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Source: *Mountain Research and Development*, Vol. 14, No. 1 (Feb., 1994), pp. 77-88
Published by: International Mountain Society
Stable URL: http://www.jstor.org/stable/3673739

MOUNTAIN RESEARCH AND DEVELOPMENT, VOL. 14, NO. 1, 1994, PP. 77-88

EROSIONAL IMPACT OF HIKERS, HORSES, MOTORCYCLES, AND OFF-ROAD BICYCLES ON MOUNTAIN TRAILS IN MONTANA

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ABSTRACT This study examined the relative impact of hikers, horses, motorcycles, and off-road bicycles in terms of water runoff and sediment yield from 108 sample plots on existing trails in or near Gallatin National Forest, Montana. A modified Meeuwig drip-type rainfall simulator was used to reproduce natural rainstorm events. Treatments of 100 passes were applied to each plot. The results confirmed the complex interactions that occur between topographic, soil, and geomorphic variables noted by others, and the difficulty of interpreting their impact on existing trails. None of the hypothesized relationships between water runoff and slope, soil texture, antecedent soil moisture, trail roughness, and soil resistance was statistically significant. Five independent variables or cross-products explained 42% of the variability in sediment yield when soil texture was added as a series of indicator variables. Ten variables combined to explain 70% of the variability in sediment yield when trail user was added as a second series of indicator variables. Terms incorporating soil texture (37%), slope (35%), and user treatment (35%) accounted for the largest contributions. Multiple comparisons test results showed that horses and hikers (hooves and feet) made more sediment available than wheels (motorcycles and off-road bicycles) and that this effect was most pronounced on prewetted trails.

RÉSUMÉ *Impact érosif des randonneurs à pied, des chevaux, des motocyclettes et bicyclettes tous-terrains, sur les sentiers de montagne du Montana.* Cette étude examine l'impact relatif des randonneurs à pied, des chevaux, des motocyclettes et bicyclettes tous-terrains, en termes de ruissellement d'eau et de production de sédiments sur 108 parcelles échantillons de sentiers de montagne situées à l'intérieur ou au voisinage de la forêt nationale de Gallantin, dans l'état du Montana. Un simulateur de pluies de Meeuwig modifié, type dégouttement, a été utilisé pour reproduire des tempêtes de pluie naturelles. Les traitements de 100 passes ont été appliqués à chaque parcelle. Les résultats confirment les interactions complexes entre les variables topographiques, édaphiques et géomorphiques qui avaient été observées par d'autres chercheurs, et la difficulté d'interpréter leur impact sur les sentiers de montagne existants. Aucune des supposées relations entre le ruissellement d'eau et la pente, la texture du sol, l'humidité antérieure, l'inégalité du sentier et la résistance du sol n'est statistiquement significative. Cinq variables indépendantes ou produits en croix expliquent 42 pour cent de la variabilité de la production de sédiments lorsque la texture du sol est ajoutée en tant que série de variables indicatrices. Dix variables se combinent pour expliquer 70 pour cent de la variabilité de la production de sédiments lorsque l'utilisateur du sentier est ajouté en tant que seconde série de variables indicatrices. Les termes incorporant la texture du sol (37 pour cent), la pente (35 pour cent) et le traitement par l'utilisateur (35 pour cent) rendent compte des contributions les plus importantes. Des comparaisons multiples des résultats de tests indiquent que les chevaux et les randonneurs (sabots et chaussures) produisent plus de sédiments que les motocyclettes et bicyclettes tous-terrains (roues) et que cet effet est plus prononcé sur les sentiers déjà humides.

ZUSAMMENFASSUNG *Erosion auf Bergpfaden in Montana verursacht durch Wanderer, Pferde, Motor- und Geländefahrräder.* Diese Studie untersucht an 108 verschiedenen Teststellen in oder nahe dem Gallatin National Forest, Montana, Nutzungsbelastungen auf Bergpfaden anhand von Abfluß und Sedimentfreigabe. Ein abgänderter Meeuwig Tropfensimulator wurde benutzt, um natürlichen Regen zu imitieren. Jede Stelle wurde 100 mal belastet. Die Ergebnisse bestätigen komplexe Wechselwirkungen zwischen topographischen, bodenbedingten und geomorphischen Variablen. Dies und die Schwierigkeit, ihre Einwirkungen auf bestehende Bergpfade zu erklären, wurde bereits von anderer Seite festgestellt. Keine der angenommenen Beziehungen zwischen Abfluß und Hangneigung, Bodenstruktur, vorhandener Bodenfeuchte, Wegoberfläche und Bodenwiderstand waren statistisch bedeutsam. Fünf unabhängige Größen oder ihre Crossprodukte erklärten 42% der Variabilitat des Sedimentertrages, wenn man die Bodenstruktur in die Reihe der Anzeigevariablen einschloß. Insgesamt zehn Variablen erklärten 70% der unterschiedlichen Sedimentfreigabe, wenn die Wegbenutzung als zweite Größe einbeschlossen wurde. Die größten Beiträge lieferte die Berücksichtigung der Bodenstruktur (37%), Hangneigung (35%) und Nutzungsart (35%). Vergleicht man viele Testresultate, dann zeigt sich, daß Pferde und Wanderer (Huf- und Trittbelastung) mehr Sediment freisetzen als Räder (Motor- und Geländefahrräder) und dies war auf nassen Wegen besonders auffällig.

INTRODUCTION

The tremendous increase in outdoor recreation during the past two decades has created crowded conditions and increased environmental impact in national forests and parks and other recreation areas (McQuaid-Cook, 1978; Cole, 1989). A 1975 survey of land managers reported substantial erosion on mountain trails during the previous decade that was attributed to dramatic increases in horse and foot travel on trails not designed to accommodate higher volumes of traffic (Godin and Leonard, 1979). Traffic has increased further during the past

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fifteen years as trail use has grown to include motorcycles and off-road bicycles in addition to horse and foot traffic.

