CARTER

OSMP Study

Relative Impact of Off-Road Bicycle and Hiker Traffic on Trail Soils: An Experimental Study, Boulder, Colorado

1200 N.E. Pacific St. #M206
Seattle, WA 98105
June 6, 1994

Brent Wheeler
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Dear Brent:

After numerous revisions and other unexpected setbacks, I successfully defended my thesis in May of this year. I have enclosed a copy for your office. Please accept my apologies for the delay in sending you these materials.

Now that my project is completed, I would like to express my appreciation to the Boulder Department of Open Space, and to you personally. Please convey my gratitude to any interested persons in the Open Space Department. Thank you for your aid in the process of gaining access to a site on which to conduct my fieldwork. In addition, thank you for the information you provided on trail construction practices and local trail-use patterns.

As you probably noticed in the header of this letter, I have recently joined my husband in Seattle, Washington. If there is any future need to contact me, correspondences should be sent to that address.

Sincerely,

Anna R. Carter

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RELATIVE IMPACT OF OFF-ROAD BICYCLE AND HIKER TRAFFIC ON TRAIL SOILS: AN EXPERIMENTAL STUDY, BOULDER, COLORADO

A Thesis
Presented to
the Faculty of Natural Sciences, Mathematics, and Engineering
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In Partial Fulfillment
of the Requirements for the Degree
Master of Arts

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by
Anna Ruth Carter
June 1994

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CHAPTER ONE

INTRODUCTION

Land managers, researchers, and environmentalists have previously exhibited much concern for recreational pressures on natural lands (cf. Appel 1950; Bryan 1977; Cole 1987). Established recreational activities, such as hiking, horseback riding, and motorized off-road vehicle usage have been blamed for degradation of the vegetation and soils of these natural areas (cf. Snyder et al. 1976; Weaver and Dale 1978; Price 1985). Within the last decade another new activity, off-road or all-terrain bicycling, has gained widespread popularity.

Objectives and Hypotheses

The intent of this study is to evaluate the physical impact of off-road cycling on trails in the Boulder area. This study compares the effects of off-road bicycle and hiker traffic on soils of newly-constructed, experimental trail segments on City of Boulder Open Space land. A second objective of the study is to determine whether gradient affects the degree of soil degradation caused by the two modes of travel. These objectives will be evaluated through soil-compaction measurements and examination of trail surface profiles.

The following hypotheses have been formulated to evaluate the above objectives:

1. As recreational usage of trails increases, compaction of soils should increase in a curvilinear fashion in which large changes occur with initial use, and additional use produces progressively smaller amounts of change (Figure 1.1). This hypothesis is based on the findings of several researchers who have noted the existence of a curvilinear relation for bulk density and penetration resistance (cf. Young and Gilmore 1976; Cole and Fichtler 1983; Cole 1985; Cole 1987).

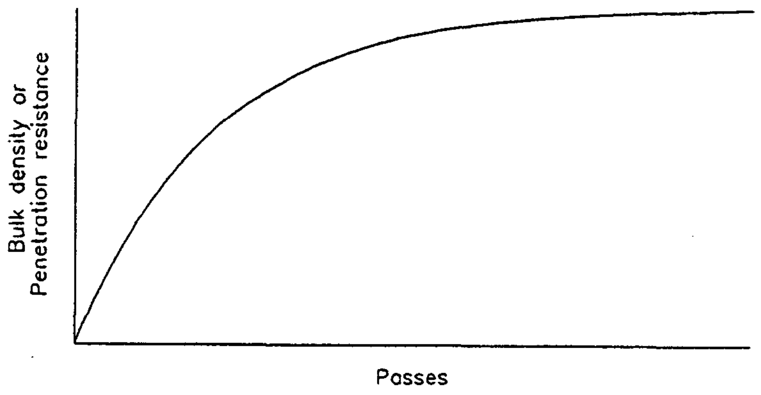

Figure 1.1. Hypothesized relation between frequency of use and compaction

2A. Bicyclists compact soils more than hikers on lanes having the same gradient. This hypothesis is based on the fact that bicyclists exert more weight per unit area on the ground than hikers. For example, the average air pressure of a tire of an off-road bicycle is 3 kg/cm^2, whereas a hiker weighing 70 kg and wearing a boot with an average area of 180 cm^2, would exert only 0.4 kg/cm^2.

2B. More compaction occurs on sloped lanes than on flat lanes traversed by the same user type. This hypothesis is based on the findings of Weaver and Dale

(1978), who observed that trails having a 15° slope experienced greater compaction by hikers, horses, and motorcycles than did flat trails.

3. The intensity of compaction decreases with depth in the soil, regardless of trail gradient or user type. This hypothesis is based on the findings of several researchers (e.g., Bates 1935; Papamichos 1966), as discussed in more detail in Chapter Two, who noted that recreational compaction is concentrated in a narrow layer of the surface soil.

4. As recreational trail usage increases, change in trail microrelief should increase. Because microrelief changes are a consequence of the displacement of soil through the processes of erosion and/or compaction, microrelief can reasonably be expected to change with continued trail use. For example, Cole (1983) measured the microrelief of the Big Creek trail in western Montana's Selway-Bitterroot Wilderness, and he noted that individual cross-sectional profiles changed progressively over a two-year span.

5A. Bicyclists produce greater changes in trail microrelief than hikers on lanes having the same gradient. This hypothesis is based upon the results of research by Weaver and Dale (1978). In their study motorcycles were found to be more damaging than hikers in terms of depth to the trail center. In addition, the researcher has observed that hikers have the ability to exercise control over their own speed. In contrast, cyclists attempting to control their speed, are prone to spin their wheels when accelerating and skid when braking. Therefore, bicyclists are probably more likely than hikers to loosen and transport soil, causing greater changes in trail microrelief.

5B. Greater changes in trail microrelief are exhibited on sloped lanes than on flat lanes traversed by the same user type. This hypothesis is supported by the research of Weaver and Dale (1978), who found that depth to the center of trails traversed by hikers, horses, or motorcycles was greater on sloped than on level sites. Increases in trail depth may be due in part to greater shearing forces that exist on slopes (Weaver et al. 1978). The amount of shear force may be calculated according to the following equation:

$$\text{shear force} = \text{gravitational force} \times \sin(\text{slope angle}).$$

On a flat trail the slope angle is $0°$, and $\sin(0°) = 0$. Therefore, no shear force exists on a flat surface. However, a 10% slope is equivalent to $5.71°$, and $\sin(5.71°) = 0.1$. Thus, shear force on a 10% slope is 10% of the gravitational force or weight applied to the slope.

Importance of the Study

Increased usage of trails for recreation in mountain areas and other semi-natural lands has created a need to evaluate human impact on the environment. Although to date there have been numerous studies (e.g., Lutz 1945, Bryan 1977; James 1979; Summer 1980; Cole 1985) that describe the environmental impact of recreationists, there have been very few (e.g., Seney 1991) that specifically concentrate on the impact of off-road bicycling. Thus, trail regulatory authorities have had little information on which to base land-use policy decisions with regard to bicycling. As a result, decisions to regulate bicycling on trails have often been influenced by the emotional arguments surrounding user compatibility and dire predictions of imminent trail decline brought about by cycling, rather than by scientific evidence.

This study may be of assistance in determining the magnitude of impact that bicycling, relative to hiking, has on the environment so that trail authorities will have objective information on which to base bicycle-related policies. Existing trail-management policies could then be reevaluated in light of the findings of this study. In addition, this study will refine understanding of the mechanism by which bicycling damages trails. With a greater understanding of the damage caused by bicycles, recreational managers may be assisted in creating more effective guidelines for future trail construction and formulating more effective regulations so as to minimize trail degradation. In addition, an increased understanding of the impact of bicycles would enhance the existing user education and trail-maintenance efforts of off-road cycling advocacy organizations such as the Boulder Off-Road Alliance.

Historical Background

In the mid-1970s a small number of cyclists in Marin County, California, began experimenting with enhanced bicycle frames and components that could be ridden off paved roads. In 1979 so-called mountain bikes were available commercially, and by 1981 Specialized had introduced the first mass-produced off-road bicycle, the Stumpjumper (Kelly 1990). Off-road bicycling quickly became one of the most rapidly expanding outdoor sports in the United States. By 1991 all-terrain bikes amounted to 50% of United States bicycle sales, with more than a 100% increase in the first three months of that year compared to 1990 (Castro 1991). In an informal survey of five bicycle retailers in Boulder, Colorado, the author was informed that between 80% and 99% of the total number of bicycles sold were marketed as all-terrain bicycles. Of course, these figures do not accurately reflect the environmental pressure introduced by off-road bicycling, as many all-terrain bikes rarely leave paved roads.

Bicycle riding on recreational trail systems has caused land-use disputes. The two primary existing user groups, horseback riders and hikers, have argued and even lobbied for restrictions on all-terrain bike access to trail systems, especially single-track trails. Disagreements between hikers and off-road bicyclists became increasingly hostile in the late 1980s, as the issue found its way into the national media (e.g., Foote 1987; Wells 1989). One source of conflict has centered around the issue of compatibility between transportation modes that fall into different speed classes. All-terrain cyclists are a medium-speed mode, generally slower than motorized vehicles, but often travelling at velocities significantly higher than hikers, joggers, or horseback riders (Barlow 1990).

Hiking and environmental groups have also raised issues related to environmental degradation, accusing all-terrain bicyclists of causing erosion and vegetation damage on existing trails. Although all users affect trails, many opponents of off-road cycling assert that cyclists are prone to short-cut switchbacks and skid, two activities viewed as negatively affecting the trail environment (Wells 1989). In 1985 the Sierra Club took the position that all-terrain bikes were mechanical vehicles detrimental to the environment and began to lobby for strict limits on bicycle access to trails (Wells 1989; Blumenthal 1990; Kelly 1990). The Club later softened that stance (Wells 1989).

In response to the emergence of the new sport and the controversy it had already caused, land-use managers began to place limits on off-road cycling as early as the mid-1980s. In some areas trails were never open to bicycle usage, whereas in other areas bicycles were initially allowed on trails with the privilege later being revoked (Kelly 1990). In 1964 the U. S. Congress passed the Wilderness Act to encourage the preservation of certain pristine areas. Section 4 (c) of this legislation, as well as title 36 CFR 293.6, forbids the use of "mechanical transport" in all designated wilderness areas. In 1984 the U. S. Forest Service expanded the definition of "mechanical transport" to include bicycles. Thus, bicycles have never been allowed in designated wilderness areas (Coelle 1989; Kelly 1990).

Much of the cycling community reacted to initial access limitations with outrage. In 1983 the National Off-Road Bicycle Association (NORBA) formed, with the stated goal of securing access to public lands. Though by 1989 NORBA had shifted its focus to off-road bicycle racing, other advocacy groups, such as the recently formed International Mountain Bicycling Association (IMBA), continued to seek trail access for their constituency (Kelly 1990). Throughout much of this debate, all-terrain cyclists have insisted that their sport causes no more environmental degradation than horseback riding or hiking. To reinforce this image, cycling enthusiasts began to form trail maintenance volunteer corps to preserve the conditions of heavily-used trail systems, and emphasized conservation-minded riding (Blumenthal 1990; Pena 1993).

In the years immediately subsequent to the emergence of this new sport, no regulations existed in the Boulder area to prohibit all-terrain bicycling. However, the city first closed all trails to bicyclists in 1983 (Kelly 1990), citing reasons such as user conflicts and environmental damage. In 1989 the City of Boulder Open Space department reopened a limited number of trails to cyclists. Today approximately one-third of the 100 miles of City Open Space designated trails are open for bicycle usage (B. Wheeler, pers. comm., 1993). After Boulder off-road cyclists' initially antagonistic reaction to access restrictions, one local organization, the Boulder Off-Road Alliance (BORA), now advocates rider responsibility on open trails. In addition, BORA volunteers actively cooperate with trail authorities in trail maintenance (K. Young, pers. comm., 1993).

CHAPTER TWO

LITERATURE REVIEW

Recreational Impacts on Vegetation

One of the most visible effects of recreational use is destruction of undergrowth. Initial injury to vegetation is the result of direct mechanical damage, including bruising and crushing (Meinecke 1928; Burden and Randerson 1972; McQuaid-Cook 1978). Cole (1985), in an experimental study in western Montana, established a series of treatment lanes through previously undisturbed vegetation to determine the response of the vegetation to differing levels of use intensity. He observed a curvilinear relation between trampling frequency and reduction in percentage vegetation cover. In other words, the majority of cover loss occurred in the first passes, and further trampling produced progressively less cover loss. Several other researchers have observed similar relations (Wagar 1964: Frissell and Duncan 1965; Bell and Bliss 1973; Dale and Weaver 1974; James et al. 1979; Cole and Fichtler 1983; Leonard et al. 1985).

Researchers have found that plant species exhibit varying degrees of vulnerability to trampling. Several studies have found graminoids (grasses and grass-like plants) to be particularly well-suited to intensive recreation (Bates 1935; Wagar 1964; LaPage 1967; Burden and Randerson 1972; Dale and Weaver 1974;

Douglas et al. 1975; Cole 1985, 1986). In contrast, lichens (LaPage 1967; Willard and Marr 1970; Burden and Randerson 1972; Bell and Bliss 1973; Kellomäki and Saastamoinen 1975) and certain brittle, woody plants (Dale and Weaver 1974) tend to be very sensitive to trampling. Mosses have been found to be both relatively unaffected (Dale and Weaver 1974; Cole 1985) and sensitive (Lutz 1945; Frissell and Duncan 1965; LaPage 1967; Cole 1986). Bates (1935) was the first to suggest that a plant's susceptibility to trampling was determined by that plant's morphological and reproductive traits.

Recreational Impact on Soil

Though not as visibly striking as the deterioration of vegetation, recreational usage also affects soils. Overall, fewer studies concentrate on recreational impact on soil; yet soil studies to date have shown that recreation does have profound effects on soil (Bryan 1977). Both comparative and experimental research show that soils in areas used for recreation are more compacted than soils of adjacent undisturbed areas. Soil compaction, as defined by Lull (1959, p. 1), is "the packing together of soil particles by instantaneous forces exerted at the soil surface resulting in an increase in soil density through a decrease in pore space." Some of the more common techniques used to quantify soil compaction in recreational areas include bulk-density, penetration-resistance, and infiltration measurements.

Compaction increases in recreational areas as the number of passes increases up to a point of maximum density. Trampled areas usually display soil bulk-densities that are 0.2-0.6 g/cm^3 greater than comparable untrampled areas (Weaver and Dale 1978). Cole (1985) and Cole and Fichtler (1983) found that soil compaction increased in a curvilinear fashion as amount of use increased. That is, initial trampling caused the majority of compaction, and additional compaction decreased with increasing usage until a steady state or maximum bulk density was attained. For example, Cole (1985) found that resistance to penetration had the greatest increase after 50-75 walks across previously undisturbed land in plots located in six vegetation habitats. The rate of compaction still increased rapidly, but not as rapidly, up to 400 passes. After 400 passes the increase in compaction was even less. Cole's results are similar to those of several studies conducted in campgrounds (Young and Gilmore 1976; Cole and Fichtler 1983). These studies compared campgrounds that were grouped into three use-classes--light, medium, and heavy. In one such study lightly-used campsites were found to be significantly different than control sites (James et al. 1979). Generally there was no significant difference between medium- and heavy-use sites.

The effects of compaction resulting from recreation are normally restricted to the surface layer of the soil. In undisturbed soil, bulk density normally increases with depth. However, Bates (1935) noted the reverse situation on a footpath. He observed that the top 3 to 5 cm of soil on the path had equal or greater density than the underlying soil. Similarly, LaPage (1962) observed that compaction was greatest in the soil's upper 15 cm. Lutz (1945) found a statistically significant difference between used campsites and unused areas in the bulk density of both the 0-10 cm and 10-20 cm soil depth increments. Papamichos (1966) noted that compaction was confined to the surface 2.5 to 5 cm in lightly- and moderately-used campsites, while in sites receiving heavy use, the depth to which compaction was measured exceeded 10 cm. In contrast to pedestrian usage, motorized off-road vehicle use causes compaction to much greater depths. Snyder et al. (1976) noted compaction to depths greater than 1 m at Panoche Hills, California, a site used for motorcycle hill-climbing between 1968 and 1970. Similar results were observed by Wilshire et al. (1978) at seven off-road vehicle sites in the San Francisco area.

Factors Affecting Soil Compaction

Soil Texture and Structure

A number of factors, including soil texture and structure, moisture content, organic content, vegetation, and presence of rocks, affect the degree of compaction. Lull (1959) asserts that soils which compact to the greatest degree--loams, sandy loams, and silt loams--have a wide range of particle sizes. In these soils a high level of compaction may be achieved because smaller grains can be pressed into the large pores between large particles. Large rocks on or in the surface soil can also affect the amount of compaction that results from trampling. At an early stage in recreational usage, rocks serve to counter compaction (Bryan 1977). Furthermore, the better-aggregated the soil, the more susceptible it is to compaction (Lull 1959). Well-aggregated soils have low bulk densities and an abundance of pore space. When these soils are trampled, the aggregates break down and the resulting particles are forced into interaggregate spaces. This process decreases pore space which produces an increase in bulk density.

Moisture Content

The moisture content of the soil is also influential in determining the degree of compaction. Lull (1959) states that the ideal amount of moisture necessary to maximize compaction with the least effort is about midway between field capacity and wilting point. Under dry soil conditions, the resistance of soil particles to rearrangement is great. However, the addition of moisture lubricates the particles, reducing soil surface tension and the soil's resistance to compaction. Consequently, less frequent and lighter trampling can do the same amount of damage on moist soils as more frequent and heavier trampling on dry soils (Lull 1959). Bryan (1977) and Willard and Marr (1970) observed that plants suffered more damage on moist sites, in part due to the greater compaction that could be achieved. However, beyond a certain threshold near saturation, further addition of moisture reduces soil density because water is forced between the soil particles keeping them separated.

Organic Content

The content of organic matter in the soil also affects the degree of compaction. Organic matter cushions the effects of trampling on the underlying mineral soil and reduces the rate and degree of compaction (Lull 1959). Cole (1985), in an experimental trampling study of six vegetation community types in western Montana, found that sites having the thickest organic horizons exhibited the least amount of compaction. Cole (1985) also found that vegetation had an effect similar to organic matter. He observed that treatment lanes with high relative vegetation cover values showed lower values for resistance to penetration.

Effects of Compaction

Infiltration Rate

Many people may not view compaction by itself as a very serious threat to the environment; however, compaction contributes to several other potentially more serious problems. Compaction has the greatest effect on larger soil pore sizes. For example, Monti and Mackintosh (1979) observed that recreational compaction affects primarily the noncapillary pores, those having a diameter greater than 500 µm. The reduction of macropore space is crucial because it is these pores that influence the soil's permeability. Loss of macropores therefore reduces the infiltration rate (Cole 1987; Steila and Pond 1989). On intensively used campsites a 20- to 30-fold decrease in infiltration rate occurred following a 60% loss in macropore volume (Monti and Mackintosh 1979). Reductions in infiltration rate of similar magnitude were observed by Lutz (1945) and James et al. (1979).

Runoff and Erosion

The lower infiltration rate of soils compacted by recreational activity may lead to increased runoff and accelerated erosion (Lull 1959; McQuaid-Cook 1978; James et al. 1979). Monti and Mackintosh (1979) point out that at campsites in northwestern Ontario, rainfall intensities during the summer months frequently exceed the infiltration rate. At one heavily used campground area in the Missouri Ozarks, sheet erosion of up to nine inches was observed (Settergren and Cole 1970). In the Panoche Hills study area, runoff and sediment yields were compared for two adjacent basins, one used by motorcycles and the other undisturbed. The two basins were assumed to have been similar in terms of vegetation and soils prior to recreational usage. The disturbed basin produced eight times the runoff volume of the unused basin, despite the fact that the slopes were steeper in the unused basin (100% versus 65% in the disturbed basin). In addition, although the sediment yield of the unused basin was undetectable, the used basin produced 857 m^3/km^2 sediment. The higher runoff and erosion rates were attributed to a lack of vegetation cover and high compaction in the disturbed basin (Snyder et al. 1976).

Organic Matter

Soil compaction also affects the amount of organic matter in the soil; however, there is some disagreement as to how organic matter is affected. Most researchers have found that an increase in soil bulk density leads to a decrease in soil organic-matter content or a complete or partial loss of organic horizons (Frissell and Duncan 1965; Dotzenko et al. 1967; Settergren and Cole 1970;

Dawson et al. 1978; Frissell 1978; James et al. 1979). Frissell and Duncan (1965) suggest the following three reasons: 1) destruction of vegetation prevents a build-up of litter, 2) trampling grinds up organic matter, and 3) organic matter is removed through increased surface runoff resulting from compaction.

In contrast, Young and Gilmore (1976) observed 30% more organic matter in the surface 15 cm of soil of used campground plots in Illinois than was present in corresponding control plots. They suggested that less moisture and oxygen was able to enter the compacted soils, thereby hindering the oxidation process. Although Monti and Mackintosh (1979) observed a complete loss of organic horizons, they also noted that in intermediate- and high-use areas of campsites, highly decomposed organic litter was transported down the soil profile via percolating water. This resulted in an increase in humus materials in the top 1-3 cm of mineral soil. When viewed in photomicrographs, the organic particles appeared in narrow, discontinuous, horizontal bands.

Moisture Content

In three Rocky Mountain National Park campgrounds, soil moisture content was found to be inversely related to bulk density, probably in response to decreased infiltration on compacted soils and lack of forest litter (Dotzenko et al. 1967). James et al. (1979) asserted that compacted soils studied in northwestern Ontario experienced very slow soil moisture recharge as a result of the soil's inability to take up water. These disturbed soils then rarely reached field capacity, resulting in frequent desiccation, particularly during the summer. The effect of compaction on field capacity varies depending, in part, on soil texture. Lutz (1945) found that field capacity of sandy soils was not significantly changed by trampling. Although trampling reduced total pore volume of the soil, the proportion of capillary pore space did not increase due to the soil's coarse texture. In contrast, he found that field capacity increased significantly on sandy loams because large noncapillary pores in that soil were reduced to capillary size. Settergren and Cole (1970) attributed a decrease in field capacity that they noted in the upper 7.5 cm of a silty clay loam to the loss of organic matter following compaction on campgrounds (Settergren and Cole 1970).

Vegetation

Damage to vegetation from trampling occurs not only directly, as explained in a previous section, but also indirectly as a result of soil compaction (Meinecke 1928; Burden and Randerson 1972; McQuaid-Cook 1978). In general, compaction is detrimental to vegetation. Root penetration is physically obstructed in compacted soils (Gupta 1933; Monti and Mackintosh 1979). Lull (1959) states that obstruction occurs at bulk densities greater than 1.4 g/cm^3 in fine-textured soils and at 1.6 g/cm^3 in coarser soils. In addition, decreased soil pore space in compacted soils may literally cause vegetation to suffocate because it impedes the entrance of oxygen into the soil (Appel 1950; Dawson et al. 1978; McQuaid-Cook 1978; Cole 1987). Furthermore, due to reduced infiltration in compacted soils, less moisture is available for plant use. For example, the moisture available for plant use was 20% less in trails used by motorcycles than in undisturbed control areas

(Snyder et al. 1976). Gupta (1933) noted that plants on compacted soils are in danger of permanent wilting because transpiration frequently exceeds infiltration.

Damage to vegetation is not limited to low-growing plants. Several studies have noted reduced tree vigor in recreational areas and have attributed this to reduced air and water availability in the soil as a result of recreational use (Appel 1950; LaPage 1962; Settergren and Cole 1970; James et al. 1979). James et al. (1979), in a study of recreational effects on jack pine, used regression techniques to show that as soil penetration resistance increased and infiltration decreased, annual stem growth and the length, area, and dry weight of needles decreased. Trees growing under moisture stress may be more susceptible to disease and early death (Settergren and Cole 1970). Meinecke (1928), whose study of redwood parks in California was one of the earliest concerning recreational disturbance, observed changes in tree roots near old roads and campgrounds. He noted that the small feeding rootlets were flattened and a large proportion were blackened and dead. He also noted that roots in these disturbed areas were found closer to the surface than in adjacent undisturbed areas. Meinecke asserted that the impairment in the operation of the rootlets could ultimately result in the degeneration of the tree itself.

Compaction also can have long-term effects on ground cover vegetation. Several studies have noted that heavy trampling causes a change in species composition and diversity. The recreation-intolerant natural vegetation community is eventually replaced with more durable secondary vegetation that was previously at a competitive disadvantage in undisturbed vegetation (James 1979). Within two years of the opening of new campsites, LaPage (1967) actually observed that cover increased despite an initial heavy loss of vegetation. He attributed this fact to a shift in plant composition. This disturbed vegetation community also contained fewer species than undisturbed vegetation (Bates 1935; LaPage 1967; James et al. 1979; Price 1985). Along trails this band of disturbed vegetation was normally no more than one to two meters wide (Dale and Weaver 1974).

Other Factors Affecting Trail Soils

Slope

Slope influences the degree of damage caused by recreation. Steeper slopes generate more surface runoff which causes more erosion (Burden and Randerson 1972; McQuaid-Cook 1978; Weaver and Dale 1978; Cole 1983). Seney (1991) found that sediment yield was directly related to slope. The incision on sloped trails concentrates water, making it flow more quickly (Bryan 1977). The faster that water flows, the greater is its ability to transport more sediment. Thus, a feedback process is initiated in which steep slopes cause trails to erode, and the resulting incisions encourage additional erosion. Weaver and Dale (1978) found that sloping sites also experienced greater compaction than flat areas for hikers, horses, and motorcycles.

