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Infiltration Studies On Ponderosa Pine Ranges Of Colorado

By E. J. Dortignac and L. D. Love

ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION
RAYMOND PRICE, DIRECTOR FORT COLLINS, COLORADO
FOREST SERVICE U. S. DEPARTMENT OF AGRICULTURE

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INFILTRATION STUDIES ON

PONDEROSA PINE RANGES OF COLORADO

by

E. J. Dortignac and L. D. Love, Foresters

Rocky Mountain Forest and Range Experiment Station[1]

Forest Service, U. S. Department of Agriculture

[1] Central headquarters maintained in cooperation with Colorado State University, Fort Collins

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INTRODUCTION

Ponderosa pine (Pinus ponderosa Lawson) ranges are characteristic of much of the Colorado mountains east of the Continental Divide (fig. 1). These timbered ranges occupy, at elevations from 6,000 to 9,000 feet, ridges, mountain slopes, foothills, steep rocky canyons, and mountain valleys. On more level areas they are intermingled with open grassland parks. Soils are variable and are developed from several parent rocks; the majority are derived from granites which disintegrate readily, producing unstable soils that erode and wash away rapidly when exposed.

Three broad vegetation classes are recognizable: (1) stands of dense timber, mainly ponderosa pine, with closed canopies and a ground cover of tree litter; (2) timbered grasslands, an open forest of ponderosa pine with a ground cover of herbaceous vegetation and pine litter; and (3) open grassland parks supporting herbaceous vegetation.

The purpose of this paper is to present results of infiltrometer studies designed to evaluate the relationships between soil, vegetation, and infiltration. These studies were conducted at the Manitou Experimental Forest from 1941 through 1954, and on the Elk Ridge Allotment in the Roosevelt National Forest in 1950 (fig. 1).

DESCRIPTION OF STUDY AREAS

The Manitou Experimental Forest is located about 25 miles northwest of Colorado Springs and encompasses an area of 25 square miles. It is representative of ponderosa pine lands in the Colorado mountains. The main study was conducted in six experimental range pastures that are 254 to 309 acres in extent (fig. 2). Two pastures were grazed heavily, two lightly, and two at a moderate rate. Utilization of herbage of perennial grasses and sedges averaged 55 percent for heavy use, 35 percent for moderate, and 15 percent for light use (Johnson, 1953). Yearling Hereford heifers were used during a 5-month grazing season that usually began on June 1 each year. The experimental pastures are located on the valley floor near Trout Creek in the headwaters of the South Platte River, at an elevation of about 7,600 feet (fig. 3A).

In addition, studies conducted in 1950 on the Elk Ridge Allotment of the Roosevelt National Forest provided data for testing the prediction formula developed from the studies at the Manitou Experimental Forest (fig. 3B).

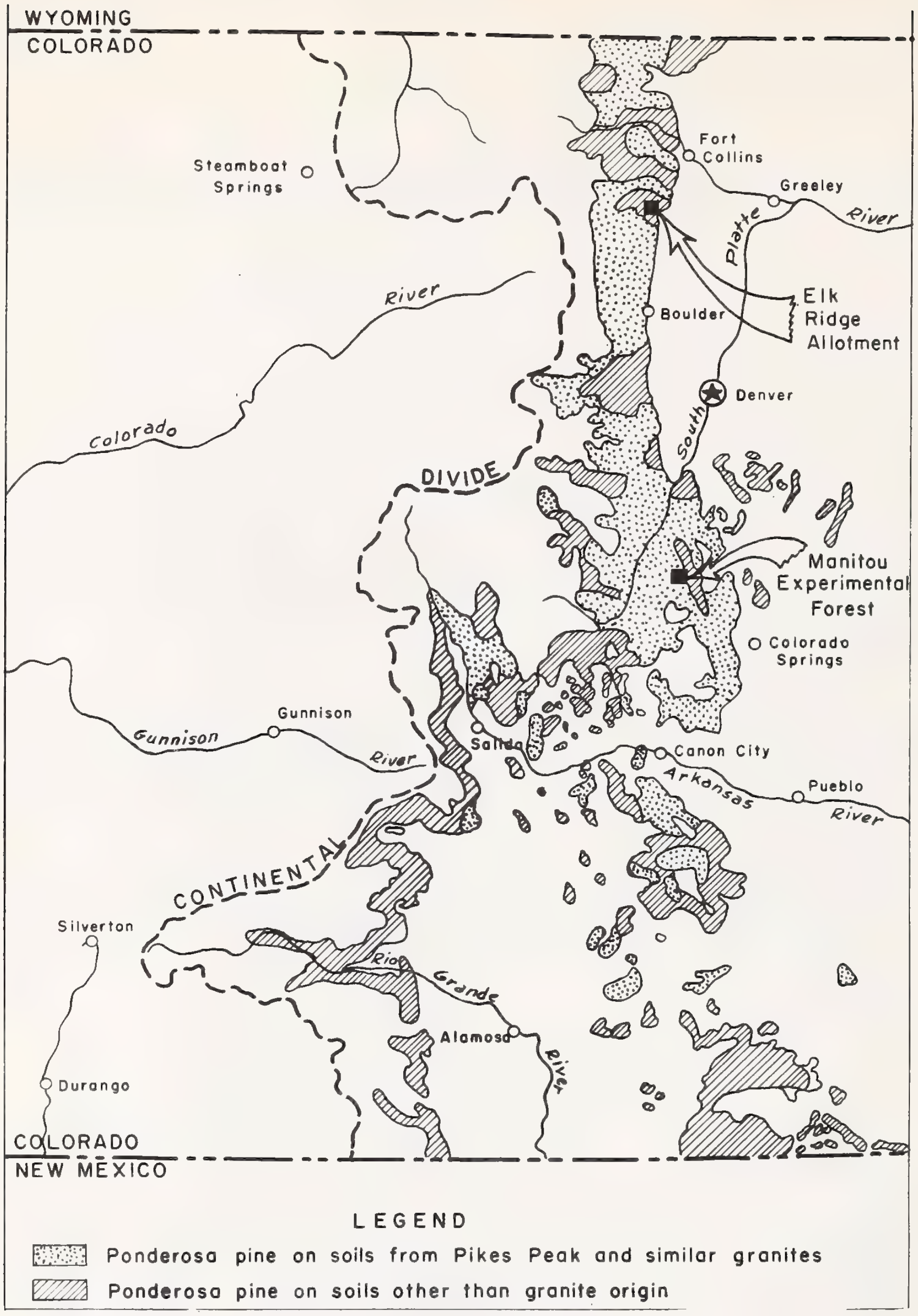

Figure 1.--Distribution of ponderosa pine ranges on soils derived from granite and other rocks in the Colorado mountains east of the Continental Divide.