Today's land managers need to assess the carrying capacities of their trail systems as they struggle to build and maintain trails that can accommodate the increased types and numbers of users. The recent popularity of off-road bicycles in particular has increased user conflicts and erosional concerns among land managers and environmental organizations (Jacoby, 1990). Land managers must evaluate the trail impacts of all users and differentiate the emotional and environmental arguments that are invoked to support and/or challenge one or more of these uses. These conflicts emphasize the need for research that: (1) develops tools to estimate the carrying capacities of trail systems, and (2) compares the impacts of different trail users.

Most of the trail studies to date have examined either the natural processes and controls that influence trail condition and/or the relationships between specific uses and impacts (e.g., Bates, 1935; Dotzenko *et al.*, 1967; Dawson *et al.*, 1974; Helgath, 1975; Bryan, 1977; Cole, 1978; Kuss and Morgan, 1980, 1984; Summer, 1980, 1986; Coleman, 1981; Fish *et al.*, 1981; Kuss, 1986; Jubenville and O'Sullivan, 1987; Hall and Kuss, 1989; Kuss and Hall, 1991). Trampling and removal of vegetation are generally the first consequences of trail formation. Trampling often increases the bulk density of the soil which, in turn, decreases soil porosity and changes moisture content, aeration, and the availability of soil nutrients in ways that contribute to further losses of existing vegetation along trails (Liddle and Greig-Smith, 1975; Weaver and Dale, 1978; Kuss, 1983; Hall and Kuss, 1989; Kuss and Hall, 1991).

Accelerated soil erosion becomes the primary problem once the vegetation is lost, especially where trails channel water which is not diverted from the tread (Cole, 1987). Slope gradient and soil loss are positively correlated (Wischmeier and Smith, 1978; Leonard and Plumley, 1978; Coleman, 1981). Slope gradient, in turn, is closely associated with type of landform (Helgath, 1975). Trails that follow the slope channel water down the trail and increase erosion compared to trails running across the slope (Bratton *et al.*, 1979). The erosion rate is also influenced by the position of the trail with respect to the top or bottom of a slope and the gradient of the slope along and across the trail. Summer (1986), for example, found that trails located below the crests of hillslopes in Rocky Mountain National Park, Colorado, had more erosion than trails located on other parts of the slope.

Another smaller group of studies has examined the differences in the impacts of foot, horse, and motorcycle traffic on trails (e.g., Ketchledge and Leonard, 1970; Dale and Weaver, 1974; Liddle, 1975; Helgath, 1975; Weaver and Dale, 1978; Bratton *et al.*, 1979; Kuss, 1983; Burde and Renfro, 1986). These studies show that different trail uses result in different erosion rates, presumably because different users exert different forces. Weaver and Dale (1978) found that horses caused greater increases in soil compaction, litter, trail width and depth compared to hikers and motorcycles. Horse traffic applies the greatest force (weight 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. Motorcycles moving uphill established a narrow rut which increased the velocity and sediment transport capacity of trail runoff. The development of this linear channel was the direct result of the imprint of the tire and the torque applied by the motorcycle which then led to increased erosion. However, motorcycles moving downhill, when torque is not needed, caused less erosion than hikers and horses which tend to loosen soil when descending a steep trail because greater forces are applied when decelerating and moving down a steep trail. Shear stresses are increased and compressional stresses are reduced on steeper slopes and this increases the quantities of loose sediment available for transport (Quinn *et al.*, 1980). Weaver and Dale (1978) suggested that motorcycles ascend gentle slopes and descend steep slopes and hikers/horses ascend steep slopes and descend gentle slopes to minimize erosional impacts.

The studies referred to above have important implications for this project, although the majority of these studies did not examine erosion along existing trails or from off-road bicycles. In particular, their results indicate: (1) the importance of rainfall intensity and slope gradient as key factors in explaining variations in soil loss on trails, and (2) that soil properties such as structure, texture, and moisture content determine the resistance to erosion and play secondary roles. Overall, these studies demonstrate the difficulty of quantifying relationships between natural variability, recreation activities, and trail degradation rates. Although several studies show trail degradation occurs regardless of specific uses and is more dependent on the geomorphic processes that occur in different landscapes, most studies to date have focused on specific trail segments or plots and on only one type of trail use.

Trail systems in national and state forests and parks weave their way through many different bedrock types, slope gradients, aspects, soils, and habitat types. Management of these trail systems requires knowledge of how people affect the environment at landscape scales in addition to knowledge of how human activities affect randomly selected sample plots and other microenvironments. Applying the results of the site-specific studies cited above to landscapes is problematic (Cole, 1987), although Helgath (1975) and Kuss and Morgan (1980, 1984) have proposed methodologies to anticipate and cope with the challenges of extending site-specific results to broader areas. Helgath (1975) suggested an index system based on "biophysical" units which would divide landforms and vegetation habitats into homogeneous environments. Each unit would have a specific potential for deterioration attached to it such that managers could strive to avoid those units where the erosive potential is high. Kuss and Morgan (1980) and Morgan and Kuss (1986) proposed using the Universal Soil Loss Equation (USLE) to estimate the carrying capacity of hiking trails. The equation, as modified by Kuss and Morgan, is written as T = RKLSC. The maximum rate of soil erosion that will permit the productivity of the land to be sustained economically and indefinitely is represented by T and calculated in terms of rainfall (R), soil erodibility (K), slope gradient (S), slope length (L), and type and extent of vegetational cover (C). Kuss and Morgan (1980, 1984) argued that this modified USLE model would help the land manager to determine when the conditions warranted measures to prevent further erosion.

The approach of this study was different because an attempt was made to separate the user effects from the natural effects. The study had three objectives: (1) quantify the relationships between water runoff and selected topographic and soil variables; (2) quantify the relationships between sediment yield and selected hydrologic, topographic, and soil variables; and (3) quantify the relative impacts of different trail uses in terms of water runoff and sediment yield on two existing mountain trails. The results not only provide new information about the relative erosional impacts of low numbers of hikers, horses, motorcycles, and off-road bicycles on existing trails traversing a variety of slopes and soils, but they also show why a simple statistical model such as the USLE should not be used to measure the carrying capacity of these trails systems.

