THESIS

SOIL MOVEMENT FOLLOWING AN INTENSE BURN

Submitted by

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In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

June, 1968

S591
D45

COLORADO STATE UNIVERSITY

June 1968

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BY Phil G. Delp

ENTITLED SOIL MOVEMENT FOLLOWING AN INTENSE BURN

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ABSTRACT OF THESIS

SOIL MOVEMENT FOLLOWING AN INTENSE BURN

A study was conducted from June to August, 1967 to evaluate the effects of an intense burn on soil and ash movement from steep mountain slopes.

Twenty study plots were established on the burn. The soil on each plot was tagged at five points with Cs-134. Rates and patterns of actual soil particle movement were established by measuring changes in radiation intensity following three summer thunderstorms.

Tagging of the soil with Rocket Red fluorescent dye provided a means of tracing soil particle movement throughout the study period. Dispersion of dye spots located on 0-1 per cent slopes provided an estimate of soil particle transport by raindrop splash. Summer soil loss was measured on each study plot.

The results indicated that rock cover is more important than slope when rainfall intensities are insufficient to produce surface runoff. However, when surface runoff is produced, slope is the controlling factor of soil movement. Raindrop splash was also found to be a prime factor in initiating soil particle movement.

Comparison of the two methods of tracing soil particle movement indicated that analogous data were obtained with either method.

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June, 1968

ACKNOWLEDGMENTS

I gratefully acknowledge Dr. W. D. Striffler for his assistance in planning this study and for his advice and constructive criticism. I also wish to offer my appreciation to the other members of my committee, Dr. E. W. Mogren and Dr. F. W. Whicker.

My appreciation is extended to Dr. R. E. Dils for his assistance in obtaining financial support. Research for this thesis was conducted under the McIntire-Stennis Cooperative Forestry Research Program.

Finally, I offer my appreciation to my wife, Marcia, whose assistance in typing and in all phases of the project has been invaluable; and whose love and companionship must be considered a part of this effort.

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INTRODUCTION

Wildfire creates a major disturbance on a forested watershed. The degree of the disturbance will vary with the intensity of the burn. A light ground fire which burns off the surface vegetation but leaves most of the soil organic matter may have only a slight temporary effect on the hydrologic conditions of the area. However, an intense ground fire which burns all the organic matter and leaves only bare mineral soil will have a longer, more serious effect. Probably the worst condition occurs after an intense fire which destroys not only the ground vegetation and organic matter but the forest canopy as well, leaving the slope totally exposed to the elements.

The effects of fire upon a watershed have long been recognized. In general, increased flood flows, sedimentation, debris production and erosion are cause for alarm to the downstream users. These effects vary not only with the extent and severity of the burn, but with slope and soil conditions, and the amount, intensity and distribution of rainfall. Therefore, a long steep highly erodible slope subjected to periodic high intensity storms is potentially a more serious problem area than other combinations of circumstances.

For these reasons research on the effects of fire has largely been concentrated in areas where fires are frequent and severe, or where fire damage on a watershed creates unusually severe problems. There are many areas, including the central Rocky Mountains, where little is known about the effects of fire, although fire may be an important problem with respect to watershed condition. Fire studies have shown varying degrees of hydrologic effects, but nearly every one has shown that burning is followed by increased surface runoff and erosion. This increased susceptibility to runoff and erosion persists for years after a burn, during the regrowth period of the soil-protecting vegetation. Colman (1953) suggests that "Future research in the hydrologic effects of fire will be most useful if it yields quantitative results obtained under more carefully defined local conditions."

A severe burn covering about 600 acres of lodgepole pine forest occurred near Comanche Reservoir in the Roosevelt National Forest in late August 1966. The fire was complete, destroying all the ground vegetation and killing the timber overstory leaving the mineral soil exposed (Fig. 1). Most of the burn occurred on steep mountain slopes ranging up to 70 per cent gradient. Since the burn lies adjacent to a municipal reservoir, there was some concern regarding the impact of the fire upon the hydrology of the area, the possibility of accelerated erosion on the slopes and subsequent sedimentation in the reservoir.

A comprehensive project including four separate studies was set up with the following objectives:

1. To determine the effect of a severe burn on soil and ash movement on steep slopes.
2. To determine its effects upon the hydrologic characteristics of the slope, including: (a) soil moisture levels, (b) relative infiltration rates, and (c) the physical and chemical characteristics of the soil.
3. To determine its effects on the chemical and biological quality of the streams.

Figure 1-- (Top) The protective mantle of litter and humus on an adjacent unburned area.
(Bottom) Unprotected mineral soil as a result of the fire.

4. To establish a series of permanent sample plots for an evaluation of vegetative re-establishment and rehabilitation of the edaphic environment.

This thesis is concerned with the effect of a severe fire on the soil and ash movement (objective 1). Sampling was conducted throughout the summer of 1967.

Chapter II

REVIEW OF LITERATURE

The effects of watershed fire on stream flow, erosion, and sedimentation have been recognized and discussed for centuries. A report made by Guiseppi Paulini in 1608 to the Most Serene Prince of the Venetian Government concerning the evils of deforestation in Venice was reported by Cessi and Alberti (undated). Paulini states:

> The numerous and great floods, and the large quantities of trash and mud which the torrents carry and deposit in the lagoon, are conditions which formerly did not exist when the mountains and valleys were covered with trees and dense forest.

He concludes:

> This is why I claim that the fires which for 100 years have many times denuded the mountains of your Serenity are the principal causes of our ills.

The same deductions have been made by observers of similar situations throughout the world. This has led to organized research efforts by fire, soil and watershed scientists in an attempt to quantify these effects. The most intensive regional research programs directed toward these problems have been, and continue to be, carried out in California.

Studies attempting to quantify the results of fire on the hydrology of an area can be put in three general classes: (1) watershed studies, (2) runoff plot studies, and (3) process studies. The process studies are those primarily concerned with infiltration which in turn has a definite effect on surface runoff and subsequently soil erosion.

Watershed Studies

Barnes, Kraebel and La Motte (1939) linked the repeated burning of the brushy slopes and overgrazing as a chief cause of accelerated erosion. Eaton (1932) speaking in terms of the Los Angeles County watersheds stated, "On a burned-off watershed it is not uncommon to have 25,000 cubic yards of debris from one square mile." He later reported that the discharge of debris from these watersheds was increased from 10 to 30 times by fire (Eaton, 1936).

Krammes (1960), at San Dimas Experimental Forest, found that destruction of the plant cover accelerated not only erosion by water, but also a mass soil movement by "dry creep". Nearly 89 per cent of the eroded material was transported during the "dry" season and was therefore attributed to this creep.

Soil movement at both the Ono and Ukish burned and unburned watersheds in northern California were statistically highly significant (Sampson, 1944). The author concluded that the soil was effectively protected against abnormal erosion by the chaparral and its understory.

As a result of local evidence in California, Connaughton (1935) suggests that much of the material eroded from the hillside as a result of fire is merely moved a short distance down the slope and never reaches a permanent stream. He states, "On the whole, accelerated erosion attributable to controlled burning cannot be considered severe even on the steep hillside of Diamond Creek."

Several studies have reported on the long term effects of fire on the hydrological characteristics of an area. Colman (1951) states: "Annual erosion rates are increased, on the average, about 35 times the first year after a complete burning of a good chaparral cover and 8 to 10 years are required for erosion rates to return to normal."

Adams, et al., (1947) p. 43, reporting on the fire studies on the Tanbark and Fern miniature watersheds at the San Dimas Experimental Forest in southern California, noted a considerable increase in the rate of runoff and erosion. These amounts, however, were not great and the watershed recovery was progressing rapidly. From unpublished data Adams et al., p. 46, pointed out that erosion was evident on the slopes for the first three years following the fire, with the highest concentration in the first two years. After the third year there was no appreciable amount of water-borne erosion.

Weaver (1952) found no indication of accelerated erosion due to fire following the prescribed burning of virgin ponderosa pine stands in the White Mountains of east central Arizona.

During the first 21 months after the chaparral cover was burned by wildfire on Arizona's 3-Bar Experimenal Watersheds, bedload sediment yields equivalent to 49,839; 21,519; and 64,446 tons per square mile were reported for watersheds A, B, and C, respectively (Glendenning, Pase and Ingebo, 1961). Sediment yields began to drop the next year after the fire (Pase and Ingebo, 1965). One watershed was seeded to grass and sprayed by herbicides to favor grass. The other watersheds were allowed to return naturally to brush. Within five years after the fire the chaparral had recovered to two-thirds pre-fire density. On the watershed sprayed to favor grass, the runoff was significantly increased compared to the watershed with natural shrub recovery. However, more sediment moves from the watersheds allowed to return naturally to brush than the one converted to grass.

Anderson and Trobitz (1949) employed a multiple regression analysis to study sediment deposition and peak discharge from 40 California watersheds following a single 1938 storm. The discharges were unusually high constituting a 100-year flood and were apparently due to the combination of relatively high pre-storm precipitation and high storm precipitation. Variables affecting sediment deposition were grouped into three categories: (1) variation in storm intensity from watershed to watershed, (2) watershed factors affecting the intensity of runoff, and (3) watershed factors affecting the amount of erosion for a given runoff. The analysis of sediment catches in 25 different reservoirs showed the following variables to affect the amount of sediment deposition resulting from the storm: precipitation, watershed area, cover density, area of old fires and barren area.

Friedrich (1951) with the Northern Rocky Mountain Experiment Station noted:

> Summer thunderstorms falling on an area severely burned the year before, gutted stream channels, washed out roads and bridges, carried away soil, destroyed recreational and aesthetic values and caused other striking damages. Adjacent, unburned areas in the path of the storm remained unharmed.

The reported fire was an extremely hot crown fire which killed all tree cover and consumed nearly all soil-protecting litter. The soil surface was quickly sealed against infiltration by a layer of ash and powdered limestone left by the fire. Friedrich further points out that those particles not trapped in the soil pores were readily carried away by the runoff water.

Rich (1962) reported the results of a wildfire in a ponderosa pine watershed in central Arizona. The burn was confined to the flattest slopes in the headwaters of the watershed. The steeper slopes in the lower reaches were unburned. Sediment measured in the weir pond and in the channel between the fire and the weir accounted for only 43 per cent of the total estimated sediment. The remainder was deposited on flat areas just outside the burn. Rich concluded that some combination of flat slopes, forest soil, surface rocks, rocks in the soil profile and forest vegetation below the burn prevented deep gully formation while the burn was being stabilized by seeded grasses and sprouts of New Mexican locust, Gambel oak, and bracken.

A study by Anderson (1954) was conducted on the mountain and valley watershed of western Oregon. Records showed that sediment discharge varied in response to differences in stream flow, soil, topography and land use.

Runoff Plot Studies

Plot studies serve to examine the processes and effects of certain treatments on hydrologic functions while holding constant or accounting for all other known influencing factors. Considerable opposition has been raised concerning the transposition of plot data to the watershed. Researchers will select plots which they consider typical of the region. However, conditions vary so widely from acre to acre and from watershed to watershed that plots seldom can be fully representative. Although transposition is limited, plot data serve to explain certain phenomena occurring in a larger, much more complex way on the watershed.

In presenting data from a number of plot studies in California, Adams et al., (1947) included observations of P. B. Rowe which appeared in his Master's thesis at the University of California. He observed that rapid revegetation occurred on the periodically burned plots. By the fifth season after the first burn, the accompanying erosion appeared to be controlled completely.

Sampson (1944) conducted plot studies at Bass Lake, California to determine the influence of a 70-year old ponderosa pine stand on the disposition of rainfall. He concluded that the annual removal of the forest floor and scant herbaceous ground cover on these plots by burning resulted in greatly increased surface runoff and erosion. A similar statement was made by Rich (1961) in discussing surface runoff and erosion in the chaparral zone in Arizona. He stated, "Where plant cover is sparse, and infiltration capacity low, surface runoff may be high. Surface flows carry considerable sediment, deepen channels and generally increase erosion."

Erosion on the undisturbed plots of ceanothus, manzanita, and buckeye brush types at North Fork, California, did not exceed 0.01 cubic yards per acre. After the plots were burned over four times in successive years, the erosion increased to between 2 and 4 cubic yards per acre per year (Lowdermilk and Rowe, 1934).

In the central Piedmont, soil losses and runoff from the unburned woods plots remained at consistently low levels throughout the years of record (Copley et al., 1944). In contrast there was a progressive increase in the annual soil losses from the burned woods which reached a maximum of 7.81 tons per acre for the year 1938.

In northern Mississippi, Meginnes (1935) found that two annual burnings on plots in mature oak timber caused an increase in erosion from 0.05 to 0.83 tons per acre per year. The same treatment on broomsedge caused an increase from 0.18 to 0.79 tons per acre per year.

Many studies have been conducted which show no effect due to burning. Veihmeyer and Johnson (1944) found no indication that runoff and erosion were accelerated on plots that were annually cut and burned. They also stated that soil moisture records indicated that the infiltration capacity of the soils on the burned plots was not impaired.

It is readily apparent that there is great variability and contradiction in research results. Adams, Ewing and Martin (1947) stated that the hydrologic response of the land to fire is an extremely complex interaction of many variables. Many hydrologic processes operate within watersheds, and operate on highly variable material with highly variable results (Anderson, 1957). As a consequence, it is especially difficult to compare results from two or more watersheds. On the other hand, in plot studies many of these independent variables can be controlled and measured.

Parameters Related To Soil Erosion

Neal (1938) working in Missouri with runoff plots on agricultural soils introduces his paper by stating:

> The factors affecting soil erosion are so many and so varied that it is difficult to determine the relative importance of each individual factor, especially under natural conditions. Even on small areas the soil varies widely in its physical characteristics and conditions, and in its ability to produce vegetation. Rainfall characteristics are so varied that the erosion caused by one rain can seldom be compared with that produced by another. The moisture condition of the soil at the time of a rain, the soil structure, the surface condition and the vegetative covering are continually changing.

He goes on to state that relative density of the runoff material increased as both the slope and the rainfall intensity increased. According to Wischmeier and Smith (1965) the rate of soil erosion on any area may be influenced more by land slope, rainfall characteristics, cover and management than by properties of the soil itself.