Microrelief

Trail microrelief (small-scale surficial features) also plays a role in recreational damage. Not only may a rough and rutted trail look unattractive, but it also may encourage further damage to the trail. For example, Bayfield (1973) found that people tended to walk along the smoothest path, and thus trail width increased as trail roughness increased, and decreased with the roughness of the surrounding ground. Sediment yield is also directly related to roughness (Seney 1991). Thus, a rough trail fosters greater erosion. Finally, some studies focus on the depth to the deepest point in the trail or to the trail's center as a measure of microrelief (e.g., Dale and Weaver 1974; Weaver and Dale 1978). It has already been stated that deeper trails result in faster flow of water and greater erosion.

Comparative Recreational Impact Studies

Several researchers have pointed out the relative lack of investigations comparing different recreational user types (Weaver and Dale 1978; Cole 1987; Seney 1991). Most studies to date concentrate on only pedestrian use. Although Summer (1980) studied trail impact of horses in Rocky Mountain National Park, she did not attempt to compare her results with other research on different users. Similarly, Snyder et al. (1976) and Wilshire et al. (1978) documented the effects of off-road vehicles without comparison to other recreational user types. This section discusses studies that compare user types.

Dale and Weaver's (1974) study in the Gallatin Valley near Bozeman, Montana, was an analytical study of previously established trails. They studied trails having only pedestrian traffic, only horse traffic, and both pedestrian and horse traffic. Although they noted that horse trails were no wider than those used by pedestrians, they did observe a difference in depth of the trails. Trails used by pedestrians and horses were several centimeters deeper than those traversed by pedestrians alone. McQuaid-Cook (1978) and Weaver and Dale (1978) had similar observations. Deeper incision resulted because horses, particularly those that had been shod, tended to loosen and move soil especially on slopes, causing greater erosion than pedestrians, who were more likely to compact the soils.

An experimental study that compared hikers, horses, and motorcycles was conducted in the Rocky Mountains near Bozeman, Montana (Weaver and Dale 1978). Flat and sloping (15°) trails were established in two habitat types, meadow and forest, and each trail was trampled by a particular type of user 1000 times during a single summer. Horses had the most and hikers the least adverse effect on vegetation cover. However, on grassy slopes, motorcycles were more destructive than horses, perhaps because of greater sliding, spinning, and braking that occurred on hills. For all other factors studied--bare trail width, depth to the trail's center, and soil compaction--horses were most damaging, followed by motorcycles, and then hikers.

Weaver and Dale (1978) also examined the differences between upslope and downslope effects. They found that motorcycles caused more damage when they ascended hills, whereas hikers and horses caused more damage during descents. The researchers suggested that, where possible, trails should be designed so that motorcycles ascend gentle slopes and descend steeper slopes, and pedestrians and horses should do the reverse.

Douglas et al. (1975) also directed an experimental study to compare the impact of equestrian and pedestrian trampling on prairie grassland. As in Weaver and Dale's (1978) study, horses were more destructive to vegetation than hikers. The reduction of the standing crop was twice as great for horses as for hikers.

Although not actually a study of different user types, Kuss' (1983) study of the impact of boot sole type is relevant because the two plots he set up in his experiment were identical and the treatment he applied on each was similar. The only difference between plots was that on one, trampling was applied by hikers who wore lug-soled boots, while on the second, hikers wore corrugated-soled footgear. Kuss measured erosion on the two plots to determine if boot-sole configuration was a factor in the amount of surface damage to a trail. He found no significant difference in the effect of various sole types based upon sediment yields from these experimental plots.

Only one scientific study to date has investigated the effects on trails of various users including all-terrain bicycles. Seney (1991) compared hikers, horses, off-road bicycles, and motorcycles in Gallatin National Forest, Montana. The approach of his study was unique in that he did experimental trampling on two already established trails. The trails, near Bozeman, Montana, had already been used for at least ten years, and all user types previously had access to them. After 100 passes over a trail segment by each individual user type, Seney measured the erosional effect of simulated rainfall. He also investigated the effects of slope and soil moisture on runoff and sediment yield. Through a series of difference-of-means tests, Seney observed that on pre-wetted plots horses and hikers (feet) caused more erosion than motorcycles and bicycles (wheels). However, the only significant difference noted between user types on dry plots was that horses produced significantly more sediment than the three other users. Seney suggested several reasons for not achieving more significant differences between users. First, the rainfall simulator only created storms having one-third the intensity of actual storms in the region. Secondly, there was no way of measuring how much soil was removed because it clung to feet and tires. Third, Seney's treatment only consisted of 100 passes. Especially since these trails were well-established prior to the study, it was unlikely that 100 experimental passes could have made a significant impact.

CHAPTER THREE

THE STUDY AREA

The study site is located northeast of Boulder, Colorado, near the intersection of Jay Road and 63rd Street (Figures 3.1 and 3.2). The site is owned by the City of Boulder Open Space Department. Experimental trails are constructed at the foot of a north-facing hillslope. A small irrigation ditch is located approximately 5 m north of these experimental plots. The elevation of the site is approximately 1,580 m above sea level.

Geology

The Upper Cretaceous Pierre Shale, composed of layers of olive-gray shale interbedded with fine-grained brown sandstones, underlies the area. The thickness of the Pierre Shale is estimated at 2,440 m (Trimble 1975).

Soils

Soil information was obtained from the U. S. Department of Agriculture (1975). The soils are primarily belongs to the Samsil and Renohill series. The parent material consists of calcareous weathered shale. The soils are calcareous throughout the profile, and soil reaction is mildly alkaline (pH=7.4-7.8) near the surface and moderately alkaline (pH=7.9-8.4) in the subsoil. The surface exhibits

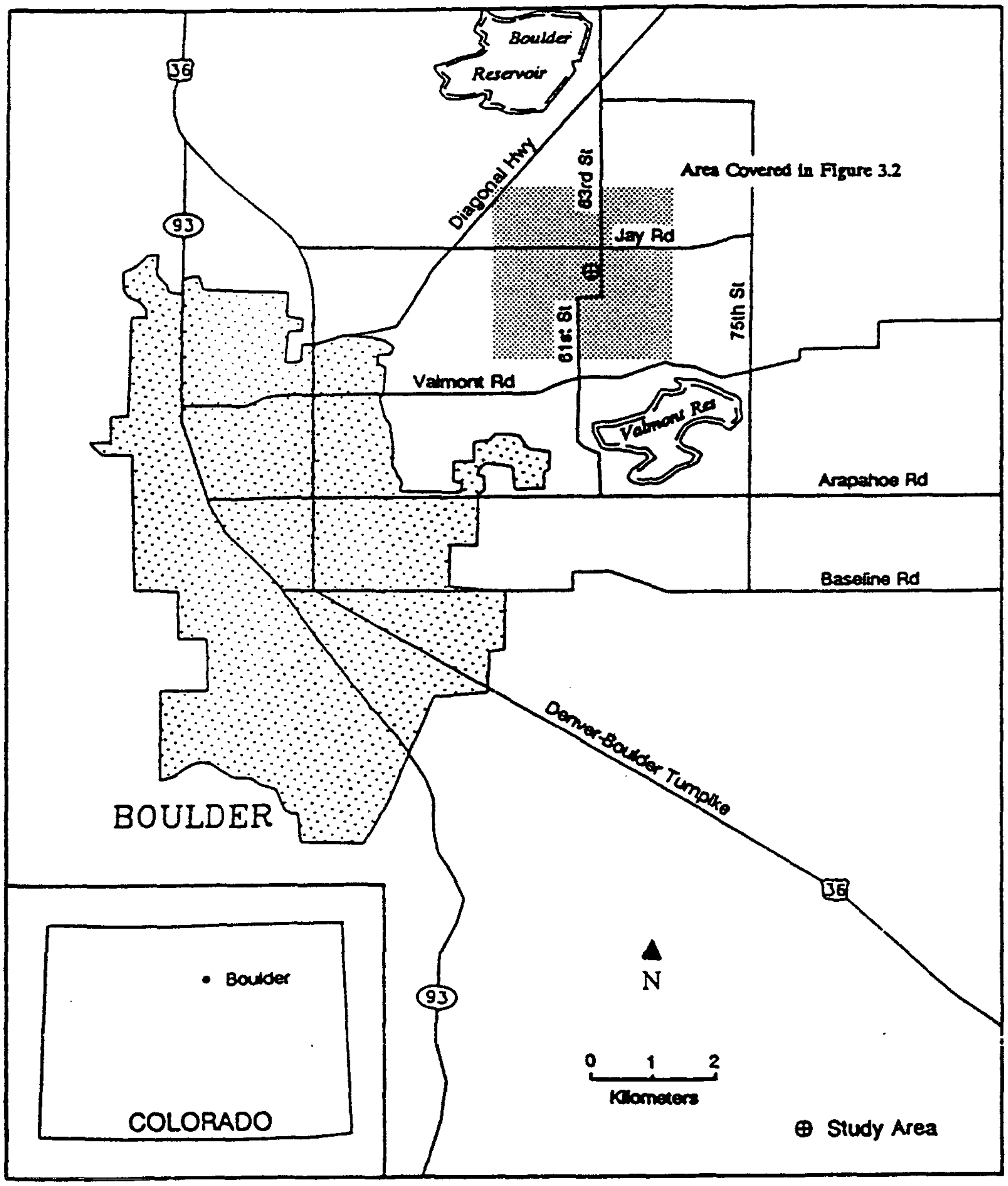

Figure 3.1. Location of study site in relation to Boulder

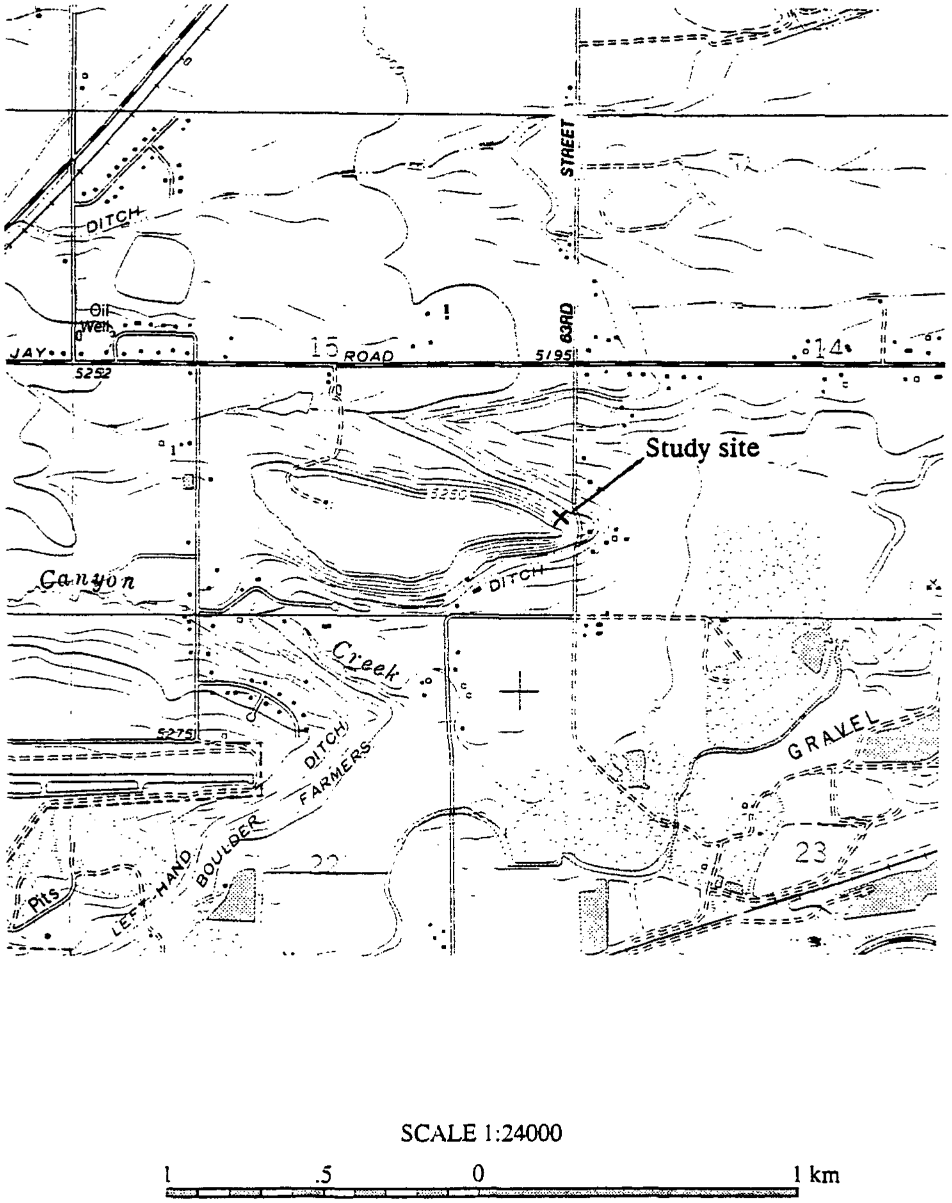

Figure 3.2. Topographic detail of study area

Source: U.S.G.S. Niwot 7.5-minute quadrangle scattered gravel and cobbles. The soils vary in texture from clay to silty clay loam. Due to soil texture the Soil Conservation Service rates these soils as having moderate to severe limitations for use as paths and trails. The soils have slow permeability, resulting in rapid runoff and high erosion potential.

Climate

Climate information was obtained from Callahan (1986), unless otherwise noted. The climate of the Boulder area is classified as a semiarid, continental type, characterized by cold, dry winters and cool, dry summers (U. S. Department of Agriculture 1975). The mean-annual temperature in Boulder is 11.1 °C. Mean winter temperature is 1.6 °C, with January being the coldest month, while average summer temperature is 21.8 °C, with July being the warmest month. Average frost-free season is 148 days, extending on average from May 8 to October 4.

Mean-annual precipitation in Boulder is 463 mm with 312 mm, or 67 percent, received during the spring and summer months. Summer precipitation is largely from convective thunderstorm activity (U. S. Department of Agriculture 1975). The maximum mean-monthly precipitation (78 mm) occurs in May, while the minimum mean-monthly precipitation (14 mm) occurs in January. Mean-annual snowfall is 1905 mm, of which 89 percent, or 1694 mm, falls during the months of November through April. Each of these months receives an average of at least 254 mm of snow. The maximum mean-monthly snowfall of 401 mm occurs in March.

Vegetation

The vegetation of the study area may be classified as a disturbed mixed-grass community (R. C. Wittmann, pers. comm., 1993). The community is considered to be disturbed due to the presence of a variety of adventive (non-native) species. Some common grasses include *Andropogon gerardii* (Big Bluestem or Turkeyfoot), *Anisantha tectorum* (Cheatgrass), *Bromopsis inermis* (Smooth Brome), *Pascopyrum smithii* (Western Wheatgrass), *Poa agassizensis* (Bluegrass), and *Stipa comata* (Needle-and-Thread). Other common herbs include *Bassia sieversiana* (Ironweed), *Convolvulus arvensis* (Creeping Jenny), *Heterotheca villosa* (Golden Aster), *Opuntia macrorhiza* (Prickly-Pear), and *Solidago missouriensis* (Smooth Goldenrod). Common shrubs in the area are *Artemisia ludoviciana* (Prairie Sage), *Gutierrezia sarothrae* (Snakeweed), and *Oligosporus dracunculus* (Wild Tarragon). A more comprehensive list of dominant plants of the study site is included in Appendix A.

CHAPTER FOUR

METHODOLOGY

Previous studies of recreation-induced damage to vegetation and soils have been primarily of two approaches, analytical or experimental. Conditions of areas disturbed by recreational use, such as trails or campsites, and those of adjacent untouched control areas with similar environmental characteristics are the subject of analytical studies (e.g., Lutz 1945; Bryan 1977; Dawson et al. 1978; Cole 1986). The analytical approach assumes that prior to use, the entire study area was homogeneous, and that there have been no significant environmental changes since the introduction of recreation. Therefore, differences in biological or edaphic characteristics between disturbed and control areas are attributed solely to recreational usage. Analytical study enables the researcher to examine long-term effects of recreation. Moreover, analytical research takes place in the actual setting under authentic trampling conditions. However, this approach has several weaknesses. Cole (1987) submits that the control area frequently is not truly identical to the condition of the disturbed area prior to recreational use. Second, LaPage (1967) points out that use of the analytical approach makes it impossible to determine how vegetation and soils respond at different stages of use. The method does not permit evaluation of the initial process or rate of change.

Use of the analytical approach also makes it difficult to control all variables that might influence the amount of change occurring on a site (Cole 1987). For example, any study that attempts to determine how various levels of recreational use affect the environment could encounter several problems. One problem is to determine how much use a site has received in the past. Usually past usage is assumed to be identical to current usage; however, use patterns may have changed through time. Another variable that may be problematic to control is user type. Separating the effects of different users is difficult, particularly if the trail is or was open to multiple user types. Even if the researcher locates trails for study that have been designated for the exclusive use of one particular user type, controlling other environmental and human-use variables may be impossible. Due to these limitations, the present research employs an experimental approach.

The experimental approach allows the researcher to control the type, method, time, conditions, and frequency of disturbance. The researcher may also choose the site of trampling so that environmental factors such as soil and vegetation type can be controlled. Experimental research usually involves repeated trampling of plots established and monitored by the researcher (e.g., LaPage 1967; Bell and Bliss 1975; Kuss 1983; Cole 1985; and Seney 1991). Sometimes artificial means such as a falling tamp are used to simulate the effects of trampling (e.g., Wagar 1964; Kellomäki and Saastamoinen 1975). However, like the analytical approach, the experimental approach also has liabilities. For example, though researchers usually attempt to imitate actual recreational-use conditions, there is an inherent artificiality in the experimental method (Cole 1987). In addition, most experimental studies are conducted over a brief time and, as a result, long-term recreational impacts cannot be assessed.

Site Design

Two experimental plots, each 4 x 10 m in dimension, are established on the study site. One of these plots is located perpendicular to the contours of the study area hillside. A clinometer is used initially to locate an area for a plot having a 10% gradient. A 10% grade is chosen for this plot because, when bicycle use is anticipated on a future trail, the Boulder Open Space Department makes particular effort to avoid construction of trails with slopes greater than 10% for a lengthy distance (B. Wheeler, pers. comm., 1993). The second plot is located at the base of the hillside parallel to the contours.

Each of the plots is divided into three lanes, each 1 m wide and 10 m long. One lane is solely for bicyclist usage. Another lane is for the exclusive use of hikers. The third lane in each plot serves as a control lane on which no trampling takes place. The control lanes are separated from their corresponding treatment lanes by a 1 m strip of vegetation to prevent accidental disturbance of these lanes during the experiment. The lanes are staked at each corner, and the edges are delineated with orange flagging tape.

"Trails" are constructed on the experimental plots according to guidelines established by the City of Boulder Open Space Department (Holland and Wheeler 1987). Vegetation is removed with a pulaski, an implement similar to a longhandled axe with a hoe blade opposite the axe face. The hoe blade on the pulaski is useful for removing vegetation, including roots, from the soil. A pick-maddox is used to dislodge large rocks from each plot. Afterwards, the bare surface is raked smooth and lightly tamped with a McLeod, an implement with rake tines opposite a wide hoe blade. The flat side of the hoe portion is used for tamping. Next, spikes are pounded into the ground at the edge of the lanes to mark locations where measurements will be taken at specified intervals. Washers are used with the spikes to increase the surface area of the spike heads so that they stay above ground. Both spikes and washers are painted bright orange to facilitate relocation in case they become hidden or buried over the course of the study.

Volunteer hikers and bicyclists trample the lanes in 1,500 passes--750 passes in each direction. Hand counters are used to tally the number of passes completed. Participants are instructed to stop and start beyond the ends of the lanes. All measurements and trampling treatments took place between 11 August and 14 September 1991.

Field Sampling

Penetrometer Measurements

Penetration resistance is used to assess the compaction caused by hiker and bicycle traffic. A pocket soil penetrometer is used to measure the soil's resistance to vertical penetration. The penetrometer is a cylindrical device with an outer tube that serves as a handle (Figure 4.1). Housed within the outer tube is a spring

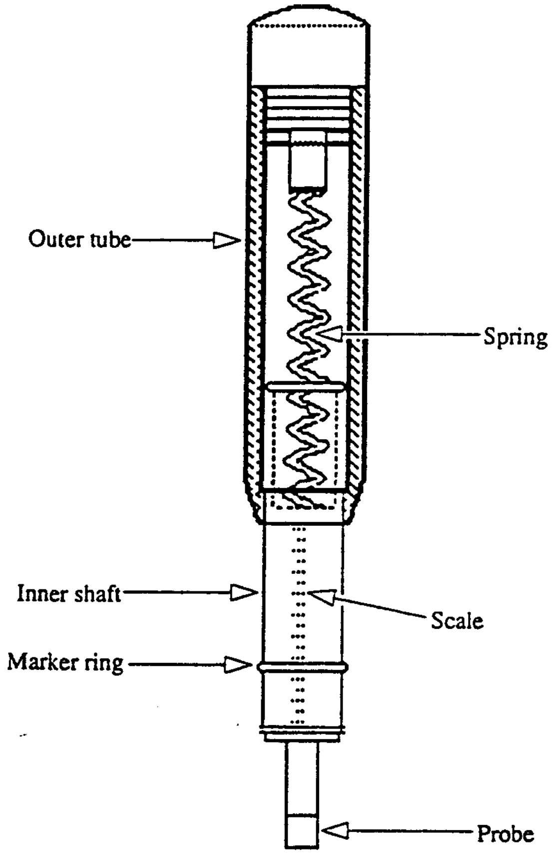

Figure 4.1. Schematic illustration showing the major components of the pocket soil penetrometer

that presses against the end of an inner shaft, causing the shaft to protrude from the tube. On the inner shaft is an engraved numeric scale that indicates the number of kilograms per square centimeter that are being exerted to push the 6.35-mm diameter probe to a depth of 6.35 mm in the soil. When pressure is exerted on this probe at the tip of the shaft, the shaft recedes into the outer cylinder against the spring's resistance. The outer tube thus pushes down a plastic marker ring along the length of the inner shaft. This ring remains in place on the scale until the penetrometer gauge is reset.

Penetrometer measurements are taken before trampling and after every 100 passes up to 1000 passes on the treatment lanes. Final measurements are taken after the application of 500 additional passes (at 1500 passes). On the control lanes, however, measurements are taken only prior to and following treatment. These measurements are taken at ten locations down the center of each lane, starting at 0.5 m from one end of the trail and continuing every meter thereafter (Figure 4.2). These positions are marked with spikes at the side of the lanes so they may be relocated for subsequent measurements.

Bulk-Density Measurements

Changes in bulk-density serve as another measure of soil compaction. Bulk density is the mass of an amount of dry soil divided by its volume (including both solid material and pore space) in g/cm^3. Compacted soils have decreased pore space and thus a decreased volume. As a result, compacted soils have greater bulk densities.

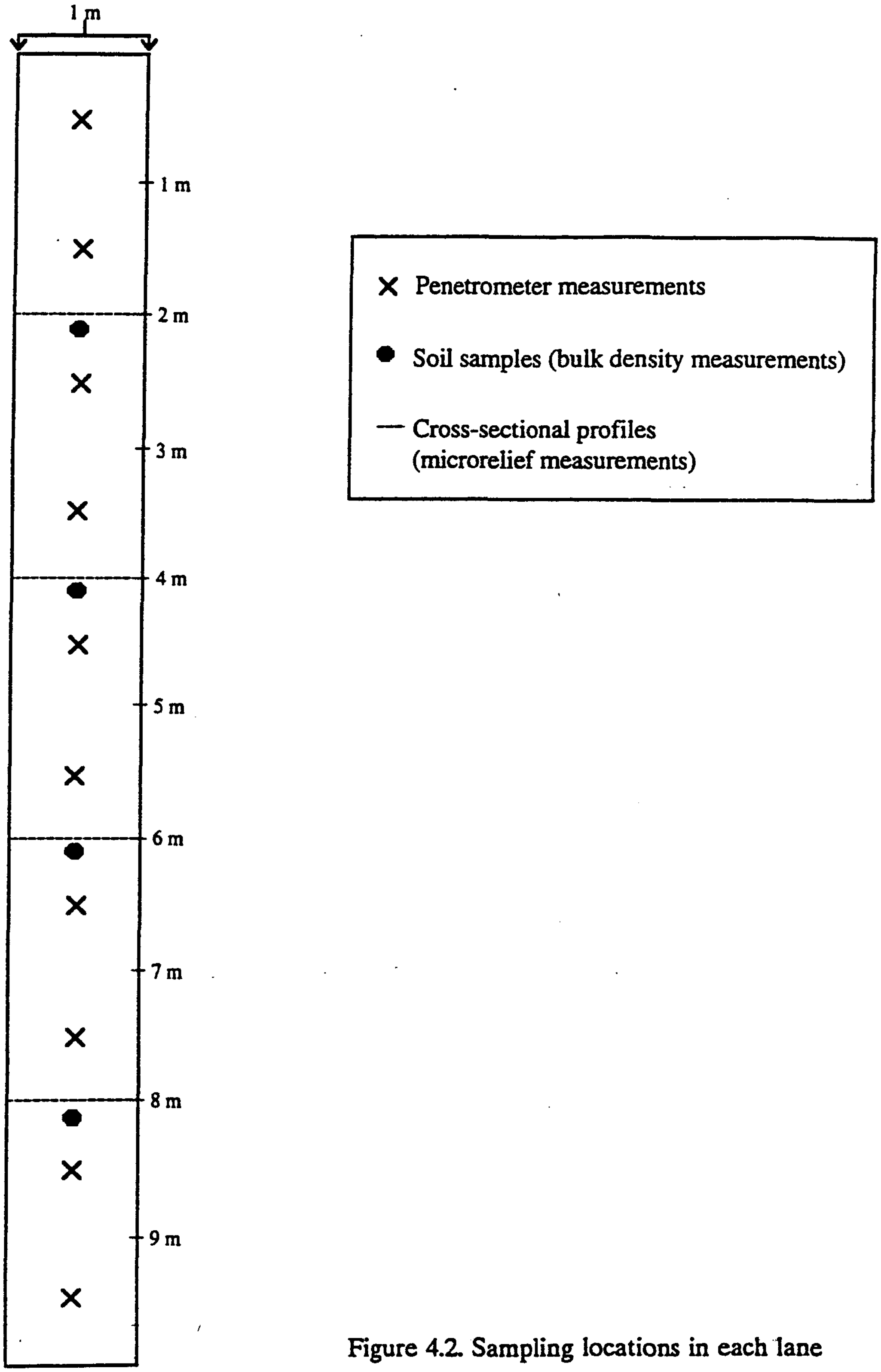

Figure 4.2. Sampling locations in each lane

A toothed 5.1-cm diameter barrel auger is used to obtain soil samples that are later analyzed in the laboratory to determine bulk density. Samples are taken at locations approximately 2, 4, 6, and 8 m down the center of each trail (Figure 4.2). At each sample site, a total of 15 cm of soil is removed in three, 5-cm increments. The holes left by the auger are then filled in with loose soil from the area surrounding the lanes. Soil samples are not taken from exactly the same location during each sampling time to avoid extracting samples from spots of the trail that have experienced previous soil removal and replacement. Thus, subsequent sets of soil samples are taken in positions several centimeters displaced from previous sampling sites. Samples are taken before treatment and after 500, 1000, and 1500 passes. The control lanes are sampled only before and after trampling of the test lanes.