DESCRIPTION OF STUDY AREA

Two existing trails near Bozeman, Montana were selected as study sites based on ease of access, availability of water from adjacent streams, long consistent sections of trail, and a diversity of slope gradients and soil textures (Figure 1). Both trails have experienced all four types of use (foot, horse, motorcycle, and off-road bicycle traffic) over the past ten years. The study sites were located in or near Gallatin National Forest, and were dominated by lodgepole pine (*Pinus contorta*) and Douglas Fir (*Pseudotsuga menziesii*) with a variety of other species occupying smaller, mostly mesic sites.

The Emerald Lake study site consisted of a 1.6 km section of trail in Gallatin National Forest. The land surface (2,000 m elevation) consists of hummocky, rolling glacial till deposits of Pleistocene age derived from layered, volcanic rock at the bottom of a U-shaped valley. These medium-textured deposits contain variable amounts of sub-rounded rock fragments and the sandy loam or loam soils are generally well-drained. Subsoil clay accumulation occurs in some locations and rock fragments in the lower soil horizons range from 35-50 percent. The soils are classified as mixed, loamy skeletal, Typic Cryoboralfs (Davis and Shovic, 1984). A dense lodgepole pine 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 is 65–90 cm and 60 percent falls as snow. Trail access for horses, hikers, motorcycles, and off-road bicycles is limited prior to May or June by the remnant snowpack and saturated surface soils.

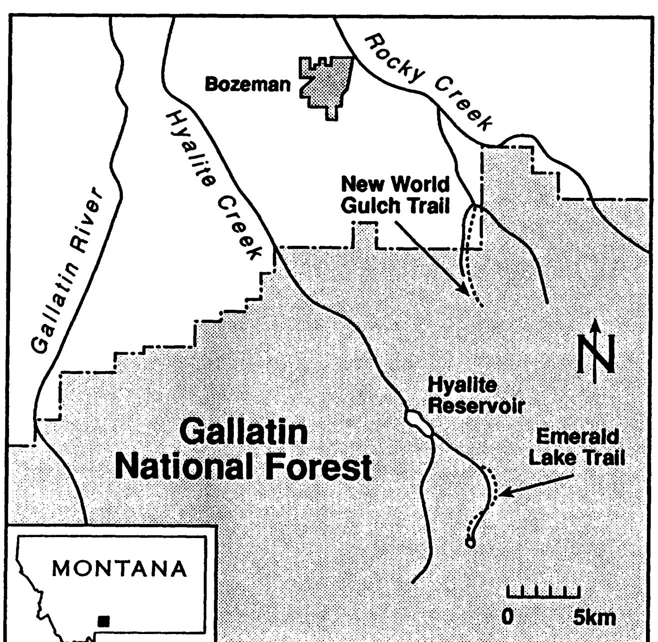

FIGURE 1. Location Map for Emerald Lake and New World Gulch Trails. The plots used for the experiments were located on relatively uniform sections of the trails shown on this map.

The New World Gulch study site was located on land immediately outside Gallatin National Forest administered by the State of Montana and consisted of a 0.8 km section of trail (1,600 m elevation). The topography consists of ridges with steep slopes and occasional small valleys or swales (Davis and Shovic, 1984). The location of ridges and swales is controlled by the underlying bedrock, with the more resistant sandstones and limestones forming ridges and shales and siltstones forming valleys. The bedrock consists of Lower Cretaceous Mowry and Thermopolis shale, Kootenai Formation sandstone and mudstone, and Jurassic Morrison Formation shale, siltstone, and mudstone (Roberts, 1964). Clay and clay loam soils have formed in material weathered from thickly-bedded sandstones and shales. The soils are moderately well-drained and classified as mixed, fine loamy Typic Cryoboralfs (Davis and Shovic, 1984). Vegetation surrounding this trail consists of perennial grasses and some Douglas Fir. This site also receives approximately 65-90 cm of precipitation and 60% falls as snow. Accessibility for horses, hikers, motorcycles, and off-road bicycles is limited in October-November and April-May due to the saturation of the predominantly clayey soils.

METHODS AND PROCEDURES

A modified Meeuwig drip-type rainfall simulator (Meeuwig, 1971a, 1971b) was used to reproduce natural rainstorm events. Treatments of 100 passes were applied to 54 sample plots located on each of the trails. The 12 sample plots used for each mode of travel represented two antecedent soil moisture conditions (dry and prewetted) and two slope gradient classes (0–6 and 8–21 percent) with three replications. The no treatment (control) case combined both antecedent soil moisture conditions and required only six plots.

Sample plot size (66 by 66 cm) was determined by the size of the containment tray for the rainfall simulator. Trail sections with uniform slope and soil conditions were selected for study plots from reconnaissance hikes along both trails in the spring of 1989. Trail sections with protruding rocks or roots were avoided, and litter and loose stones were removed prior to the treatments. Soil pits were dug adjacent to and across each trail section prior to the field experiments and the Keys to Soil Taxonomy (Soil Survey Staff, 1988) was used to describe and classify the soils.

FIELD EXPERIMENTS AND MEASUREMENTS

User treatments were assigned to sample plots based on the availability of the user (hiker, horse and rider, Honda XL125 motorcycle and rider, mountain bike and rider) and the antecedent soil moisture and slope gradient conditions needed for each experiment. Four-to-six experiments consisting of the tasks summarized in Table 1 were completed each field day.

Slope gradient, trail roughness, and soil resistance were measured prior to the treatments (Task 1). Slope gradient was measured with a Brunton compass and a 3.0 by 0.6 m board placed 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 the depth was measured. High values represented depressions and low values high spots on the trail. The variance was computed and treated as trail roughness. Soil resistance was measured at 11 points along two transects with a Soiltest, Inc. CN-970 proving ring penetrometer. This cone-type penetrometer 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 (basal area 6.34 cm^2, conical area 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 of the cone (12.35 cm^2) because the measurements were used only for relative comparisons between trail users.