Friedrich (1955) indicates that whether a fire is planned or wild does not effect the seriousness of the damages caused by the fire. The seriousness of a fire depends on several important factors: the size and intensity of the burn; the soil characteristics; the steepness of slope; the amount and character of precipitation to which the burned area is subject following the fire; the type of vegetation present before the fire; the length of time the soil will be bare before revegetation occurs; the type and amount of vegetation that comes back after the burn; the proportion of the watershed unit affected by the fire; the characteristics of associated unburned portions of the watershed unit; and the condition and ability of the stream channel to carry increased flows in an orderly manner.

Copeland (1963) in a paper presented before the Federal Interagency Sedimentation Conference at Jackson, Mississippi, states:

> Sediment production as a result of erosion on damaged watersheds indicates the loss of control over water in its contact with the soil. . . . High intensity storms are common over much of the United States and particularly in the Intermountain states . . . seldom do these storms occur when the soil mantle is saturated; rather they occur when the soil mantle has the capacity to store several inches of water. The critical characteristic is that the rainfall intensities of these cloud bursts frequently exceed the infiltration rate of the soil, especially, when plant cover is depleted, and overland flow is then inevitable.

Studies conducted on the Davis County Experimental Watersheds determined that mud-rock-flow type floods, which are frequently composed of as much as 60 per cent solids with boulders weighing from 100 pounds to 100 tons, originated on soil-covered watersheds from which plant cover had been materially reduced, or destroyed, by grazing and fire. They occur as a result of intense rainfall of short duration (1 to 2 inches in 15 to 30 minutes) (Croft, 1961). Baver (1956) pp. 426-430 stated that the amount and velocity of runoff are dependent upon (1) rainfall characteristics, (2) the slope and the area of the land, and (3) the ability of the soil to absorb and transmit water through the profile. Colman (1951) p. 277 states:

> Only when the characteristics of rainfall, soil, slope and revegetation in particular places are taken into account in burning studies will we know the conditions under which the damaging hydrologic effects of fire are severe, light, or inconsequential.

Colman explains that the significance of runoff and erosion depends on the quantities involved, and these vary widely from place to place in response to differences in local conditions. Soils differ in their susceptibility to surface flow and erosion both before and after they are burned over. Steep slopes are affected differently from gentle slopes. In some places plant regrowth is quick and dense after a fire; in others it is slow and sparse. Where rains are prevailingly gentle, burning will not ordinarily be followed by severe surface washing. Where intense rains are frequent, burning is a much more serious threat.

On agricultural plots, Duley and Hays (1932) found that the relative erosiveness of a sandy soil was dependent largely on the degree of slope and the rate of rainfall. Woodland burning did not greatly increase erosion on sandy soils which were located on gently rolling or flat areas in southern forests (Dunford and Weitzman, 1955). They found, however, that fire on steep chaparral slopes has been extremely detrimental when heavy rains followed. Further, the severity of the erosion following fire is proportional to the amount of vegetation and organic material removed, the steepness of the slopes burned and the type of precipitation that follows. Erosion on mountainous slopes in southern Idaho was affected about equally by the character of the vegetative cover and the steepness of the slope (Craddock and Pearse, 1938).

Many statements on the effects of specific variables on runoff and erosion can be added to the preceding ones. Factors most often associated with erosion and which will be covered in detail below are: (1) climate, (2) soil, (3) vegetation, (4) topography, and (5) individual fire characteristics. Baver (1956) p. 430 states:

> The complete solution of the erosion problem depends upon an evaluation of each of the variables with respect to each other. Knowledge about the nature of erosion as well as effective control methods can be advanced only by investigating the interrelationships of the factors mentioned.

He goes on to state that the two types of variables influencing erosion are those that can be controlled and those that are directly uncontrollable (e.g., climate, the degree of slope of the land and certain physical characteristics of the soil which cannot be directly controlled).

The major climatic factors that influence runoff and erosion are precipitation, temperature and wind. Precipitation, of course, is the most important and is the factor discussed here. Temperature affects runoff as far as it contributes to changes in soil moisture between rains, determines whether the precipitation will be in the form of rain or snow and changes the absorptive properties of the soil for water by causing the soil to freeze to an appreciable depth. Wind will be primarily related to its influence on the angle and impact of the raindrops (Baver, 1956, p. 432).

Precipitation As Rain

The amount, intensity and distribution of the rainfall help to determine the dispersive action of the rain upon the soil, the amount and velocity of runoff and the losses due to erosion (Baver, 1956, p. 432). Blumenstock (1939) has indicated the importance of precipitation characteristics, such as rainfall intensity and duration and storm frequency. It is generally recognized that with an increase in rainfall intensity there is a tendency for both runoff and erosion to increase (Lutz and Chandler, 1946, p. 449). Duley and Miller (1923) in some of the earliest erosion studies in the country concluded that the character of the rainfall largely determined the amount of soil erosion.

Raindrop Splash

Splash erosion is the first effect of a rainstorm upon the land. The impact of raindrops furnishes a major part of the energy for erosion. Osborn (1955) p. 127 states, "The total energy of raindrops has been calculated as being equal to roughly 100 horsepower on an acre during rainfall of 0.1 inch an hour and 250 horsepower at 2 inches an hour." Amount and intensity of rainfall, the diameter of the raindrops and the velocity of the drops as they strike the soil determine their erosive capacity. The amount of soil set in motion by a single drop is directly proportional to the square of the velocity of the drop (e.g., a drop 1 millimeter in diameter falling at its terminal velocity of 10 feet a second will move fine sand particles) (Osborn, 1955, p. 127). Osborn goes on to state:

> Raindrops are relatively unimportant in the transportation of the detached materials, although the cumulative effects under some conditions may be considerable.

> The soil particles and droplets of soil charged water that are thrown into the air travel varying distances in all directions from the point of impact of each drop. On level ground when the drops strike from a vertical direction, the effects tend to cancel one another, leaving the same amount of soil on the area at the end of the rain. But such conditions are uncommon; the slope of the land and direction of the wind give a predominant direction to the travel of the splashed soil.

Measurements on an open field of 10 per cent slope showed three times as much downhill movement as uphill movement of splashed soil.

Runoff and Erosion

When the rate of rainfall exceeds the intake capacities of the soil, water that is not absorbed where it falls moves across the land as surface flow. It gains energy as it travels downslope, and it also dislodges and transports soil. Runoff water sets soil in motion by a process of scouring. Velocity and turbulence, energy expressions of surface runoff, depend on the amount of water involved and the slope and configuration of the land over which it moves. Storm intensity is important in determining the amount of water available for runoff.

Adams et al., (1947) p. 32 considered rainfall intensity one of the most important factors affecting runoff and erosion in southern California where relatively low total rainfalls of high intensity are common. Nichols and Sexton (1932) conclude that the intensity of rainfall was more important than the total amount in causing erosion. The rate of erosion varied as some power of the intensity. At the central Piedmont on agricultural land, Copley et al., (1944) found that storms of 1 to 2 inch total amounts with intensity in excess of 1.5 inches per hour for at least a 5-minute period caused the greatest total soil loss per year.

Other reports emphasize the relative importance of rainfall intensity on runoff and erosion. The results of tests in Missouri by Neal (1938) showed that the intensity of rainfall was by far the most important factor affecting runoff and erosion. Again in Missouri, Duley and Hays (1932) determined that a 2-inch rain falling in a 30-minute period on cultivated runoff plots caused seven times as much erosion on the steeper slopes as a 1-inch rain falling in the same length of time.

Soil Properties and Vegetative Cover

Much as been written concerning the effects of both soil properties and vegetative cover on infiltration, runoff, and erosion. Colman (1953) p. 276 states that fire in dense brushlands on steep slopes holds the key threat of runoff and erosion, for it accomplishes very complete baring of the soil.

Soil Properties

The amount of surface runoff is influenced to a marked degree by the soil properties which affect (1) infiltration rate and permeability and (2) those properties that resist the dispersion, splashing, abrasion and transportation forces of the rainfall and runoff (Baver, 1956, p. 447; Adams, Kirkham, and Schultes, 1958; and Smith and Wischmeier, 1962). The specific soil properties can be subdivided into the effects of: (1) soil texture, (2) soil structure (including surface features), (3) soil cover, and (4) organic matter.

Size and texture of soil particles has been shown to determine to a great extent the amount of erosion on any given soil (Lutz, 1934 and Middleton, 1930). Litter was more effective in reducing runoff and erosion on fine-textured soils than on coarse-textured soils; and the fine-textured soils repeatedly yielded the greatest amount of sediment (Lowdermilk, 1930).

Connaughton (1935) thought that the coarse, loose granitic soil of the fire area in the Payette National Forest emphasized the effect of slope and intensity of fire on erosion. Adams, Kirkham and Schultes (1958) concluded that in general the greater the sand percentage, the higher the infiltration rate and the lower the runoff and wash erosion.

Yoder (1936) found that aggregates, rather than textural separates, were the particles primarily involved in the erosion process in the case of structural soils. Epstein, Grant and Struchtemeyer (1966) found that removing rocks larger than 3.81 centimeters from field runoff plots increased erosion and runoff, and decreased infiltration and soil moisture content. Friedrich (1955) observed that as raindrops beat upon the unprotected soil surface following a fire, the fine particles of soil and ash are stirred about and washed into the tiny spaces between the larger particles making the soil surface practically impervious to water.

Organic matter has generally been found to be lower in burned soils. Dyrness et al., (1957) in Washington reported that severe burning reduced organic matter to about 40 per cent of the amount found in the undisturbed forest soil. Penabokke and Quirk (1957) stated that the stability of some soils is probably due to a control by the organic matter on the rate of wetting. Wooldridge (1964) found that under good conditions of vegetative cover and adequate litter there were no significant differences between erosion hazards of soil from basalt or sandstone parent materials. Slash burning in the Douglas fir region has often resulted in an extremely hot fire that destroys much of the humus and organic matter (Youngberg, 1953). Subsequently the loose surface soils are commonly subject to erosion during the winter rains.

Studies on burned ponderosa pine sites in California by Biswell and Schultz (1957) showed no indication of surface runoff or erosion that could be related to burning itself. However, a sufficient layer of partially decomposed duff remained after burning to maintain high infiltration and percolation rates. Dunford (1954), in a study to determine the runoff and erosion resulting from the removal of the protective forest floor, found that complete removal brought immediate response in terms of flashier runoff and increased erosion. Ursic (1966), Pillsbury (1953), Pope et al., (1946) and Diebold (1942) noted similar results.

Vegetative Cover

Smith and Wischmeier (1962) state, "The greatest deterrent to soil erosion is cover. Cover and management influence both the infiltration rate and the susceptibility of the soil to erosion." Munns, Preston and Sims (1938) p. 611 stated that soil losses from forests are from 10 to 0.01 per cent of those from cultivated fields and frequently smaller than the losses from grasslands.

Kotok (1931) reported that burning of vegetation and litter in brush areas in southern California resulted in an increase of erosion up to 1000 times that on unburned areas. A set of mathematical models were developed by Anderson (1949b) to estimate the effect of single forest fires or specific management programs on sedimentation. He estimated the average annual sedimentation under the present fire conditions and the amount of sedimentation which would occur if the annual burn was reduced through protection to 0.2 per cent of the area concerned. From the model it was estimated that an increase in cover density from 10 to 95 per cent would reduce peak discharge by 61 per cent (Anderson, 1950). Anderson (1951) in California, estimated that if cover density were increased on a watershed from 31 to 47 per cent, erosion would be reduced to 44 per cent of original rate.

Eaton (1936) pointed out that rates of debris movements where mountain slopes are involved depend primarily on the condition of natural mountain vegetative cover. Hornbeck (1967) found that clearcutting of a watershed in West Virginia did not result in alarming increases in turbidity (used as an index to the amount of erosion taking place on the watershed). He stated that no extensive damage of the forest floor occurred.

Weaver and Harmon (1935) state, "Other factors being equal, the intensity of erosion is directly proportional to the decrease in vegetation, both above and below ground." Musgrave and Free (1936) claim that litter serves as a filter to remove soil particles from infiltrating water before it enters the soil proper. Soil not covered with such litter can more easily become dislodged and carried along with the infiltrating water. The transported soil clogs the pores and reduces subsequent infiltration thereby increasing surface flow.

A good vegetative cover, such as a thick sod or a dense forest, offsets the effects of climate, topography and soil on erosion (Baver, 1956, pp. 440-441). The vegetative canopy absorbs the impact of the raindrops and thereby minimizes the destructive effects of the beating action of the rain on soil structure. Vegetation acts as a filter to infiltrating sôil charged water preventing the clogging of the soil pores. Any vegetative cover acts as an impediment to runoff water, reducing its velocity and preventing the concentration of this water. As a result, the cutting action of the water on the soil surface is reduced.

Topography

Slope characteristics are important factors in determining the amount of runoff and erosion. Baver (1956) lists the degree and length of slope as the two essential features of topography that are concerned with runoff and erosion. He goes on to say that of the two, the degree of slope is usually the most important from the standpoint of the severity of erosion. In general, runoff and erosion increase with an increase in the degree of slope (Conner et al., 1930; Duley and Hays, 1932; Connaughton, 135; Renner, 1936; and Neal, 1938).

One of the first comprehensive studies of the effect of slope on soil loss was published by Zingg (1940). He concluded that soil loss varies as the 1.4 power of the per cent slope and as the 1.6 power of the slope length. Renner (1936) found that the degree of erosion varied directly with gradient up to about 35 per cent.

Weir (1932) commented that the carrying away of material by moving water is governed by the amount of water, the slope of the land, and the obstacles which are placed in the way of its free movement. Diseker and Yoder (1936) found that on slopes below about 10 per cent the amount of erosion more than doubled as the degree of slope increases twofold.

The effect of length of slope on erosion seems to vary considerably with the type of soil (Baver, 1956). In general, it has been determined that length of slope either has no effect on runoff (Pope et al., 1946) or that runoff decreases with length of slope (Copley et al., 1944; and Duley and Ackerman, 1934). However, soil losses increased as length of slope increased (Copley et al., 1944; and Pope et al., 1946).

On the Sierra Ancha Experimental Forest in Arizona, Hendricks and Johnson (1944) correlated the intensity of fire and subsequent damage with the topography. The steeper portions of the watershed were found to be more susceptible to runoff and erosion damage.