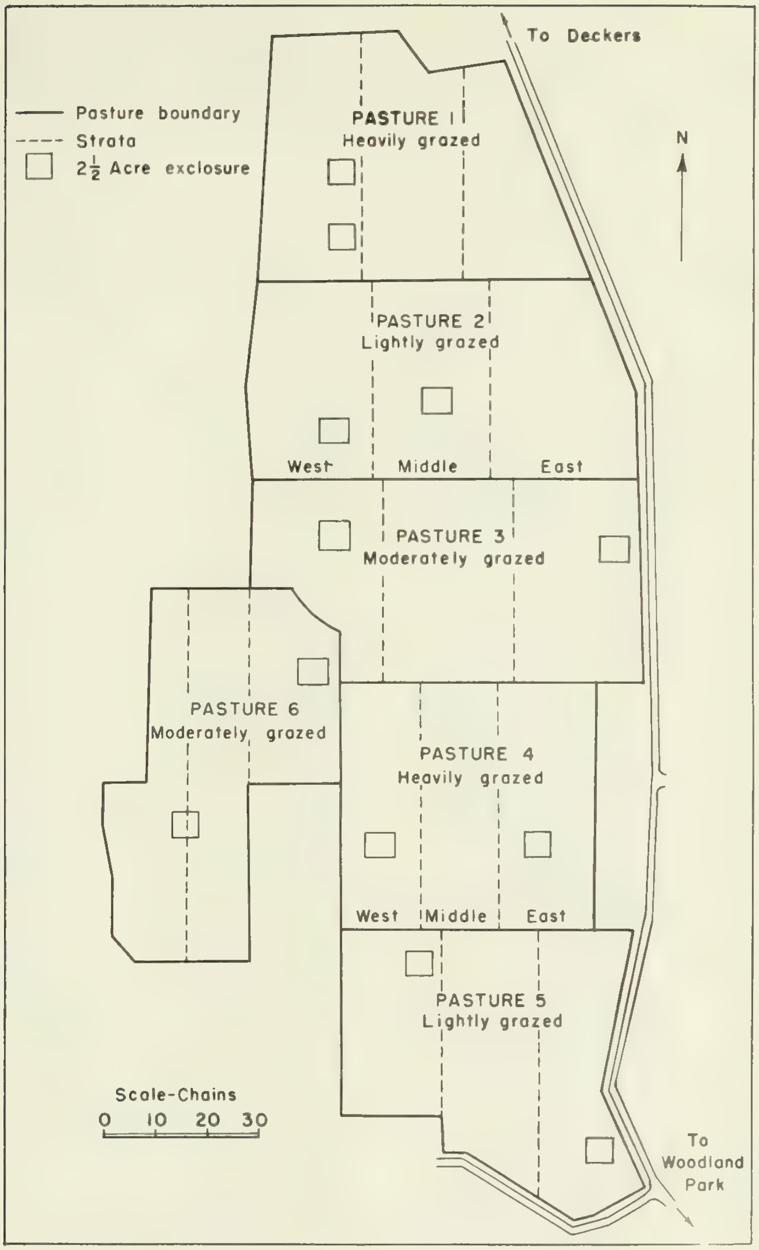

Figure 2.--Experimental range pastures, Manitou Experimental Forest.

Figure 3. --A, Panorama of Manitou experimental range pastures; B, Panorama of study area, Elk Ridge allotment.

Climate

The yearly temperature at the experimental forest averages about 45°F. The mean monthly temperature for January is 27°F; for July 60°F. On the average, there are 113 days in the growing season, with the frost-free period extending from May 28 to September 18. Annual precipitation has averaged about 15 inches; of this, 80 percent was received between April 1 and September 30, often falling at high intensities (fig. 4). Yearly precipitation between 1938 and 1954 has varied from 7.6 to 23.6 inches (table 1).

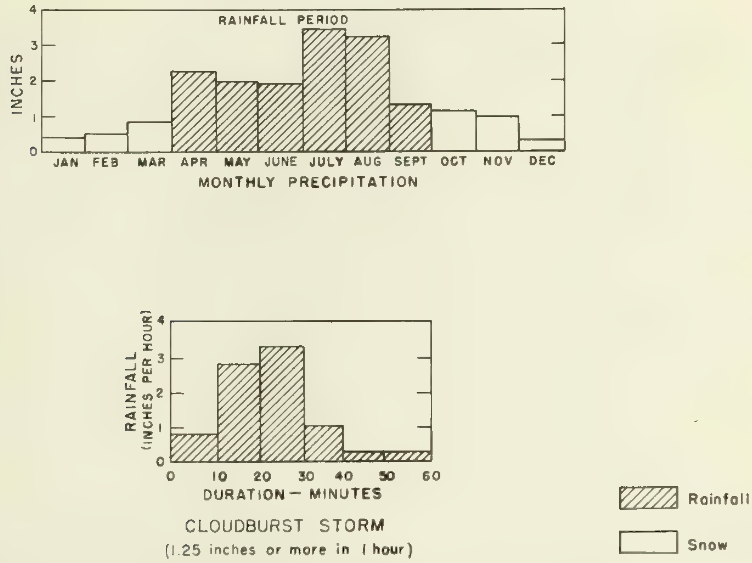

Figure 4.--Distribution of the annual precipitation at Manitou and the pattern of an average high-intensity summer storm.