Soil samples were also taken prior to each experiment for laboratory texture and moisture determinations (Task 1). Further soil moisture samples were taken after the rainfall events that constituted the second and sixth tasks. Trail roughness and soil resistance measurements also were taken as part of the third, fourth, fifth, and seventh tasks. Different pairs of transects were used for each set of soil resistance measurements.

The second task consisted of no activity for dry treatments and a rainstorm if the treatment was to be applied to a prewetted plot. The rainfall simulator was erected over the plot and a 20-minute rainstorm with a constant intensity of 127 mm hr^{1} was applied. The modified Meeuwig simulator used in the study had a 61 by 61 by 2.5 cm plexiglass water chamber with 500 drip needles made from hypodermic tubing. An electric motor was used to rotate the chamber to randomize the raindrops and a 18.9-liter plastic container was elevated 20 cm above the water chamber to provide a continuous supply of water. The Meeuwig simulator was chosen because of its easy assembly and modest water requirements, although its small size (155 cm drop fall height) meant that the kinetic energy of the simulated rainfall events was roughly one-third that of natural rainstorms (Schmid, 1988).

The third and seventh tasks listed in Table 1 included the collection of the surface runoff and sediment yield produced by the simulated rainstorms at the downslope end of each plot. A collection tray which funneled water and sediment into 0.76-liter plastic containers was used and the contents were emptied into larger 3.8-liter containers for transport back to the laboratory.

The application of the appropriate bicycling, hiking, horseback riding, and motorcycling treatments consisted

TABLE 1

Data collection activities

1	Soil samples collected for laboratory texture and antecedent soil moisture measurements; slope gradient, trail roughness and soil resistance measurements taken.
	Tasks 2 and 3 skipped for dry treatment plots
2	Meeuwig rainfall simulator erected over plot and 20 minute, 127 mm hr^{-1} rainstorm applied.
3	Water runoff and sediment yield collected; soil samples taken for laboratory soil moisture measurements; trail roughness and soil resistance measured (again).
	Tasks 4 through 7 completed for all plots
4	First 50 bicycle, hiker, horse, and motorcycle passes applied; trail roughness and soil resistance measured (again).
5	Second 50 bicycle, hiker, horse, and motorcycle passes applied; trail roughness and soil resistance measured (again).
6	Meeuwig rainfall simulator erected over plot and 20 minute, 127 mm h^{-1} rainstorm applied.
7	Water runoff and sediment yield collected; soil samples taken for laboratory soil moisture measurements; trail roughness and soil resistance measured (again).

TABLE 2
Sediment yield multiple regression results (without trail user)

Variable	Parameter estimate	Partial R^2	Model R^2	Prob > F	F
Intercept	30.64			0.0001	29.11
Slope × clay[1]	5.79	0.18	0.18	0.0001	15.85
TR × sandy clay[2]	0.20	0.17	0.35	0.0001	48.53
Slope	1.49	0.04	0.39	0.0055	7.91
TR × clay[3]	0.23	0.02	0.41	0.0231	5.26
SM × loam[4]	0.39	0.01	0.42	0.0411	4.24

[1]Slope × clay represents the slope continuous variable and clay indicator variable cross-product.
[2]TR × sandy clay represents the antecedent trail roughness continuous variable and sandy clay indicator variable cross-product.
[3]TR × clay represents the antecedent trail roughness continuous variable and clay indicator variable cross-product.
[4]SM × loam represents the antecedent soil moisture continuous variable and loam indicator variable cross-product.

of two sets of 50 passes so that soil resistance and trail roughness could be measured after 50 and 100 passes (Tasks 4 and 5). Passes of at least 4 m in length were made so that users could mimic a "natural" trail gait.

LABORATORY PROCEDURES

The soil moisture, soil texture, water runoff, and sediment yield samples were analyzed at Montana State University's Soil Testing Laboratory. The soil texture samples taken from each plot (Task 1) were hand-textured using the method described by Thien (1979). Wet soil moisture samples were weighed, oven-dried for 24 hours at 110°C, and then reweighed. Percent soil moisture equaled moist soil weight minus dry soil weight divided by dry soil weight. The water runoff samples were weighed using a Mettler PE 6000 digital scale, placed in a soil drying room (18°C) until all the water had evaporated from the containers, and then reweighed. Twenty-five 3.8-liter containers were weighed to determine the average weight of the containers, and this weight was subtracted from the dry sediment and container weights to determine sediment and water runoff masses.

STATISTICAL METHODS

Two statistical tests were used to examine the erosional impacts of the different trail users. Bivariate and multiple regression models were used to quantify relationships between the topographic and soil variables (independent variables), water runoff, and sediment yield (dependent variables). Human impacts were superimposed on these natural controls and the multiple comparisons test was then used to evaluate the relative impacts of different trail users.

The REG (regression) module in SAS (Freund and Littell, 1986) was used to develop bivariate and multiple regression models. The bivariate models compared water runoff and sediment yield with slope gradient (X_1), antecedent soil moisture (X_2), trail roughness (X_3), soil resistance (X_4) and water runoff (X_5) (when sediment yield was treated as the dependent variable). The multiple regression models were built in three stages. The first model incorporated the five continuous variables used for the bivariate models. The second and third models incorporated these same continuous variables and indicator variables for soil texture and trail user, respectively.

Three soil texture indicator variables and fifteen cross-product variables representing the interaction effects between these indicator variables and the five continuous variables tried in the first model were added to the second regression model. The inclusion of the indicator variables divided the entire data set into four soil textural classes or subgroups representing clay, sandy clay, loam, and sandy loam soils. The three indicator variables were added such that X_6=1 for clay soils and 0 in all other cases, X_7=1 for sandy clay soils and 0 in all other cases, and X_8=1 for loam soils and 0 in all other cases. The plots with sandy loam soil textures were represented by the default case in which X_6=X_7=X_8=0. This choice was arbitrary (i.e., one of the other texture groups could have served as the default case), although it did mean that the coefficients for the terms incorporating the other indicator variables were computed relative to the sandy loam texture reference group.