Because dry soils in the study plots are likely to fall out of the auger, the sampling locations are moistened a few hours prior to sampling to make the soil more cohesive. Trampling treatment does not resume until the soil has dried out again. The soil samples are placed in ziploc bags, stored in cans labeled with the trail location and sampling time, and transported to the laboratory. The procedures for laboratory analysis are described in a later section of this chapter.

Microrelief Measurements

The microrelief of each trail's surface is determined by constructing cross-sectional profiles of each lane. These profiles are constructed by means of a point-frame. The point-frame created for this study consists of a piece of aluminum channel slightly more than 1 m in length (Figure 4.3). Two rods pass perpendicularly through both ends of the channel, supporting the channel above ground. To level the entire unit, either end of the channel may be loosened from its rod and raised or lowered. At the bottom of one of the rods is a crossbar with spikes on each end that may be pressed into the soil next to the lane to stabilize the frame. This crossbar swivels so that the frame may be tilted forward or backward. The aluminum channel has 21 holes spaced at 5-cm intervals through which metal pins slide. All pins are banded with tape at a uniform height to serve as reference marks.

At measurement times the apparatus is placed over the sampling locations, perpendicular to the orientation of the lane. Each time the frame is used, it is relocated in the same place, so that subsequent measurements may be compared directly. Thus, the height of the frame is adjusted each time by raising or lowering it so that a dowel may fit precisely between the aluminum channel and the spike marker along the side of the trail. In addition, the apparatus has two levels mounted perpendicularly to each other to insure front-to-back and side-to-side leveling. Once the frame is set up, the 21 pins are lowered, and the vertical distance along each pin from the top of the channel to the band on the pin is measured to the nearest 0.5 mm. When plotted, these measurements approximate the trail's cross-sectional profile.

Profiles are constructed across each lane at locations 2, 4, 6, and 8 m down the lanes (Figure 4.2). These locations are marked with spikes so that the same locations may be used at each measuring time. On the treatment lanes

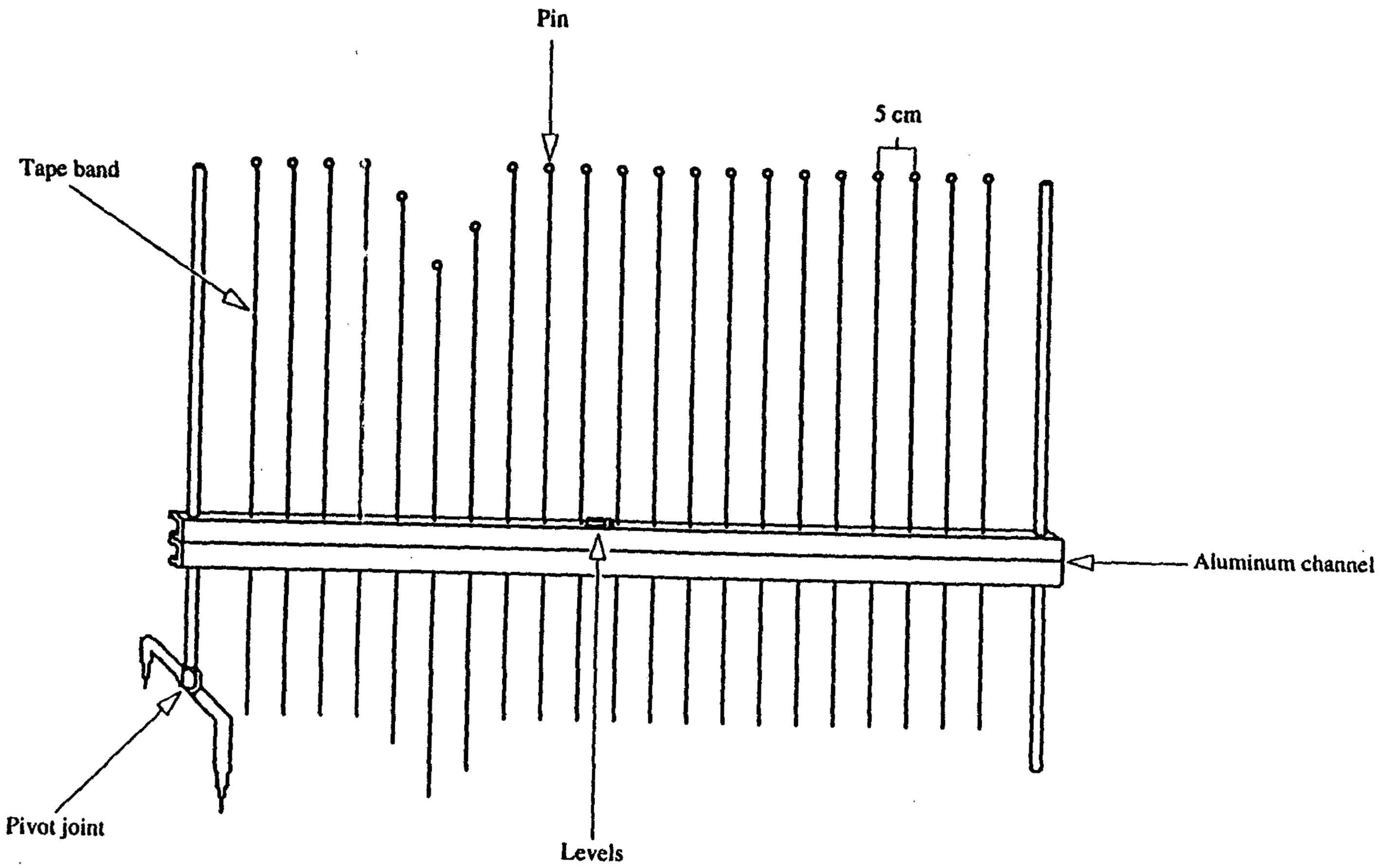

Figure 4.3. Schematic illustration showing the major components of the point frame

measurements are taken prior to trampling and after 200, 400, 600, 800, 1000, and 1500 passes. Measurements on the control lanes occur before and after completion of experimental trampling.

Laboratory Procedure

The soil samples are analyzed to determine bulk density. The following procedure is utilized for each soil sample:

1) The bagged sample is removed from the soil can, and the empty container is weighed to the nearest tenth of a gram.

2) The soil is emptied from the bag into the can, and the open can is placed in an oven at 105 °C for 24 hours. This step ensures that all moisture is removed from the soil.

3) The can of soil is removed from the oven and the lid is replaced to prevent the soil from rehydrating. The container of dry soil is cooled on an aluminum plate and then weighed to the nearest tenth of a gram.

Data Analysis

Preliminary analysis is conducted on the soil sample data to determine each sample's bulk density. To calculate the dry weight of the soil (s), the weight of the can (c) is subtracted from the total weight of the can and oven-dry soil (cs):

$$s = cs - c.$$

To obtain the bulk density (B.D.) of each sample, the weight of the oven-dry soil is divided by the volume (v) of a 5-cm increment of the auger barrel (102.14 cm^3):

$$B.D. = s \div v.$$

Preliminary computations are also performed on the trail surface profile data. To quantify the change in microrelief, the absolute value of the area between cross-sectional trail surface profiles at 0 and 1500 passes is calculated. Larger areas represent greater changes in microrelief. This calculation is performed as illustrated in Figure 4.4.

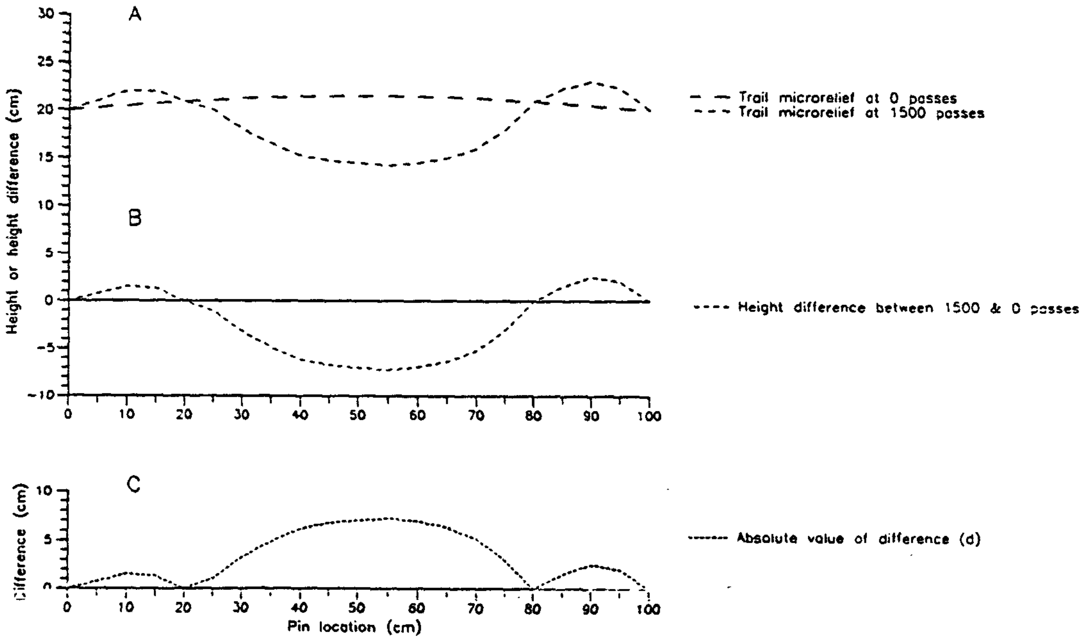

Figure 4.4 Calculation of change in microrelief

Cross-sectional profiles at 0 and 1500 passes for a hypothetical lane are depicted in Figure 4.4 A. The profile at 0 passes is subtracted from the profile at 1500 passes (Figure 4.4 B), and the absolute value of the difference is calculated (Figure 4.4

C). The area below the curve in Part C is then approximated using the Trapezoidal Rule:

$$\text{Area} = \left(\frac{d_0 + d_n}{2} + \sum_{i=1}^{n-1} d_i \right) \cdot s$$

where

d_0 = absolute value of the difference at the first pin location (0 cm),

d_i = absolute value of the difference at the *i*th pin location,

d_n = absolute value of the difference at the last pin location (100 cm),

and

s = spacing between pin locations (5 cm for this study).

All statistical operations are conducted with Minitab software. A difference of means test is selected as the appropriate method to make comparisons between bicycle and hiker lanes and between sloped and flat lanes. For comparisons within a lane after various pass totals, a matched pairs t-test is selected. The matched pairs test is appropriate in this instance because the data are not independent since the measurements are taken on the same lanes but after different use levels. A pair consists of one measurement taken at a particular location on a lane after a certain number of passes and a second measurement taken in the same location after additional passes. In a matched pairs test, the differences between the pair-by-pair data are computed before the test statistic is calculated. The test statistic is essentially the same as for a single-sample t-test except that the differences are substituted for the single-sample data.

Matched pairs t-tests are used to determine whether individual lanes have changed significantly in terms of compaction after varying levels of use. Therefore, the penetration resistance data for each lane after two levels of usage are compared (i.e. flat bicycle lane at 1000 passes vs. the lane at 1500 passes, etc.). The same procedure is followed for bulk-density data.

Difference of means tests are performed to determine if user type has an impact on the extent of compaction on a trail. Consequently, penetration resistance of lanes having the same gradient is compared (i.e. flat bicycle lane vs. flat hiker lane, and sloped bicycle lane vs. sloped hiker lane). To ascertain whether the degree of compaction is affected by slope, difference of means tests are used to compare the penetration resistance of trails having the same user types (i.e. sloped bicycle lane vs. flat bicycle lane, and sloped hiker lane vs. flat hiker lane). As a second means of assessing compaction, bulk densities are compared in a similar manner. Difference of means tests are also used to determine if the control lanes remain unchanged between the beginning and end of trampling of the treatment lanes. To determine whether user type or gradient affects microrelief, difference of means tests are used to compare the cross-sectional areas between the 0- and 1500-pass profiles of each lane. Additional detail concerning statistical analysis is located in Chapter Five.

CHAPTER FIVE

RESULTS

This chapter is divided into three parts. In the first section, penetration-resistance data of the experimental lanes are compared to determine the extent of soil compaction caused by hikers and bicyclists on lanes with flat and sloping gradients. In the second section, compaction of the two user types on the two slopes is evaluated in terms of soil bulk-density data. The depth to which cyclists and hikers compact soils is also discussed. Finally, in the third section, cross-sectional profiles of each experimental lane are presented to assess the extent to which different users affect trail microrelief on varying grades.

Penetration Resistance

Penetration resistance is measured with a pocket soil penetrometer before the experiment and every 100 passes thereafter up to 1000 passes, and at 1500 passes. Measurements on the control lanes occur only before and after completion of trampling on the treatment lanes. Due to incorrect use of the instrument, no data are available between 0 and 500 passes[1]. For this reason, it is impossible to

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[1] After construction of the experimental lanes but before initial measurements were made, the research equipment, including the penetrometer, was tried out. At

confirm from existing data whether the treatment and control lanes were similar in terms of penetration resistance prior to the experiment. However, because the experimental lanes were newly and consistently constructed, the researcher suspects that at that time, penetration resistance of all lanes would have been close to 0 kg/cm^2 (See footnote 1).

Mean penetration resistance (n = 10 for each lane) of the four treatment lanes and two control lanes is presented graphically in Figure 5.1. Penetration-resistance data, means, and standard errors are also recorded in Appendix B. Between 500 and 1000 passes, penetration-resistance of both bicycle and hiking lanes oscillates, rather than steadily increases or decreases. At 1000 passes mean penetration resistance is actually 0.77, 0.12, 0.20, and 0.48 kg/cm^2 lower than it was 500 passes earlier on the flat bicycle, sloped bicycle, flat hiker, and sloped hiker lanes, respectively. This oscillation and net decrease in penetration resistance is contrary to the hypothesis that compaction should increase in a curvilinear fashion. In contrast, between 1000 and 1500 passes mean penetration resistance increases 2.50, 1.57, 1.77, and 1.63 kg/cm^2 for the flat bicycle, sloped bicycle, flat hiker, and sloped hiker lanes. It should be noted that the soils were dry throughout the first

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this time all the lanes were covered with very loose soil. Several test measurements were taken with the penetrometer on each lane; however, all the readings were 0 kg/cm^2. Therefore, it was decided (erroneously) that the entire penetrometer probe should be inserted into the soil rather than only the outer 6.35 mm of the probe. However, within a few hundred passes the penetrometer was consistently registering the maximum reading, even though it was obvious that the soil had not yet become that compacted. Therefore, at 500 passes the researcher resumed taking penetrometer measurements to a depth of 6.35 mm.

Figure 5.1. Mean penetration resistance

1000 passes of trampling when a net decrease in penetration resistance is observed. In contrast, the significant increase in penetration resistance between 1000 and 1500 passes is noted following the only substantial precipitation which fell during the study. This precipitation event occurred after 1100 passes.

Evaluation of Hypothesis 1

Matched pairs t-test results are used to compare penetration resistance at different sampling times to determine the effect of use on each trail. For each lane the difference between the 10 measurements taken after the two usage levels specified in the left column of Table 5.1 is calculated. From these differences a t value is computed. The tests are one-tailed because it is assumed that penetration resistance increases with trail use (i.e. direction is predicted). The p-values summarized in Table 5.1 indicate the probability that the two sets of data are from different populations. A value of 0.05 or less indicates two statistically significant different sets of data at a 5% level of significance.

For each treatment lane, the p-values for tests comparing penetration resistance at 1000 passes to that at 500 passes are all greater than 0.05, indicating that none of the trails changed significantly between these usage levels. In contrast, between 1000 and 1500 passes, the p-values for all treatment lanes are less than 0.05. Thus, the penetration resistance of the four lanes is significantly greater after 1500 passes than after 1000 passes.

Table 5.1

P-values showing effect of trail use on penetration resistance

	Lane*			
Test (n = 10)	BF	BS	HF	HS
1000 - 500 passes	1.00	0.70	0.870	1.00
1500 - 1000	0.000	0.000	0.000	0.000

*The abbreviations BF, BS, HF, HS, CF, and CS refer to the flat bicycle, sloped bicycle, flat hiker, sloped hiker, flat control, and sloped control lanes, respectively. These abbreviations are used in subsequent tables.

Note: Statistically significant differences at the 5% level of significance are underlined.

If the penetration resistance data had followed a curvilinear relation with use as hypothesized, significant increases in penetration resistance would have been expected to occur after initial passes, and with additional passes changes in penetration resistance would become insignificant. This is contrary to what was actually observed in the experiment. However, there is insufficient data to reject hypothesis 1 because at 1500 passes the penetration resistance of all treatment lanes was still increasing. It is impossible to ascertain whether with additional trail usage, penetration resistance will ultimately level off, or decrease and increase erratically.

Evaluation of Hypothesis 2A

At any usage level between 500 and 1500 passes, the two bicycle lanes exhibit greater mean penetration resistance than the two hiker lanes (Figure 5.1). Difference of means tests comparing penetration-resistance data from the bicycle and hiker lanes having similar gradients are used to determine if there are differences between trails with respect to user type (Table 5.2). Because of the high variability of means exhibited between 500 and 1000 passes, all data for each trail at 500, 600, 700, 800, 900, and 1000 passes are combined. For this comparison sample size is 60 (ten measurements at each of the six usage levels). The data (n = 10) at 1500 passes are tested separately. Because it is hypothesized that bicyclists should compact soils more than hikers, the tests are one-tailed.

Table 5.2

P-values showing user type impact on soil penetration resistance

	Passes	
Test	500 to 1000 (n = 60)	1500 (n = 10)
BF - HF	0.000	0.037
BS - HS	0.000	0.006

Note: Statistically significant differences at the 5% level of significance are underlined.

Despite the fluctuations that occur between 500 and 1000 passes, the penetration resistance of the lanes used by bicyclists is significantly greater than that of corresponding lanes used by hikers. Though this significant difference in terms of penetration resistance exists between user types, conclusions regarding hypothesis 2A are not offered because penetration resistance never reached a steady state for any of the lanes as predicted. The hypothesis may be true nonetheless, but sufficient data to establish this as a fact were not acquired.

Evaluation of Hypothesis 2B

It is hypothesized that sloped lanes should exhibit greater compaction than flat lanes having the same recreational user type. One-tailed difference of means tests are used to test the statistical significance of the difference between the penetration resistance of flat and sloping lanes having similar users (Table 5.3).

Table 5.3

P-values showing effect of gradient on penetration resistance

Test	Passes 500 to 1000 (n = 60)	 1500 (n = 10)
BS - BF	0.64	0.80
HS - HF	0.55	0.89

Note: Statistically significant differences at the 5% level of significance are underlined.

No significant differences in penetration resistance between trails of varying grades are noted. In addition, because penetration resistance has not reached a steady state by 1500 passes, the ultimate conditions of penetration resistance of the trails remains unknown. Therefore, conclusions concerning the hypothesis that sloped lanes should exhibit greater compaction than flat lanes, in terms of penetration resistance, remain uncertain.

Bulk Density

Soil compaction is also assessed with bulk-density measurements. Bulk density is calculated at three depth increments for soil samples taken after 0, 500, 1000, and 1500 passes on the treatment lanes. The control lanes are sampled only prior to and following trampling on the treatment lanes. A summary of bulk-density data for each trail is recorded in Appendix C. Mean bulk-density data (n = 4 for each lane) and standard errors are summarized in Table 5.4.

In general, bulk density of the soil from the surface to 5 cm depth increases with use in each of the four treatment lanes (Table 5.4, Figure 5.2). However, bulk density of the flat bicycle lane remains relatively constant between 500 and 1000 passes as does the bulk density of the sloped hiker lane between 500 and 1500 passes. Overall between 0 and 1500 passes, mean bulk density of the flat bicycle lane, sloped bicycle lane, flat hiker lane, and sloped hiker lane increases 0.38, 0.33, 0.51, and 0.27 g/cm^3, or 43%, 38%, 60%, and 36%, respectively. Probably as a result of the soil settling through time on the freshly constructed lanes, bulk density increases 0.18 g/cm^3 (25%) on the flat control and 0.17 g/cm^3 (23%) on the sloped control lane.

Changes in bulk densities of soil in the 5-10 cm depth increment are less consistent through use (Table 5.4, Figure 5.3). Bulk density of the two bicycle lanes and the flat hiker lane increases initially but later decreases. Between 0 and 1500 passes, the overall change in bulk density is 0.10 g/cm^3 on the flat bicycle lane, an 8% increase; -0.02 g/cm^3 on the sloped bicycle lane, a 2% decrease; and

Table 5.4

Mean bulk-density data and standard errors for each lane

Increment (cm)	Pass	BF	BS	HF	HS	CF	CS
		Mean bulk density (g/cm^3)					
0-5	0	0.88 ±0.03	0.86 ±0.06	0.85 ±0.04	0.76 ±0.05	0.73 ±0.04	0.73 ±0.04
0-5	500	1.18 ±0.07	0.96 ±0.21	1.07 ±0.06	1.02 ±0.05		
0-5	1000	1.18 ±0.07	1.03 ±0.05	1.19 ±0.06	1.01 ±0.03		
0-5	1500	1.26 ±0.15	1.19 ±0.02	1.36 ±0.18	1.03 ±0.06	0.91 ±0.06	0.90 ±0.03
5-10	0	1.22 ±0.05	1.14 ±0.10	1.34 ±0.08	1.07 ±0.10	1.30 ±0.05	1.34 ±0.09
5-10	500	1.52 ±0.15	1.31 ±0.06	1.39 ±0.10	1.10 ±0.02		
5-10	1000	1.45 ±0.03	1.33 ±0.05	1.58 ±0.11	1.26 ±0.09		
5-10	1500	1.32 ±0.09	1.12 ±0.12	1.37 ±0.09	1.35 ±0.13	1.14 ±0.12	1.23 ±0.04
10-15	0	1.37 ±0.06	1.38 ±0.06	1.41 ±0.05	1.32 ±0.05	1.43 ±0.03	1.50 ±0.09
10-15	500	1.40 ±0.04	1.35 ±0.09	1.37 ±0.08	1.43 ±0.19		
10-15	1000	1.35 ±0.05	1.33 ±0.06	1.42 ±0.13	1.30 ±0.04		
10-15	1500	1.60 ±0.06	1.38 ±0.04	1.56 ±0.09	1.58 ±0.11	1.72 ±0.10	1.40 ±0.11