Table 1.--Annual precipitation at Manitou Experimental Forest for the period 1938 to 1954

Year	Precipitation	Year	Precipitation	Year	Precipitation
	Inches		Inches		Inches
1938	19.72	1945	19.18	1952	13.66
1939	7.57	1946	16.67	1953	15.10
1940	15.41	1947	23.55	1954	12.87
1941	20.28	1948	12.38		
1942	18.60	1949	15.49		
1943	13.67	1950	11.61	Average	15.33
1944	15.15	1951	9.70		

Topography

There is a large variation in topography within the pastures. In general, the western third of each pasture is rough and irregular, but to the eastward the land surface is much less broken. Gently sloping land prevails over much of the eastern part of all range pastures. Land slopes vary from less than 1 percent to about 30 percent in the eastern section and from 2 percent to 50 percent in the irregular western end. Average land slope over the range pastures is 9 percent. Though all three vegetation types are found throughout the pastures, the timbered zone predominates in the western part and grassland predominates in the eastern.

Soils

The soils inthe range pastures are developed from alluvium derived from the disintegration of Pikes Peak granite. This alluvium is deposited on fans of three different ages (Retzer, 1949) and as a result, the soils developed on these materials have three different degrees of profile development.

The old alluvial fans occur at the highest elevation and occupy about 15 percent of the pastures. The young fans are at the lowest elevation in small pockets and as narrow bands along the drainageways. Intermediate fans occur topographically between the old and young fans and occupy more than three-fourths of the range pasture area.

Soils on intermediate fans have brown or dark brown, gravelly or sandy loam surface soils and average about 10 inches thick. Subsoils are bright or reddish brown, sandy or gravelly clay loam. Although moderately dense and compact, this subsoil is permeable. Slopes average less than 10 percent.

Surface soils on the old high fans are similar to those on intermediate fans in thickness and texture. But the B horizon is more developed, denser, and less permeable than that on intermediate fans. This subsoil extends to depths of 20 inches or more.

Soils on the young fans are characterized by stratified, loose sands and gravels without a subsoil or B horizon and with a very poorly developed surface or A horizon. Surface textures are variable but are usually sandy or gravelly loams.

The substratum or C horizon on all three soil types is composed of stratified layers or lenses of loose, coarse materials that are permeable to water.

Soils contain about 15 percent by weight of coarse material between 2 mm. and one-half inch in size. Clay content is low, averaging between 5 and 8 percent in the first 3 inches of surface soil. The major clay type is kaolinite, which does not swell much on wetting. Organic matter approximates 5 percent in the first inch of surface soil. The pH averages about 6.5, with a range from 6.0 to 8.0. The fertility level is generally low (Retzer, 1954) in comparison with soils developed from basic igneous, limestone, and shale rocks.

Vegetation

The vegetation is a combination of bunchgrass and ponderosa pine timberland with numerous scattered grassy openings or parks (fig. 5). This vegetation consists of three distinct subtypes described as follows:

Grassland -- Areas supporting a cover of mixed grasses and forbs in open parks and small openings in the timbered zone. Predominant grasses are mountain muhly (Muhlenbergia montana [Nutt.] Hitchc.) and Arizona fescue (Festuca arizonica Vasey). Less frequent herbaceous plants are blue grama (Bouteloua gracilis [H. B. K.] Lag.), little bluestem (Andropogon scoparius Michx.), Parry danthonia (Danthonia parryi Scribn.), sleepygrass (Stipa robusta [Vasey] Scribn.), sedge (Carex spp.), yarrow (Achillea lanulosa Nutt.), pussytoes (Antennaria aprica Greene), trailing fleabane (Erigeron flagellaris A. Gray), and fringed sagebrush (Artemisia frigida Willd.).

Pine-grass -- Areas supporting an open overstory of ponderosa pine and an understory of mixed grasses and forbs (fig. 6). The composition of the herbaceous cover is similar to that in the grassland, but is less dense.

Pine-litter -- Areas under ponderosa pine crowns supporting little or no herbaceous vegetation, but with considerable accumulation of tree litter that usually covers the entire surface soil (fig. 7). Sedges are much more common than grass species in this cover type.

Figure 5.--Grassland in experimental range pastures. Low-growing mountain muhly and taller Arizona fescue in foreground.

Figure 6.--Pine-grass in experimental range pastures. The herbaceous vegetation is less dense than in the grassland shown in figure 5.

Figure 7.--Surface condition on the pine-litter type. Herbaceous vegetation is extremely sparse.

Past Use

Prior to the establishment of the Manitou Experimental Forest, parts of the range pastures had been severely grazed by livestock, open park areas cultivated, and most of the timbered area logged. The six experimental range pastures did not isolate any of these past uses, but included within them various proportions of land heavily grazed, cultivated and logged. The infiltration capacities of the soils so disturbed may have been below their potential at the beginning of the study. This past disturbance influenced the results of the present investigation.

By the time the experiment began in 1941, the condition of the range was somewhat improved over that existing when the experimental forest was established. Conservative grazing was practiced, starting in 1937, and the range pastures were not grazed in 1940.

ELK RIDGE ALLOTMENT

The Elk Ridge Allotment of the Roosevelt National Forest occupies the headwaters of the Little Thompson River southwest of Loveland, Colorado (see fig. 1). This allotment comprises about 23,000 acres.

Climate and Topography

Although no measurements exist for precipitation, temperature, or duration of frost-free days, it is believed the climate of this area is similar to that of the Manitou Experimental Forest. Data gathered from Estes Park, Colorado, a few miles west of the allotment, and Boulder, Colorado, situated south of the allotment, lend validity to these assumptions (Reid and Love, 1951).

Topography of the area is similar to that of Manitou and is representative of ponderosa pine ranges (see fig. 3B) occurring on soils derived from granite and schist, and a mixture of these two rocks.

Soils

Soils strongly reflect characteristics of the mantle rocks from which they are derived. The main soils are: (1) residual soils in the uplands developed from hard bedrock of granite and granite-schist mixture, and (2) the alluvial soils in the valleys, lowlands, pockets, and fans derived from granite and schist materials.

Vegetation

Vegetation consists of forests on the slopes and ridgetops, with grassland, meadow, and aspen (*Populus tremuloides* Michx.) parks scattered throughout the valley bottoms, on benches, and at heads of small drainages. The grassland type differs somewhat in composition from that at Manitou in that Kentucky bluegrass (*Poa pratensis* L.) is by far the most abundant and important species. Ponderosa pine is the main tree species but aspen, lodgepole pine (*Pinus contorta* Dougl.), limber pine (*Pinus flexilis* James), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), Engelmann spruce (*Picea engelmannii* Parry), and blue spruce (*Picea pungens* Engelm.) also occur in variable amounts, as at Manitou.