Overall, the inclusion of the indicator variables and interaction terms meant that different regression models were prepared for each soil texture class. The coefficients computed with this type of regression model are often referred to as shift coefficients because they permit the coefficients to change or shift from one class to the next. The multicollinearity problems sometimes encountered with this approach were minimized by running the model with all the possibilities (i.e., the 5 continuous variables, 3 indicator variables, and 15 interaction variables), deleting the non-significant terms, and running the model again. The stepwise option was used with the REG procedure and 0.05 significance level to select the variables included in the final regression model reproduced in Table 2.

The addition of a second series of indicator variables representing five trail user classes or subgroups (hiker, horse, motorcycle, off-road bicycle, and null treatment cases) was accomplished with the third multiple regression model. Four indicator variables were added such that X_9=1 for hikers and 0 in all other cases, X_{10}=1 for horses

TABLE 3
Sediment yield multiple regression results (with trail user)

Variable	Parameter estimate	Partial R^2	Model R^2	Prob > F	F
Intercept	29.33			0.0001	46.96
Slope[1]	1.72	0.18	0.18	0.0001	15.01
Slope × horse[2]	2.18	0.15	0.33	0.0001	16.81
TR × clay[3]	0.21	0.13	0.46	0.0001	77.74
Water runoff × sandy clay × horse[4]	0.15	0.05	0.51	0.0001	20.66
Water runoff × loam × horse[5]	0.06	0.04	0.55	0.0005	12.86
SM × clay[6]	1.17	0.04	0.59	0.0001	27.31
SM × loam × motorcycle[7]	0.91	0.04	0.63	0.0001	17.93
SM × clay × hiker[8]	-1.04	0.03	0.66	0.0012	11.17
SM × sandy clay × horse[9]	-2.12	0.02	0.68	0.0039	8.73
Slope × clay × motorcycle[10]	-4.60	0.02	0.70	0.0142	6.24

[1]Slope represents the slope continuous variable and default cases for the soil texture (sandy loam) and user treatment (control) indicator variables.

[2]Slope × horse represents the slope continuous variable and horse indicator variable cross-product.

[3]TR × clay represents the antecedent trail roughness continuous variable and clay indicator variable cross-product.

[4]Water runoff × sandy clay × horse represents the water runoff continuous variable and clay and horse indicator variable cross-products.

[5]Water runoff × loam × horse represents the water runoff continuous variable and loam and horse indicator variable cross-products.

[6]SM × clay represents the antecedent soil moisture continuous variable and clay indicator variable cross-product.

[7]SM × loam × motorcycle represents the antecedent soil moisture continuous variable and loam and motorcycle indicator variable cross-products.

[8]SM × clay × hiker represents the antecedent soil moisture continuous variable and clay and hiker indicator variable cross-products.

[9]SM × sandy clay × horse represents the antecedent soil moisture continuous variable and sandy clay and horse indicator variable cross-products.

[10]Slope × clay × motorcycle represents the slope continuous variable and clay and motorcycle indicator variable cross-products.

and 0 in all other cases, $X_{11}=1$ for motorcycles and 0 in all other cases, and $X_{12}=1$ for off-road bicycles and 0 in all other cases. The null treatment or control plots were represented by the default case in which $X_9=X_{10}=X_{11}=X_{12}=0$. The multicollinearity problems were again minimized by running the model with all the possibilities (i.e., a total of 5 continuous, 7 indicator, and 95 interaction variables), deleting the non-significant terms, and running the model again. The stepwise option and 0.05 level of significance were used to select the terms in this third model as well.

The inclusion of interaction terms with one continuous and two indicator variables in the final model (see Table 3 for details) indicates how the impact of one classification (i.e., user type) varied significantly over the categories (i.e., soil texture classes) of the other classification. The default case in Table 3 refers to the sandy loam soil texture class (as in Table 2) and the control or null treatment plots. This approach allowed the impacts of specific trail users to be differentiated from other trail users based on differences in soil texture as well as the other measured variables.

Although the multiple regression models described above provided information about the relative impacts of the different trail users to the extent that the indicator variables and interaction effects representing one or more trail users were incorporated in the third model, a more direct test was needed to assess the relative impacts of different trail users. The multiple comparisons test within the GLM (General Linear Model) module of SAS (Freund *et al.*, 1986) was used to develop models which compared users in terms of water runoff and sediment yield. The Bonferroni option was chosen to compare means from samples of unequal sizes and least-squared means were used because the use of 108 samples (24 for hiking, horse, motorcycling, and off-road bicycling, respectively; but only 12 for the control case) meant the study design was not balanced.

The multiple comparisons test performs a t test on every pair of means and compiles the results in a series of tables. The rows and columns list pairs of treatments and the numbers reported in Table 4 show the probability that the two means came from samples drawn from the same population. Values of less than 0.05 are **in bold** and indicate statistically significant differences between the plots in terms of water runoff or sediment yield behavior for different pairs of trail users. Values larger than 0.05 indicate only that the differences between the population means, if any, were not large enough to be detected with the sample sizes used in this study (Ingraham *et al.*, 1988).