Figure 5.2. Mean bulk density: 0–5 cm increment

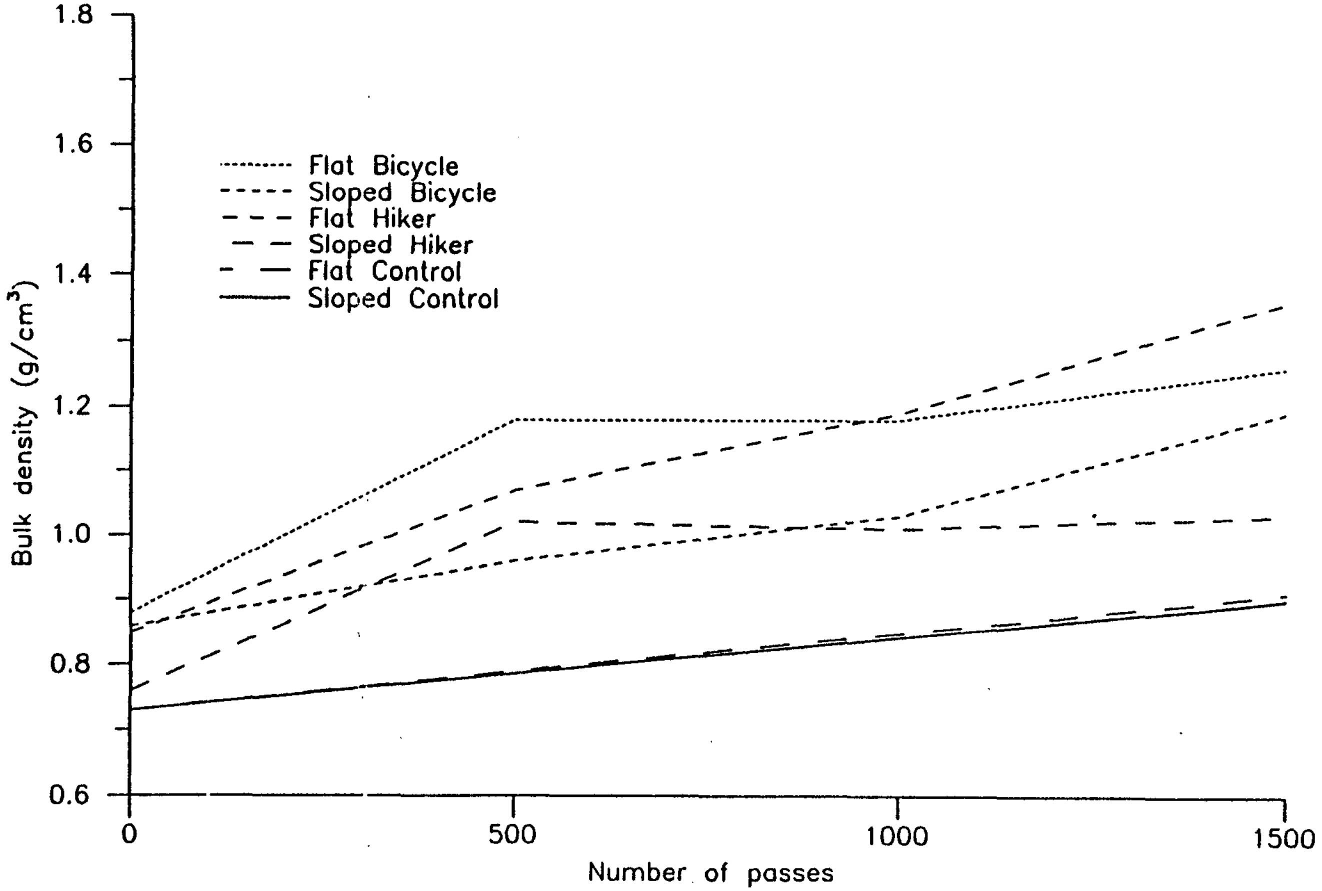
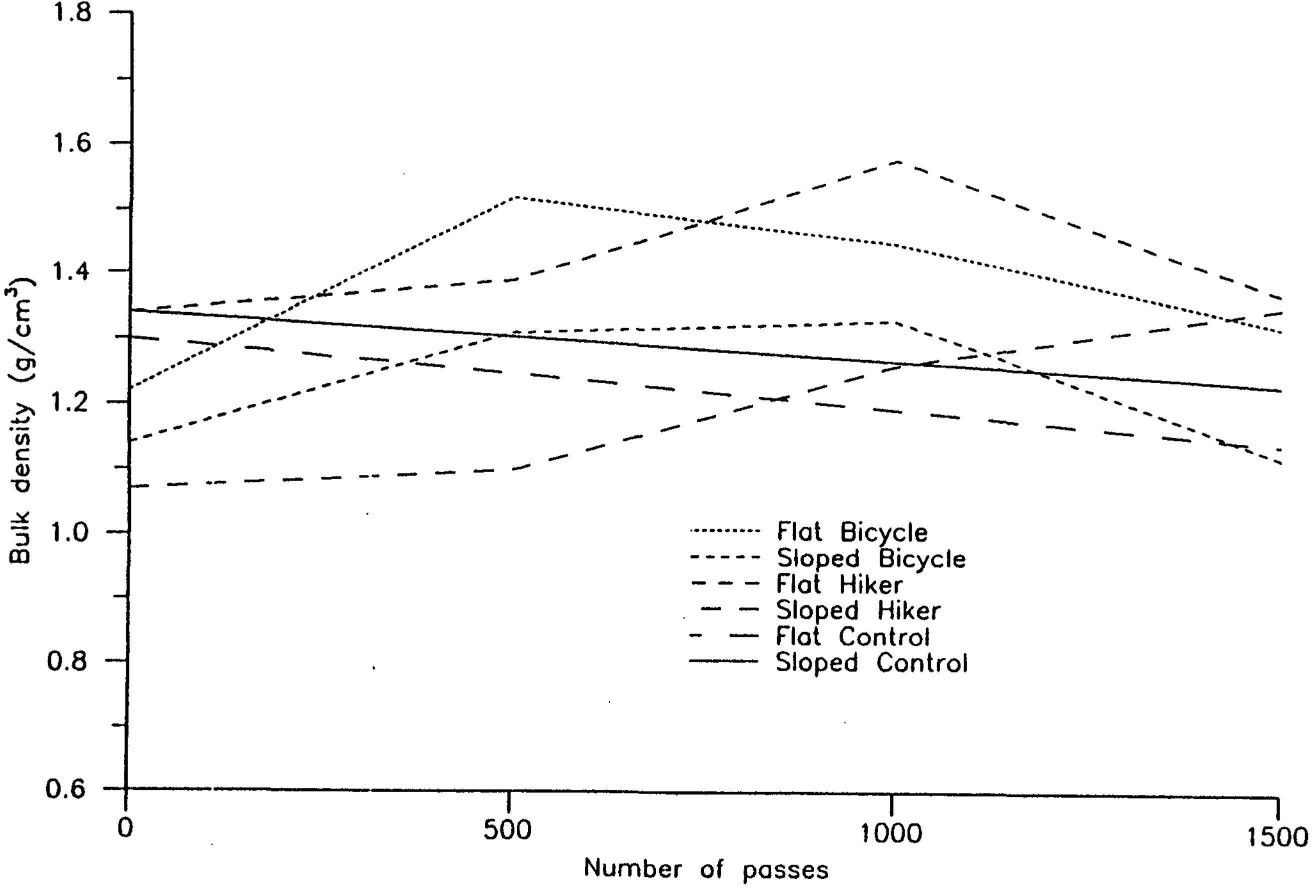


Figure 5.3. Mean bulk density: 5-10 cm increment



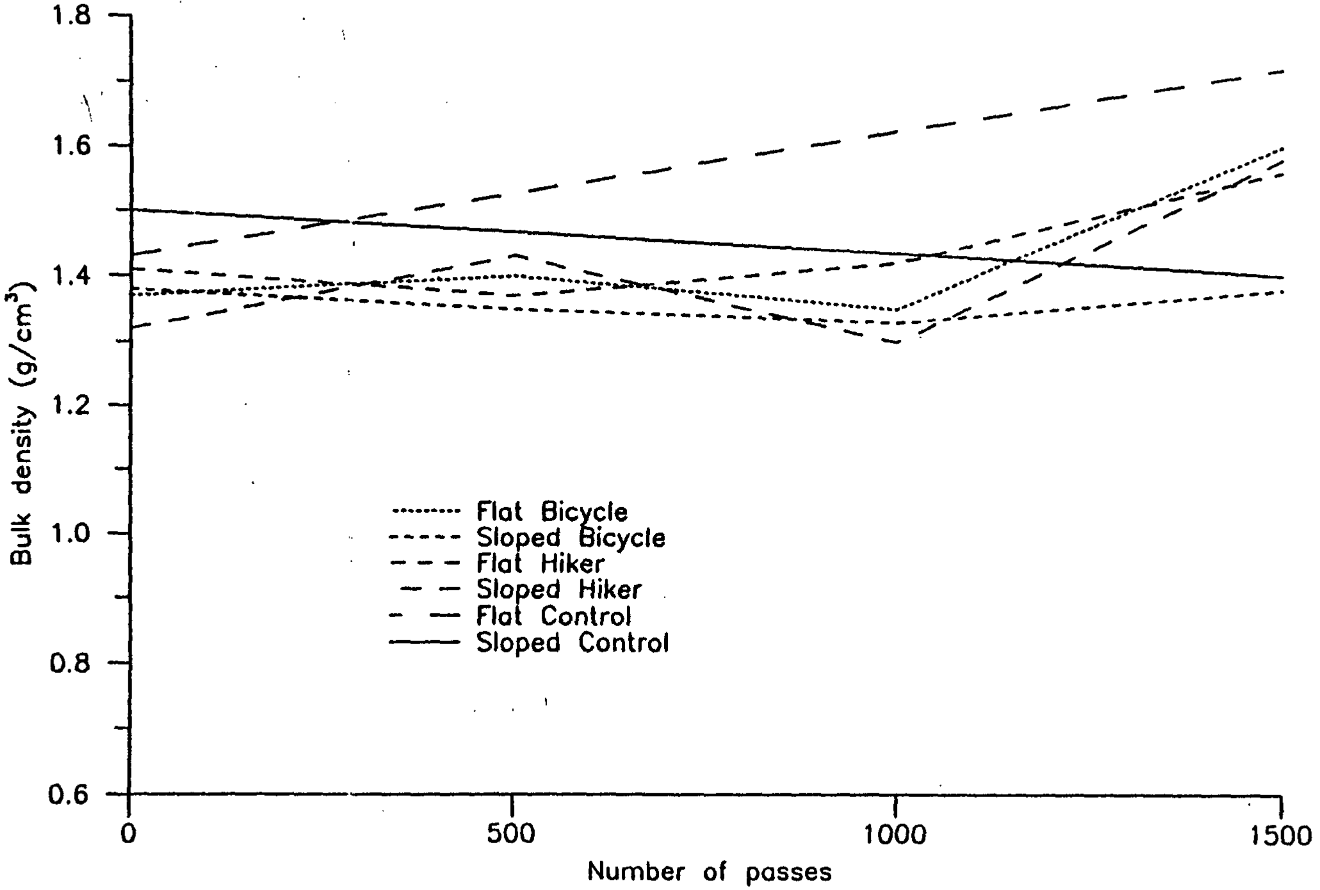
0.03 g/cm^3 on the flat hiking lane, a 2% increase. In contrast, the bulk density of the sloped hiker lane consistently increases for a total change of 0.28 g/cm^3 (26%) after 1500 passes. Bulk density decreases 0.16 g/cm^3 (12%) on the flat control lane and 0.11 g/cm^3 (8%) on the sloped control during the experiment. These decreases in bulk density of the control lane are highly suspect because they seem to defy logic and natural expectations. They may be indications of experimental error in the method of data collection.

In all treatment lanes bulk density of the 10-15 cm soil increment remains fairly constant up to 1000 passes (Table 5.4, Figure 5.4). Between 1000 and 1500 passes, bulk density increases for all treatment lanes except the sloped cyclist lane which remains relatively constant. Specifically, between 0 and 1500 passes bulk density increases by 0.23 g/cm^3 (17%), 0 g/cm^3, 0.18 g/cm^3 (13%), and 0.26 g/cm^3 (20%) on the flat bicycle, sloped bicycle, flat hiker, and sloped hiker lanes, respectively. The bulk density of the flat control lane increases more in absolute terms (0.29 g/cm^3 or 20%) than any of the treatment lanes at the 5-10 cm depth and the 10-15 cm depth between 0 and 1500 passes. The bulk density of the sloped control decreases 0.10 g/cm^3 (7%). As stated previously, a decrease in bulk density on a control lane may raise doubts concerning the accuracy of the bulk density data.

Evaluation of Hypotheses 1 and 3

For each lane matched pairs t-tests are used to compare soil bulk-density after various levels of use during the experiment (Table 5.5). One-tailed tests are

Figure 5.4. Mean bulk density: 10–15 cm increment



used for data from the treatment lanes because it is predicted that bulk density increases with use. Two-tailed tests are conducted on control lanes because no direction is predicted. Sample size is four for all tests.

Table 5.5

P-values showing effect of trail use on bulk density

A: 0-5 cm Increment

	Lane					
Test (n = 4)	BF	BS	HF	HS	CF	CS
500 - 0 passes	0.005	0.21	0.02	0.045		
1000 - 500	0.49	0.54	0.17	0.57		
1500 - 1000	0.31	0.029	0.19	0.38		
1500 - 0	0.032	0.011	0.034	0.015	0.046	0.073
B: 5-10 cm Increment						
500 - 0 passes	0.054	0.16	0.32	0.39		
1000 - 500	0.67	0.40	0.13	0.10		
1500 - 1000	0.71	0.93	0.88	0.24		
1500 - 0	0.16	0.54	0.43	0.11	0.23	0.37
C: 10-15 cm Increment						
500 - 0 passes	0.58	0.59	0.63	0.33		
1000 - 500	0.61	0.61	0.46	0.77		
1500 - 1000	0.17	0.35	0.21	0.026		
1500 - 0	0.11	0.52	0.17	0.04	0.041	0.17

Note: Statistically significant differences at the 5% level of significance are underlined.

For the 0-5 cm increment of soil, a statistically significant increase in bulk density occurs only between 0 and 500 passes and between 0 and 1500 passes on the flat bicycle, flat hiker, and sloped hiker lanes (Table 5.5 A). Bulk density does not increase significantly on the sloped bicycle lane until the interval between 1000 and 1500 passes.

A statistically significant increase in bulk density at the 0-5 cm depth increment also occurs on the flat control lane between the beginning and end of the experiment. In addition, at the 10% level of significance, the increase in bulk density on the sloped control lane is statistically significant. These significant increases in bulk density on the control lanes raise doubts concerning the validity of significance of changes on the treatment lanes. It is uncertain whether changes on the treatment lanes would have occurred naturally had no trampling taken place on them, or whether the changes on the treatment lanes are actually greater than those occurring on the control lanes and may be partially attributable to trampling.

No statistically significant increases in bulk density in the 5-10 cm increment of soil result from trail use (Table 5.5 B). In the 10-15 cm soil increment, bulk density increases significantly on the sloped hiker trail between 1000 and 1500 passes and between 0 and 1500 passes (Table 5.5 C). However, there seems to be no explanation for this increase in bulk density, bringing into question the statistical results. It is assumed that any increases in soil bulk density at this soil depth could be detected in overlying soil layers. Yet, at the 5-10 cm depth increment no significant increases in bulk density are noted. Interestingly, a statistically significant increase in bulk density is also recorded for the flat control lane between 0 and 1500 passes, although no experimental treatment occurred on this lane, and the layer (5-10 cm depth) of soil immediately above does not increase significantly.

Because of the questionable nature of the results, conclusions are indeterminate regarding the hypothesis that compaction increases in a curvilinear fashion with use. For the same reason, no conclusions are drawn concerning the hypothesis that compaction caused by hikers and bicyclists decreases with depth.

Evaluation of Hypothesis 2A

The hypotheses that bicycles cause greater soil compaction than hikers on trails having the same gradient, and that compaction for both user types is greater on sloping than flat lanes, were already discussed in terms of penetration resistance. These hypotheses are now evaluated in terms of bulk density. Difference of means tests compare the bulk densities of soil samples from bicycle lanes to hiker lanes (Table 5.6). Also included in Table 5.6, in a column entitled "aggregate", are p-values from tests in which the bulk-density data from 500, 1000, and 1500 passes are combined. Because it is assumed that the lanes had similar bulk densities prior to trampling treatment, tests comparing trails at 0 passes are two-tailed, while tests comparing data after various amounts of trampling are one-tailed.

At 0 passes, there are no statistically significant differences between lanes used by cyclists or hikers which show that the lanes are similar in terms of bulk density and, therefore, bias has not been incorporated in the experimental design.

Table 5.6

P-values showing user type impact on bulk density

		Passes				
Test	Depth (cm)	0	500	1000	1500	aggregate*
BF - HF	0-5	0.53	0.15	0.53	0.66	0.50
(n = 4)	5-10	0.25	0.25	0.83	0.64	0.57
	10-15	0.67	0.38	0.67	0.35	0.50
BS - HS	0-5	0.28	0.58	0.38	0.040	0.15
(n = 4)	5-10	0.66	0.022	0.26	0.88	0.42
	10-15	0.52	0.65	0.34	0.89	0.80
B - H	0-5	0.22	0.26	0.47	0.41	0.27
(n = 8)	5-10	0.74	0.073	0.64	0.89	0.53
	10-15	0.88	0.61	0.56	0.86	0.78

*Sample size for the "aggregate" column is n x 3.

Note: Statistically significant differences at the 5% level of significance are underlined.

During the experiment there are no significant differences in bulk density between the flat bicycle lane and the flat hiker lane, regardless of depth or number of passes (Table 5.6). Thus, on lanes that are flat, user type does not seem to affect bulk density. Two significant differences in bulk density between the sloped bicycle and hiker lanes are apparent. One such difference is at depth 5-10 cm, 500 passes. The other significant difference between the two sloped treatment lanes is at depth 0-5 cm, 1500 passes.

Results of tests in which the combined bulk-density data of both flat and sloped bicycle lanes are compared with that of both flat and sloped hiking lanes are shown in the section of Table 5.6 labeled "B - H". In the section "B - H" sample size is eight (two lanes of different gradients, each with four samples). Calculated p-values could be interpreted to mean that user type has no effect on compaction of newly formed trails. Although the data suggest that hypothesis 2A, bicyclists cause greater changes in compaction than hikers, should be rejected, it must be remembered that doubts have been raised regarding the validity of the data. Therefore conclusions concerning hypothesis 2A are indeterminate.

Evaluation of Hypothesis 2B

The hypothesis that sloped lanes exhibit greater compaction than flat lanes having the same user type is tested with difference of means tests of bulk density of the treatment lanes (Table 5.7). Tests comparing lanes prior to trampling are two-tailed, as are tests comparing the control lanes. All other tests are one-tailed because sloped lanes are hypothesized to exhibit greater compaction than flat lanes.

At 0 passes flat lanes and corresponding sloped lanes are similar in terms of bulk density, showing that no bias has been incorporated in the experimental design (Table 5.7). At 500, 1000, and 1500 passes there are also no statistically significant differences between lanes of varying grades. The statistical evidence suggests that the hypothesis that sloped lanes experience greater increases in bulk density than flat lanes be rejected. However, conclusions remain uncertain due to the questionable nature of the data.

Table 5.7

P-values showing effect of trail gradient on bulk density

		Passes				
Test	Depth (cm)	0	500	1000	1500	aggregate*
BS - BF (n = 4)	0-5	0.79	0.75	0.93	0.66	0.95
	5-10	0.54	0.85	0.95	0.88	0.98
	10-15	0.91	0.69	0.58	0.97	0.95
HS - HF (n = 4)	0-5	0.26	0.75	0.97	0.91	0.99
	5-10	0.092	0.97	0.97	0.54	0.99
	10-15	0.31	0.39	0.77	0.43	0.61
S - F (n = 8)	0-5	0.37	0.93	1.00	0.94	1.00
	5-10	0.061	0.98	0.99	0.83	1.00
	10-15	0.52	0.47	0.82	0.90	0.88
CS - CF (n = 4)	0-5	0.97			0.88	
	5-10	0.72			0.51	
	10-15	0.49			0.10	

*Sample size for the "aggregate" column is n x 3.

Note: Statistically significant differences at the 5% level of significance are underlined.

Trail Microrelief

Cross-sectional profiles across each trail are constructed at four locations. Profiles are measured after 0, 200, 400, 600, 800, 1000, and 1500 passes on the treatment lanes. On control lanes profiles are measured before and after trampling of the test lanes. The profiles of all trails at all locations and measurement passes are included in Appendix D.

Representative cross-sectional profiles of all trails are presented and described. A profile of the flat control lane, located 6 m from one end of the trail, is illustrated in Figure 5.5. This lane's microrelief changes only slightly between the beginning and end of the experiment. In fact, the average absolute difference between pin heights at 0 and 1500 passes for all four profile locations is only 0.35 cm. At all four measurement locations, aggradation is observed.

Similarly, the profile of the sloped control lane at 4 m (Figure 5.6) exhibits an average difference in pin heights for the four profile locations of only 0.29 cm. Toward the top of the slope, the lane exhibits slight degradation, whereas near the bottom of the slope, the lane displays aggradation, possibly evidence of soil eroding from above and being deposited below.

In contrast to the control lanes, which exhibit little change in terms of microrelief, the lanes used by hikers and cyclists exhibit notable change. The profile of the flat hiker trail, location 6 m (Figure 5.7), develops a slight depression within the first 200 passes. Observations during the experiment confirm that this depression is where hikers walked most frequently. At 1500 passes, the approximate width of this depression varies between 25 and 45 cm, depending on location. The maximum depth of this depression, compared to the pre-treatment trail surface, ranges between 1.0 and 1.5 cm. The flat hiking lane also exhibits aggradation of soil on either side of the depression.

The changes in microtopography of the flat bicycle lane at location 2 m are depicted in Figure 5.8. Although little change in microrelief occurs until 400 passes are completed, major changes occur within the first 200 passes at the other