Past Use

History of the Elk Ridge Allotment is similar to that of Manitou Experimental Forest, where severe grazing by livestock, cultivating of open park areas, and logging of forest lands occurred (Reid and Love, 1951). The allotment is now grazed by cattle during the period June 1 to September 30. Infiltration studies made on the allotment in 1950 were in connection with an analysis of the range-watershed conditions and were not part of the designed experiment conducted at Manitou Experimental Forest. Because the infiltrometer measurements involved the same instrumentation and procedures as employed on the Manitou range pastures, they form a useful means for testing the infiltration concepts developed at Manitou and are reported in this paper.

METHODS

INFILTRATION MEASUREMENTS

The Rocky Mountain infiltrometer (Dortignac, 1951), an artificial rainfall-simulator, was used to measure all infiltration rates (fig. 8). With this system, artificial rain is applied to an area of about 40 square feet on and surrounding the 2.5-square-foot infiltrometer plot. Wetting a large area surrounding the plot simulated conditions during natural rainfall and tended to reduce subsurface lateral movement of water through the soil. Intensities of applied rainfall varied slightly during the 50-minute test periods, although relatively constant water pressures were maintained. Likewise, average rainfall rates between tests varied from 4 to 5 inches an hour, but averaged about 4.50 inches.

Clear mountain spring water was used to sprinkle plots. The temperature of this water was reasonably constant throughout the study. Duley and Domingo (1943) found, in their sprinkling experiments, that water at 70°F. entered the soil at the same rate as water at 40°F. The temperature of water used in the experiments was well within this range.

During the first part of the rainfall application, water is retained by the infiltrometer plot frames, troughs, and rainfall applicators in initial wetting; interception storage by living and dead organic materials; and in filling of ground depressions, or "miniature reservoirs." There is no accurate way of determining the actual amount of water entering the soil soon after rainfall begins. However, after a short time (3 to 5 minutes) surface runoff usually begins indicating that initial wetting, interception, and depression storage is largely satisfied by this time. Once a relatively uniform rate of surface runoff has been attained, rainfall minus surface runoff equals infiltration. Surface runoff and rainfall were measured at 5- or 10-minute intervals. From these periodic measurements, average retention[2] rates were calculated.

The infiltration results presented, unless stated otherwise, refer to the average infiltration rate during the last 20 minutes of the 50-minute rainfall application on prewetted soils. This average rate is termed f_c. Figure 9 shows the relationship between rainfall, surface runoff, retention, infiltration, and the runoff portion of surface detention[3] that is obtained during a typical infiltrometer test on wet surface soil.

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[2] Retention is the difference between applied rainfall and surface runoff occurring at any given time (Horton, 1933).

[3] Surface detention is that part of rain remaining on the ground surface during natural or artificial rainfall and either runs off or is absorbed by infiltration after rain ceases (Horton, 1933). It includes depression storage and surface runoff in transit.

Figure 8.--A, Rocky Mountain infiltrometer during the field operation in grassland; B, Closeup of rainfall applicator, rainfall troughs, and runoff plot which are enclosed by tarpaulin windbreaks during field tests.