TABLE 4

Sediment yield multiple comparisons test results

User treatment	Mean sediment yield (g)	Bicycle	Control	Hiker	Horse	Motorcycle
		p values				
A. *Sediment yield prior to user treatments on prewetted plots* (n=54)						
Bicycle	69	–				
Control	59	0.46	–			
Hiker	38	**0.04**	0.14	–		
Horse	60	0.53	0.93	0.11	–	
Motorcycle	65	0.81	0.67	0.06	0.70	–
B. *Sediment yield following user treatments on prewetted plots* (n=54)						
Bicycle	63	–				
Control	65	0.81	–			
Hiker	63	0.98	0.80	–		
Horse	96	**0.01**	**0.01**	**0.01**	–	
Motorcycle	83	0.06	0.08	**0.04**	0.18	–
C. *Sediment yield differences prior to and following user treatments on prewetted plots* (n=54)						
Bicycle	–2	–				
Control	7	0.57	–			
Hiker	21	0.19	0.38	–		
Horse	34	0.03	0.09	0.40	–	
Motorcycle	15	0.33	0.64	0.70	0.24	–
D. *Sediment yield following user treatments on dry plots* (n=54)						
Bicycle	58	–				
Control	61	0.68	–			
Hiker	55	0.76	0.49	–		
Horse	75	**0.02**	0.16	**0.01**	–	
Motorcycle	59	0.89	0.76	0.65	**0.03**	–

RESULTS

PREVIOUS HISTORY

The soil profile descriptions prepared for the soil pits provided information about prior trail use and user impacts. Both the Emerald Lake and New World Gulch trail soil profiles differed from their off-trail counterparts with respect to the A and Bt horizons. The A horizons were missing (eroded) from both trail sites, so that the Bt horizons represented the soil surface. The removal of the A horizon meant that approximately 5 and 7 cm of soil had been eroded along the Emerald Lake and New World Gulch trails, respectively.

NATURAL CONTROLS

The initial regression results were not very encouraging in that none of the relationships between water runoff and soil texture, slope, antecedent soil moisture, trail roughness, and soil resistance was statistically significant, and only two of five bivariate sediment yield relationships were statistically significant. Variations in slope and antecedent trail roughness explained 12.7 and 10% of the variability in sediment yield, respectively. None of the relationships proposed between sediment yield and antecedent soil moisture, soil resistance, and water runoff was significant.

The switch to multiple regression and the inclusion of soil texture as a series of indicator variables improved model performance. The multiple regression analysis divided the plot data into four groups based on soil texture and produced five independent variables that explained 42% of the variability in sediment yield. The first four terms in Table 2 combined to explain 41% of the variability in sediment yield. The first and third terms indicate that steeper slopes combined with clay and sandy clay soils produced more sediment. Similarly, the second and fourth terms show that increased terrain variability (roughness) combined with sandy clay and clay soils produced more sediment. The inclusion of the slope gradient and antecedent trail roughness continuous variables in these cross-product variables is to be expected given the bivariate regression results, and their inclusion in this model simply indicates that their coefficients (i.e., the response of sediment yield to changes in slope steepness and/or antecedent trail roughness) differed significantly between the four soil texture classes. Steep slopes have been positively correlated with sediment yield in many environments and the cross-products combining antecedent trail roughness and fine-textured (i.e., clay or sandy clay) soils presumably indicate that more sediment was available for removal in these circumstances.

The fifth cross-product combining antecedent soil moisture and loam soils indicates that the response function for this combination was statistically significant and different from the response functions estimated for the other soil moisture/texture combinations. Even though this fifth cross-product explained only 1% of the variability in sediment yield here, the results from the inclusion of another series of indicator variables representing user types reported in the next section suggest a larger and more complex role for this continuous variable. Overall, the inclusion of cross-products in this model indicates that the relationships between sediment yield and three of the natural controls (i.e., slope steepness, antecedent trail roughness, and soil moisture) varied with different soil textures.

RELATIVE IMPACTS

The addition of four new indicator variables to accommodate trail use meant that as many as five continuous variables, seven indicator variables, and 95 cross-products were considered with water runoff and sediment yield as the dependent variables when multiple regression was used to explore the relative impacts of different trail users. Both models used the results from the rainstorms which followed user treatments (n=108). None of the independent variables was related to water runoff at the 0.05 significance level, suggesting that the variability of water runoff cannot be statistically explained by the independent variables, at least as they were measured in the study. Ten interaction variables combined to explain 70% of the variability in sediment yield from the sample plots (Table 3). The default soil texture (i.e., plots with sandy loam soils) and user subgroups (i.e., the control or null treatment case) appeared in two and three terms, respectively. The variability in slope gradient on the control plots with sandy loam soils, for example, explained 18% of the variability in sediment yield. The variability in slope gradient on horse plots with sandy loam soils and antecedent trail roughness on control plots with clay soils explained 15 and 13% of the variability in sediment yield, respectively. These first three terms combined to explain 46% of the variability in sediment yield. The parameters indicate that steeper slopes and increased terrain variability were associated with higher sediment yields. Some of the other terms are more difficult to explain; for example, wet control plots and wet hiker plots on clay soils were linked with high and low sediment yields, respectively.

This particular model was different from the earlier one in that five trail treatments, represented by as many as four additional indicator variables and 80 additional cross-products, were added. The 67% increase in R^2 (from 42% to 70%) can be attributed to the inclusion of this second series of indicator variables, although the appearance of terms including both sets of indicator variables means that the impact of user type is modified by the soil texture class in question (Table 3). The contributions of the different variables to the ten significant terms provided a rough guide to their cumulative impacts and confirmed that three variables stood out: soil texture (37%), slope (35%), and user treatment (35%). Antecedent soil moisture, antecedent trail roughness (both 13%), and water runoff (9%) made smaller contributions while antecedent soil resistance had no impact.

User treatments, of course, are of most interest here and following the last approach, their contributions to the ten significant terms can be isolated as follows: horse traffic appeared in four terms that explained 26% of the variability in sediment yield, motorcycle traffic appeared twice (6%), and hiking appeared in one term (3%). It is difficult to take this type of analysis further, although certain relationships are suggested. All four terms including horses were positively correlated with sediment yield, whereas one of the motorcycle terms was positively correlated and the other negatively correlated with sediment yield. The hiking terms are also problematic in that they include other variables that were positively and negatively correlated with sediment yield in different model terms.

The multiple comparisons test in SAS was used to explore the relative impacts of the different trail users with respect to water runoff and sediment yield in more detail. There were no statistically significant different pairs of means for water runoff. These results confirmed: (1) that the trails used for the five treatments were similar in terms of their water runoff behavior prior to the treatments, and (2) the multiple regression results showed that user treatment did not significantly alter runoff behavior.