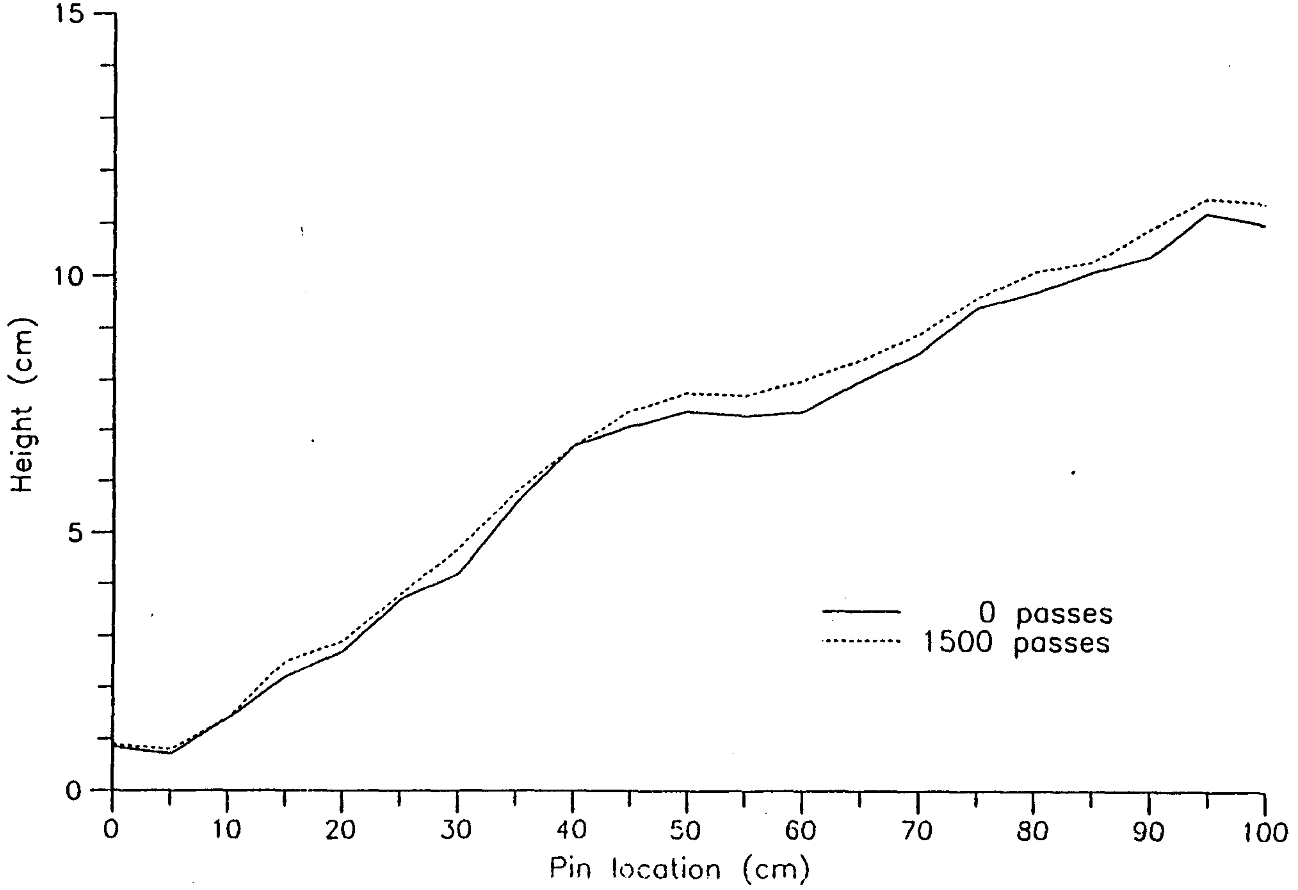


Figure 5.5. Profile of flat control lane: location 6 m

Figure 5.6. Profile of sloped control lane: location 4 m

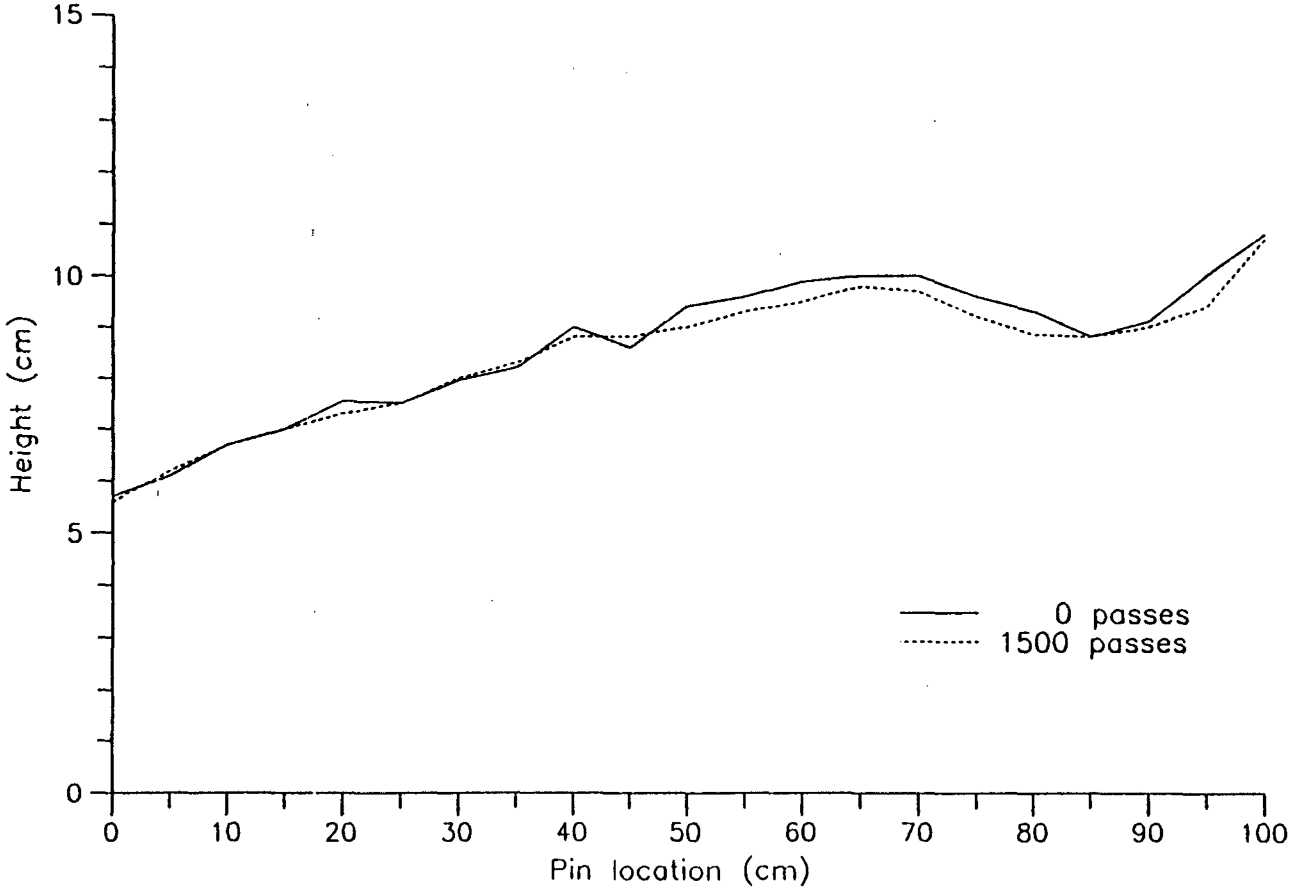


Figure 5.7. Profile of flat hiker lane: location 6 m

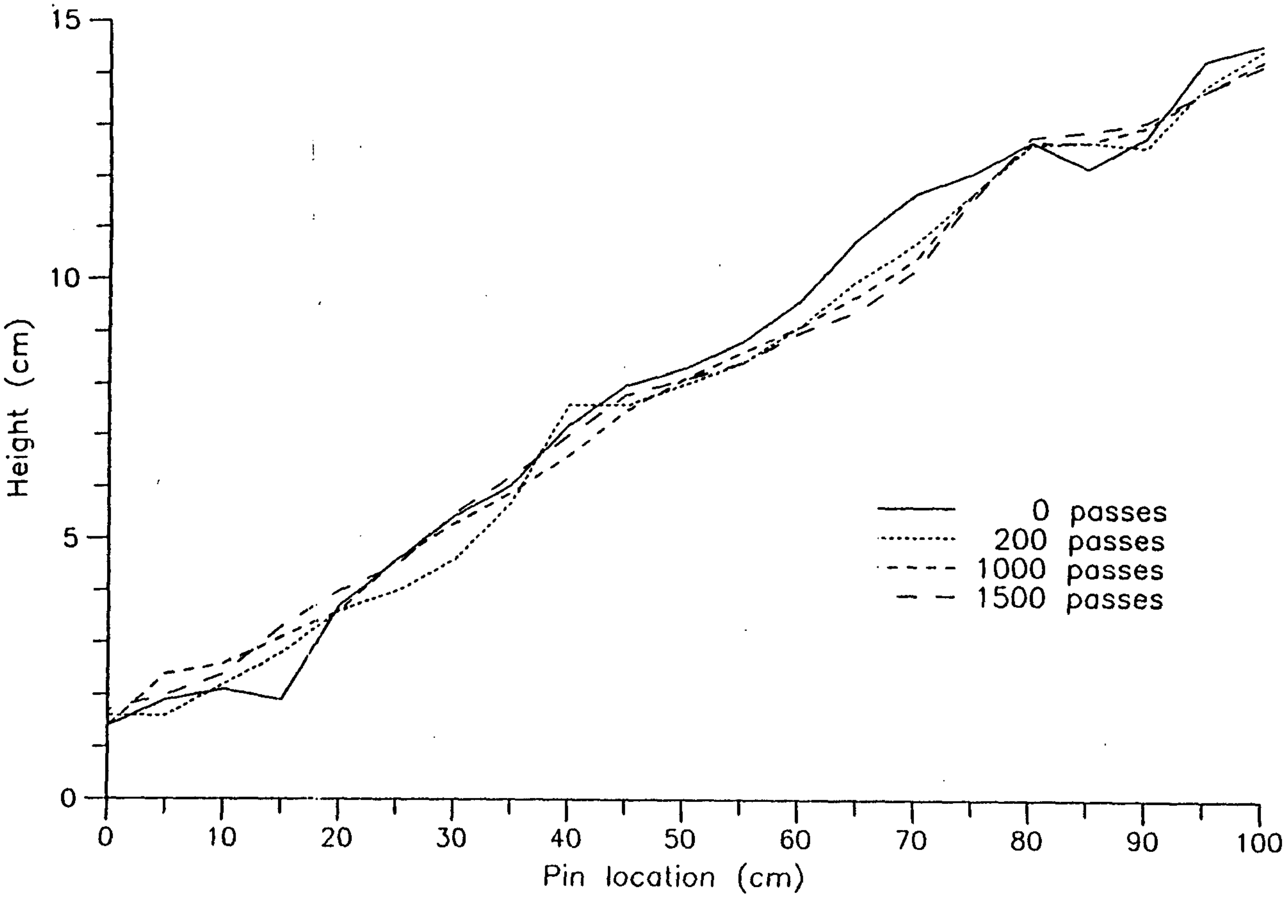
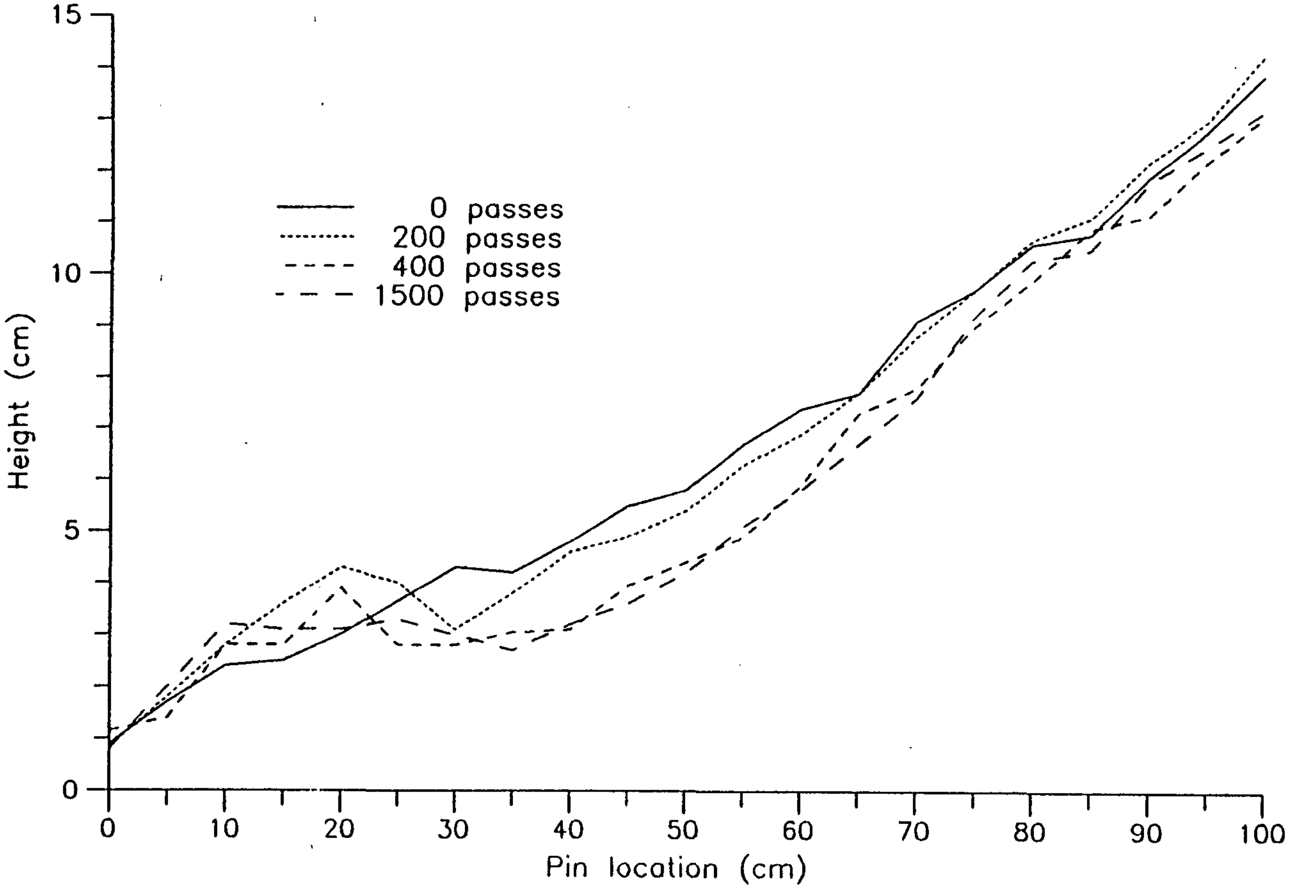


Figure 5.8. Profile of flat bicycle lane: location 2 m



three profile locations. Additional passes beyond 400 produce only minor changes. A depression forms in the flat bicycle lane that, by the conclusion of experimental treatment, varies in width between approximately 40 and 70 cm, depending on location. Among the four locations, the greatest depth of this depression at 1500 passes ranges from 1.2 to 2.0 cm. Aggradation occurs on both sides of the depression, with greater accumulation of soil on the downslope side of the trail. (At location 2 m, however, aggradation occurs on only the downslope side of the lane.)

The microtopography of the sloped hiker lane at location 4 m is illustrated in Figure 5.9. Almost immediately this lane develops a slight depression that widens with use.[2] At 1500 passes the depression varies between 30 and 40 cm in width (less than 10 cm at location 2), and between 1.2 and 1.5 cm in depth (only 2 mm at location 2) for locations 4 m, 6 m, and 8 m. Soil accumulates on both sides of the depression. Unlike the flat treatment lanes, where initial change in microrelief is rapid and subsequent change is much less rapid, changes in the surface of the sloped hiker lane seem to occur gradually with use.

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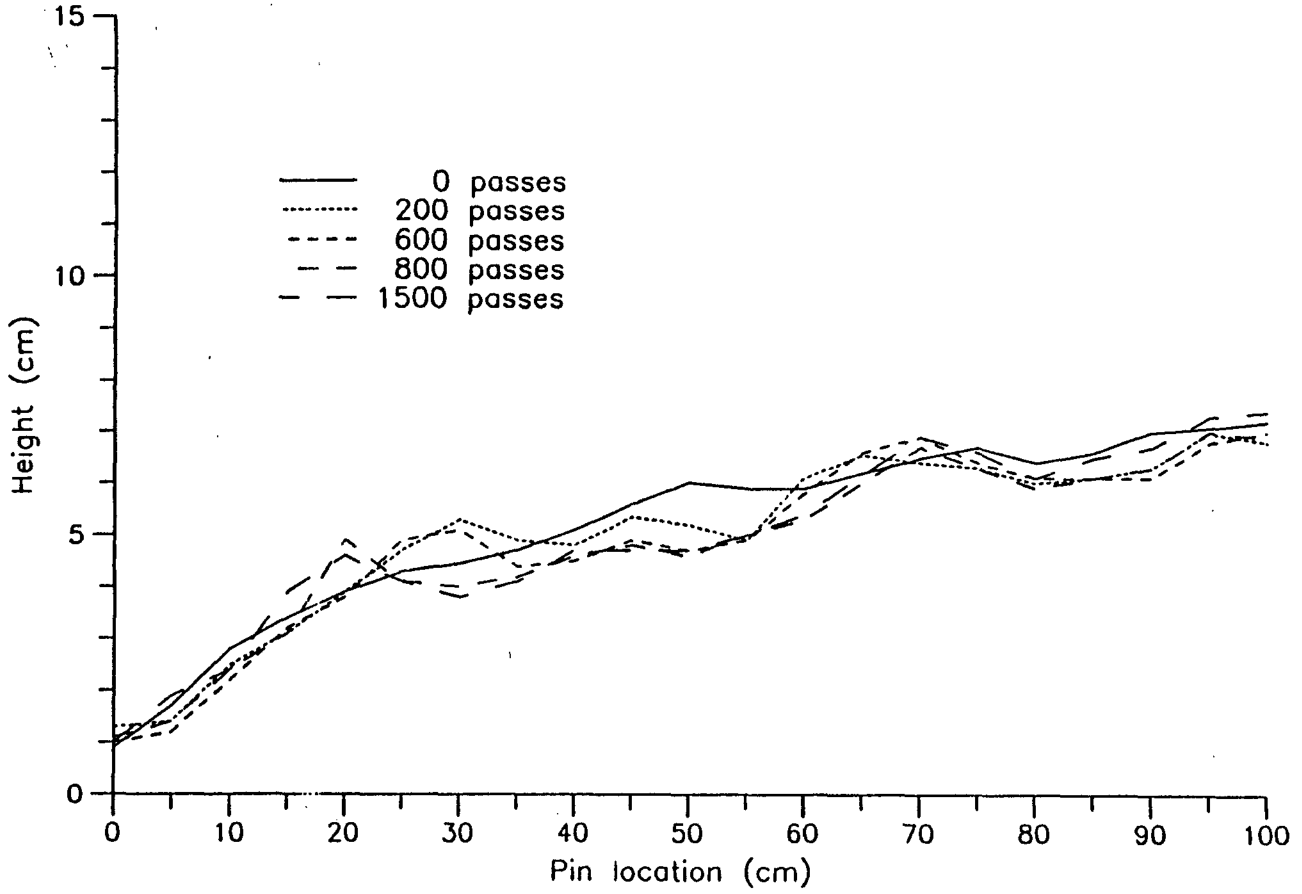
[2] Generalizations concerning the sloped hiker lane do not include location 2 m because the profiles at location 2 m seem to be anomalous. At this location a slight depression develops and later virtually disappears. In addition, there is considerable aggradation across most of the lane, even though this location was at the top of the lane where aggradation is less likely to occur. It is presumed that the anomalous profiles may be the result of experimental error. For example, the point frame may not have been set up at precisely the same height for each measuring interval; or at some point during the experiment, the spike which served as the height reference for the frame, may have sunk or accidentally been driven into the ground by one of the study participants.

Figure 5.9. Profile of sloped hiker lane: location 4 m



The changing microrelief of the sloped bicycle lane is depicted in Figures 5.10 and 5.11. The depression formed by the bicyclists is quite apparent. The depression is less severe in terms of both width and depth at the top (location 2 m) than at the bottom (location 8 m) of the lane. The depression at 1500 passes varies between roughly 50 and 75 cm in width, and its maximum depth at 1500 passes ranges from 2.2 to 4.2 cm. Soil accumulates toward the lower side of the trail, particularly at location 8 m.

Evaluation of Hypothesis 4

Hypothesis 4 states that changes in trail microrelief increase with increases in trail use. To evaluate this hypothesis, cumulative changes in cross-sectional area are plotted for each lane (Figure 5.12). Data for the curve is obtained by the following operation: at 200 passes the change in area between cross-sectional profiles at 0 and 200 passes is plotted; at 400 passes the previously calculated area is added to the change in area between 200 and 400 passes and is plotted; etc. It should be noted that this calculation may not necessarily be the same as the change in area between the cross-sectional profiles at 0 and 400 passes because the area is based upon absolute changes in surface profiles. As shown in Figure 5.12, cross-sectional area continues to change as use increases. Therefore, hypothesis 4 is accepted.

Figure 5.10. Profile of sloped bicycle lane: location 4 m

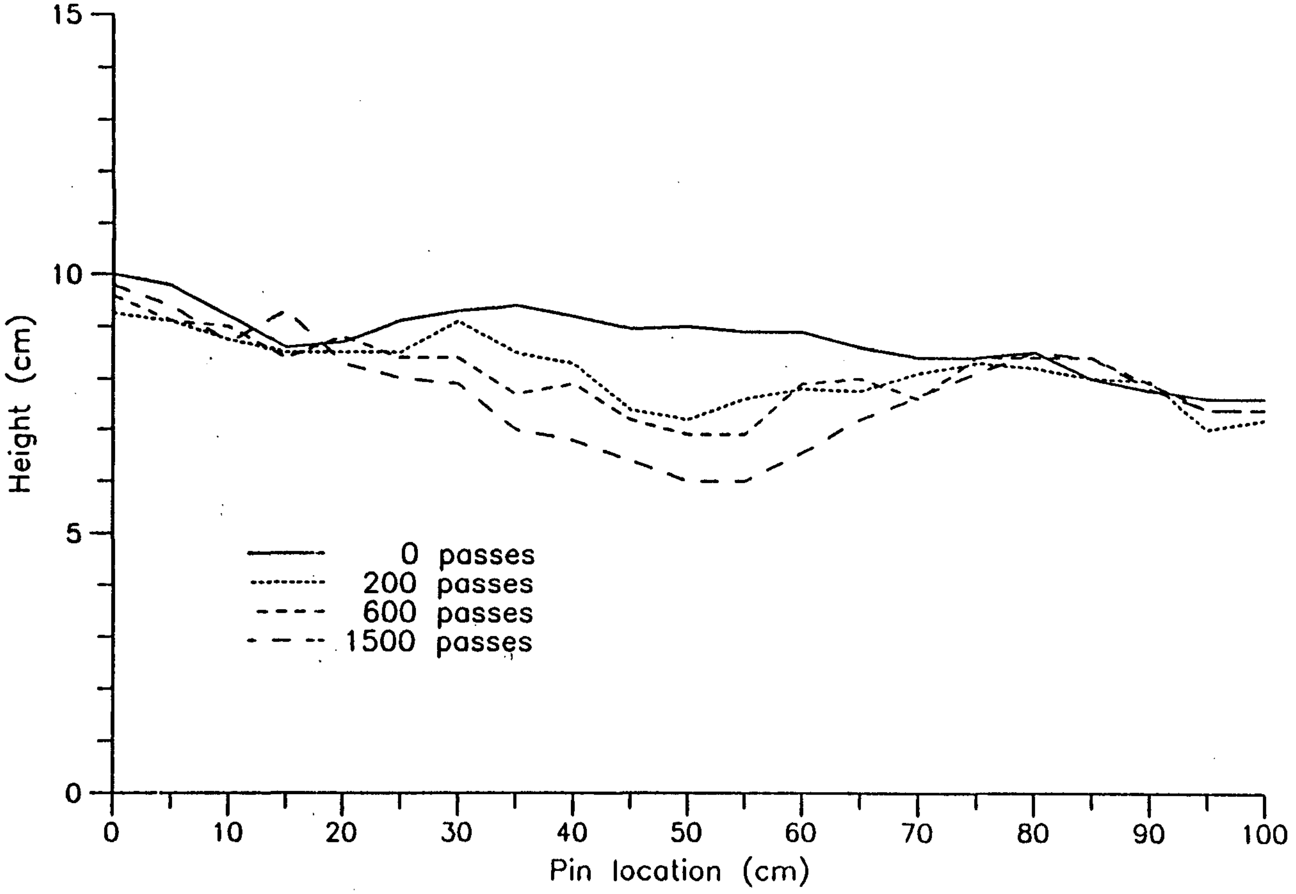


Figure 5.11. Profile of sloped bicycle lane: location 8 m

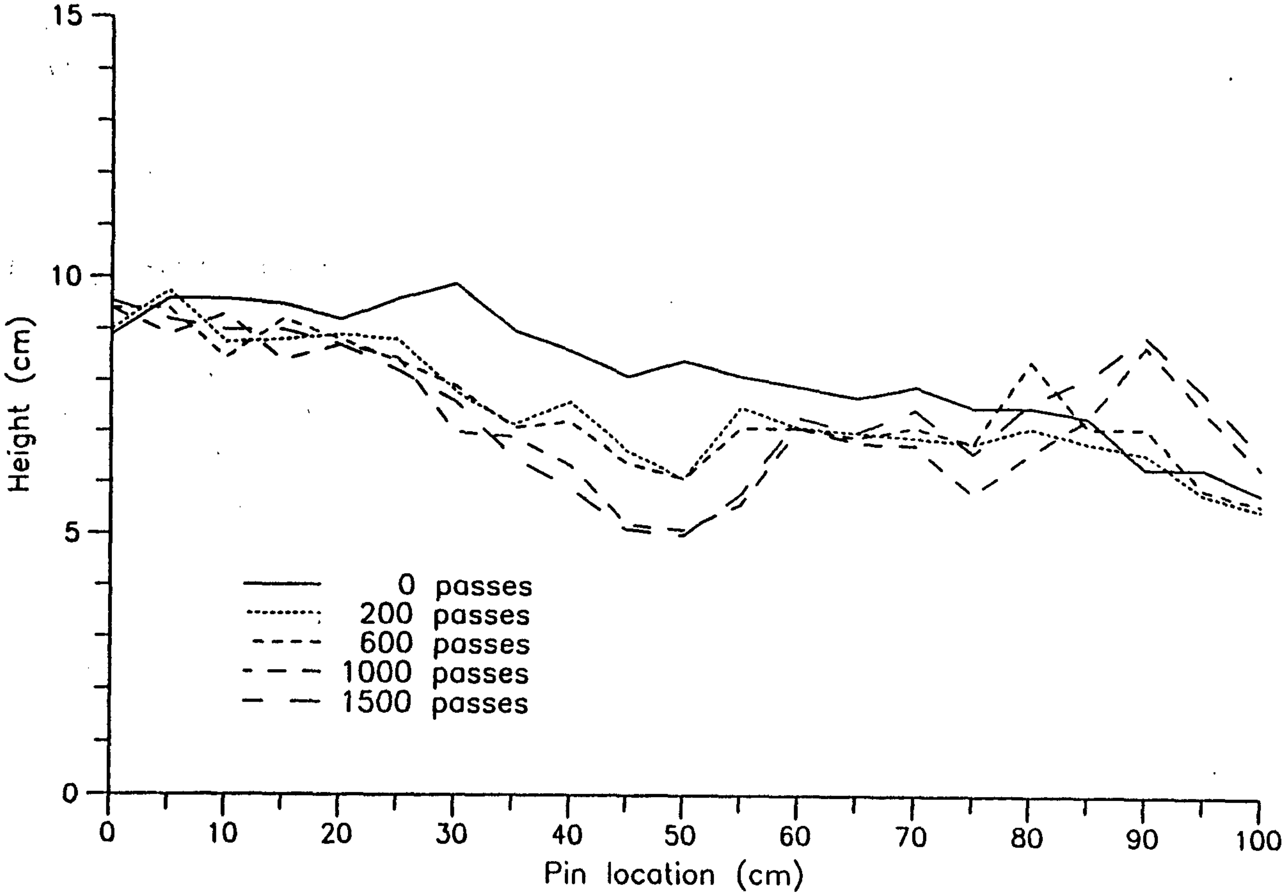
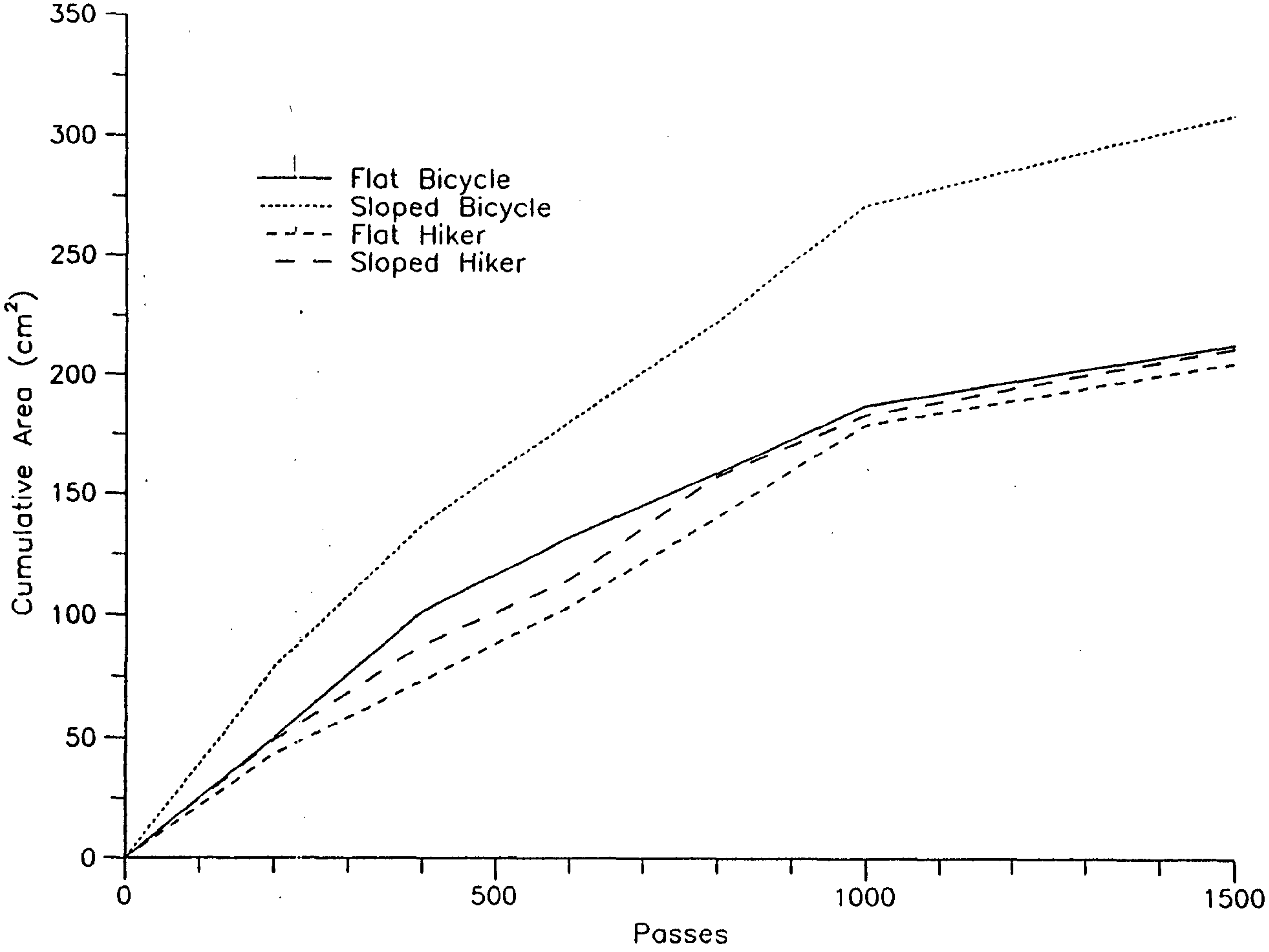


Figure 5.12. Cumulative change in cross-sectional area between profiles at consecutive measurement intervals



Evaluation of Hypotheses 5A and 5B

As described in Chapter Four, the area under the curve representing the absolute difference between the cross-sectional profiles at 0 and 1500 passes, is calculated for each lane (Table 5.8).