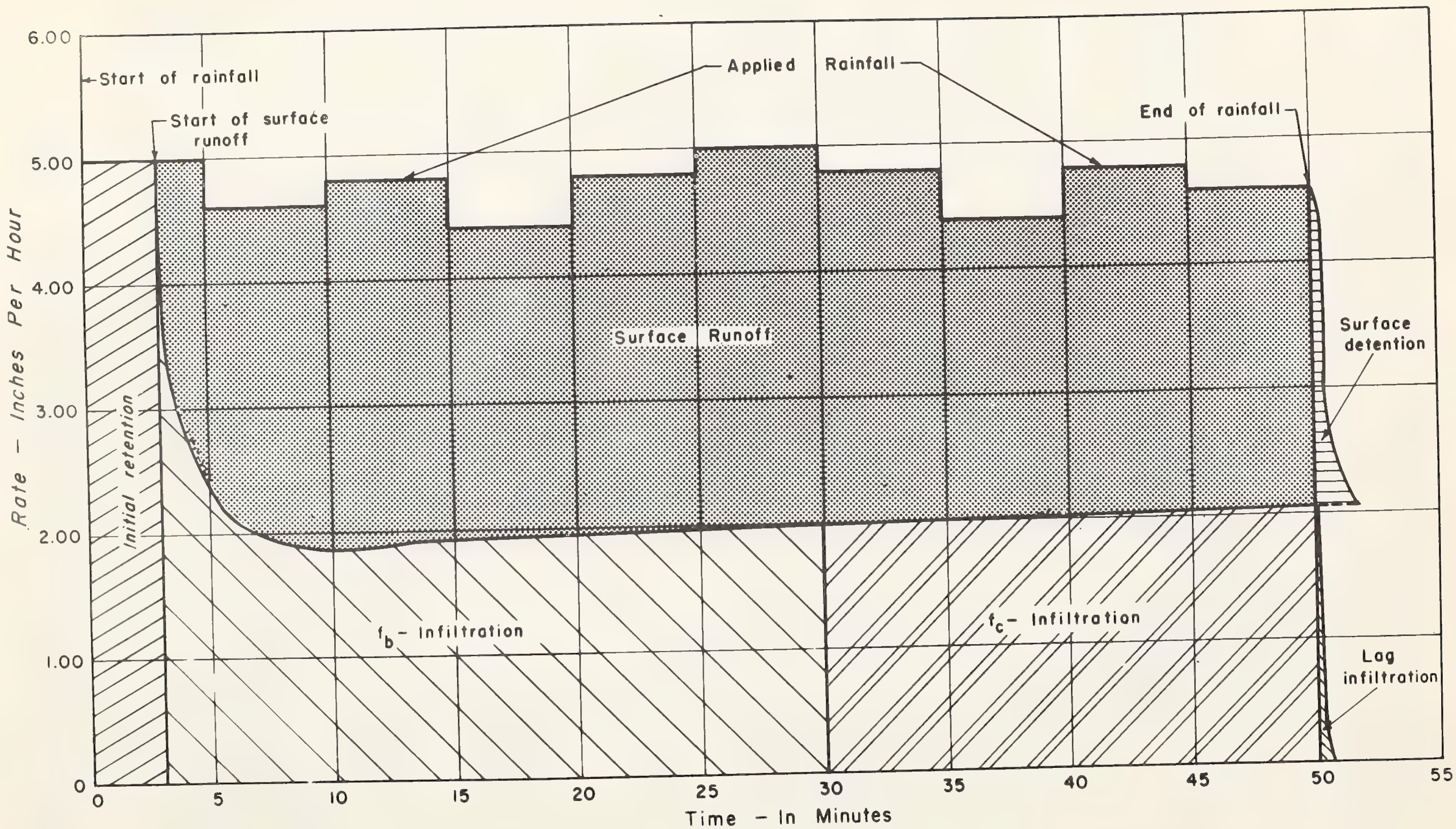

Figure 9. --Schematic drawing of applied rainfall, surface runoff, and infiltration obtained with the Rocky Mountain infiltrometer on wet surface soil.

Pasture infiltration tests at Manitou were started in the summer of 1941. Additional tests were made in 1942, 1946, and 1952. Infiltration tests were conducted in July and August during each year except in 1946 when the field work was done in August and September.

In locating infiltrometer plots an attempt was made to reduce sampling errors caused by variations in soil, cover, and topography. Three sampling sites were taken at random within each pasture-topographic subdivision (stratum) to represent the three cover-type conditions (see fig. 2). At each sampling site, two locations for infiltration measurements were randomly selected. In this manner, two infiltration tests were made in each cover type within each topographic stratum of each of the six pastures, for a total of 108 plots. Thus, in each of the six pastures, 18 infiltrometer plots were selected and distributed as follows:

Location in pasture	Topography (stratum)	Cover type	Number of plots
West	Rough	Grassland	2
		Pine-grass	2
		Pine-litter	2
Middle	Intermediate	Grassland	2
		Pine-grass	2
		Pine-litter	2
East	Gentle	Grassland	2
		Pine-grass	2
		Pine-litter	2

All areas within the pastures had an equal chance of being drawn. When a plot position fell on roads or trees, the sample was rejected and new numbers were drawn. No sample was inaccessible to the equipment, though cutting trees and pruning limbs were sometimes necessary. Slope was measured on all plots and varied from 0.5 to 50 percent.

The Elk Ridge infiltration sampling data are reported elsewhere (Reid and Love, 1951). The methods were similar to those used at Manitou.

MEASUREMENTS OF ORGANIC MATERIALS

The living and dead aboveground organic materials were collected from each infiltration plot except in 1942 before soil samples were taken. They were stored in paper sacks for weighing when air-dried. The live materials included only the current year's growth of herbaceous plants and was obtained by clipping at the ground line.

The dead organic materials included all dead parts of herbaceous plants, as well as other organic materials found on the ground surface. Maximum size of tree branches collected was 1 inch in diameter and 6 inches in length. Larger sized branches were removed from the field plot before conducting tests. The dead materials contributed by the ponderosa pine trees were not segregated by litter and duff. It was found impractical to separate undecomposed material from the partially decomposed material.

SOIL MEASUREMENTS

Pore Volume

The general formula for total pore volume of each soil core was calculated as:

$$\text{Total pore volume in percent} = 100 - \frac{(\text{Bulk density} \times 100)}{\text{Particle density}}$$

where $$\text{Bulk density} = \frac{\text{Weight of ovendry soil}}{\text{Volume of soil, water, and air}}$$

and $$\text{Particle density} = \frac{\text{Weight of soil particles}}{\text{Volume of soil particles}}$$

Total pore volume and the proportions of capillary and noncapillary pores were determined from soil samples by two methods: First, in 1946, bulk-density samples were taken on 54 plots (all plots in pastures 1, 2, and 3) after soils had drained to field capacity. (Field capacity is herein defined as the relatively constant moisture content of the soil in place after sufficient time has elapsed following saturation to allow free gravitational drainage or percolation of water from large pores.) This field procedure, previously described (Dortignac, 1950), involved taking $4\frac{1}{2}$-inch diameter soil cores by 1-inch increments to the 3-inch depth.

Particle density of the soil was determined by the pycnometer method (Smith, 1943). The air trapped in the water when this method was used was displaced by boiling. It is noteworthy that although evenly distributed random samples were taken in pine-litter and grassland, at 0-1 inch and 2-3 inch soil depth, the differences in the mean values were less than error. The overall mean of 2.50 ± 0.01 proved to be the best expression of particle density.

With bulk density and particle density values measured, the general formula was solved for total pore volume. It was believed that water remaining in the soil after adequate field drainage would represent the volume of capillary pores. Then, by subtracting the volume of capillary pores from the volume of total pores, an index of noncapillary pores was provided.

In the second method, used in 1952 and 1954, soil cores were obtained with cylinders $2\frac{1}{2}$ inches in diameter. In 1952, a 2-inch length of soil core was taken at the surface and a 4-inch length core at the top of the B (subsoil) horizon. In 1954, soil cores were taken for the 0-2 inch depth. Bulk density of the soil cores was determined by the method described above. The same particle density values obtained in 1946 were used in 1952 and 1954. The general formula was then solved for total pore volume.

To determine an index for capillary pore volume soil cores were analyzed by means of the tension table designed by Leamer and Shaw (1941). Moisture retained by the soil at 100 cm. of tension was used. Then, by the subtraction of the volume of capillary pores from the volume of total pores a second but somewhat different index of noncapillary pores was computed.

This same subtraction method used in 1952 and 1954 was used in calculating the quantity of noncapillary pores of soils tested in 1950 on the Elk Ridge Allotment (Reid and Love, 1951).