The results from Part A of Table 4 suggest that the trails used for the five treatment types were not similar in terms of their sediment yield behavior prior to the treatments. Trail plots used for hikers were statistically different from one of the other groups (off-road bicycles) at the 0.05 level and all groups at the 0.15 significance level. Therefore the sample design did incorporate some bias with respect to sediment yield. This particular result suggests that less sediment was available for detachment and entrainment on the hiker plots since the water runoff volumes generated from the plots prior to the user treatments were not significantly different.

The sediment yields reported in Part B of Table 4 indicate that horse plots produced significantly more sediment than the bicycle, control, and hiker trail plots at the 0.05 significance level. Trail plots used by motorcycle were significantly different from one of the other groups (hiker) at the 0.05 level and bicycle and control plots at the 0.15 significance level. Hiker and bicycle plots were not significantly different from each other or the control plots. The treatments were applied to prewetted plots and these results presumably indicate differences in sediment availability. The first sediment yield has been subtracted from the second sediment yield for the plots receiving two rainstorms in Part C of Table 4. These results focus attention on the differences due to the treatments and they remove some or possibly all of the bias inherent in sample plot selection. They confirm that the horse plots are different from the bicycle and hiker plots at the 0.05 and 0.10 significance levels, respectively. Indeed, hikers produced the second largest increase in sediment yield following horse treatments, and overall the horse and hiker differences suggest that hooves and feet make more sediment available for removal than wheels on prewetted soils. The results in Part D of Table 4 indicate horse traffic produced significantly more sediment than the other users on dry plots as well.

DISCUSSION

An understanding of the natural processes and controls operating on trails is necessary before trail users can be added and their impacts isolated from those of the physical site characteristics (Dale and Weaver, 1974; Helgath, 1975; Bratton *et al.*, 1979; Quinn *et al.*, 1980; Summer, 1980, 1986; Kuss, 1986; Jubenville and O'Sullivan, 1987). The results from this study help to clarify some of the important relationships between trail users, water runoff, and sediment yield. The following discussion examines their broader significance.

Two sets of findings emerged from this study which probably apply to many (if not most) environments. The first was that trail use by horses produced greater sediment yields than trail use by other users. This result is similar to those from earlier studies by Dale and Weaver (1974), Weaver and Dale (1978), and Bratton *et al.* (1979), although further comparisons are difficult because of differences in study design. The second and perhaps more important result was that the greatest sediment yields were generated on prewetted trails. This result occurs because the application of rainfall and the increases in soil moisture that follow reduce soil resistance which, in turn, reduces the trail's ability to bear a moving load. Helgath (1975), Bryan (1977), Weaver and Dale (1978), and Bratton *et al.* (1979) all noted a strong connection between soil moisture conditions and a soil's ability to bear a moving load. Weaver and Dale (1978), for example, noted that trails located on poorly drained soils are usually wider, deeper, and less uniform (i.e., display greater roughness) than trails located on well-drained sites. These soil moisture results have important implications for trail managers and suggest that trail damage can be minimized by limiting trail use when soils are wet.

The remainder of the results from the current study are noteworthy in at least two other respects: (1) they demonstrate the complexity of the geomorphic, soil, and topographic variables and the difficulty of quantifying their effects on erosion rates, and (2) they serve to highlight some of the challenges and pitfalls that await those attempting to unravel these complex relationships across a range of landscapes. The remainder of the discussion examines these challenges and pitfalls and, in doing so, illustrates the complex interactions which occur between human and environmental variables in most recreational environments.

There are two possible reasons for our failure to identify any significant relationships between water runoff and the slope, soil texture, antecedent soil moisture, trail roughness and soil resistance variables: (1) the study did not evaluate the variables in ways that the natural variability of the sample plots was captured, or (2) the study did not measure all of the relevant variables (i.e., there were no significant relationships between these variables). The first explanation may apply to the antecedent soil moisture, trail roughness, and soil resistance measurements. Trail roughness, for example, may not have been sampled frequently enough (each time) to accurately represent the roughness (micro-relief) of plot surfaces. Trail roughness encourages ponding which increases infiltration and reduces runoff. The density (number) of measurements (each time) may not have been great enough to capture this effect. Similar problems may have affected the antecedent soil moisture and soil resistance measurements.

Turning to the second explanation, two potentially important variables (elapsed time of water application and the swelling properties of clays found at the New World Gulch site) were not measured. Although 41.75 mm of water was applied in every case, the application time varied between 20 and 23 minutes. This variability meant that the application rate was reduced as much as 15% (109 mm hr^{-1}) compared to the desired rate of 127 mm hr^{-1}. Most of these problems occurred on the New World Gulch trail, since these sample plots were located beside a stream which carried a noticeable sediment load. The practice of allowing the water to settle and using only the upper portion of water in the container was able to prevent most but not all of the sediment from being processed through the rainfall simulator. This meant that some of the needles used as drip formers by the rainfall simulator were blocked for some applications. The potential impact was the same as with the measurement problems noted above since lower intensities may produce more infiltration and less runoff. The failure to examine the clay mineralogy at the different sites and to incorporate these results in the regression analysis may represent another important omission. These clays can absorb more water than non-swelling clays and hence the clay mineralogy may have helped to decipher some of the differences in runoff behavior between plots. Smectites (swelling clays) may have been present at the New World Gulch sample plots (Davis and Shovic, 1984).

The potential impact of these shortcomings was greater for water runoff since the same independent variables were much more successful in explaining the variability in sediment yield. Slope and antecedent trail roughness produced significant relationships when bivariate models were developed and five independent variables or cross-products combined to explain 42% of the variability in sediment yield when multiple regression was used. Soil texture (introduced as a series of indicator variables), slope, and antecedent trail roughness were included in at least two of these terms. The influence of these slope and soil characteristics on trail erosion has also been documented in other studies (Bryan, 1977; Weaver and Dale, 1978; Bratton *et al.*, 1979; Quinn *et al.*, 1980; Coleman, 1981; Fish *et al.*, 1981; Kuss, 1983, 1986; Jubenville and O'Sullivan, 1987).