Table 5.8

Cross-sectional areas representing soil displacement after 1500 passes

location (m)	BF	BS	HF	HS	CF	CS
	Area between 0 and 1500 passes (cm^2)					
2	88.25	77.00	51.13	*	24.25	20.75
4	77.75	117.00	49.25	44.25	39.25	20.75
6	63.50	157.75	47.25	71.75	28.13	26.75
8	86.75	139.88	47.50	83.50	40.63	45.88
Mean	79.06	122.90	48.78	66.50	33.06	28.53
Standard error	5.68	17.40	0.90	11.60	4.06	5.95

*No area is calculated for HS location 2 m because the profiles are anomalous.

One-tailed difference of means tests are used to compare the treatment lanes with corresponding control lanes in terms of these areas (Table 5.9 A). Because the areas calculated for all treatment lanes are significantly greater than those calculated for control lanes, it is therefore concluded that recreational trampling causes greater changes in microrelief than occur as a result of natural processes.

Hypothesis 5A asserts that cyclists should cause greater changes in trail microrelief than hikers on trails having the same gradient. This hypothesis is evaluated with one-tailed difference of means tests that compare cross-sectional areas that represent the change in microrelief of each lane after 1500 passes

(Table 5.9 B). The cross-sectional areas of bicycle lanes are significantly greater than those of the hiker lanes. Therefore, hypothesis 5A is accepted.

Table 5.9

Comparison of trails in terms of changes in areas between cross-sectional surface profiles at 0 and 1500 passes

A: Treatment vs. control lanes

Test (n = 4)	p-value
BF - CF	0.001
BS - CS	0.007
HF - CF	0.016
HS - CS	0.031

B: Comparison of user types

BF - HF	0.007
BS - HS	0.027
B - H*	0.004

C: Comparison of gradients

CS - CF	0.56
BS - BF	0.048
HS - HF	0.13
S - F*	0.035

*n = 8

Note: Statistically significant differences at the 5% level of significance are underlined.

Hypothesis 5B maintains that sloped lanes should exhibit greater changes in trail microrelief than flat lanes traversed by the same recreational user. Cross-sectional areas between the 0- and 1500-pass surface profiles of sloped lanes are compared with corresponding areas of flat lanes using difference of means tests

(Table 5.9 C). When comparing the cross-sectional areas of control lanes, the test is two-tailed; when comparing treatment lanes, the tests are one-tailed. As expected, on control lanes gradient has no effect on the magnitude of change in microrelief. Likewise, the sloped and flat hiking lanes do not differ significantly. However, the change in microrelief of the sloped bicycle lane is significantly greater than that of the flat bicycle lane. Therefore, hypothesis 5B is accepted for lanes used by bicyclists but rejected for lanes used by hikers. Interestingly, if areas of the two sloped treatment lanes are combined and compared with the two flat treatment lanes ("S - F" in Table 5.9), the resulting difference is statistically significant. This outcome may indicate that small sample size prevented establishment of a significant difference between the hiking lanes.

CHAPTER SIX

DISCUSSION

Status of Hypotheses and Discussion

It is hypothesized that a curvilinear relation exists between amount of trampling and compaction, in which increases in compaction caused by a given number of passes decreases as number of passes increases. Conclusions regarding this hypothesis in terms of penetration resistance are uncertain because the experiment terminated at 1500 passes, after a dramatic increase in penetration resistance had just been exhibited. Therefore it remains unknown whether penetration resistance would have reached a steady-state level with the application of additional passes beyond 1500.

Several points need to be made in regard to penetrometer measurements. First, the instrument may misrepresent penetration resistance of the soil surface if a thin layer of loose soil is pushed over a measurement location. Second, penetrometers are highly sensitive to rocks and roots in the soil (Papamichos 1966; Cole 1985). Although an attempt was made to avoid any visible obstructions in the soil when measuring penetration resistance, rocks or roots that were not visible may have contributed to the variability of results. Furthermore, pocket soil penetrometers are imprecise and therefore highly variable (Cole 1985). Davidson

(1965) notes that penetrometers are accurate only to ±20%, and he suggests that other techniques should be used to supplement results. This variability may be the source of the shifting nature of penetration resistance between 500 and 1000 passes (refer to Figure 5.1). Cole (1985) observed erratic results in penetration resistance, similar to those observed in this study, in his research of experimental trampling of six vegetation habitat types in western Montana. He suggests that some of this variability in results may be compensated for by taking more measurements. Despite the variability, he still observed a rapid increase in penetration resistance within the first 50-75 passes, a lesser increase up to 400 passes, and then a leveling off with additional passes up to 1600.

Due to the method of trail construction in this study, the surface soil of lanes was loosened prior to the application of any passes. During the first 1100 passes, the surface soil remained loose and had a highly disaggregated structure that is believed to be caused by mechanical wear on the dry soil. It must be remembered that the penetrometer measures only the top 0.64 cm of the soil. The effect of walking and riding on this dry soil was to pulverize and loosen the soil, causing soil particles to become disaggregated in this narrow layer. Therefore, in the first 1000 passes penetration resistance remained relatively low, and actually decreased, though not significantly.

In contrast, the rapid increase in penetration resistance observed between 1000 and 1500 passes might be attributed to rain. The only rainstorm that took place during the experiment occurred after 1100 passes. Although no treatment was administered during the storm, nor did treatment resume until the soil had dried for a period of 24 hours, trail use following precipitation may be the reason for increased penetration resistance at this time. Precipitation may have generated runoff, causing the layer of loose soil to be eroded off the lanes and leaving behind a more compact surface layer. Alternatively, turbid surface runoff may have caused deposition of fine-grained soil particles between larger particles. In addition, raindrop impact may itself cause compaction (Toy and Hadley 1987). These latter two factors result in the formation of a surface crust that may be documented by an increase in penetration resistance (Cole 1987). This surficial seal may then prevent infiltration which may lead to increased runoff and erosion. Once the surface of the lanes became more firm and cohesive after the rainstorm at 1100 passes, possibly by one of the above-mentioned processes, the effect of walking/riding was to compact rather than to loosen this narrow surface layer. Therefore, penetration resistance increased significantly following the rainstorm.

It is hypothesized that on trails having similar gradients, bicyclists should cause greater soil compaction than hikers. Although the penetration resistance on lanes used by cyclists is significantly greater than on lanes used by hikers, the hypothesis may not be accepted without additional data beyond 1500 passes because it is not known whether the ultimate steady state value of the hiker lanes might approach that of the bicycle lanes at a later time. Moreover, the hypothesis should not be accepted because the significantly greater penetration resistance observed on bicycle lanes may have been artificially increased as compared to that on lanes used by hikers due to the method used to obtain measurements. Throughout the experiment the researcher noted ruts in the bicycle lanes. These ruts were transient and continuously formed and reformed when wheels passed over the soil. The mounds between the ruts were composed of accumulations of unconsolidated soil. For consistency, penetration-resistance measurements were always taken in the ruts closest to the center of the lane at each sampling location. Penetration resistance in the bicycle lanes may therefore be biased. For example, if all measurements had been taken precisely in the center of each lane, regardless of whether they were in ruts or mounds of unconsolidated soil, mean penetration resistance of the bicycle lanes may have been found to be lower than what was observed in this study.

Soil compaction was also assessed with bulk-density measurements. Conclusions regarding bulk-density data are uncertain because experimental error is suspected in the data collection. There are several sources of evidence for this suspicion. It is noted in Chapter Five that the sloped and flat control lanes at the 5-10 cm depth and the sloped control lane at the 10-15 cm depth actually decrease in bulk density between 0 and 1500 passes. The other controls increase through time, which as suggested, may be due in part to the soil settling on the freshly constructed lanes. The impact of rainfall may be another reason the control lanes increase in bulk density. However, for some of the control lanes to become less compact defies logic and natural expectations. Therefore, it must be assumed that the decreased bulk density on control lanes may be attributed to experimental error. Secondly, the spread of the mean bulk-density data at 0 passes, particularly at the 5-10 cm increment and the 10-15 cm increment (refer to Figures 5.3 and 5.4), may also be indicative of a lack of accuracy in the data. Theoretically, at 0 passes bulk densities of all trails should be similar. However, it is noted that the spread of data between the lanes at 0 passes is often larger than the changes observed on individual lanes, raising the question of whether the spread of data is due to real differences or to experimental error.

The primary source of error was in the process of collecting the soil samples for determination of bulk density. Extraction of samples with constant volume was difficult with the core method. One factor affecting volume of the sample was the difficulty of seeing when the inscribed depth-increment lines on the auger barrel were exactly even with the soil surface. Secondly, the samples generally were not very cohesive, causing some of the soil to fall out of the auger barrel before the sample could be transferred to a container. Any soil which fell out of the auger was scooped out of the hole and combined with the rest of the sample, a highly imprecise technique. In an attempt to minimize these difficulties in removing whole samples, the soil was moistened a few hours prior to sampling. However, even with this additional procedure, some soil still fell out occasionally. Although wetting the soil may have helped to keep the sample cohesive, it may have created another problem. Moisture in the soil causes swelling of clays which may reduce the bulk density of soil samples. This method has no way of compensating for changes in bulk density due to changes in volume related to varying moisture contents.

Extracting soil samples with a barrel auger is also problematic in an area, such as Boulder, which is characterized by gravelly soils. A few of the soil samples in this study were not obtainable due to rocks. Finally, rocks in the soil samples may also cause artificial inflation of the bulk-density values. Therefore, the accuracy level of this method of calculating bulk density may be such that it is not sensitive enough to determine changes in bulk density as caused by recreational trampling.

Furthermore, Lull (1959) suggests that another reason bulk density differences may be difficult to ascertain is due to difficulties in measuring the density of the layers most greatly affected. These layers may be difficult to sample, particularly with a soil auger, because of their shallowness.

Although this study does not find that user type or gradient affects the degree of compaction, statistically significant differences between cyclists and hikers and between sloped and flat lanes in terms of bulk density may in fact exist. It has already been noted that experimental error may be responsible for some of this study's tenuous conclusions, but significant differences between users may be masked also by the small sample size. With a small sample size, statistical significance is more difficult to prove. A small sample size reduces the degrees of freedom which in turn increase the critical value of the *t* statistic. The critical value must be equaled or exceeded to prove statistical significance. In other words, a small sample size requires differences to be quite pronounced and consistent to establish statistical significance (Blalock 1960). Therefore, a small sample size is more likely to increase the probability of type II error, which is failing to reject a null hypothesis when in fact it is false (Champion 1981).

It is hypothesized that compaction caused by both hikers and bicyclists should decrease with depth in the soil. Studies that have examined the depth of recreational compaction caused by pedestrians on trails and in campgrounds have found that compaction is generally concentrated near the surface of the soil (cf. Bates 1935; Lutz 1945; LaPage 1962; Papamichos 1966). However, results regarding this hypothesis are inconclusive. As stated previously, the significant increases in bulk density noted at the 10-15 cm soil increment on the sloped hiker and control flat lanes lack physical explanation since increases in bulk density in the layer above are not noted. The statistically significant increase on the control lane is even more puzzling since no treatment took place on this lane. Additional experimentation would be necessary to draw more definitive conclusions and to determine if these incomprehensible increases can be replicated or if they result from experimental error.

It is hypothesized that bicyclists cause greater changes in trail microrelief than hikers on lanes having similar gradients. In this study, changes in microrelief are assessed with cross-sectional areas that show the displacement of soil following 1500 passes of use. This hypothesis is accepted because the calculated cross-sectional areas for bicycle lanes are larger than those of corresponding hiker lanes. Weaver and Dale (1978) also examined the microrelief of experimental trails by measuring depth at the center of trails. They found that horse usage caused greatest trail depths, followed by motorcycles, and then hikers. They argued that this was due to the greater "plowing action" that occurs as greater pressures are applied by heavier users (p. 456). This explanation also applies to this study, as cyclists exert greater pressure due to the smaller bearing surface of tires than do hikers.

Larger changes in the trail surface caused by cyclists also may be due in part to the torque that must be applied to accelerate or ascend a slope. The application of this force can cause bicycle wheels to spin, loosening and moving soil so that a depression is formed. Likewise, deceleration may be an erosive process, because when braking, cyclists are prone to skid. Furthermore, as a bicycle wheel rotates, the tire cleats might exert a scooping action on the soil. Hikers, however, are more capable of controlling speed through muscular control, causing less soil to be detached and transported. In contrast, Seney (1991) observed that both horses and hikers made more sediment available for transport than motorcyclists or off-road bicyclists. However, in Seney's study the differences were only noted on trails that had been pre-wetted.

Bicyclists may also cause greater changes in microrelief than hikers due to their tendency to weave. Bicyclists have greater difficulty than hikers maintaining a straight course unless the cyclists have achieved sufficient momentum. Therefore, their impacts on the trail surface are more widespread. (This concept may also explain the tendency for the depression in the sloped bicycle lane to be wider at the bottom than at the top of the lane. When riding uphill cyclists tend to swerve back and forth until a sufficient velocity is gained near the top of the trail.)

Changes in microrelief may be attributed to compaction and/or erosion. Seney's (1991) study examined only erosion as caused by simulated rainfall. He found no differences between off-road bicycling and hiking in terms of sediment yield. However, he suspected that the inability to establish statistical significance was due to the small number of treatments applied (only 100 passes on trails that had been in use for ten years) and/or the shortcomings of the rainfall simulator that produced storms of only one-third the intensity of natural storms.

It is hypothesized that as a result of recreational use, sloped lanes undergo greater changes in trail microrelief than flat lanes. Because the cross-sectional areas showing displacement of soil through use are greater for the sloped bicycle lane than the flat bicycle lane, the hypothesis is accepted for this user type. A possible physical explanation is that pedaling a bicycle on the flat lane does not require as much force as ascending the sloped lane, and bicyclists are less likely to slide. Furthermore, braking need not be as intense or prolonged on a flat trail; therefore, bicyclists have a lesser impact on the flat lane.

Other researchers have examined the relationship between slope and factors related to microrelief. Cole (1983) found a significant direct relationship between trail slope and maximum trail depth on two trails in the Selway-Bitterroot Wilderness of Western Montana. Similarly, Seney (1991) found slope to be related to sediment yield. Weaver and Dale (1978) also noted that changes in trail depth were greater on sloped than flat lanes for all users (hikers, horses, and motorcycles). One reason offered for greater incision on slopes was that the bared soil on slopes was more susceptible to water erosion (Weaver et al. 1978). However, for this study, this factor did not play a major role because, as previously stated, only one major rainstorm occurred during the experiment; and it took place after over two-thirds of the experiment was complete.

No significant difference is found between the microrelief of flat and sloped hiking lanes, and hypothesis 5B is rejected for this user type. A possible explanation is that the difference between the two gradients in this study was not great enough to cause hikers to alter their hiking behavior between the sloped and flat lanes to cause a noticeable difference in microrelief. Observations during trampling showed that hikers seemed to be equally in control on both flat and sloped lanes. However, a statistically significant difference may exist, but the small sample size used in analysis may have prevented its detection. In contrast, Weaver and Dale (1978) found hikers to be more damaging on sloped trails than on level trails. However, the slopes in their study were steeper (27%) than the slopes in this study (10%), and shearing forces are greater on steeper slopes, causing hikers to be more damaging. Weaver and Dale also found hikers to be more damaging when moving downhill rather than uphill because hikers attempt to minimize energy output. When ascending a slope, hikers minimize energy usage by placing their feet carefully and controlling acceleration. When moving downhill, however, "they accelerate (via gravity) and decelerate (via bones, elastic connective tissue and muscles) sharply because this requries (sic) less energy than a smoother descent under greater muscular control (Weaver et al. 1979, p. 97)."

Management Implications

Recommendations for management of bicyclists on trails will be made based on observations of profiles of the experimental lanes. This study finds bicyclists to be more damaging than hikers in terms of trail microtopography. Of the bicycle trails, the one that was most deeply incised was located on a 10% slope. As stated in Chapter Two, incised trails tend to concentrate the flow of runoff generated from precipitation (cf. Bryan 1977; Burden and Randerson 1972; McQuaid-Cook 1978; Weaver and Dale 1978; Cole 1983). Channelized water flows quickly, providing more energy to transport soil and fostering erosion. Accelerated erosion in turn creates a deeper incision, commencing a feedback process. Furthermore, Seney (1991) recognized that trail roughness is directly related to sediment yield, and as noted previously, the bicycle lanes in this study were composed of ruts and mounds of loose soil. Therefore, during a rain storm this loose soil would be available for downslope transport. As stated in Chapter Three, during the summer months precipitation in Boulder is primarily convective in nature. Convective storms generate large amounts of precipitation in a short time span, often exceeding the infiltration rate of soils, especially those that have had porosity reduced due to compaction. Because these months correspond to peak times for trail usage, the added erosional potential of cyclists should be of concern. For these reasons, managers should consider restrictions of bicyclists on steeply sloping terrain. One type of restriction would be to limit bicycle usage to relatively flat trails. New trails which may be used by cyclists should be constructed so as to limit both the angle and length of sloping trail sections.

However, such limitations will undoubtedly be objectionable to many off-road cycling enthusiasts whose primary objective is to seek challenging terrain. Therefore, an alternative to restrictions on cyclists would be to construct new trails and update old trails with these users in mind. Weaver et al. (1979) have observed that the presence of stone, roots, mud, or manure on the trail tends to cause recreational users to wander, spreading their impacts over a wider area. More importantly, obstacles such as these may cause bicyclists to brake suddenly. Because bicycles tend to be most damaging when their wheels skid, obstacles on the trail should be minimized. Furthermore, trails that widen on slopes might also be appropriate for cyclists so that any ruts that develop may be dispersed over a larger area and less likely to concentrate water, creating an incision. Finally, on trails designated for use by off-road bicyclists, it may be advisable to space water bars more frequently than managers have traditionally seen fit. Water bars will decrease the erosion potential of a trail by deflecting water off the trail before it has time to gain enough momentum to pick up much soil. Water bars that are composed of a flexible material, such as rubber, are preferable because they can be ridden over easily.

Finally, before managers make policy decisions regarding off-road bicycle usage of trails, guidelines for what constitutes acceptable wear on a trail should be established. Although cyclists may cause more damage to trails than hikers, their effects may fall within the guidelines of acceptable wear and therefore restrictions or trail-design changes may not require implementation.

An Improved Study Design

Several weaknesses in the methodology of this research have already been noted. Therefore, this section suggests possible modifications to the research design that may facilitate more effective evaluation of the original research objectives/hypotheses. Aspects of the original research method that should be preserved are also indicated.

It is recommended that the experimental approach be retained in a revised design of this research because it is the most effective way to separate the impacts of bicyclists from other users by isolating many of the variables which may affect results. In addition, the experimental approach permits isolation of the impacts of another common recreational user--hikers--to serve as a reference for comparison. Furthermore, this approach is the only way to examine initial impacts and rates of change.

As stated previously, a major weakness of this study is that sample size was quite small, making it difficult to draw concrete conclusions regarding compaction. Therefore, experimental plots used in future research should be larger and contain more lanes so that more replicates of measurements can be taken, providing for a more rigorous statistical analysis.

The short length of the lanes in this research was another problem, particularly for cyclists. Switching directions at the end of the lane was time-consuming and inconvenient. Longer lanes in a modified research design would not only lessen this concern, but would also grant more space for additional measurements. Furthermore, in the current study the experimental lanes were built wider than many trails on Open Space lands because it was assumed that cyclists might require the space; however, it was observed during treatment that cyclists did not require the full width of the trail.

Based on the above observations, it is suggested that at least three trails be built for each user on both flat and sloped plots. An equal number of trails should be constructed to serve as control lanes. All lanes should be separated by "buffer strips" of vegetation at least 30 cm wide. The buffer strips should prevent movement of soil from one lane to another. Usage of the first three lanes by bicycle, hiker, or control should be determined by random selection, and that pattern should be systematically repeated in the remaining six lanes. In addition, trails should be at least 20 m in length and should not exceed 60 cm in width. Another way in which to alleviate problems that cyclists had in turning around at the end of lanes, might be to construct trails shaped like oval tracks which would permit continuous flow of traffic.

Trampling for the current study took place for only one month and at random times when study participants were available. In addition, the number of passes that were administered to each trail at each trampling time varied. Because the effects of trampling may differ with the rate and intensity of treatments, and because these trampling conditions did not simulate actual recreational circumstances, the results obtained may be inherently artificial. In an attempt to overcome this deficiency, it is suggested for future research that a schedule of trampling be established in which a certain number of passes are administered on appointed days each week. For example, 50 passes could be applied two or three days per week between mid-May and mid-September (1700-2550 passes total). Alternatively, the trampling schedule could be based upon an analysis of actual trail usage in the area. The proposed schedule would encourage trampling on the experimental lanes simultaneously with the peak season of actual trail usage.

Another source of artificiality in the treatment applied in the current study was that throughout trampling the soil was dry for the most part, and it was therefore relatively resistant to compaction. Because actual trail use occurs under a variety of soil moisture conditions, it might be important to incorporate trampling treatments under varying soil moisture levels into future research. If a schedule such as that suggested above is adhered to, a variety of weather conditions (and therefore soil moisture conditions) might be encountered. A controlled application of water might also be considered in further research; however it is recognized that such an effort could encounter considerable practical difficulties, such as in maintaining an even spread of water over the study site and in distributing water over a large area in a potentially remote location.

The problems with the methods of assessing compaction used in this study, penetration resistance and bulk density as determined by the core method, were discussed previously. Therefore, alternate techniques of assessing compaction, such as the clod method or the radiation method, are proposed for future research (Black 1965). In the clod method air-dried soil peds are weighed to determine mass, coated with a waterproof substance, submerged in water and reweighed to determine volume of the paraffin and the soil, and bulk density is then computed. The clod method is ideal for soils containing large amounts of clay. In the radiation method gamma rays are transmitted through the soil from one probe containing a radioisotope to another probe containing a geiger counter. With proper calibration, the method can be used to estimate bulk density because transmission of gamma radiation changes with soil properties including bulk density. These techniques may provide a higher level of accuracy in determining soil density and may also be more sensitive to slight changes in bulk density than were the methods used in this study.

In each lane ten measurements should be taken at 2-m intervals. At each measurement location, soil should be removed in three, 5-cm increments. Because there are three lanes for each user type on each gradient, a total of 30 observations will be obtained for each depth increment, providing a sound sample size for statistical analysis. In this study soil samples were taken only at 500-pass intervals. However, to accurately characterize the expected curvilinear relation, samples should be taken prior to trampling and at 200-pass intervals on treatment lanes during the early part of the study. When bulk density begins to level off, measurements may be taken less frequently.

In this study the control lanes were only measured before and after trampling took place. Both net increases and net decreases in bulk density were observed on the control lanes; however, because no intermediate data were taken, there was no basis for determining whether trends existed. It is unknown whether the increases or decreases were the result of measurement error or natural causes. In a future study measurements made on the control lanes at the same intervals as on treatment lanes might provide data which could shed light on the source of such observations.

The point-frame created for use in the current study worked well for measuring trail surface microrelief, and therefore it is recommended for use in future research. One problem with the frame mentioned in Chapter Five was the possibility that one of the spikes had been driven further into the ground during trampling by one of the study participants. Because the spikes serve as a height reference for the frame and therefore should remain at a constant elevation above ground, it is suggested that they be positioned in the buffer strips between lanes where they are less likely to be disturbed, rather than at the edge of lanes as they were in this study.

Microrelief measurements should be taken in each lane at ten locations (not the same as soil sample locations), spaced at 2-m intervals. The point-frame pins should again be spaced at 5-cm intervals, for a total of 13 pins across a 60-cm trail. Measurements should be taken before trampling and after every 200 passes on both treatment and control lanes.

A final recommendation is to analyze data as they are collected. Continuous analysis should permit the researcher to determine whether to continue taking data at the suggested intervals or less frequently. For example, if it was observed that a measured parameter increased in curvilinear fashion with increasing use, fewer measurements might be required once the steady-state was reached. Also, unusual results might indicate problems that might need modification in the method of data collection to prevent further collection of erroneous data.

Other future research efforts should continue to investigate off-road bicycle environmental impacts, as little research has been performed in this area. Future research possibilities include examination of other types of environmental degradation caused by cyclists, including studies of sediment yield and erosion. Future research should also address factors that influence the amount of damage caused by bicyclists, such as soil type, soil moisture content, and type of tires.