Fire Characteristics

From the studies of fire that have been discussed, it is evident that burning has an indirect effect on soil erosion. Fire causes structure and texture changes in soil (Steenkamp, 1928; Komoshita, 1937; Puri and Asghar, 1940; and Blow, 1955), and clogging of pore space thereby reducing infiltration rates and subsequently increasing runoff and erosion (Tarrant, 1956a and 1956b). Destruction of vegetation by fire leaves bare mineral soil exposed to the dispersive action of raindrops and the erosive forces of surface flow.

In the case of a severe fire the mineral soil was exposed over extensive areas while single light fires hardly affected the organic layer below the litter (Burns, 1952). Cooper (1961) found that erosion and soil exposure, in the White Mountains of Arizona, was significantly increased by burning.

<u>Summary of Fire Research Relating to Erosion</u>

Although fire studies have shown varying effects on the hydrology of an area, nearly every one has shown an increase in runoff and erosion as a result of burning. Sampson (1944) stated:

> Many factors have been shown to influence the rate of runoff and amount of soil eroded. Rarely, however, can one use the factors obtained by the various investigators for quantitative application to other areas, for no two experimental units embody the same combination of soil, climate, topography, vegetation, and experimental procedure.

These remarks are particularly applicable to watershed studies.

Some general statements can be made concerning the effects of the parameters on erosion. As slope increases, runoff has been found to increase. Increases in length of slope increases erosion while runoff either remains the same or decreases. On denuded plots, runoff and erosion have increased with (1) a progression toward finer textured and less porous mineral soil, (2) a decrease in vegetative and litter soil cover, and (3) an increase in storm precipitation intensity and amount. Most of the effects of fire are due to the baring of the soil surface to rainfall and surface runoff.

Colman (1953) states, "Future research in the hydrologic effects of fire will be most useful if it yields quantitative results obtained under more carefully defined local conditions." He later concludes:

> Only the recognition of all factors that influence fire's effects upon the water and soil will lead to complete understanding of the hydrologic consequences of burning. Only when the characteristics of rainfall, soil, slope, and vegetation in particular places are taken into account in burning studies will we know the conditions under which the damaging hydrologic effects of fire are severe, light, or inconsequential.

Tracing Soil Particle Movement

Radioactive Tagging

Wooldridge (1965) states:

> Studies of soil erosion haven't identified rates of travel of soil particles over soil surfaces nor have they indicated sources of eroding soil or patterns of soil particle movement. This leaves the question unanswered as to when a transient soil particle should be termed an eroding soil particle. Common usage has relied on measurement of moving soil particles at some point in their course and the labeling of this transient soil as erosion loss.

Radioisotopes allow the continual tracing of activity bands representing the movement of tagged particles.

Much has been written in recent years on using radioactive tracers to study movement of suspended sediment and bedload in river channels. Research using radioisotopes has contributed to knowledge of sediment transport and deposition in rivers and estuaries (Feely et al., 1961; and McHenry and McDowell, 1962). This has been accomplished by tagging sediment samples in the laboratory with radioactive Sc-46, Ag-110, P-32 and BaLa-140, then replacing these tagged samples in the environment where sediment movement was determined.

Slow neutron irradiation has been utilized in the activation of both natural and artificial sediments. The irradiation of quartz and natural sediments has been employed by Goldberg and Inman (1955), Inman and Chamberlain (1959), Crickmore (1961) and Crickmore and Lean (1962).

Goldberg and Inman (1955) found that P-32 ($T_{\frac{1}{2}}$ = 14.3 days, beta emitter, 1.70 Mev) was the principal radioisotope resulting from the slow neutron irradiation of natural quartz sand. The beta particles emitted from P-32 are readily adsorbed (penetrating ability = 0.2 inch in water), making in situ measurements impractical. Inman and Chamberlain (1959), however, utilized these emissions to study beach sand movement at the Scripp Institute of Oceanography. Surface and core samples were taken from the experimental area and the individual samples analyzed by autoradiographic technique. This made it possible to record the presence of individual irradiated grains on photo-sensitive film.

Gilbert et al. (1958) used sand grains labeled by adsorption (sic) of Ag-110 to investigate sand movement in the Figueira da Foy Harbor (Portugal). Silver-110 added to the sand as a solution of silver-110 nitrate was subsequently reduced to metallic silver by sunlight. Fifty to 70 per cent of the activity was fixed permanently on the grains. Eight hundred millicuries of this isotope, contained in 4000 kilograms of sand, was placed on the harbor floor. Samples were collected, the silver was extracted from the sand and analyzed in the laboratory. The long half-life (270 days) together with the added sensitivity gained by sampling and chemical extraction of the isotope, permitted measurements to be made for several months.

Surface labeling has been used with other radioisotopes in a variety of tracer experiments. Davidson (1958) studying the sand movements in Sweden using Cr-51 ($T_{\frac{1}{2}}$ = 28 days, 0.32 Mev) concluded that this isotope was not satisfactory because of its low gamma emissions and poor penetrating ability.

Sc-46 ($T_{\frac{1}{2}}$ = 85 days, 0.89 and 1.12 Mev), has been bonded to the surface of quartz grains by McHenry and McDowell (1962). A selected size fraction of sand was separated by sieving; the heavy mineral fraction was removed by bromoform and the iron oxide coating subsequently removed by Jeffries' treatment (Jeffries, 1946). Sand prepared in this manner was found to readily adsorb Sc-46 from a solution of Sc-46 Cl. Slow heating with an infrared light followed by heating to 800° to 1000° C. was sufficient to bond the isotope to the quartz.

Fe-59 ($T_{\frac{1}{2}}$ = 45 days, 2 gammas of energy, 1.098 and 1.298 Mev) was used by Wooldridge (1965) to tag bare soil. Three hundred microcuries of Fe-59 in solution as $FeCl_3$ in 0.1N HCl was applied to the soil in 5 foot lines along a contour. Movement of the radioactivity in the field was detected with both Geiger-Muller and scintillation survey meters. Wooldridge (1965) concluded that "Applying Fe-59 to a denuded soil surface in a diluted HCl solution offers a usable method for tracing soil particle movement. . . ."

Several aspects of sediment transport by tracer techniques are reported in an extensive article by Arlman, Santema and Svasek (1958). The authors stressed the importance of a sufficient number of tracer particles and particle activity to give statistically meaningful results under the conditions of the test, i.e., for the detector sensitivity and the area over which the tracer is dispersed, both horizontally and vertically.

Both Geiger-Muller (GM) and scintillation detectors have been utilized for activity measurements of the labeled sediment. GM detectors are simple, rugged, and can be produced in large sizes. They require only a stable power supply and rate meter for field use. The disadvantages of this system are, however, the inability to distinguish or discriminate between photon energies, low efficiency for gamma radiation and a limited useful radiation intensity range (McDowell, 1963).

Fluorescent Dye Coating

The natural fluorescence of certain pigments, minerals, and bacterial cultures has been observed for many centuries. An interesting assortment of daylight and near ultraviolet fluorescent dyes have become commercially available since the end of World War II.

Yasso (1965) in testing various tracer techniques indicated that fluorescent dyes offered a tremendous possibility as a method to follow soil particle movement. He also stated that coatings of the dye were insoluble in fresh or saline water.

Lean and Crickmore (1966) used a point injection of soil particles tagged with rhodamine B dye to measure sand discharge. An ultraviolet light was used to trace the particles while they were in the channel. Samples were taken at specified intervals and the number of tagged particles in each sample was counted to determine volume distribution of dye particles along the channel bed. Other pervious work has been summarized by Russell (1960).

Chapter III

RESEARCH DESIGN AND METHODS

Study Area Description and Location

The fire was located in the north central portion of the Little South Fork of the Cache la Poudre Watershed on sections 2, 3, 10, and 11, R74W, T4N, 7th PM (Fig. 2). The Little South Watershed is located in north central Colorado, Larimer County, approximately 30 miles west of Fort Collins and 14 miles north of Estes Park. A detailed description of the watershed is contained in a watershed analysis of the drainage (Johnson et al., 1962).

Comanche Reservoir, a municipal reservoir, was constructed in 1901 by the City of Greeley, Colorado. The reservoir was originally retained by terminal moraines and was subsequently reinforced by an earth dam constructed with materials from adjacent glacial and alluvial deposits (Cerrillo, 1967). Adjudicated water rights for Comanche Reservoir are 2,629 acre feet; however, these amounts have never been physically attained, due to high seepage loss through the retaining materials.

Cerrillo (1967) lists the bedrock of the area as Precambrian igneous and metamorphic rocks which were overlain by Pinedale I stade during the Wisconsin glacial period. Soils on the steeper slopes tend to be relatively immature and coarse. These immature soils, along with fracturing and jointing in the igneous and metamorphic rocks, cause the infiltration rates to be relatively high.

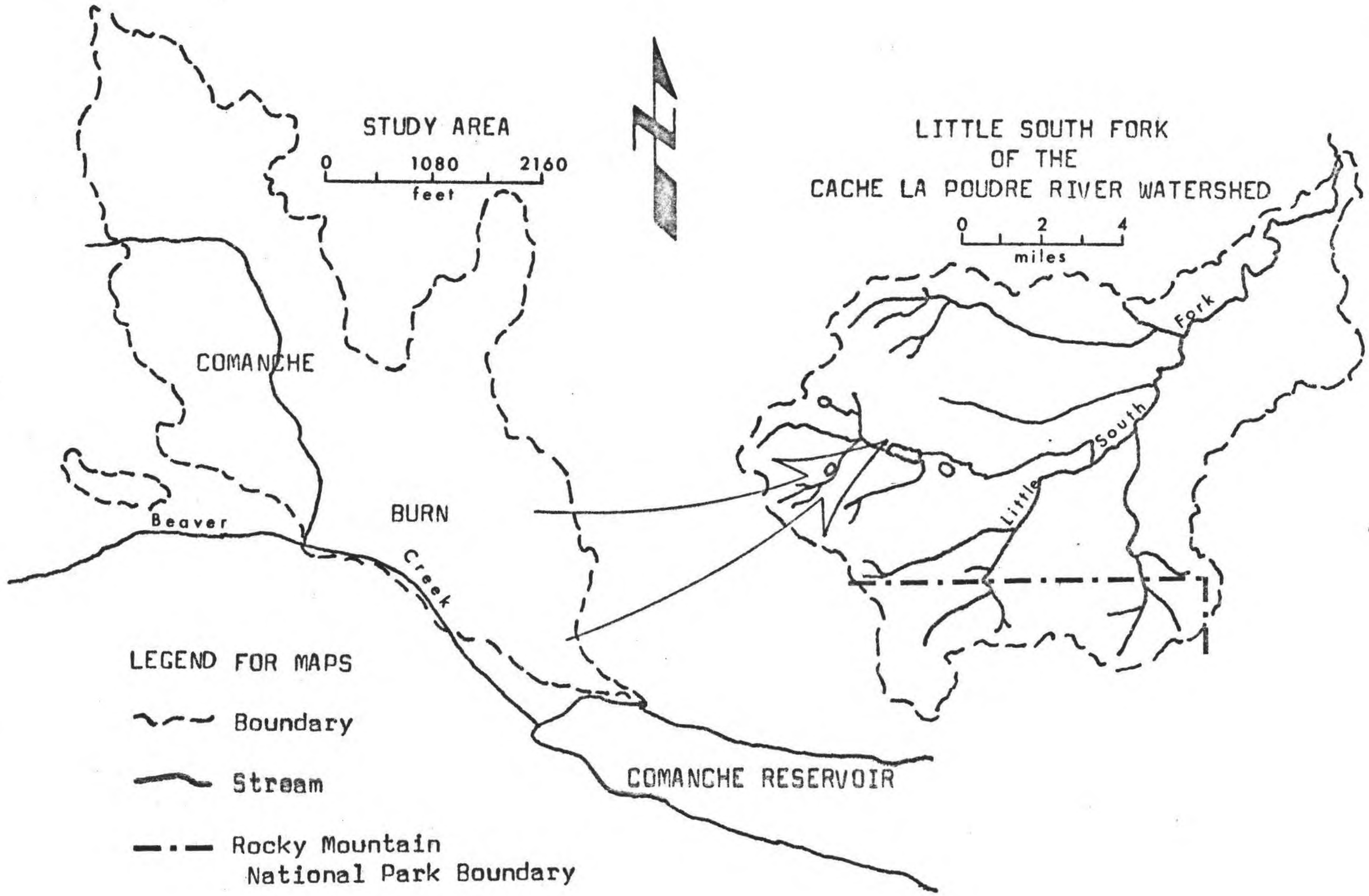

Figure 2-- Map showing the location of the study area within the Little South Cache la Poudre River Watershed.

Preliminary Investigations

Many sedimentation and erosion studies have used radioactive tracers to follow particle movement. In a majority of these studies particles have been tagged in the laboratory and then placed in the field. In this study, however, a field method of tagging the top few millimeters of soil was needed. Cesium-134 ($T_{\frac{1}{2}}$ = 2.07 years, beta energy, 0.657 Mev) was decided upon after it had been tested on soil samples taken from the study area.

Seven soil samples were prepared by packing the soil into cylinders 1 inch in diameter and 6 inches in length. Each soil column was treated with 2 ml of 0.01 uc/ml Cs-134 solution. One was used as a control, the only treatment being the application of 0.02 uc of Cs-134. Different amounts of water were applied to the other six soil columns. Following the treatment the soil was sampled in 2 mm sections to a depth of 10 mm and counted in a scintillation counter. By comparing the number of counts obtained from each 2 mm section to background counts, the relative abundance of cesium in each section was determined. Very little cesium was observed at depths greater than 4 mm (Table 1). This suggests that cesium transport occurred only during application and once absorbed formed a stable tag on the soil particle.

A similar method was used on the gravel from the burn to determine if the Cs-134 was permanently fixed to the grains. Particles greater than 2 mm were separated from a soil sample and placed in a 500 ml beaker. This was treated with 10 ml of the 0.01 uc/ml Cs-134 solution. The particles were then submerged in 100 ml of distilled water. One milliliter samples of the solution were taken every 2 days and counted.