Texture

Soil textures were determined by the hydrometer method, described by Bouyoucos (1936), with specially designed specific gravity hydrometers. One hydrometer, ranging from 1.005 to 1.030, measured sand content and a second hydrometer (0.995 to 1.010) measured silt and clay content. The time of immersion of the hydrometer was calculated according to Stokes' law (length of the hydrometer stem between the surface of the suspension and the center of the volume of the bulb was used as depth). Gravel and rock larger than 2 mm. were segregated by sifting, and is expressed as a percentage of total soil sample collected in the field. Sand, silt, and clay percentages were based on material smaller than 2 mm. Dispersion was obtained by addition of Calgon ($Na_6F_6O_{18}$) and sodium silicate (water glass).

Moisture

Infiltrometer tests were conducted on prewetted soils on all plots. The standard procedure was to prewet soils 6 to 24 hours before the infiltrometer test by a 20-minute initial sprinkling at the 4.5 inches per hour intensity. In 1952 and 1954, the prewetting application was eliminated and two infiltration tests, 1 day apart, were conducted on each plot. This procedure provided a measure of infiltration under both dry and wet soil conditions.

Each plot was covered with a 7-foot square canvas tarpaulin after the initial sprinkling. The tarpaulin was removed just before beginning the infiltrometer tests on prewetted soil. The intent was to reduce evaporation and transpiration losses while the surface soil drained to approximate uniform moisture conditions.

Soil moisture samples were taken at selected depths before each infiltration test on wetted surface soils in 1946 and 1954 as follows:

1946 (Inches)	1954 (Inches)
0- 6	0- 6
6-12	6-12
12-24	12-18
24-36	18-24

The samples were obtained from the wetted area about 6 inches outside the plot frame with a soil tube described by Veihmeyer (1929). Texture and relative moisture content of each sample was estimated in the field. Holes were carefully refilled with soil similar to that removed, and tamped to approximately the original density.

After each wet-run infiltrometer test, tarpaulins were replaced over the plots to prevent evaporation for a period to allow the soils to drain to field capacity. This drainage time varied from 2 to 6 days. After the drainage period, soil-moisture samples were taken adjacent to each plot at the depths previously stated.

Moisture content of the soil was determined by weighing samples before and after ovendrying at 105°C. This same laboratory procedure was used in measuring the water held at field capacity and under listed tensions.

EXCLOSURES

In 1940, before beginning the experiment, two fenced exclosures, 2.5 acres in size, were located at random in each pasture at Manitou (see fig. 2). Exclosures were established to provide a measure of the effect of cattle exclusion on vegetation and infiltration.

In 1941, infiltration measurements were taken at random but stratified by cover types in each exclosure concurrently with sampling the overall pastures. In 1947, and again in 1954, infiltration measurements were made on randomly selected paired plots, one inside and one outside the exclosures in pine-grass and grassland. Infiltrometer plots outside exclosures were located at random between 25 and 300 feet from the fence to prevent sampling where cattle might concentrate.

RESULTS

RELATION OF INFILTRATION TO COVER TYPE

In the preliminary infiltration tests conducted in 1941 on the pastures, it was found that infiltration varied with cover type (table 2). The infiltration rate in pine-litter averaged higher than in pine-grass and grassland, which were similar. By 1946, and continuing to 1952, there was a reduction in the infiltration rate of the grassland so that a difference existed between the three cover types:

	Average f_c infiltration		
Year	Grassland	Pine-grass	Pine-litter
	- - - (Inches/hour) - - -		
1941	1.98	1.96	2.51
1942	1.72	1.86	2.10
1946	1.41	1.91	2.67
1952	1.59	1.96	2.07

To determine why infiltration was related to cover type and to investigate what soil and vegetation properties were most important required the evaluation of a number of factors. This evaluation involved a large number of soil and vegetation properties measured on the same plot.

RELATION OF INFILTRATION TO DEAD ORGANIC MATERIAL

Of all the vegetation factors measured, the one most consistently associated with infiltration was the aboveground dead organic materials.

In the years sampled, the mass of dead organic material was greatest in the pine-litter type and least in grassland (table 2). This was also true of infiltration rates, except in 1941 when pine-grass and grassland averaged about the same, as pointed out in the previous discussion.

The quantity of dead organic material measured on infiltrometer plots at the start of the study in 1941 was associated with higher f_c infiltration rates (table 2). A correlation coefficient of 0.364 for 108 observations in all cover types was significant.

Commencing in 1946 and continuing through the study, a stronger relation was obtained between dead organic material and infiltration rates. Correlation coefficients for 36 observations within each cover type in the overall pastures by years were:

Year	Pine-litter	Pine-grass	Grassland
1946	0.707**	0.717**	0.481**
1952	0.401**	0.432**	0.337*

** Significant at 1 to 99 odds.
* Significant at 1 to 19 odds.

The value of litter in increasing infiltration and reducing surface runoff has long been recognized (Colman, 1953; Kittredge, 1948). Litter accumulation on the surface soil breaks the impact of falling raindrops (Osborn, 1954), impedes or slows down surface runoff by providing roughness of surface through miniature barriers, prevents concentration of surface flow, reduces the detrimental effects of soil compaction caused by trampling and tends to leave the soil surface porous, spongy, irregular, and receptive to water intake. The reduction in detrimental splash and surface waterflow, in turn, reduces soil erosion and turbidity of runoff water and thus maintains high infiltration rates. Johnson (1940), in one of the early studies at Manitou, found that removal of 3 inches of litter under the ponderosa pine forest caused an immediate reduction in f_c infiltration from 1.52 to 0.92 inch an hour.

RELATION OF INFILTRATION TO LIVE ORGANIC MATERIAL

Live organic materials in grassland were related to infiltration in 1941 and 1946. For example, the correlation between f_c infiltration and live organic materials was 0.356 in 1941 and 0.409 in 1946 (data taken from table 2). Yet, in 1952, there was no relation between these two factors, as indicated by a correlation coefficient of 0.061. Nevertheless, when all 3 years' data were combined the correlation between f_c infiltration and live organic materials was increased to 0.420, which was highly significant.

The lack of correlation in 1952 is attributed to the small quantity of live herbaceous material produced in this drought year.

RELATION OF INFILTRATION TO SOIL PORE VOLUME

1946 Results

Noncapillary pore volume was found to be the most important soil factor related to infiltration. Bulk density, noncapillary, and capillary pore volume are summarized by cover type and soil depth in table 3. Noncapillary porosity was much greater in the first inch than in the second or third inch of soil. Also, noncapillary porosities were highest in the pine-litter and lowest in the grassland type.