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APPENDIX A

STUDY AREA PLANT SPECIES
(non-comprehensive)

	Scientific Name	**Common Name**
Grasses	*Andropogon gerardii*	Big Bluestem or Turkeyfoot
	*Anisantha tectorum**	Cheatgrass
	*Bromopsis inermis**	Smooth Brome
	*Bromus japonicus**	Japanese Brome
	Chondrosum gracile	Blue Grama
	Elymus trachycaulus	Wild Rye
	Pascopyrum smithii	Western Wheatgrass
	Poa agassizensis	Bluegrass
	Poa compressa	Canada Bluegrass
	Sporobolus cryptandrus	Sand Dropseed
	Stipa comata	Needle-and-Thread
	*Thinopyrum ponticum**	Slender Wheatgrass
Other Herbs	*Argemone hispida*	Prickly Poppy
	*Asparagus officinalis**	Asparagus
	*Bassia sieversiana**	Ironweed
	Brickellia eupatorioides	
	*Camelina microcarpa**	False Flax
	*Chenopodium album**	Goosefoot or Lamb's Quarters
	Cirsium ochrocentrum	Thistle
	*Convolvulus arvensis**	Creeping Jenny
	Eriogonum effusum	Wild Buckwheat
	Grindelia squarrosa	Gumweed
	Heterotheca villosa	Golden Aster
	Liatris punctata	Gayfeather
	*Linaria vulgaris**	Butter-and-eggs
	Lygodesmia juncea	Skeletonweed
	Machaeranthera pinnatifida	Tansy Aster
	*Melilotus albus**	White Sweet-clover
	Opuntia macrorhiza	Prickly-Pear
	Oxybaphus linearis	Narrow-leaved Umbrella-wort
	Psoralidium tenuiflorum	

	*Rumex crispus**	Curly Dock
	*Salsola australis**	Russian-thistle
	Senecio spartioides	Butterweed or Groundsel
	*Sisymbrium altissimum**	Jim Hill Mustard
	Solidago missouriensis	Smooth Goldenrod
	Thelesperma megapotamicum	
	*Tragopogon dubius**	Salsify or Oyster-plant
	Verbascum thapsus	Great Mullein
	*Virgulus falcatus**	Aster
Shrubs	*Artemisia frigida*	Silver Sage
	Artemisia ludoviciana	Prairie Sage
	Gutierrezia sarothrae	Snakeweed
	Oligosporus dracunculus	Wild Tarragon
	Yucca glauca	Spanish Bayonet

* adventive species

Note: Scientific names conform to the nomenclature of Weber and Wittmann (1992).

APPENDIX B

PENETRATION RESISTANCE DATA

		BF[1]	BS	HF	HS	CF	CS
passes	location (m)		Penetration resistance (kg/cm^2)				
500	0.5	1.00	0.75	0.25	0.25		
	1.5	1.00	0.75	0.75	1.00		
	2.5	1.25	1.00	0.50	0.50		
	3.5	1.25	1.25	1.00	0.75		
	4.5	1.75	1.00	0.75	0.50		
	5.5	2.25	0.25	0.25	0.50		
	6.5	0.75	1.25	0.50	0.75		
	7.5	2.00	0.75	1.50	0.75		
	8.5	0.50	1.25	0.75	0.25		
	9.5	1.25	1.75	0.50	0.50		
	Mean	1.30	1.00	0.68	0.58		
	Standard error	0.17	0.13	0.12	0.08		
600	0.5	1.00	0.50	0.00	0.75		
	1.5	0.75	0.50	1.25	0.50		
	2.5	1.00	1.00	0.50	0.75		
	3.5	1.00	0.50	0.25	0.50		
	4.5	1.25	0.75	0.00	0.50		
	5.5	0.75	0.75	0.50	0.00		
	6.5	0.75	1.00	0.00	0.25		
	7.5	1.00	0.25	0.25	0.50		
	8.5	1.00	0.50	0.50	0.50		
	9.5	0.75	1.00	1.25	0.50		
	Mean	0.93	0.68	0.45	0.48		
	Standard error	0.05	0.08	0.15	0.07		

passes	location (m)	BF[1]	BS	HF	HS	CF	CS
		Penetration resistance (kg/cm^2)					
700	0.5	1.75	0.75	0.50	1.50		
	1.5	1.25	1.25	0.50	0.00		
	2.5	2.00	0.75	0.50	0.50		
	3.5	0.75	1.00	0.50	1.00		
	4.5	1.00	1.00	0.00	1.25		
	5.5	1.00	0.00	0.00	0.50		
	6.5	1.00	1.00	0.00	0.50		
	7.5	1.25	1.00	0.50	0.00		
	8.5	0.00	0.50	0.50	0.50		
	9.5	0.50	3.50	0.75	0.50		
	Mean	1.05	1.08	0.38	0.63		
	Standard error	0.18	0.29	0.09	0.16		
800	0.5	0.75	1.00	0.00	0.75		
	1.5	1.00	0.00	0.75	1.25		
	2.5	0.75	1.00	0.50	0.75		
	3.5	0.50	1.00	0.00	0.00		
	4.5	1.25	0.75	0.00	0.75		
	5.5	0.00	0.50	0.50	0.00		
	6.5	0.00	0.00	0.00	0.50		
	7.5	0.50	0.00	0.00	0.75		
	8.5	0.50	0.75	0.00	0.50		
	9.5	0.50	0.50	0.75	0.00		
	Mean	0.58	0.55	0.25	0.53		
	Standard error	0.12	0.13	0.11	0.13		
900	0.5	1.00	1.25	0.50	0.00		
	1.5	1.00	3.25	0.50	0.00		
	2.5	1.00	1.00	0.00	0.50		
	3.5	1.00	0.50	0.00	0.00		
	4.5	1.25	0.50	0.00	0.00		
	5.5	1.50	0.00	0.75	0.00		
	6.5	0.75	0.75	0.50	0.00		
	7.5	1.50	1.00	0.50	0.50		
	8.5	0.75	0.75	0.50	0.75		
	9.5	0.00	0.50	0.50	0.75		
	Mean	0.98	0.95	0.38	0.25		
	Standard error	0.14	0.28	0.09	0.11		

		BF[1]	BS	HF	HS	CF	CS
passes	location (m)	Penetration resistance (kg/cm^2)					
1000	0.5	0.75	0.75	0.00	0.50		
	1.5	0.00	1.00	0.75	0.50		
	2.5	1.00	0.75	0.50	0.00		
	3.5	0.00	0.50	0.50	0.00		
	4.5	1.00	0.75	0.00	0.00		
	5.5	0.75	1.75	1.00	0.00		
	6.5	0.50	0.50	0.00	0.00		
	7.5	0.75	1.00	0.50	0.00		
	8.5	0.50	1.25	0.50	0.00		
	9.5	0.00	0.50	1.00	0.00		
	Mean	0.53	0.88	0.48	0.10		
	Standard error	0.13	0.13	0.12	0.07		
1500	0.5	2.50	3.25	2.00	1.25	2.00	0.00
	1.5	2.75	2.25	1.00	1.00	1.00	0.00
	2.5	3.50	2.25	3.75	1.00	0.50	0.50
	3.5	3.25	1.75	3.50	1.00	0.50	0.50
	4.5	4.00	2.00	1.00	1.50	0.50	0.00
	5.5	2.75	2.25	2.75	0.50	0.50	0.50
	6.5	4.25	3.00	1.25	3.00	0.75	0.50
	7.5	3.25	2.75	3.00	2.25	0.00	1.00
	8.5	2.25	4.00	3.00	2.50	0.50	0.00
	9.5	1.75	3.25	1.75	1.00	0.50	0.00
	Mean	3.03	2.68	2.30	1.50	0.68	0.30
	Standard error	0.25	0.22	0.33	0.26	0.17	0.11

[1] The abbreviations BF, BS, HF, HS, CF, and CS represent the flat bicycle, sloped bicycle, flat hiker, sloped hiker, flat control, and sloped control lanes.

APPENDIX C

BULK DENSITY DATA

Increment (cm)	Pass	Location (m)	BF[1]	BS	HF	HS	CF	CS
			Bulk density (g/cm^3)					
0-5	0	2	0.90	1.02	0.95	*[2]	0.67	0.70
0-5	0	4	0.79	0.79	0.80	0.86	0.83	0.76
0-5	0	6	0.92	0.73	0.86	0.69	0.73	0.82
0-5	0	8	0.91	0.90	0.78	0.72	0.68	0.62
0-5	500	2	1.32	1.17	1.04	0.98		
0-5	500	4	1.01	*	1.14	1.04		
0-5	500	6	1.13	0.75	1.19	1.14		
0-5	500	8	1.26	*	0.92	0.91		
0-5	1000	2	1.31	0.93	1.08	1.01		
0-5	1000	4	1.25	1.15	1.12	0.92		
0-5	1000	6	0.97	0.94	1.21	1.04		
0-5	1000	8	1.20	1.08	1.35	1.05		
0-5	1500	2	1.47	1.19	1.12	1.15	0.96	0.94
0-5	1500	4	0.94	1.24	1.10	1.08	1.02	0.92
0-5	1500	6	1.07	1.19	1.86	1.00	0.76	0.82
0-5	1500	8	1.55	1.13	1.35	0.89	0.89	0.91
5-10	0	2	1.26	1.33	1.55	0.91	1.27	1.16
5-10	0	4	1.23	0.97	1.23	1.35	1.41	1.39
5-10	0	6	1.31	1.29	1.41	0.95	1.17	*
5-10	0	8	1.06	0.97	1.19	1.09	1.34	1.47
5-10	500	2	1.24	1.32	1.66	1.04		
5-10	500	4	1.51	1.45	1.41	1.12		
5-10	500	6	1.94	1.16	1.22	1.10		
5-10	500	8	1.38	1.33	1.26	1.15		

			BF[1]	BS	HF	HS	CF	CS
Increment (cm)	Pass	Location (m)	Bulk density (g/cm^3)					
5-10	1000	2	1.50	1.40	1.50	1.32		
5-10	1000	4	1.41	1.30	1.89	1.03		
5-10	1000	6	1.45	1.19	1.55	1.44		
5-10	1000	8	*	1.43	1.38	1.25		
5-10	1500	2	1.37	0.91	1.49	1.07	0.81	1.22
5-10	1500	4	1.56	1.19	1.43	1.25	1.27	1.19
5-10	1500	6	1.19	0.94	1.10	1.69	1.10	1.18
5-10	1500	8	1.17	1.43	1.46	1.40	1.37	1.34
10-15	0	2	1.35	1.23	1.25	1.30	1.41	1.47
10-15	0	4	1.37	1.52	1.48	1.46	1.40	1.31
10-15	0	6	1.22	1.42	1.45	1.31	1.38	1.48
10-15	0	8	1.53	1.34	1.44	1.22	1.52	1.75
10-15	500	2	1.34	1.25	1.31	1.24		
10-15	500	4	1.48	1.25	1.29	1.19		
10-15	500	6	*	1.28	1.26	1.29		
10-15	500	8	1.38	1.61	1.62	2.01		
10-15	1000	2	1.44	1.24	1.56	1.19		
10-15	1000	4	1.26	1.23	1.17	1.30		
10-15	1000	6	1.35	1.39	*	1.30		
10-15	1000	8	*	1.47	1.53	1.41		
10-15	1500	2	1.56	1.39	1.79	1.39	*	1.27
10-15	1500	4	1.73	1.46	1.46	1.76	1.72	1.31
10-15	1500	6	*	1.39	1.58	1.60	1.55	1.30
10-15	1500	8	1.52	1.26	1.40	*	1.89	1.74

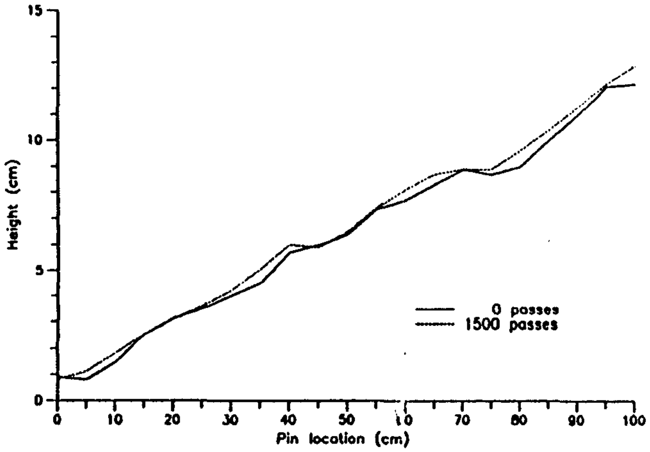
[1] The abbreviations BF, BS, HF, HS, CF, and CS represent the flat bicycle, sloped bicycle, flat hiker, sloped hiker, flat control, and sloped control lanes.

* Indicates missing samples.

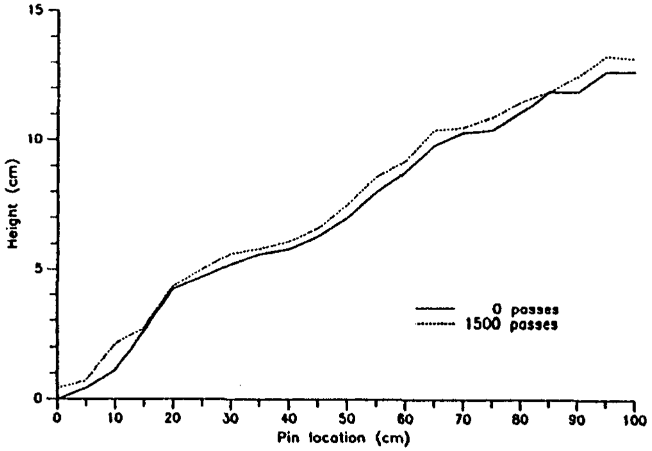
APPENDIX D

TRAIL CROSS-SECTIONAL PROFILES

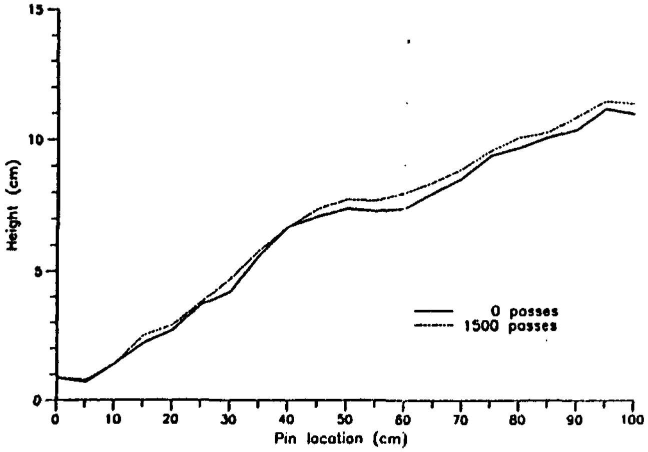
Profile of Flat Control Lane: Location 2 m



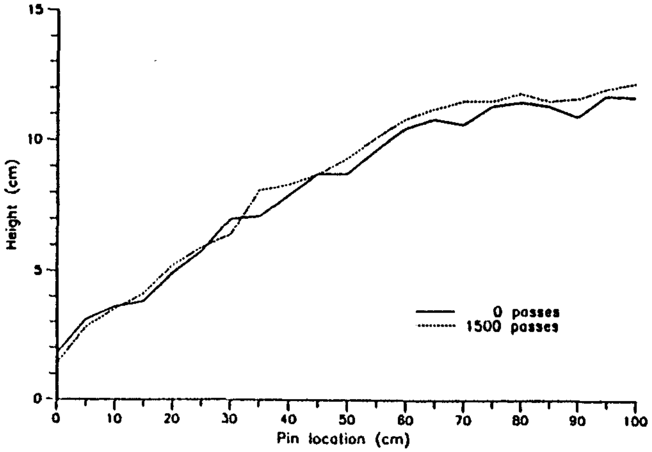
Profile of Flat Control Lane: Location 4 m



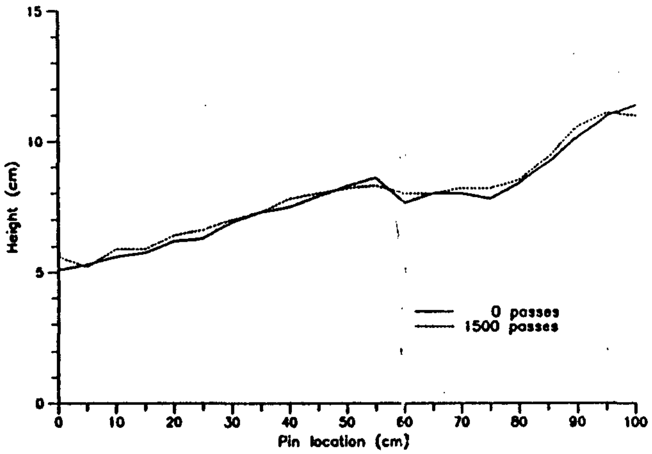
Profile of Flat Control Lane: Location 6 m



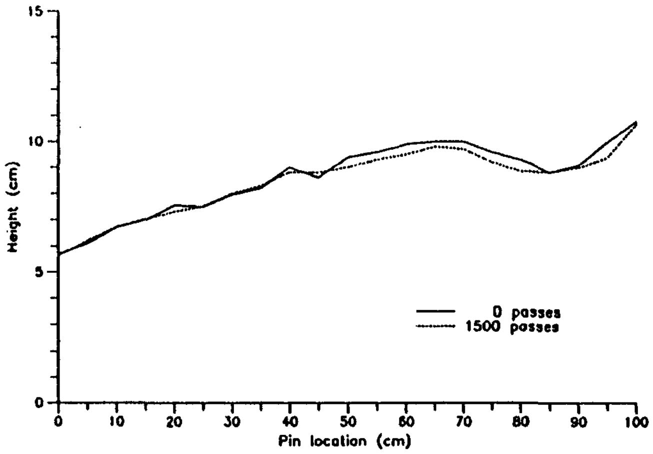
Profile of Flat Control Lane: Location 8 m



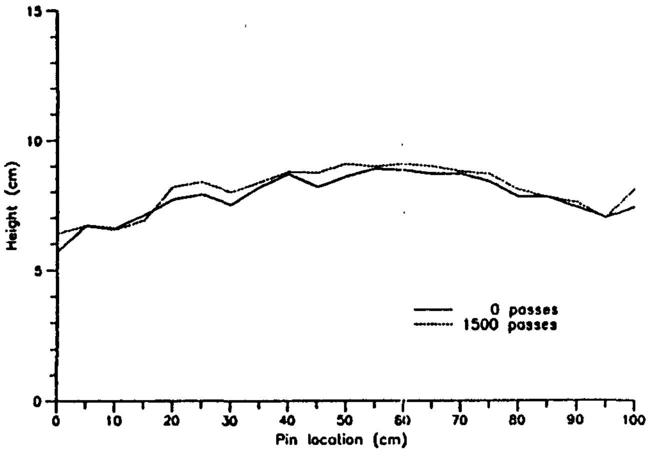
Profile of Sloped Control Lane: Location 2 m



Profile of Sloped Control Lane: Location 4 m



Profile of Sloped Control Lane: Location 6 m



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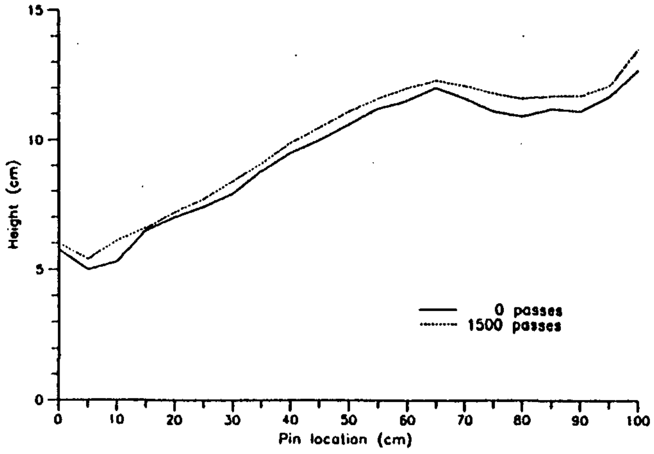
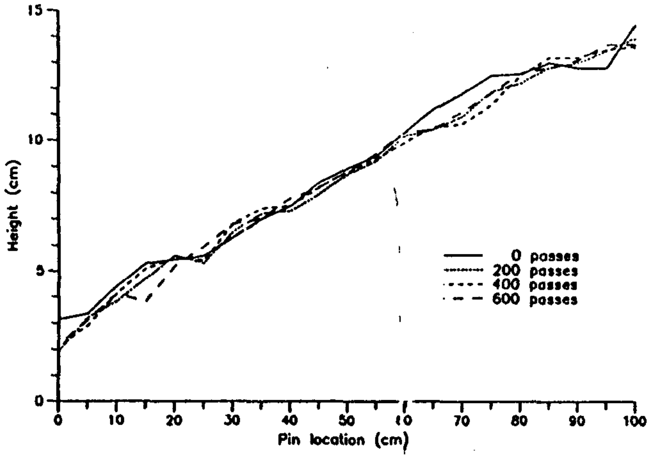


Profile of Flat Hiker Lane: Location 2 m



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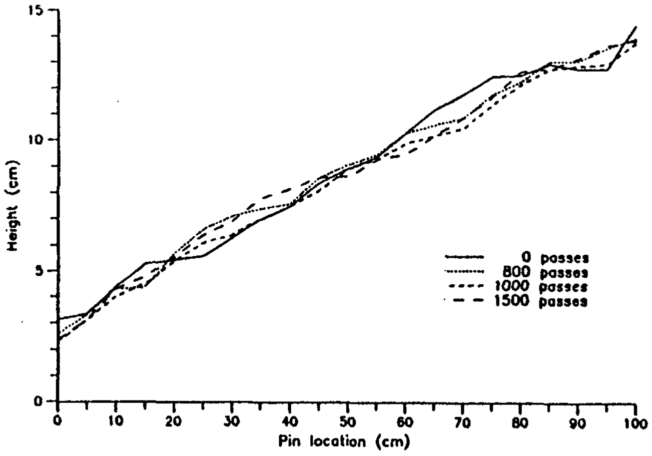

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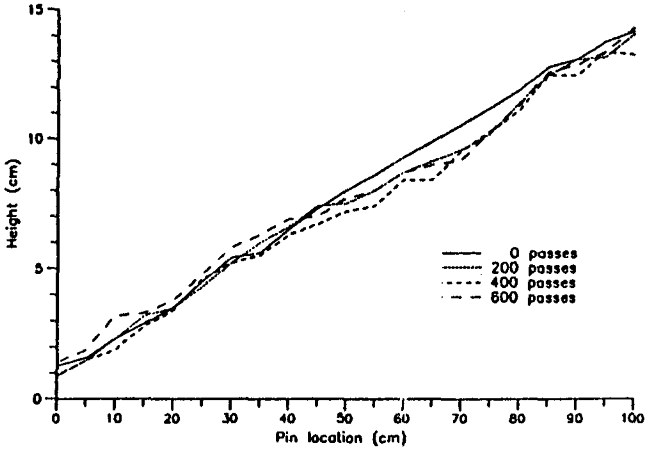
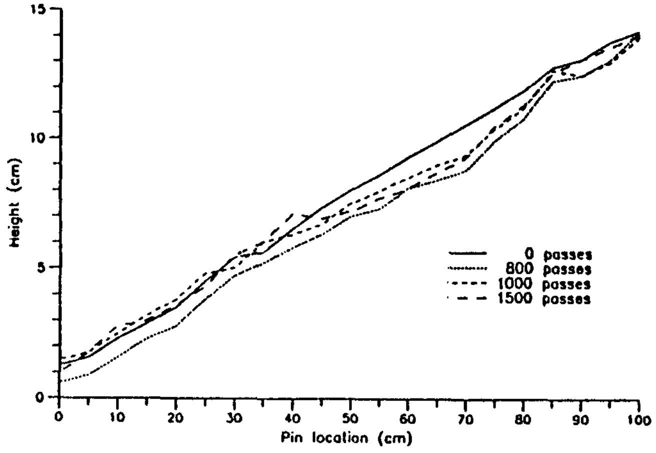


Profile of Flat Hiker Lane: Location 4 m



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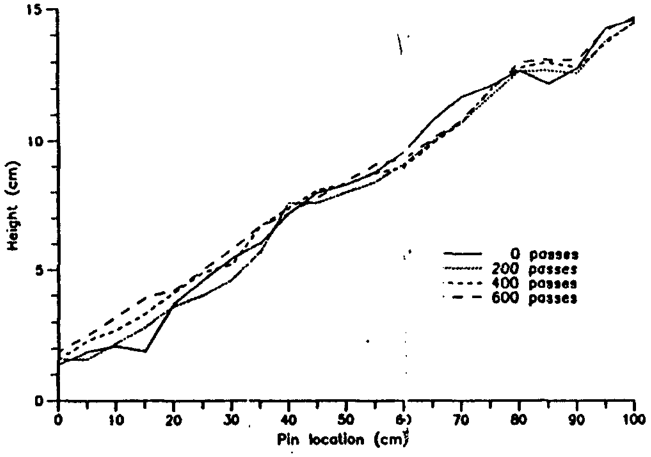
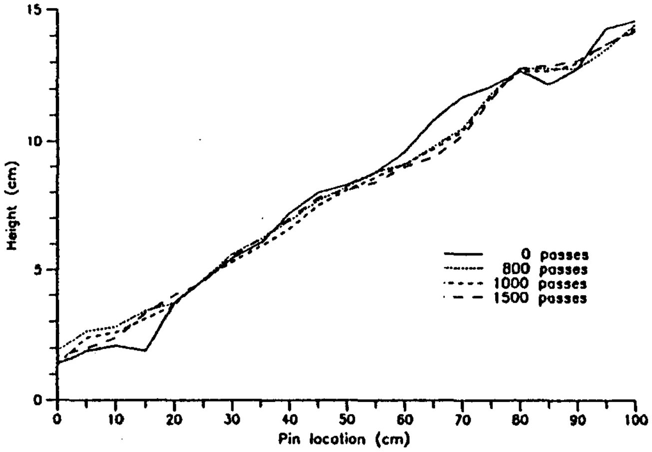
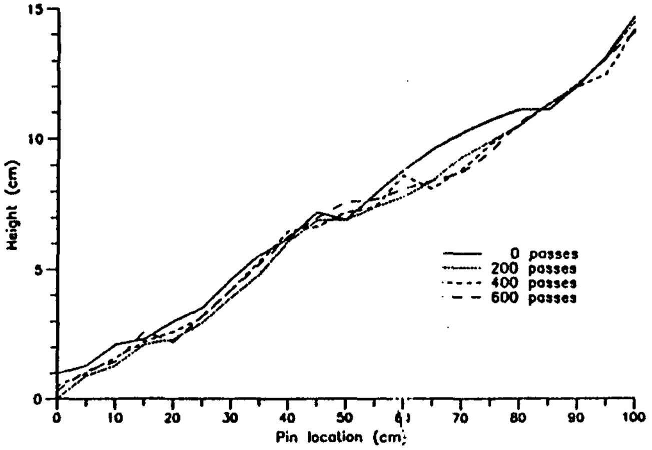