Table 1-- The relative abundance of Cs-134 in each soil section following treatment. Treatment consisted of applying different amounts of water to each soil column.

Sample	Total Amount of Water Applied (inches)	Amount of Water Applied At One Time (inches)	Net Activity (counts/min.) 0-2 mm	2-4 mm	4-6 mm	6-8 mm	8-10 mm[a]
1 (control)	0.00	0.00	1150	260	15	0	0
2	0.25	0.25	1057	358	56	15	0
3	2.00	2.00	1160	409	48	11	2
4	10.00	10.00	1040	221	36	6	6
5	50.00	50.00	1126	345	42	16	11
6	0.25	0.025	1076	306	41	9	2
7	10.00	1.00	1103	297	51	20	8

[a]Soil depths at which sections were removed for counting.

No appreciable amount of Cs-134 was washed off the grains by the water during a 30-day period.

Plot Installation

The plots were designed to determine the effects of slope gradient, per cent rock cover above the plot and amount of precipitation on total soil movement and total soil loss during the summer. Area of upslope obstruction and 30-minute precipitation intensity were added to the three parameters above and related to soil movement during each storm. The area of upslope obstruction is defined for this study as the surface area of any object, upslope from the tagged points, capable of diverting surface runoff. These were subjective measurements based on the dimensions of the object.

Twenty plot locations were plotted on aerial photographs of the Comanche Burn. These plots were located according to slope position with six plots on the upper one-third of the slope, eight on the middle one-third of the slope, and six at the base of the slope (Fig. 3). The aerial photographs were then used to establish these plots in the field. Slope gradient, per cent of rock cover, and background radiation were measured at the time of plot installation.

The slope gradient of each plot was measured with an Abney level. Two stakes placed 6 feet apart in a line perpendicular to the direction of slope were used as reference points. Rock cover above the plot was estimated by randomly placing a 1-foot square shaped wire on the ground and estimating the per cent rock cover in the square. The average of five random estimates was used as the rock cover for that plot.

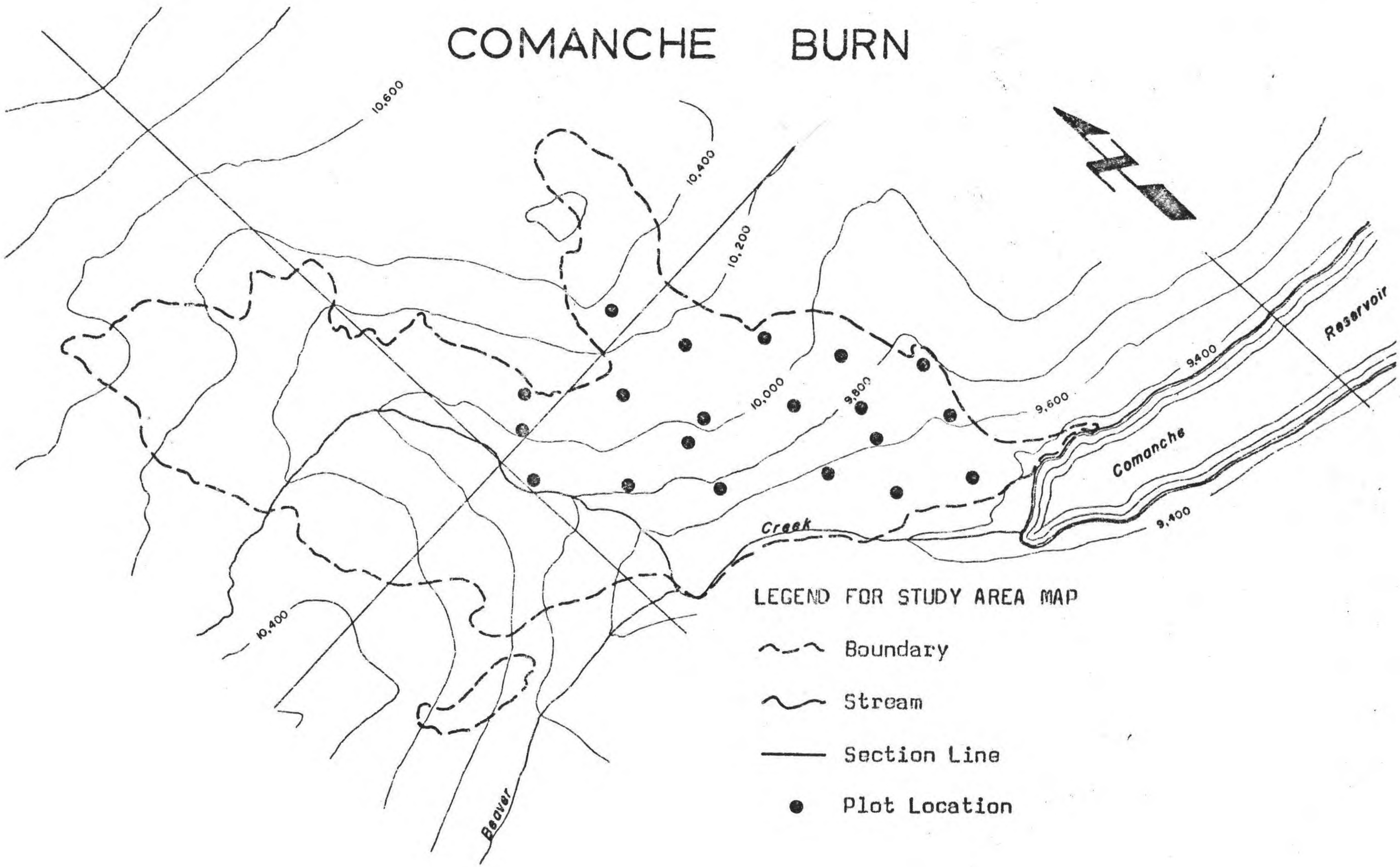

Figure 3-- Map showing location of study plots.

One recording raingage and five standard raingages were placed on the burn. Thiessen polygons were constructed to delineate the area represented by each raingage (Fig. 4). Storm duration and 30-minute intensity were taken from a 24-hour chart on the recording raingage. The 30-minute intensities for the other gages were computed using the following ratio where R is the total rainfall in inches at the recording gage, R_{30} is the total rainfall in inches for the first 30 minutes of the storm at the recording gage, S is the total rainfall in inches measured at the standard raingage, and S_{30} is the total volume in inches for a 30-minute period at the standard raingage:

$$S_{30} = \frac{R_{30}\ S}{R}$$

Doubling the 30-minute volume gives the intensity for that storm.

Plot Treatment and Measurements

Quantitative measurement of soil movement and the related parameters were carried out on each of the plots. Measurements were taken to determine downslope movement during individual thunderstorms, maximum downslope summer soil movement, soil movement by raindrop splash, and total summer soil loss.

Soil Particle Movement Using Cs-134

Each plot was monitored for background radiation using a Geiger-Muller end window survey meter. The detector tube was shielded with 1/4 inch lead to reduce background radiation and to limit the counting radius.

The soil on each plot was tagged at five points with 0.02 uc of 0.2 uc/ml Cs-134. A 100 lamba pipette attached to a syringe aided in

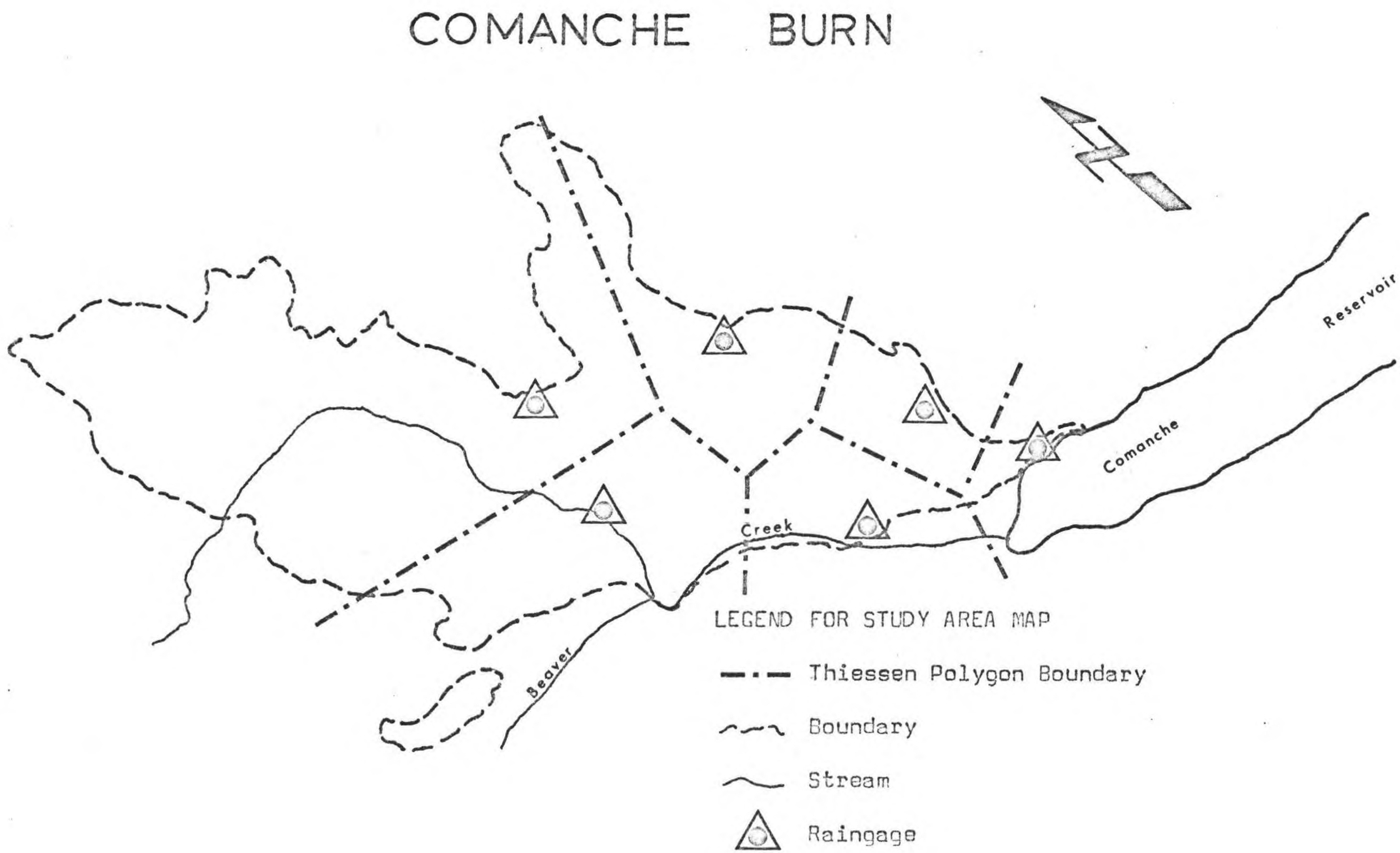

Figure 4-- Map showing Thiessen polygons.

the application of Cs-134 to the soil. Soil movement produced by the storms of August 15, 16, and 28 was traced with a GM end window survey meter (Fig. 5). Measurements taken following the storm of August 30 are not presented due to measurement errors caused by the dispersion of the tagged soil particles.

Soil Particle Movement Using Fluorescent Dye

The progressive downslope movement of soil was traced using Rocket Red fluorescent dye and an ultraviolet light. Rocket Red dye was selected for its fluorescent properties and for its ability to be detected with the naked eye.

The powder dye was mixed according to the manufacturer's instructions, one part dye to ten parts acetone. It was applied to the soil on five plots in a line perpendicular to direction of slope. The slope of these plots ranged from 5 per cent to 60 per cent and represented all slopes on the burn. It was applied using an insect sprayer and a cardboard with a slit 1 inch wide by 4 feet long. The dye adhered to the soil particles as the acetone evaporated.

Measurements were taken after dark using an ultraviolet light to locate the dyed particles. Nails were placed in the soil next to the particles. The next day the distance of movement was measured. Johnson (personal communication), in a study on Comanche Peak, found a similar method to work satisfactorily in tracing the soil movement produced by sheep grazing.

The above technique was also used to observe dye particle dispersion due to raindrop impact. The dye was applied to the soil in spots 4 inches in diameter. These spots were placed on slopes with gradients

Figure 5-- (Top) Application of Cs-134 to soil using a syringe and a 100 lamba pipette.
(Bottom) Monitoring of tagged soil using a GM survey meter with the detector tube shielded.

less than 1 per cent. All particle movement was assumed to be produced by raindrop impact.

Summer Soil Loss

Soil loss during the summer was obtained by measuring from a steel tape stretched between two stakes on each plot to the ground surface. Twelve measurements (one every 6 inches) were taken on each plot. This gave the macro-relief of the ground surface, perpendicular to the direction of slope. If a measurement happened to fall on a rock, limb, or other obstruction, it was disregarded.

Data Analysis

The summer's plot data were punched onto standard 80-space IBM cards. Analysis was carried out through the facilities of the Colorado State University Computer Research Center on a CDC 6400. A standard stepwise regression computer program was furnished by the Center for the analysis. This program computes a sequence of multiple linear regression equations in a stepwise manner. At each step, one variable is added to the regression equation. The variable added is the one which makes the greatest reduction in the error sum of squares. Equivalently it is the variable which has highest partial correlation with the dependent variable partialed on the variables which have already been added; and equivalently it is the variable which, if it were added, would have the highest F value. When F values become too low, variables are automatically removed.

It was realized that of the two statistical parameters commonly used to determine how successfully a collection of variables within an equation predicts the dependent variable, the coefficient of determination (R^2) and the standard error of the estimate (SE est.), the latter is probably a better estimate. Often, the coefficient of determination increases for an equation as more variables are added without necessarily making the resulting equation a better predictor. However, if upon adding additional variables the SE est. is reduced appreciably while at the same time R^2 is increased, the resulting equation will be a more precise estimator of the dependent variable.

A graphical analysis of soil movement during the summer and of dye spot dispersion is presented in a later chapter.