The failure of water runoff to explain any of the variability in sediment yield, either by itself or as part of one or more cross-products, presumably indicates that sediment yield from existing trails is detachment-limited rather than transport-limited. This result may be due to the relatively small size of the sample plots and the low intensity of the storms that were applied, although similar results have been obtained in other erosion studies (e.g., Wischmeier and Smith, 1978). The addition of four new indicator variables and their cross-products to the multiple regression models to examine the relative impacts of the different trail uses confirmed this state of affairs in that: (1) no significant relationships were uncovered between water runoff and the indicator variables, and (2) ten independent variables and cross-products combined to explain 70% of the variability in sediment yield. This second result is impressive. Treating the cumulative contributions of the different variables to the final result as a rough guide to their contributions confirmed that soil texture (37%), slope (35%), and user treatment (35%) had the most impact. Water runoff (9%) was one of three variables that made smaller contributions.

The multiple comparisons test results further clarified the roles of the different treatments and in particular showed that horses and hikers (hooves and feet) make more sediment available than wheels (motorcycles and off-road bicycles) on prewetted trails and that horses make more sediment available on dry plots as well (Table 4). The failure to distinguish between the other treatments may have been due to three problems with the study design. Two of the shortcomings have to do with the concept of geomorphic thresholds and the third with mechanical removal of sediment from the sample plots.

Schumm (1977) noted that the behavior of geomorphic systems may differ greatly when different external and internal stresses are applied. The thresholds that define when changes are initiated vary across space and through time since the minimum energy that must be applied varies with the environment. Kuss (1986) applied this concept to recreational trails, noting that almost any rainstorm or level of use would impact new trails but that very large storms or very heavy use is needed to initiate change on existing trails. These thresholds will vary with the type and quantity of use as well as with climatic, soil, and topographic conditions. Two problems with the current study may have reduced our ability to distinguish between hiker, off-road bicycle, and motorcycle uses: (1) the limitations of the rainfall simulator, and/or (2) the small number of treatments (i.e., 100 passes).

The most important limitation with the modified Meeuwig rainfall simulator is that it produces rainstorms of only one-third the intensity of natural rainstorm events. We experienced several natural rainstorm events in the field and observed greater quantities of water runoff flowing down the trail from these events compared to our rainfall simulator events. The impact of rainfall intensity on the relationships between pre-existing trail conditions (i.e., trail history) and threshold values is not obvious. However, the restrictions placed on the duration and intensity of rainstorms applied in this study decreased the likelihood that threshold values were attained, especially since the study focused exclusively on existing trail segments. The application of only 100 passes (for all four treatments) probably contributed to the failure to attain the appropriate thresholds for all but horse traffic. Lull (1959) suggested impact per unit area could help account for the relative impact of different trail uses. Horses produce the greatest impact per unit area and as a result, horses produced the greatest net change in this study. Other treatments may not have been applied enough times or in conjunction with large enough simulated rainstorms for statistically significant differences to show up between them.

The failure to measure the quantities of soil removed with feet and tires from the prewetted plots may have contributed to the lack of statistically significant differences between the measured sediment yields for the hiker, motorcycle, and bicycle plots as well. The mechanical removal of sediment in these ways was observed on most prewetted plots. Most of the moist soil was removed and a dry soil surface was exposed as the treatments were applied to some plots. The quantities of sediment removed in these ways may need to be combined with those that were measured in order to quantify the relationships between the independent variables and sediment yield more precisely.

The solutions to these last three potential problems would have required the expenditure of more time and effort at each plot. The experiments conducted for this study covered a larger number of sites than most previous studies and required two or three people in the field for approximately 30 days. The choice of a more elaborate rainfall simulator, the application of intense disturbance (i.e., more hiker, horse, motorcycle, and mountain bike passes), and/or the measurement of mechanical erosion from plots would require a larger fieldwork component and/or a study that examined fewer plots.

CONCLUSIONS

Trail use in the last ten years has seen a dramatic increase in off-road bicycles. In many cases off-road bicyclists use the same trails as hikers, horseback riders, and motorcyclists, so that this additional use compounds erosional concerns. The results of this study provide land managers with some new data summarizing the relative impacts of four different users on two existing trails in southwest Montana. In particular, the results indicate that: (1) the natural processes occurring on the two trails used for this study are complicated and difficult to decipher; (2) sediment yield is detachment-limited rather than transport-limited (at least for low intensity storms in the types of environments examined in this study); (3) horses produced significantly larger quantities of sediment compared to hikers, off-road bicycles, and motorcycles; and (4) the greatest sediment yields occurred on wet trails.

The results also indicate why future research may need to examine higher intensities of use (500-1000 passes), increased rainfall intensities, wet soil conditions (longer or heavier rainstorms), and mechanical as well as water-driven erosion processes. Higher levels of use and rainfall would increase the likelihood of exceeding the thresholds at which change is initiated. Site specific studies are required to show when different users exceed these erosion thresholds on new and existing trails. Although the results from these studies would help land managers in assessing the carrying capacities of their trail systems, there remains the challenge of extrapolating the results from small sample plots like those used in this study to other locations and larger areas. The discovery in this study that wet sites are more susceptible than dry sites to erosion damage may help if future studies can demonstrate a link between trail segments that have experienced substantial trail erosion and landscape positions with consistently high soil-water contents.

ACKNOWLEDGEMENTS

We thank Wade Stoelting, Tori Robson, and Angela Nielsen for their assistance with field work. Clayton Marlow, Cliff Montagne, Robin Tierney, and several anonymous reviewers provided valuable comments on earlier drafts of the paper. This study was partially funded by the Bozeman District Office of the Gallatin National Forest, the USDA-Forest Service Intermountain Research Station, and the International Mountain Bike Association. Contribution no. J-2750 of the Montana Agricultural Experiment Station.

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