The relationship (from table 3) between porosity of the top 3 inches of soil and cover type coincided with that between infiltration and cover type:

Table 2.--Basic data, Manitou range pastures

Cover type and strata	f_c - infiltration, Wet runs, 1941	1942	1946	1952	Organic material, Dead, 1941	1946	1952	Organic material, Live, 1941	1946	1952	Noncapillary pores, Min. in top 3 in., 1946	Noncapillary pores, 0-2 inches, 1946	1952	Sand, 1946, 0-1 in.	Sand, 1946, 2-3 in.	Sand, 1952, 0-2 in.	Initial soil moisture 1946, 0-6 in.
	- Inches per hour -				- - - - Grams per plot - - - -						- - - - - - - - Percent - - - - - - - -						
PASTURE 1																	
Pine-litter:																	
West	3.27	0.56	1.33	1.44	1208	691	98	1	0	2	21	33	32	68	68	71	11.7
	2.34	1.20	2.32	1.28	832	464	433	12	1	1	26	34	28	62	68	73	12.7
Middle	1.24	3.68	4.18	2.92	774	623	183	0	0	0	29	34	30	--	--	74	14.9
	2.34	3.89	2.85	4.29	939	630	650	0	0	0	21	23	24	--	--	78	16.1
East	4.07	1.26	3.63	3.52	807	936	763	0	4	0	16	29	30	--	--	78	12.9
	2.89	.49	1.24	1.66	881	520	487	0	7	0	22	30	28	--	--	67	18.0
Pine-grass:																	
West	2.04	2.22	2.01	1.98	241	248	173	32	33	7	16	24	29	53	66	72	9.5
	1.55	1.49	.43	1.31	255	330	198	56	5	16	20	25	18	53	53	64	9.5
Middle	1.40	3.05	2.63	1.74	375	163	256	17	36	7	27	32	19	--	--	62	13.9
	.97	2.67	2.98	1.30	205	410	172	36	13	5	19	28	20	--	--	60	12.3
East	.94	3.28	1.11	1.56	666	236	108	43	18	9	13	22	24	--	--	83	19.0
	1.14	2.15	1.18	1.37	549	134	152	49	6	5	20	27	19	--	--	71	14.3
Grass:																	
West	1.75	1.48	.94	.97	324	40	48	35	10	9	19	19	16	--	--	47	9.7
	2.08	1.16	1.71	1.57	159	13	143	100	24	13	15	26	15	--	--	58	13.3
Middle	1.59	1.93	1.19	1.20	350	81	16	203	18	17	19	22	20	--	--	52	17.1
	1.72	1.20	.73	1.22	209	136	6	210	17	12	16	24	15	--	--	59	12.7
East	1.80	2.01	.77	1.71	321	71	136	110	13	14	19	22	24	66	46	59	11.4
	1.02	.88	.48	1.10	166	31	32	106	18	11	23	24	14	67	67	69	15.4
PASTURE 2																	
Pine-litter:																	
West	2.39	1.49	3.82	1.13	498	783	446	1	18	0	27	33	35	75	77	76	12.4
	1.57	1.93	4.55	1.95	451	968	206	2	2	0	27	29	31	72	71	72	6.5
Middle	1.83	2.18	2.00	3.36	594	456	678	0	5	0	26	27	37	58	60	76	5.6
	1.56	1.76	1.44	1.94	919	337	414	0	15	0	24	26	30	69	70	72	13.0
East	3.46	1.40	1.33	.68	1816	335	527	12	4	0	17	26	28	68	65	76	6.7
	2.68	2.54	2.07	1.06	1455	340	748	0	0	0	14	24	35	60	63	67	4.4
Pine-grass:																	
West	1.54	2.90	1.44	3.17	396	75	270	68	64	6	23	28	22	72	74	57	15.7
	1.29	3.01	1.89	1.69	390	187	268	78	16	3	22	30	29	72	74	75	9.8
Middle	2.59	2.42	1.11	1.17	390	73	275	67	10	3	8	13	21	62	65	75	9.4
	2.57	1.29	1.60	3.18	799	74	188	129	7	8	10	13	27	65	68	84	7.7
East	1.28	1.99	1.54	1.29	106	353	149	83	22	9	15	21	21	70	69	60	15.4
	1.29	2.30	1.19	1.99	253	404	330	69	9	12	12	20	28	70	72	66	6.1
Grass:																	
West	.39	1.16	1.11	1.38	38	112	60	190	60	11	15	21	21	62	61	63	23.6
	1.18	1.19	1.21	2.16	122	96	375	179	51	5	15	19	26	65	62	68	18.2
Middle	2.08	1.38	1.79	1.24	409	92	63	111	29	9	8	14	18	--	--	50	12.6
	1.84	2.76	.96	2.00	152	71	100	131	62	17	8	16	21	--	--	60	13.0
East	2.33	2.48	.68	2.88	145	12	34	99	34	21	6	11	27	52	46	68	8.9
	3.21	1.35	.83	1.63	57	16	15	226	38	14	4	13	21	56	65	54	20.1
PASTURE 3																	
Pine-litter:																	
West	2.60	.95	2.16	1.07	577	323	334	8	1	0	35	36	24	71	71	70	13.5
	2.26	.64	2.06	1.72	638	522	413	6	2	0	14	22	29	67	66	70	17.7
Middle	2.73	2.91	2.30	.85	713	677	520	8	4	13	21	27	39	61	70	79	13.9
	2.41	2.84	4.65	3.56	782	908	673	0	3	4	28	31	42	70	70	67	17.8
East	2.25	2.49	1.82	1.17	865	378	590	0	1	1	17	23	21	65	63	56	16.2
	1.67	2.31	1.30	2.34	791	612	466	5	4	0	10	21	32	65	67	72	17.8
Pine-grass:																	
West	1.81	1.63	3.87	2.10	659	483	320	47	27	9	19	28	33	78	75	55	18.0
	2.82	1.60	4.71	1.96	351	307	200	64	32	4	22	31	34	78	81	72	13.7
Middle	2.73	2.92	.54	1.66	336	33	183	55	67	7	8	13	24	59	53	56	21.3
	2.17	1.62	.85	3.94	687	182	195	87	19	7	12	20	30	68	63	63	15.8
East	2.13	2.69	1.20	.63	153	259	84	46	22	4	13	20	13	64	65	69	12.7
	1.72	1.42	1.85	1.21	237	290	66	67	29	6	8	19	23	66	65	69	10.6
Grass:																	
West	2.85	1.79	2.16	1.63	155	275	165	155	23	12	13	22	24	71	69	52	14.6
	2.46	1.74	1.95	1.96	98	240	247	181	33	7	20	22	15	71	69	58	17.8
Middle	2.62	3.07	.71	2.66	106	34	121	143	34	6	19	24	22	53	54	55	16.1
	2.34	2.66	1.15	1.60	66	49	173	221	66	17	13	21	11	51	53	57	22.5
East	1.17	2.33	1.39	.60	431	165	45	80	46	15	12	19	8	53	59	42	11.1
	1.52	2.75	.99	2.10	356	82	108	108	54	12	10	20	15	49	53	57	6.1