Chapter IV

RESULTS

Summer Precipitation

Due to the orographic effect of the mountains, most storms in the vicinity of the study area are convective storms. These storms are characterized by high intensities for short durations. Comparison of the precipitation records from the Pingree Park Weather Station for the months of June through August, 1961-1966 with those for the same months of 1967, indicate that precipitation during the study period was normal. This weather station is located approximately 2½ miles southeast of the study area. The records were as follows:

	June	July	August
Average precipitation (1961-67) (in.)	2.46	2.62	2.30
Precipitation for 1967 (in.)	2.24	2.48	2.81
Maximum precipitation (1961-67) (in.)	3.84	3.79	4.19
Minimum precipitation (1961-67) (in.)	1.16	2.08	0.49

The distribution of precipitation during the study period, along with maximum 30-minute intensities, is shown in Figure 6. Precipitation during the period occurred primarily as rainfall. During the first part of the study it was not uncommon to observe hail stones mixed with the rain. The storm of June 28 did, however, have a sufficient amount of hail to cover the ground surface with approximately one-quarter inch of hail stones.

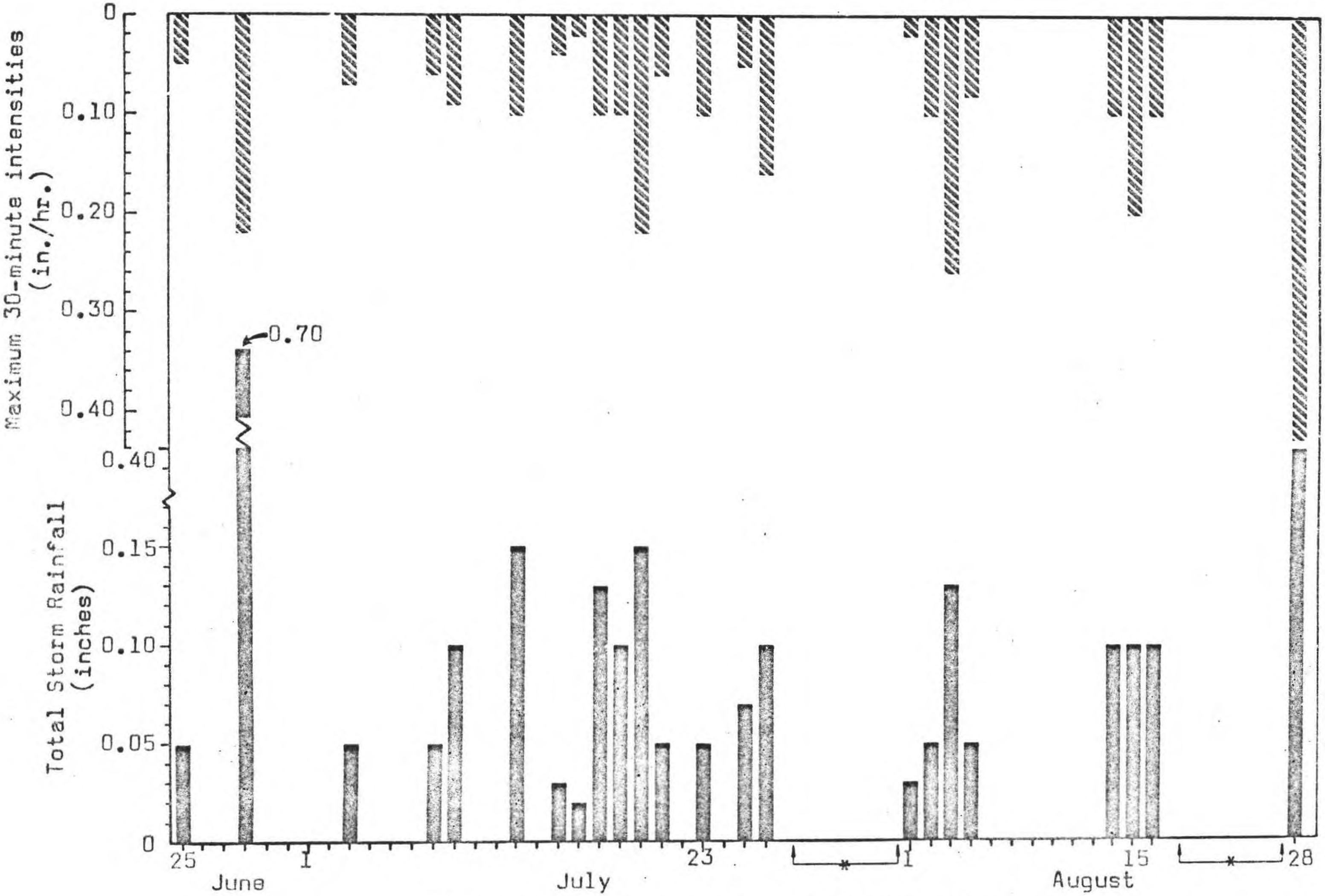

Figure 6-- Histogram of rainfall distribution and intensity during the study. (*Period of no rainfall.)

Particle Movement Using Cs-134

Data on soil movement following the storms of August 15, 16, and 28 are presented in Appendix A. A stepwise regression analysis was run and models generated as follows: (1) total movement during the three storms, (2) maximum movement during the storms, and (3) movement during individual storms.

Movement for All Three Storms

Statistical analysis of the collective soil movement data from all three storms yielded the following model:

$$M = 0.124 + 0.393S + 0.163RC + 0.136A + 0.447P_i$$

$$R^2 = 0.419 \qquad SE\ est. = 0.176 \qquad N^1 = 300 \qquad (1)$$

where:

M is the distance of downslope soil movement for the storm event (ft.)

S is the slope gradient (per cent)

RC is the per cent of rock cover immediately upslope from the tagged points (rocks with surface area greater than 2 in.^{2})

A is the area of upslope obstruction (ft.^{2})

P_i is 30-minute rainfall intensities (in./hr.)

Thirty-minute rainfall intensity and slope gradient accounted for the most variation in downslope soil movement (19.8 per cent and 13.7 per cent, respectively).

Maximum Movement During Each Storm

A second stepwise regression was run using the data corresponding to the maximum soil movement on each plot for each individual storm. The following model was generated:

---

[1]Number of observations.

$$M = 0.171 + 0.254S + 0.774RC + 0.414P_i$$

$$R^2 = 0.838 \qquad SE\ est. = 0.103 \qquad N = 60 \qquad (2)$$

In this model, rock cover was the most significant variable accounting for 71.8 per cent of the variance in downslope soil movement. Thirty-minute rainfall intensity accounted for only 9.6 per cent of the variance in M in this model.

Individual Storm Movement

The storms were then separated into individual events and models generated as follows:

August 15 Storm

$$M = 0.242 + 0.357S + 0.180RC + 0.155A$$

$$R^2 = 0.289 \qquad SE\ est. = 0.179 \qquad N = 100 \qquad (3)$$

August 16 Storm

$$M = 0.224 + 0.284S + 0.141RC + 0.111A$$

$$R^2 = 0.202 \qquad SE\ est. = 0.178 \qquad N = 100 \qquad (4)$$

August 28 Storm

$$M = 0.254 + 0.587S + 0.242RC + 0.213A$$

$$R^2 = 0.452 \qquad SE\ est. = 0.187 \qquad N = 100 \qquad (5)$$

It is interesting to note that rock cover was the independent variable picked first for models 3 and 4, but slope gradient was picked first in model 5.[2] Other regression models are presented in Table 2.

[2]Surface runoff was produced during this storm.

Table 2-- Selected models from storm movement data.

Model[a]	Equation	First Variable Picked	Variation in M Accounted for by First Variable	R^2	SE est.	N
1-a	$M = 0.124 + 0.393S + 0.163RC + 0.136A + 0.447P_i$	P_i	0.188	0.419	0.176	300
1-b	$M = 0.129 + 0.396S + 0.162RC + 0.135A + 0.622P$	P_s	0.178	0.408	0.177	300
1-c	$M = 0.240 + 0.410S + 0.187RC + 0.160A$	S	0.157	0.283	0.198	300
2-a	$M = 0.171 + 0.254S + 0.774RC + 0.414P_i$	RC	0.718	0.838	0.103	60
2-b	$M = 0.180 + 0.245S + 0.763RC + 0.568P_s$	RC	0.718	0.829	0.106	60
3-a	$M = 0.242 + 0.358S + 0.178RC + 0.155A$	RC	0.150	0.289	0.179	100

Table 2-- Continued.

Model	Equation	First Variable Picked	Variation in M Accounted for by First Variable	R^2	SE est.	N
4-a	$M = 0.224 + 0.284S + 0.141RC + 0.111A$	RC	0.107	0.202	0.178	100
5-a	$M = 0.254 + 0.587S + 0.242RC + 0.213A$	S	0.268	0.452	0.187	100

[a]Model notation refers to the equations listed in the text.

Soil Particle Movement Using Fluorescent Dye

Total Summer Soil Movement

Total maximum downslope soil movement was measured on July 14 and 25 and August 13, 15, 16, and 28. A maximum downslope movement of 25.5 feet occurred on a slope of 62 per cent. Graphical analysis of the data showed a positive linear relationship between maximum movement and slope gradient (Appendix B). A graphical presentation of the progressive downslope particle movement is also presented in Appendix B.

Maximum soil movement during the storm of August 28 was 1.2 feet. On plots of similar slope, maximum movement of the dye lines approximate the movement measured by the radioactive method.

Raindrop Splash Movement

Dye spot movement was measured on July 14, 25, and August 13. Movement was also measured for the storms of August 14, 15, and 28. The progressive soil movement is shown graphically in Figure 7. Maximum dispersion of dyed soil particles during the study period amounted to 6 feet (Appendix B). Since all dye spots were located on slopes with gradients less than 1 per cent, particle movement was assumed to be due entirely to raindrop splash. This assumption is substantiated by Neal (1938) who found that soil losses from relatively flat slopes (0-2 per cent) were not materially different for any given precipitation intensity.

Summer Soil Loss

Soil loss from the plots was also measured on July 14, 25, August 13 and also for the storms of August 14, 15, and 28. Average

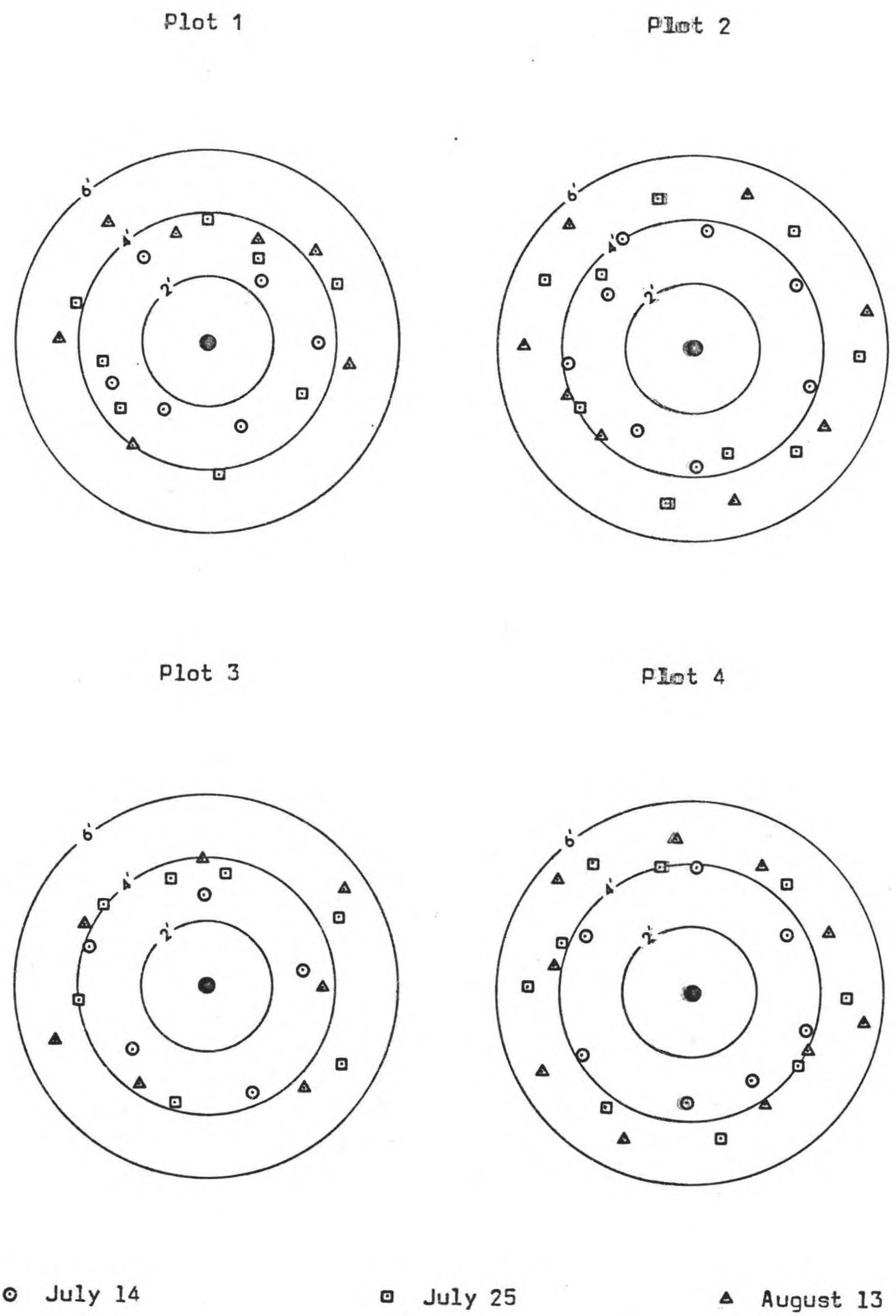

Figure 7-- Total dispersion of soil particles by raindrop splash during the periods June 25-July 14, July 15-July 25, and July 25-August 13.

