |
|--|---|
| 1 | Collection of soil samples for soil texture and antecedent soil moisture measurements; slope, trail roughness and soil resistance measurements were taken. |
| <u>Skip tasks 2 and 3 for dry treatment plots.</u> | |
| 2. | Meeuwig rainfall simulator was erected over the plot and a 20 minute rainstorm with an intensity of 127 mm hr ⁻¹ was applied. |
| 3. | Water runoff and sediment yield were collected; soil samples were taken for subsequent soil moisture measurements; and trail roughness and soil resistance were measured (again). |
| <u>Conduct tasks 4 through 7 on all plots.</u> | |
| 4. | Treatments were applied (i.e., 50 hiking, bicycling, horseback riding and motorcycling passes); trail roughness and soil resistance were measured (again). |
| 5. | Treatments were applied (i.e., an additional 50 hiking, bicycling horseback and motorcycling passes); trail roughness and soil resistance were measured (again). |
| 6. | Meeuwig rainfall simulator was erected over the plot and a 20 minute rainstorm with an intensity of 127 mm h ⁻¹ was applied. |
| 7. | Water runoff and sediment yield were collected; soil samples were taken for subsequent soil moisture measurements; and trail roughness and soil resistance were measured (again). |

of the cone; hence, the range values on the indicator dial could have been doubled to reflect the smaller base area. These values were not doubled because they were only used for relative comparisons between types of trail use, so that the measurement scale was not of prime importance. Soil resistance values are expressed in kg of force per cm²