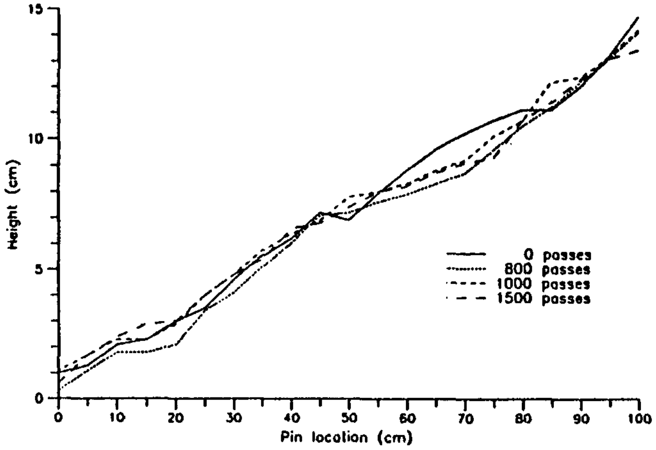
Profile of Flat Hiker Lane: Location 6 m



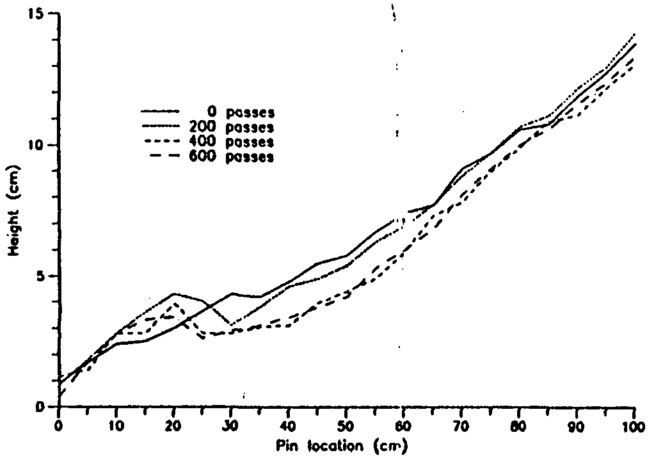
Profile of Flat Hiker Lane: Location 8 m



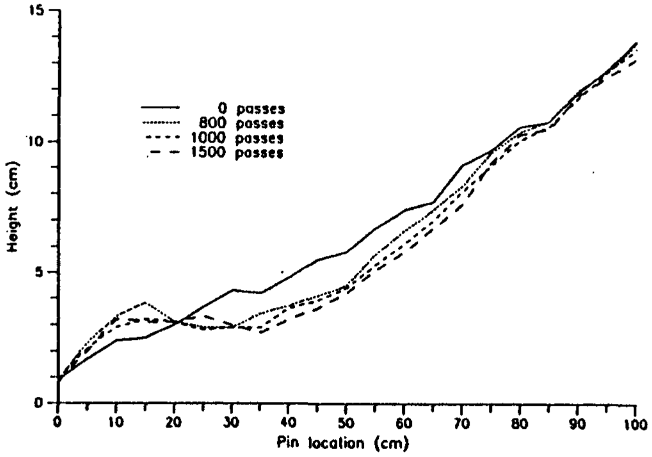
Profile of Flat Hiker Lane: Location 8 m



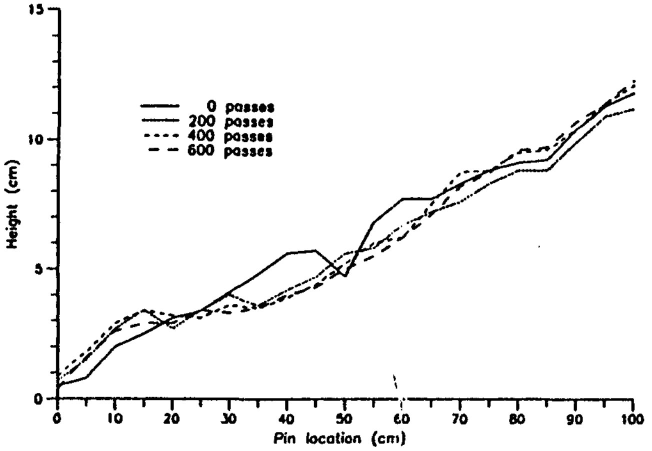
Profile of Flat Bicycle Lane: Location 2 m



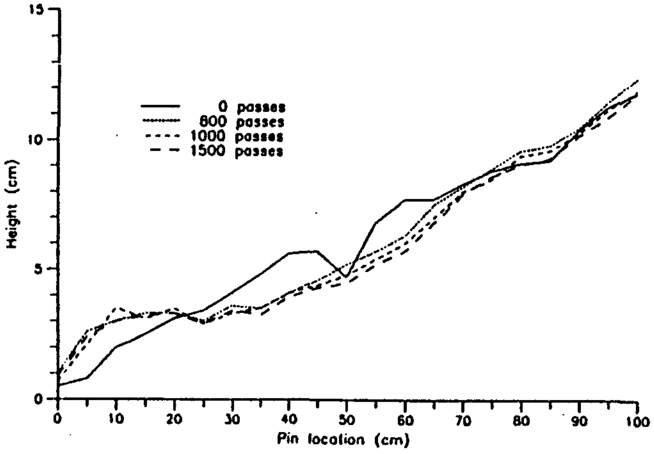
Profile of Flat Bicycle Lane: Location 2 m

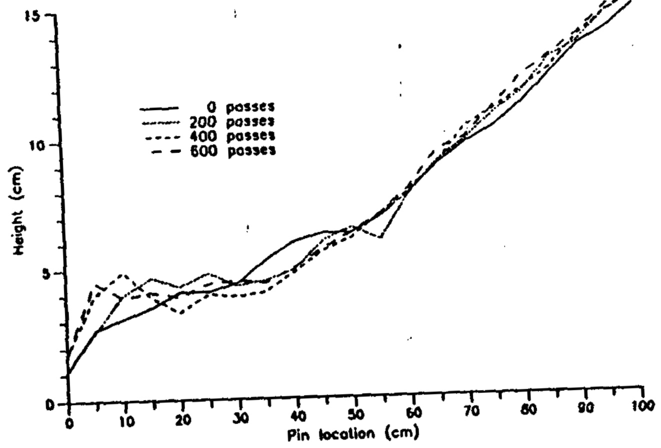


Profile of Flat Bicycle Lane: Location 4 m

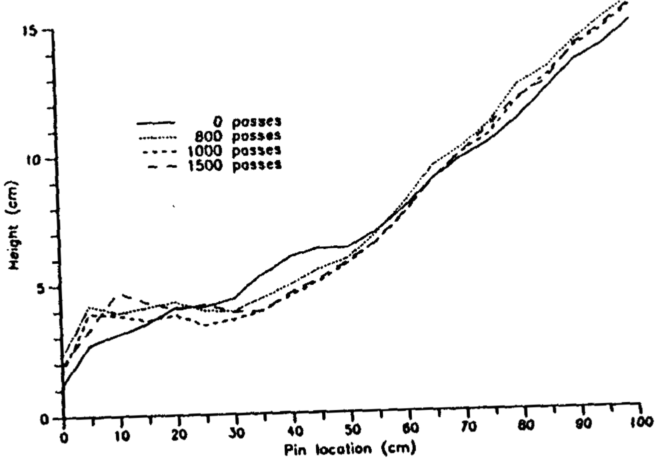


Profile of Flat Bicycle Lane: Location 4 m

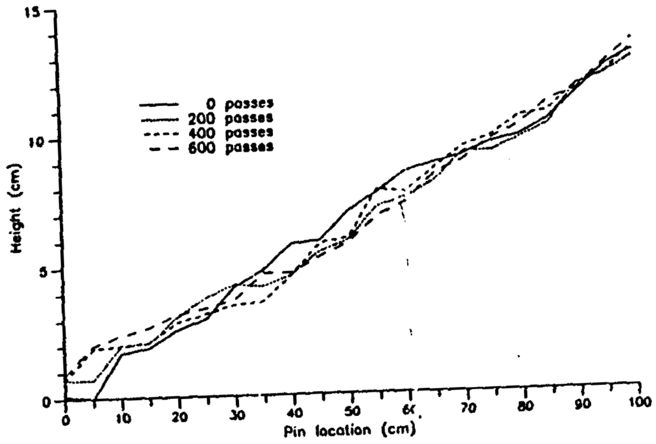




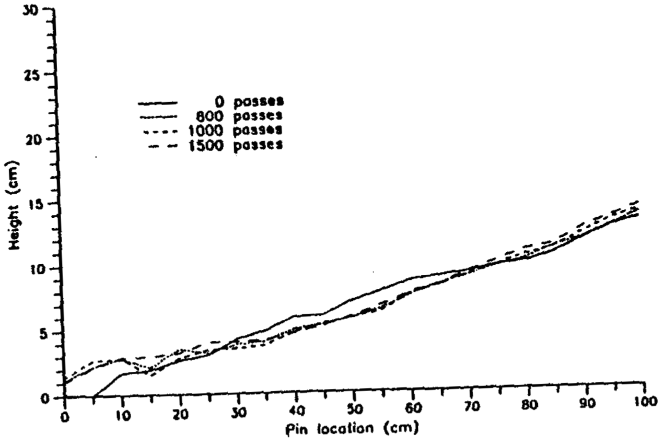
Profile of Flat Bicycle Lane: Location 6 m



Profile of Flat Bicycle Lane: Location 6 m

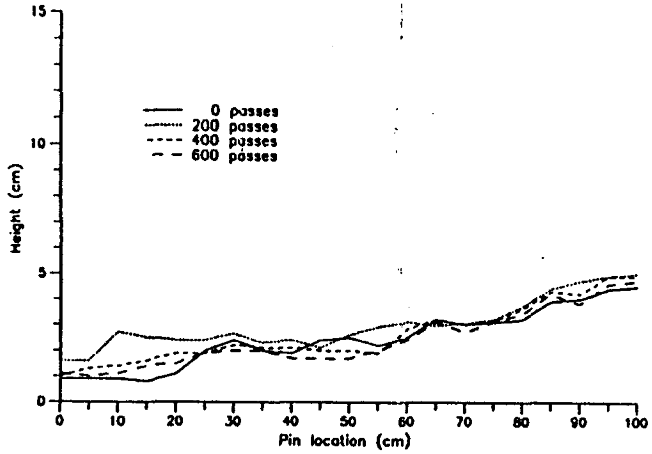


Profile of Flat Bicycle Lane: Location 8 m

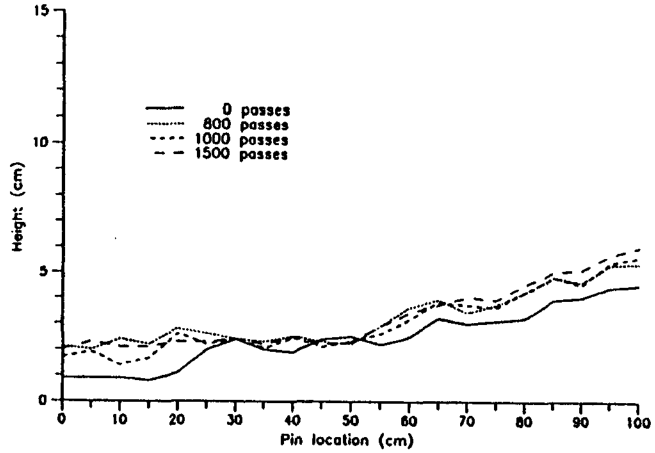


Profile of Flat Bicycle Lane: Location 8 m

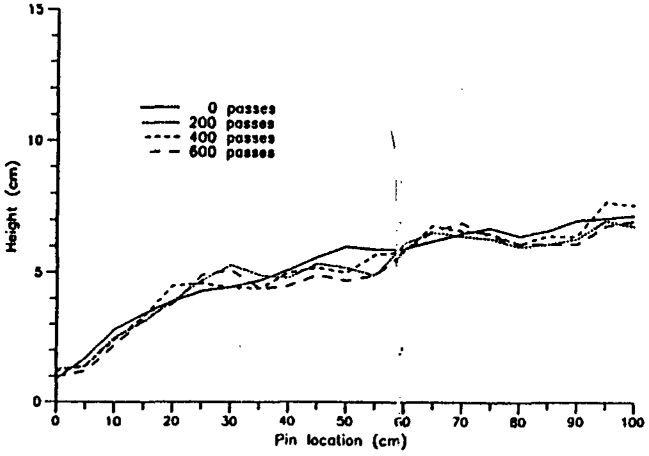
Profile of Sloped Hiker Lane. Location 2 m



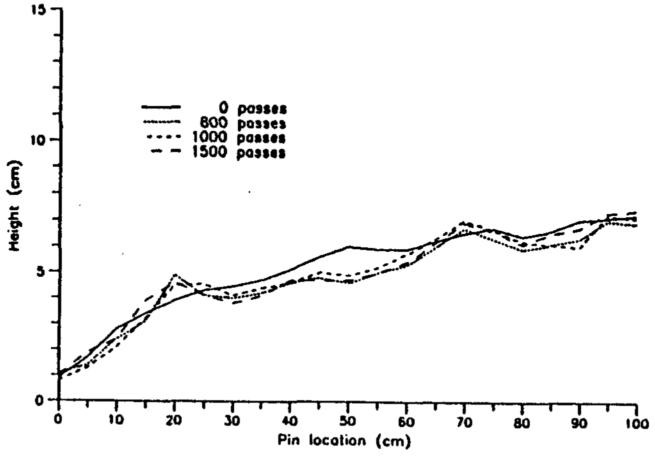
Profile of Sloped Hiker Lane: Location 2 m

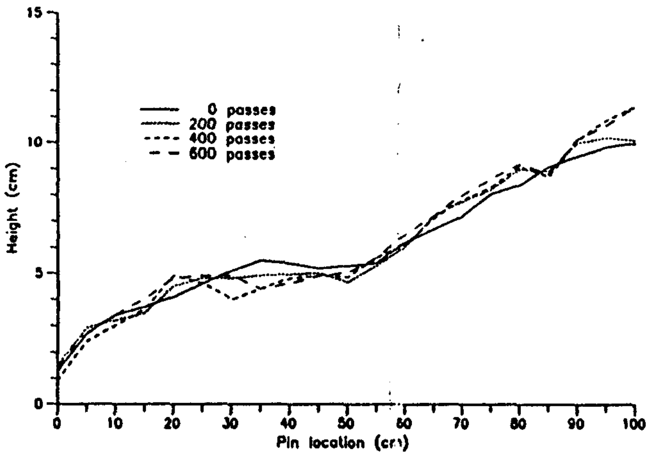


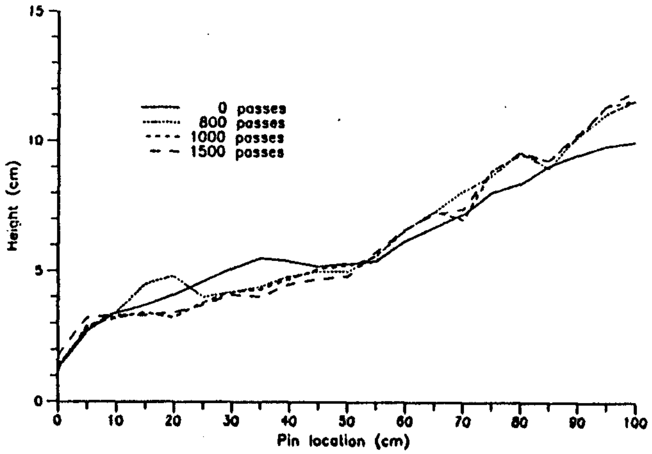
Profile of Sloped Hiker Lane. Location 4 m

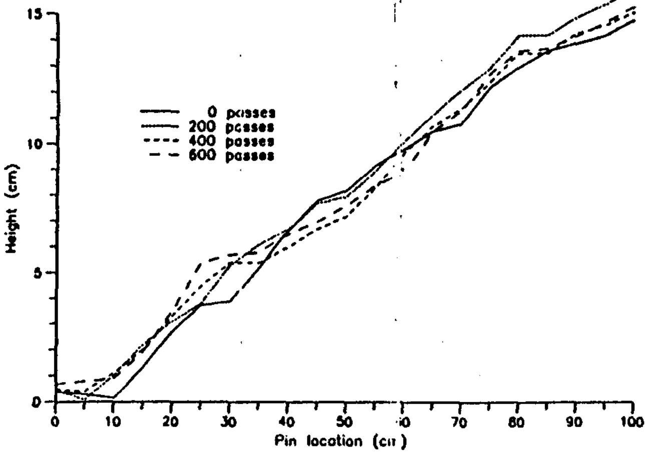


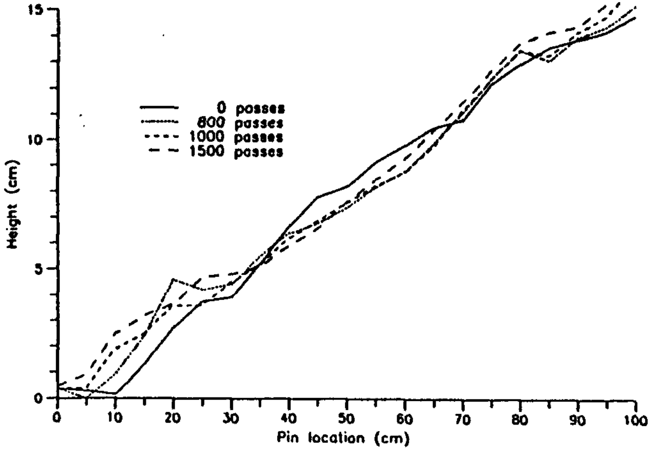
Profile of Sloped Hiker Lane: Location 4 m



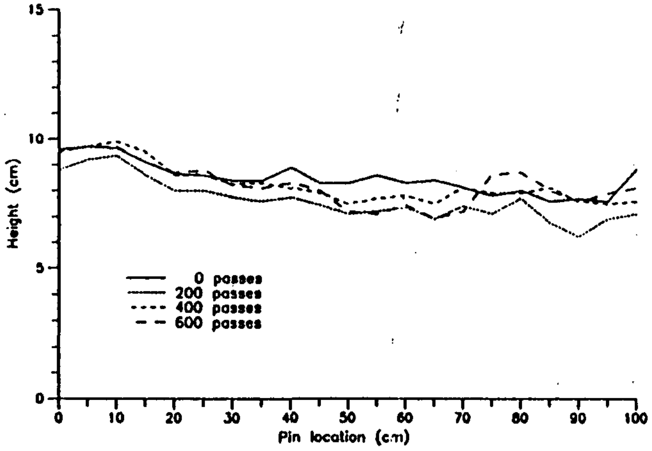

Profile of Sloped Hiker Lane: Location 6 m


Profile of Sloped Hiker Lane: Location 6 m

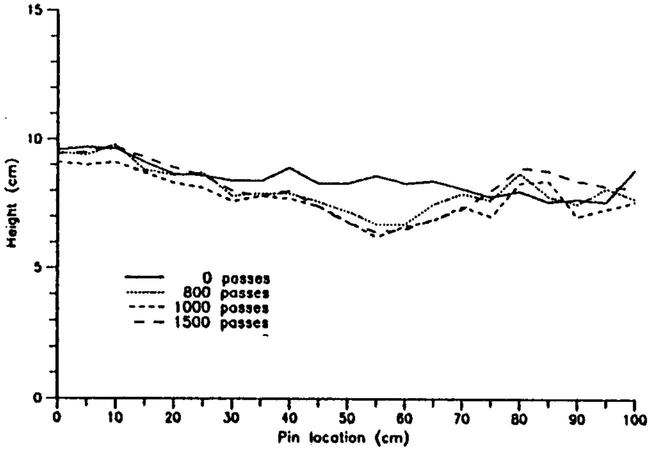

Profile of Sloped Hiker Lane: Location 8 m


Profile of Sloped Hiker Lane: Location 8 m

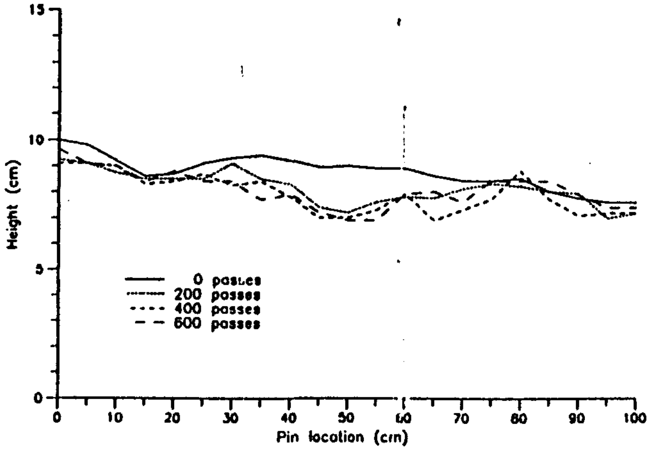
Profile of Sloped Bicycle Lane: Location 2 m



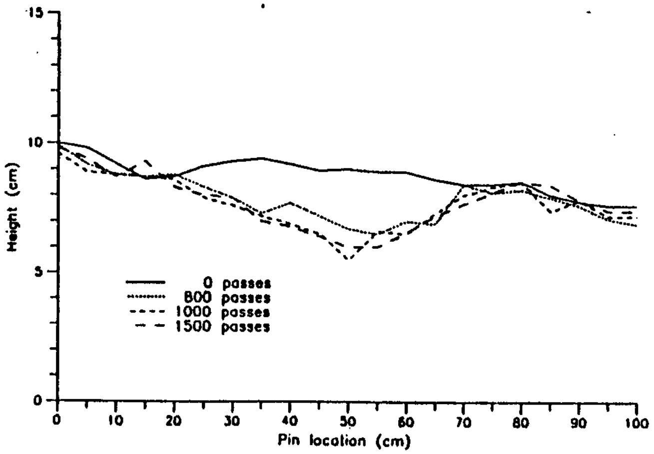
Profile of Sloped Bicycle Lane: Location 2 m



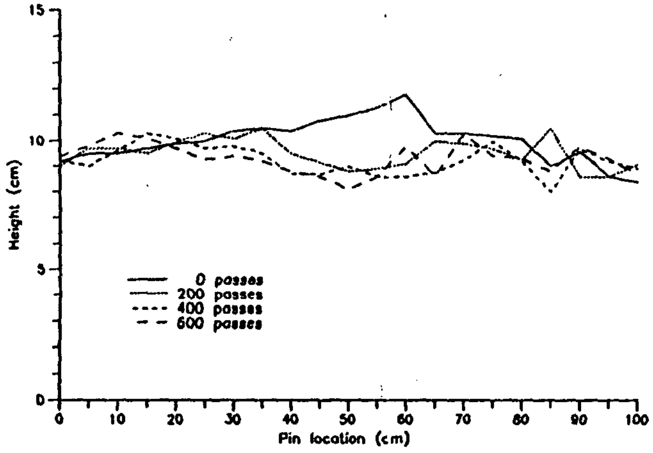
Profile of Sloped Bicycle Lane: Location 4 m



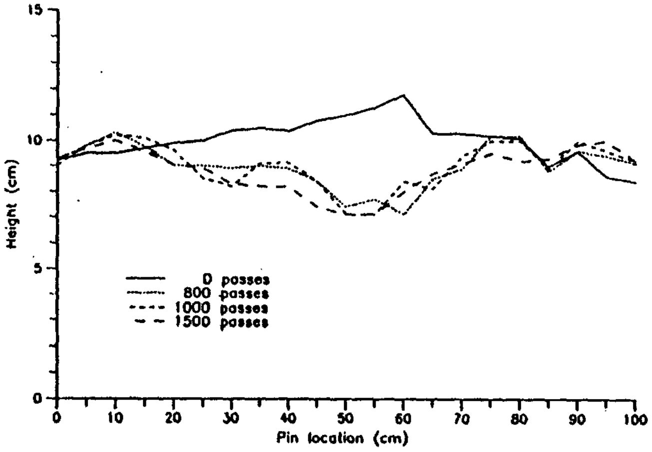
Profile of Sloped Bicycle Lane: Location 4 m



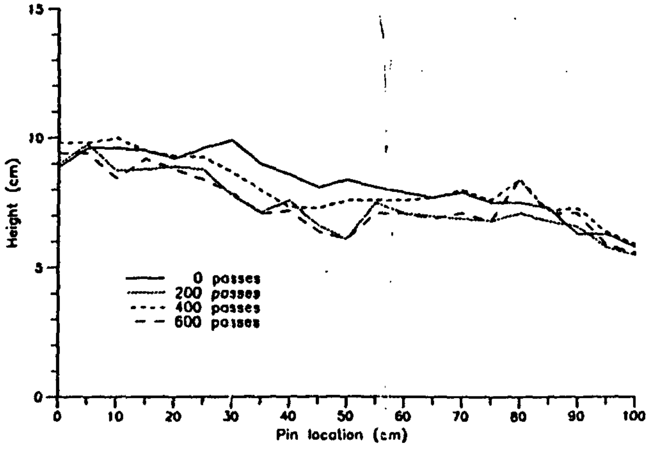
Profile of Sloped Bicycle Lane: Location 6 m



Profile of Sloped Bicycle Lane: Location 6 m



Profile of Sloped Bicycle Lane: Location 8 m



Profile of Sloped Bicycle Lane: Location 8 m