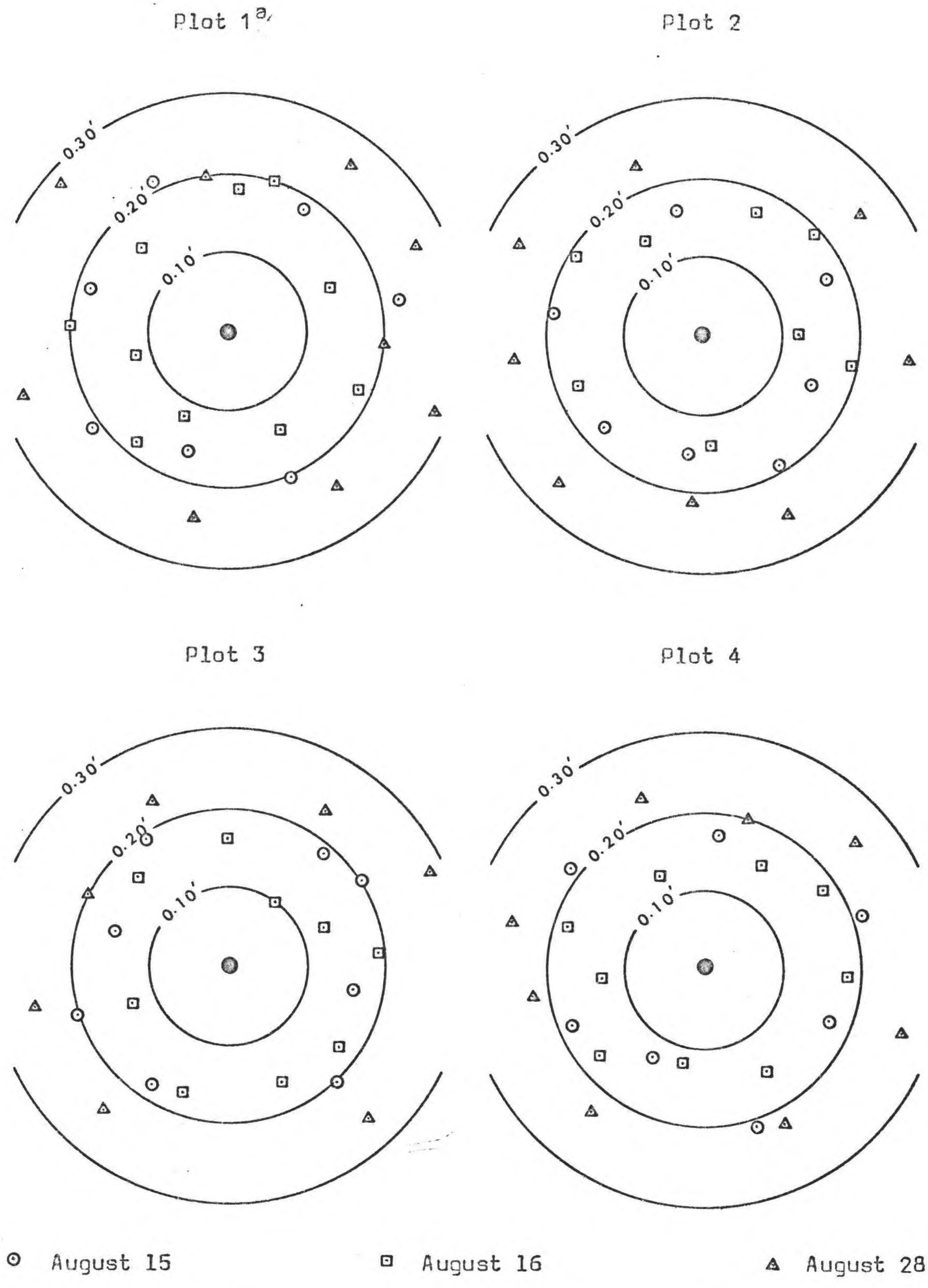

Figure 7-- Dispersion of soil particles by raindrop splash during the (cont.) storms of August 15, 16, and 28. (Dye spot is not to scale)

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[a]Note change of scale.

soil loss on the burn during the study was 0.25 inches. Although rainfall for the first three periods was 2 inches, very little soil loss was observed. No soil loss occurred during the storms of August 14 and 15. Soil loss for the storm of August 28, however, was seven-sixteenths of an inch.

Daily Observation

A camera and careful observation following storms were an indispensible means of noting soil erosion from the burn. Several ravines and low areas were watched for evidence of surface runoff and subsequent soil and ash deposition. The deposition of soil and ash in ravines varied; however, it was found to exceed 6 inches in depth in several places (Fig. 8). Gullies began to form on slopes having the more mature soils (Fig. 9).

Slope stability was observed to decrease as the summer progressed. Water action eroded away the small particles that helped stabilize the larger rocks. Toward the end of the study period, soil, gravel, and even large rocks were easily dislodged. Once dislodged, these particles would travel indefinite distances downslope, dislodging other particles in their path. These rolling particles were stopped only by some larger object.

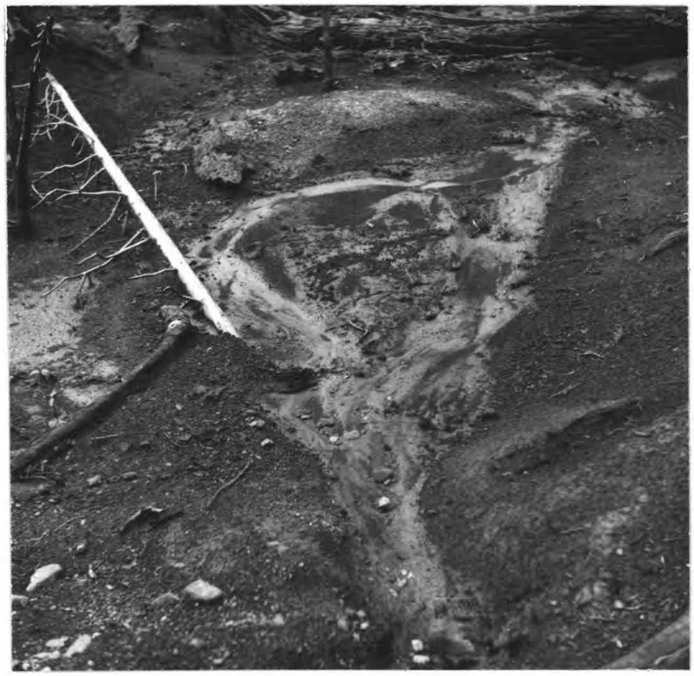

Figure 8-- (Top) Evidence of surface runoff is seen by soil and ash deposition on the fire road.
(Bottom) Six inches of soil and ash has been deposited in the ravine since the fire.

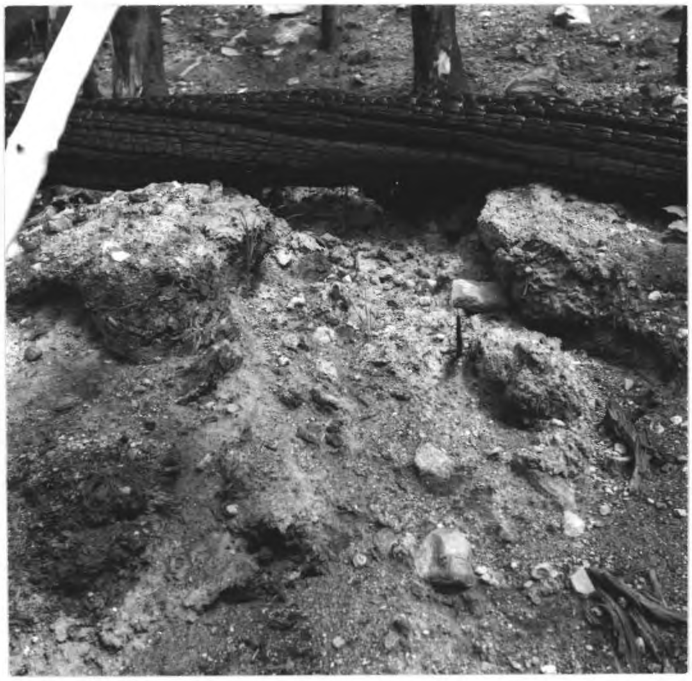

Figure 9-- (Top) Concentrated surface runoff has eroded the surface soil initiating a gully.
(Bottom) Evidence of gully development on a study plot. Note the small amount of rock cover and maturity of surface soil.

Chapter V

DISCUSSION

Soil movement was observed both on the slopes and flat areas. Only one storm during the study period had a duration and intensity capable of producing runoff. Movement during this storm was noticeably more than movement during the other storms.

Results indicate that comparable data is obtained using either fluorescent dye or radioactive material to tag soil particles. It is felt, however, that better results could be obtained using a 400 to 600 uc spike of Cs-134 or similar isotope on a line application 4 to 6 feet long. Radioactive tagging offers an advantage over fluorescent dye in the method used to detect particle movement. Detection is possible in the field with a portable GM or scintillation survey meter, whereas detection of dye particles requires the use of an ultraviolet light. This usually means observations must be made after dark or that samples must be taken and observed in the laboratory.

Soil Particle Movement Using Cs-134

Five point application of 0.2 uc of Cs-134 along a contour gave a good measure of soil erosion pattern. Measurements were taken following three thunderstorms. The activity was reduced to where it was not significantly above background by the end of the fifth storm. This rapid decrease in activity was due to the low activity of the initial application and subsequent dispersion of tagged particles during the thunderstorms.

Movement During All Three Storms

The results obtained from the stepwise regression analysis indicated that 30-minute rainfall intensity had the highest correlation to soil movement of any of the other parameters (Table 2). Changing precipitation variables from 30-minute intensity to total storm rainfall did not affect R^2 or SE est. to any extent. Low R^2 values were observed for 30-minute rainfall intensities and rainfall amount. A similar observation was made by Smith and Wischmeier (1962) who stated that even for specific storms, soil loss was poorly correlated with rainfall amount. Poor correlation was also exhibited for soil loss with maximum 5-, 15-, or 30-minute intensities. They also stated that good correlation with 30-minute intensities was found only on steep slopes or sandy loam soils.

Maximum Movement During Each Storm

Use of maximum movement data to generate equations increased the R^2 and decreased the SE est. from those obtained in the above analysis. Upslope rock cover, the most important variable, accounted for 71.8 per cent of the variation in M.

The change in R^2, SE est. and variable importance is primarily due to the soil being tagged at individual points instead of along a continuous line. In a recent study on frozen and snow-covered plots (where observed rainfall amounts and intensities and infiltration rates were similar to those observed during this thesis study), Haupt (1968) states, "Generally, plants, litter, and snow cover dissipate raindrop energy and increases infiltration, but exposed rock usually accelerates overland flow and erosion." Overland flow erodes and transports detached soil particles. Exposed rock apparently accelerates the erosion process by concentrating the flow in surface openings between rocks. Thus, as surface flows are increasingly confined soil losses increase. These surface flows will disappear rapidly, however, due to increasing slope length (Duley and Ackerman, 1934; and Copley et al., 1944). Although runoff occurs only for a short distance during these storms, it is capable of transporting dislodged soil particles. These incremental distances of particle movement account for the downslope soil movement incurred during the storms.

Macro-relief, upslope from the tagged points, may also be an important variable because of its influence in directing surface runoff. In discussing the erosion in California, Weir (1932) concluded that the carrying away of material by moving water is governed by the amount of water, the slope of the land, and the obstacles which are placed in the way of its free movement. Area of upslope obstruction was not highly significant in the regression model because of the relatively high linear correlation that exists between rock cover and area of upslope obstruction ($R = 0.457$). A linear correlation also exists between area of upslope obstruction and slope ($R = 0.425$) and between slope and rock cover ($R = 0.501$).

Individual Storm Movement

The statistical results obtained by analyzing each storm independently do not depict the significance of the data. Very poor values of R^2 resulted in the stepwise regression analysis. However, it did indicate a change in variable importance from rock cover for the August 15 and 16 storms to slope gradient for the August 28 storm. This suggests that when storm intensity increases enough to produce runoff, slope gradient becomes a more important variable. Neal (1938), working with runoff plots, found the density of material observed in runoff increased as both the slope and the rainfall intensity increase.

Wooldridge (1965), in a discussion of the results obtained using Fe-59 to trace soil particle movement, stated:

> Rates and patterns of soil particle movement suggest that once a soil particle starts moving, it continues to do so. This apparent finding was supported by very abrupt radiation gradients in early phases of the study with a continual lengthening of gradients but still with a high zone of radiation near the line of application.

This was also found to be true for the soil movement observed during this study. Soil movement occurred at all tagged points on the study plots and demonstrated differential rates of movement.

Soil Particle Movement Using Fluorescent Dye

Downslope Soil Movement

Differential movement of the dye lines resulted as shown in Appendix B. Patterns and rates of soil particle movement downslope from these lines also substantiate the findings of Wooldridge. A good correlation was found between total movement and slope. Although rainfall during the study period was low, movement of particles was found to exceed 20 feet.

The movement mechanism seems to be twofold. First raindrop impact dislodges the soil particles, then surface runoff transports these dislodged particles short distances. This runoff, as previously discussed, is produced only for short distances by reduced surface area of exposed mineral soil. When storms are large enough to produce surface runoff over the entire area, slope is a major factor due to its effect on runoff velocity.

Soil movement traced by Cs-134 for each storm was not materially different than that traced with fluorescent dye. Generally, more movement was observed using the fluorescent dye. The particles that were located further downslope were fine sand or silt particles and could only be observed under an ultraviolet light. Apparently this difference in distance moved was for the most part dependent on the particle size (i.e., very fine sand or silt particles located further downslope than the concentrated band of radioactivity will not be detectable because of the small amount of activity associated with the individual particles).

Raindrop Splash

Baver (1956) p. 429 states, that the amount, intensity, and distribution of rainfall help to determine the dispersive action of the rain upon the soil. Dye spot dispersion during the study indicated that rainfall intensity and amount (and subsequent impact with the soil) accounted for as much as 6 feet of movement. Movement of soil particles around the dye spot were compared to the particle movement observed on plots with slopes less than 5 per cent. Movement on these plots was not substantially different than movement observed around the dye spots. This led to the conclusion that soil movement on the flatter slopes was due entirely to raindrop splash. A study by Neal (1938) also found that soil losses from slopes of 0-2 per cent were not materially different for any given rain intensity.

The amount of particle dispersion associated with raindrop splash suggests that this is also an important factor in soil particle movement. Again a dual erosion mechanism is suggested. Since movement on the flatter slopes very closely coincides with raindrop splash movement, it seems likely that another factor is involved in soil particle movement on the steeper slopes. Osborn (1955, p. 127) states that on 10 per cent slopes soil particle movement due to raindrop splash was found to be three times greater downslope than upslope. This movement by raindrop splash, however, did not account for the amount of movement observed on the burn. A possible explanation is that surface runoff produced by the rock cover above the plots transported the soil particles dislodged by raindrop impact incremental distances downslope.

Summer Soil Loss

The soil loss that was observed on the area during the study was relatively small, with the greatest amount of soil loss occurring on steep slopes having little rock cover and more mature soil. Epstein, Grant, and Struchtemeyer (1966) found that soil loss decreased with an increase in stone content. The effect of rock cover on soil loss was not determined in this study due to the complication caused by the interrelationship of rock cover, area of upslope obstruction and slope. Generally the effect of slope seems to override the effect of the other two variables.

The results of this study indicate that very little soil movement occurred as a result of the wildfire. Slope stability, however, was reduced by water action removing smaller particles which stabilized the larger ones. Some movement of large particles (greater than 2 mm) occurred during the latter part of the study. This movement was primarily due to what Krammes (1960) calls "dry creep". This may be described as downslope movement by gravity and not necessarily associated with rainfall.

The importance of this study was in the comparison of the different methods of tracing soil movement, and the determination of the amount of movement produced by raindrop splash. Favorable results were obtained by both the fluorescent dye and Cs-134. Tracing particle movement with Cs-134 was more convenient since the method used in tracing the particles allowed field observations to be made during the day.

Due to the orographic effect of the mountains, storms in the Central Rocky Mountains tend to be convective storms of short duration and high intensity. Most of these produce little to no surface runoff over a large area. This leaves raindrop splash as the important method of soil transport.

Chapter VI

SUMMARY AND CONCLUSIONS

In June 1967 a study was conducted on the Comanche Burn to determine the effects of an intense burn on soil movement. Twenty study plots were established on the area. Soil movement data were related to slope gradient, per cent of rock cover upslope from the tagged points, area of any obstruction that could direct runoff, precipitation amount, and 30-minute precipitation intensity.

Although the burn was complete, destroying the forest canopy, understory vegetation, and all litter and humus; soil erosion was not a problem during the study. During intense thunderstorms, however, soil particles would become entrained and transported considerable distance downslope.

Two methods of tracing soil movement were employed and results compared. Rocket Red fluorescent dye was used to tag the soil along a contour line 4 feet long. Downslope movement of this line was followed during the study period. A maximum soil movement for the study period of 25.5 feet was observed on a 62 per cent slope.

A radioactive tag of 0.2 uc of Cs-134 was applied to the soil on each plot at five points along a contour. Soil movement during the storms of August 15, 16, and 28 was traced using a GM survey meter. Statistical analysis of the data showed that storm intensity accounted for the most variance in soil movement produced during these storms. However, analysis of the maximum soil movement data for the storms indicated that rock cover was the most important variable. A large increase in R^2 and a reduction in SE est. also resulted.

A stepwise multiple linear regression analysis was used to generate models relating soil movement to its parameters. A change in variable importance, from rock cover for the storms of August 15 and 16 to slope gradient for the August 28 storm, was noted. This change was a result of the runoff produced by the storm of August 28. Pronounced evidence of this surface runoff during this storm was observed throughout the area. It resulted in a maximum soil movement of 1.2 feet.

The results obtained from dye line movement and Cs-134 movement were not materially different.

Dye spots were located on slopes with gradients less than 1 per cent in an effort to estimate soil movement from raindrop splash. Dispersion of the dyed particles during the study period amounted to as much as 6 feet. This particle dispersion during the storms of August 15, 16, and 28 was compared to the tagged soil movement for the corresponding storms. The results indicated that raindrop splash accounted for the total movement observed on the flatter slopes, and also suggested that it was the major initiating force for soil movement on the slopes.

Soil particle movement was found to be produced by the combined action of raindrop splash and surface runoff (produced by upslope rock cover). Raindrop impact dislodges the soil particles which are then transported short distances by runoff. These incremental distances, integrated during the study period account for the observed movement.

Average net soil loss during the study period was 0.25 inches. The storm of August 28 accounted for a 0.09 inch loss of soil. Less loss of soil was observed on plots with high rock cover.

Suggestions for Future Studies

The nature of this study and its results suggest certain areas of future study which may provide additional information concerning the effects of an intense burn on soil movement from steep slopes in the Central Rocky Mountains. Ideally, this study of soil movement following an intense burn should be followed by a study to ascertain the amount of soil moved during storms and relate it to rates of movement. This would involve the establishment of runoff plots with collection tanks and a much longer term of study to observe a wider range of rainfall amounts and intensities.

Several ravines on the study area carried runoff during high intensity thunderstorms. This suggests that a sedimentation study could be conducted using these ravines as natural runoff plots. The area drained by each ravine could be determined from aerial photographs and the volume of soil loss per acre thereby determined.

A study to determine the long term effects of fire on soil movement should be conducted. This would involve an evaluation of the rate and density of revegetation on the area and also a continuation of soil erosion measurements, preferably by runoff plots. Other independent variables that could be included are: slope length, area of drainage, infiltration capacity and particle movement produced by raindrop splash.

Another suggestion for future research would be the tracing of soil movement during a longer period of one or two years. This would serve to determine the rate of soil movement during the snowmelt runoff period. Applying 400 to 600 uc of Cs-134 (or similar isotope, e.g., Zn-65 or Sc-46) in a 4 to 6 foot line along the contour would provide a better measure of the soil erosion pattern than point tagging of the soil.

Because this study did not conclusively evaluate the effects of wildfire on soil movement in the Central Rocky Mountain Region, additional research would be valuable. Such studies should include a wider range of rainfall intensities and should attempt to determine soil movement produced on steep slopes during periods of frost heaving and snowmelt runoff.

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A P P E N D I X

APPENDIX CONTENTS

Appendix A. Plot measurements showing rock cover, area of upslope obstruction, 30-minute intensities, precipitation amount, and downslope soil movement of Cs-134 tagged particles for each storm event.

Table A.1

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 1 - Slope 33%			
011	0.40	0.014	0.500	0.320	0.620
012	0.50	0.027	0.560	0.332	0.745
013	0.50	0.834	0.572	0.330	0.750
014	0.30	0.007	0.406	0.535	0.581
015	0.20	-----[a]	0.300	0.225	0.352
Precipitation Amount (in.)			0.07	0.05	0.38
30-minute precipitation intensities (in./hr.)			0.14	0.05	0.55

Table A.2

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 2 - Slope 61%			
021	0.10	0.083	0.296	0.150	0.485
022	0.10	0.331	0.339	0.232	0.510
023	0.30	-----	0.403	0.360	0.692
024	0.30	0.110	0.437	0.365	0.749
025	0.30	0.663	0.582	0.485	0.802
Precipitation Amount (in.)			0.12	0.12	0.43
30-minute precipitation intensities (in./hr.)			0.24	0.12	0.65

[a]Indicates a 0.00 measurement.

Table A.3

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 3 - Slope 44%			
031	0.60	0.167	0.815	0.626	0.921
032	0.70	0.028	0.762	0.671	0.909
033	0.40	0.007	0.506	0.358	0.605
034	0.80	0.139	0.883	0.727	1.162
035	0.80	0.111	0.917	0.752	1.376
Precipitation Amount (in.)			0.12	0.12	0.43
30-minute precipitation intensities (in./hr.)			0.24	0.12	0.65

Table A.4

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 4 - Slope 1%			
041	0.05	-----	0.232	0.172	0.250
042	0.05	-----	0.254	0.200	0.250
043	0.05	-----	0.137	0.127	0.178
044	0.05	-----	0.223	0.236	0.250
045	0.05	0.083	0.207	0.165	0.292
Precipitation Amount (in.)			0.10	0.10	0.40
30-minute precipitation intensities (in./hr.)			0.20	0.10	0.58

Table A.5

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 5 - Slope 62%			
051	0.20	0.056	0.297	0.158	0.604
052	0.20	-----	0.334	0.226	0.558
053	0.15	-----	0.221	0.121	0.540
054	0.30	0.324	0.520	0.490	0.786
055	0.30	0.167	0.470	0.402	0.602
Precipitation Amount (in.)			0.10	0.10	0.40
30-minute precipitation intensities (in./hr.)			0.20	0.10	0.58

Table A.6

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 6 - Slope 63%			
061	0.60	-----	0.907	0.809	1.052
062	0.30	0.083	0.706	0.621	0.891
063	0.30	-----	0.700	0.561	0.918
064	0.20	-----	0.592	0.501	0.662
065	0.10	-----	0.387	0.276	0.401
Precipitation Amount (in.)			0.17	0.21	0.45
30-minute precipitation intensities (in./hr.)			0.34	0.21	0.62

Table A.7

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 7 - Slope 24%			
071	0.05	-----	0.207	0.107	0.400
072	0.05	-----	0.116	0.096	0.386
073	0.05	0.834	0.254	0.195	0.509
074	0.10	0.834	0.334	0.296	0.570
075	0.20	0.028	0.361	0.300	0.581
Precipitation Amount (in.)			0.17	0.21	0.45
30-minute precipitation intensities (in./hr.)			0.34	0.21	0.62

Table A.8

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 8 - Slope 60%			
081	0.10	0.779	0.483	0.398	0.535
082	0.05	0.086	0.257	0.206	0.292
083	0.30	0.936	0.566	0.510	0.691
084	0.10	-----	0.133	0.096	0.485
085	0.05	-----	0.407	0.351	0.541
Precipitation Amount (in.)			0.10	0.10	0.40
30-minute precipitation intensities (in./hr.)			0.20	0.10	0.58

Table A.9

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 9 - Slope 43%			
091	0.60	0.904	1.071	0.960	1.238
092	0.70	0.334	0.964	0.906	1.142
093	0.70	0.111	0.816	0.786	1.031
094	0.50	0.028	0.739	0.698	0.819
095	0.80	0.083	0.935	0.895	1.101
Precipitation Amount (in.)			0.17	0.21	0.45
30-minute precipitation intensities (in./hr.)			0.34	0.21	0.62

Table A.10

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 10 - Slope 16%			
101	----	-----	0.434	0.302	0.453
102	----	-----	0.401	0.381	0.396
103	----	-----	0.467	0.406	0.486
104	----	0.150	0.375	0.281	0.432
105	----	-----	0.484	0.430	0.530
Precipitation Amount (in.)			0.17	0.21	0.45
30-minute precipitation intensities (in./hr.)			0.34	0.21	0.62

Table A.11

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 11 - Slope 53%			
111	0.05	-----	0.325	0.298	0.410
112	0.10	-----	0.450	0.396	0.450
113	0.10	-----	0.473	0.412	0.535
114	0.10	0.083	0.535	0.510	0.551
115	0.10	-----	0.362	0.332	0.503
Precipitation Amount (in.)			0.09	0.07	0.30
30-minute precipitation intensities (in./hr.)			0.18	0.07	0.44

Table A.12

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 12 - Slope 42%			
121	----	-----	0.312	0.289	0.416
122	----	0.010	0.250	0.202	0.368
123	----	-----	0.284	0.241	0.392
124	----	-----	0.224	0.195	0.341
125	----	-----	0.455	0.425	0.471
Precipitation Amount (in.)			0.09	0.07	0.30
30-minute precipitation intensities (in./hr.)			0.18	0.07	0.44

Table A.13

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 13 - Slope 29%			
131	----	-----	0.250	0.210	0.320
132	----	-----	0.313	0.296	0.371
133	----	-----	0.250	0.210	0.320
134	----	-----	0.224	0.198	0.312
135	----	0.012	0.340	0.312	0.370
Precipitation Amount (in.)			0.10	0.09	0.34
30-minute precipitation intensities (in./hr.)			0.20	0.09	0.49

Table A.14

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 14 - Slope 29%			
141	----	-----	0.371	0.330	0.371
142	----	-----	0.286	0.240	0.340
143	----	-----	0.286	0.238	0.340
144	----	-----	0.224	0.186	0.312
145	----	-----	0.250	0.201	0.323
Precipitation Amount (in.)			0.09	0.07	0.30
30-minute precipitation intensities (in./hr.)			0.18	0.07	0.44

Table A.15

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 15 - Slope 32%			
151	----	-----	0.250	0.216	0.321
152	----	-----	0.224	0.195	0.312
153	----	-----	0.153	0.102	0.290
154	0.05	-----	0.339	0.300	0.371
155	0.05	-----	0.313	0.291	0.340
Precipitation Amount (in.)			0.09	0.07	0.30
30-minute precipitation intensities (in./hr.)			0.18	0.07	0.44

Table A.16

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 16 - Slope 24%			
161	0.05	0.751	0.224	0.186	0.290
162	0.05	-----	0.153	0.102	0.340
163	----	-----	0.285	0.216	0.355
164	0.05	-----	0.288	0.220	0.311
165	0.10	-----	0.340	0.299	0.410
Precipitation Amount (in.)			0.10	0.09	0.34
30-minute precipitation intensities (in./hr.)			0.20	0.09	0.49

Table A.17

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 17 - Slope 18%			
171	0.20	-----	0.512	0.486	0.510
172	0.30	0.286	0.550	0.502	0.607
173	0.10	-----	0.500	0.461	0.487
174	0.30	0.125	0.351	0.302	0.435
175	0.10	-----	0.410	0.382	0.455
Precipitation Amount (in.)			0.10	0.09	0.34
30-minute precipitation intensities (in./hr.)			0.20	0.09	0.49

Table A.18

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet) Aug. 15	Aug. 16	Aug. 28
		Plot 18 - Slope 1%			
181	----	-----	0.240	0.236	0.240
182	----	-----	0.200	0.210	0.201
183	----	-----	0.241	0.240	0.261
184	----	-----	0.224	0.227	0.219
185	----	-----	0.285	0.275	0.288
Precipitation Amount (in.)			0.09	0.07	0.30
30-minute precipitation intensities (in./hr.)			0.18	0.07	0.44

Table A.19

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet)		
			Aug. 15	Aug. 16	Aug. 28
		Plot 19 - Slope 41%			
191	0.30	-----	0.654	0.631	0.720
192	0.20	-----	0.600	0.581	0.631
193	0.05	-----	0.420	0.396	0.672
194	0.10	-----	0.480	0.460	0.749
195	0.20	-----	0.543	0.520	0.631
Precipitation Amount (in.)			0.10	0.09	0.34
30-minute precipitation intensities (in./hr.)			0.20	0.09	0.49

Table A.20

Sub-plot	Rock Cover (per cent)	Area of Upslope Obstruction (feet)	Downslope Soil Movement (feet)		
			Aug. 15	Aug. 16	Aug. 28
		Plot 20 - Slope 38%			
201	0.05	-----	0.315	0.289	0.372
202	0.40	0.083	0.686	0.682	0.771
203	0.20	0.004	0.564	0.521	0.606
204	0.20	-----	0.476	0.430	0.562
205	0.30	0.021	0.702	0.661	0.770
Precipitation Amount (in.)			0.10	0.09	0.34
30-minute precipitation intensities (in./hr.)			0.20	0.09	0.49

Appendix B. Soil particle movement using fluorescent dye.

Table B.1-- Measurements of soil movement using fluorescent dye.

	Plot	Slope (per cent)	Net Soil Movement (feet) July 14	July 25	Aug. 13	Aug. 27	Aug. 28	Total Summer Movement
Precipitation Amount (inches)			1.23	0.54	0.22	0.26	0.43	2.68
	1	62	21.2	1.6	0.7	0.8	1.2	25.5
	2	33	10.9	1.0	0.4	0.5	0.8	13.6
	3	1	3.2	0.4	0.1	0.1	0.3	4.1
	4	53	19.0	1.3	0.6	0.7	1.1	22.7
	5	16	7.2	0.6	0.3	0.3	0.5	8.9

Table B.2-- Soil movement resulting from raindrop splash for the periods June 25-July 14, July 15-July 25, and July 25-August 13.

Date of Measurement	Plot Number	Total Precipitation (inches)	Dye Spot Dispersion (feet)	Average Net Dispersion (feet)
July 14	1	1.23	3.42	
			3.21	
			3.20	
			2.82	2.94
			2.50	
			2.50	
	2	1.23	3.91	
			3.80	
			3.80	
			3.74	
			3.72	3.59
			3.62	
			3.06	
			3.04	
	3	1.23	3.82	
			3.60	
			3.03	3.26
			3.01	
			2.82	
	4	1.23	3.86	
			3.84	
			3.72	
			3.61	3.60
			3.44	
			3.42	
			3.36	
July 25	1	0.54	4.44	
			4.22	
			4.16	
			3.76	
			3.40	0.91
			3.38	
			3.30	
			3.00	

Table B.2-- Continued.

Date of Measurement	Plot Number	Total Precipitation (inches)	Dye Spot Dispersion (feet)	Average Net Dispersion (feet)
July 25 (cont.)	2	0.54	5.11	
			4.96	
			4.91	
			4.78	
			4.72	0.97
			4.54	
			3.90	
			3.69	
			3.41	
	3	0.54	4.87	
			4.61	
			4.03	
			3.97	0.93
			3.72	
			3.53	
			3.46	
	4	0.54	4.99	
			4.95	
			4.79	
			4.64	
			4.45	0.96
			4.39	
			4.20	
			4.02	
			3.96	
Aug. 13	1	0.22	4.71	
			4.45	
			4.37	
			3.96	0.18
			3.56	
			3.52	
			3.42	
	2	0.22	5.47	
			5.30	
			5.14	
			5.01	
			4.93	0.25
			4.75	
			4.10	
			3.89	

Table B.2-- Continued.

Date of Measurement	Plot Number	Total Precipitation (inches)	Dye Spot Dispersion (feet)	Average Net Dispersion (feet)
Aug. 13 (cont.)	3	0.22	5.23	
			4.97	
			4.38	
			4.24	0.26
			3.95	
			3.66	
			3.58	
	4	0.22	5.36	
			5.32	
			5.14	
			4.98	
			4.71	
			4.62	0.26
			4.41	
			4.22	
			4.09	
			3.97	

Table B.3-- Soil movement resulting from raindrop splash for the storms of August 15, 16, and 28.

Date of Measurement	Plot Number	Total Precipitation (inches)	30-minute Precipitation Intensity (in./hr.)	Net Soil Movement (feet)	Average Soil Movement (feet)
Aug. 15	1	0.10	0.20	0.22	
				0.21	
				0.21	
				0.20	0.19
				0.18	
				0.18	
				0.16	
	2	0.10	0.20	0.19	
				0.19	
				0.17	
				0.17	0.17
				0.16	
				0.15	
				0.15	
	3	0.10	0.20	0.20	
				0.20	
				0.20	
				0.19	
				0.18	0.18
				0.18	
				0.16	
				0.15	
	4	0.10	0.20	0.21	
				0.21	
				0.21	
				0.18	0.18
				0.17	
				0.17	
				0.13	
Aug. 16	1	0.10	0.10	0.20	
				0.20	
				0.18	
				0.18	
				0.17	
				0.15	0.16
				0.14	
				0.14	
				0.12	
				0.12	

Table B.3-- Continued.

Date of Measurement	Plot Number	Total Precipitation (inches)	30-minute Precipitation Intensity (in./hr.)	Net Soil Movement (feet)	Average Soil Movement (feet)
Aug. 16 (cont.)	2	0.10	0.10	0.19	
				0.19	
				0.19	
				0.17	
				0.17	0.16
				0.14	
				0.14	
				0.12	
	3	0.10	0.10	0.19	
				0.17	
				0.17	
				0.16	
				0.16	0.15
				0.16	
				0.13	
				0.13	
				0.10	
	4	0.10	0.10	0.18	
				0.18	
				0.18	
				0.17	
				0.15	0.15
				0.15	
				0.13	
				0.13	
				0.12	
Aug. 28	1	0.40	0.58	0.28	
				0.28	
				0.27	
				0.26	
				0.26	0.25
				0.24	
				0.24	
				0.20	
				0.20	

Table B.3-- Continued.

Date of Measurement	Plot Number	Total Precipitation (inches)	30-minute Precipitation Intensity (in./hr.)	Net Soil Movement (feet)	Average Soil Movement (feet)
Aug. 28 (cont.)	2	0.40	0.58	0.26	
				0.26	
				0.26	
				0.25	
				0.25	0.24
				0.24	
				0.23	
				0.21	
	3	0.40	0.58	0.28	
				0.26	
				0.25	
				0.24	0.24
				0.23	
				0.23	
				0.20	
	4	0.40	0.58	0.26	
				0.25	
				0.25	
				0.23	
				0.23	0.23
				0.22	
				0.22	
				0.20	

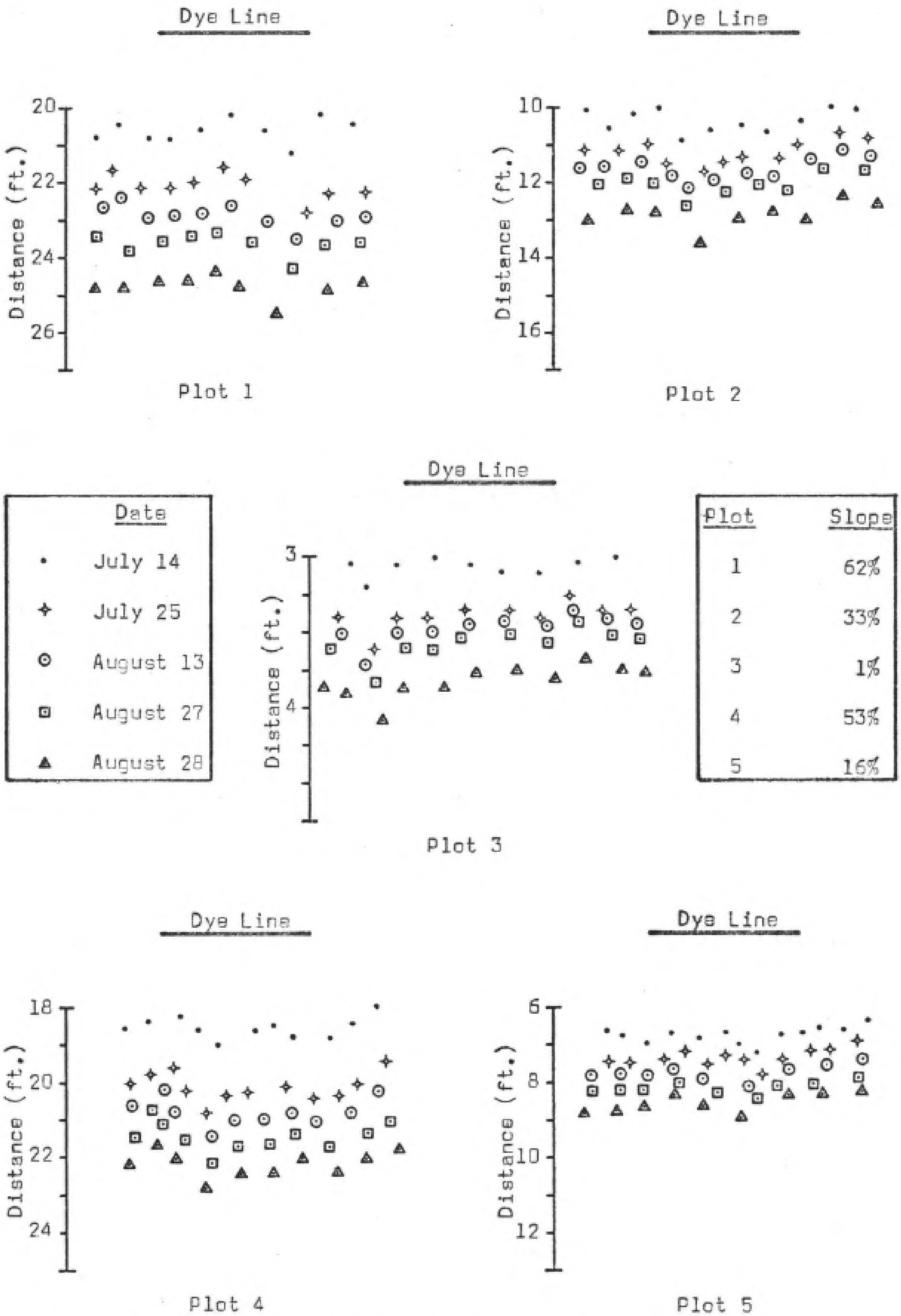

Figure 8.1-- Differential movement of dye particles.

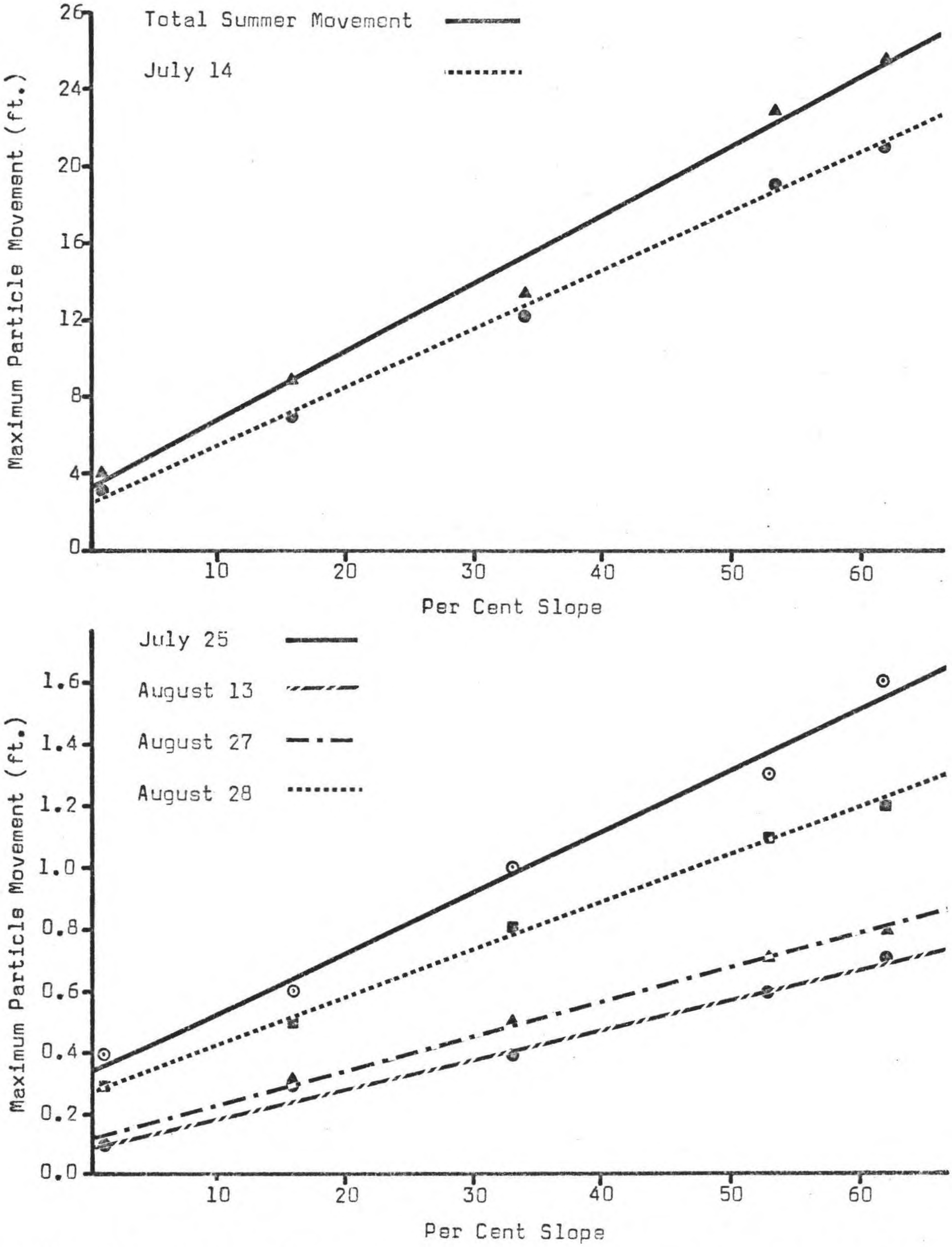

Figure B.2-- Plots showing the relationship between slope gradient and maximum downslope particle movement from the dye lines.