Table 2.--Basic data, Manitou range pastures (continued)

Cover type and strata	f_c - infiltration Wet runs 1941	1942	1946	1952	Organic material Dead 1941	Dead 1946	Dead 1952	Live 1941	Live 1946	Live 1952	Noncapillary pores Min. in top 3 in. 1946	Noncapillary pores 0-2 inches 1946	0-2 inches 1952	Sand 1946 0-1 in	Sand 1946 2-3 in.	Sand 1952 0-2 in.	Initial soil moisture 1946 0-6 in.
	- Inches per hour -				- - - - Grams per plot - - - -						- - - - - - - - Percent - - - - - -						
PASTURE 4																	
Pine-litter:																	
West	1.25	3.20	1.54	0.88	793	622	614	0	1	0	--	--	44	--	--	79	16.1
	2.62	.92	2.36	1.76	903	351	375	0	31	1	--	--	28	--	--	79	13.6
Middle	3.27	2.61	3.18	3.47	1175	350	462	0	4	0	--	--	33	--	--	76	17.1
	2.62	1.80	3.40	1.15	1796	596	345	0	2	1	--	--	21	--	--	65	15.8
East	2.44	2.06	.60	2.06	542	262	459	0	1	0	--	--	27	--	--	76	4.5
	2.83	1.23	1.07	1.40	503	345	372	2	1	0	--	--	26	--	--	63	10.7
Pine-grass:																	
West	1.94	1.39	3.30	1.51	361	318	160	53	15	7	--	--	28	--	--	73	14.0
	3.11	1.49	1.94	2.52	521	156	108	58	43	2	--	--	28	--	--	76	10.9
Middle	2.05	2.34	.71	2.63	510	326	178	106	12	9	--	--	23	--	--	69	19.3
	2.73	1.53	.55	1.95	501	55	242	81	13	5	--	--	29	--	--	69	28.2
East	1.97	1.74	1.33	1.23	672	106	31	84	4	2	--	--	22	--	--	77	13.4
	1.45	1.72	1.53	1.48	996	102	145	80	9	3	--	--	26	--	--	58	10.1
Grass:																	
West	1.91	.70	1.27	1.01	283	68	102	229	22	7	--	--	23	--	--	79	16.2
	1.81	1.76	1.44	1.51	152	169	130	158	26	22	--	--	33	--	--	82	19.5
Middle	1.08	.28	.06	1.29	261	54	17	189	28	13	--	--	10	--	--	47	15.5
	1.53	1.76	.59	1.49	388	123	34	144	13	14	--	--	17	--	--	58	11.8
East	1.76	.62	3.14	1.89	318	469	31	120	35	20	--	--	22	--	--	76	14.9
	1.56	.55	1.89	1.29	114	208	18	129	48	15	--	--	24	--	--	79	15.4
PASTURE 5																	
Pine-litter:																	
West	2.65	2.02	2.15	3.23	1300	459	381	8	4	13	--	--	33	--	--	81	14.2
	4.06	3.43	2.44	2.69	1057	209	423	2	4	2	--	--	33	--	--	75	14.8
Middle	2.74	1.86	4.05	3.64	1134	463	782	0	17	0	--	--	35	--	--	79	6.4
	2.95	1.50	3.89	2.52	888	713	1320	0	1	0	--	--	27	--	--	48	12.0
East	2.01	1.75	3.15	1.54	974	685	555	2	9	0	--	--	34	--	--	76	11.5
	2.84	2.94	3.46	1.98	909	546	468	0	1	0	--	--	26	--	--	78	13.3
Pine-grass:																	
West	1.52	1.17	1.55	1.85	267	168	110	78	10	10	--	--	23	--	--	63	6.4
	1.79	2.29	1.98	1.28	386	220	118	73	19	10	--	--	24	--	--	63	12.2
Middle	3.12	1.60	1.79	2.18	793	210	210	35	17	4	--	--	26	--	--	76	13.1
	1.90	1.51	1.73	1.62	182	153	190	44	21	4	--	--	26	--	--	76	19.4
East	2.91	1.50	1.59	1.72	737	387	333	54	20	10	--	--	32	--	--	62	14.7
	1.56	1.18	1.44	3.16	489	188	196	47	18	20	--	--	33	--	--	16	17.8
Grass:																	
West	3.47	2.42	1.69	1.91	444	647	116	184	15	14	--	--	12	--	--	57	18.1
	2.03	2.73	1.14	1.64	277	538	230	223	23	17	--	--	28	--	--	58	23.1
Middle	1.84	.98	2.52	1.30	249	37	67	216	32	15	--	--	17	--	--	49	22.7
	1.86	2.00	.78	1.31	219	43	163	36	23	8	--	--	17	--	--	58	16.4
East	2.42	1.33	.94	1.14	94	93	78	166	30	17	--	--	23	--	--	60	16.4
	1.37	1.57	2.28	1.56	194	65	44	103	61	12	--	--	19	--	--	67	12.9
PASTURE 6																	
Pine-litter:																	
West	2.31	1.95	3.13	1.77	1014	1000	615	34	54	0	--	--	28	--	--	80	6.4
	2.89	1.67	7.12	3.87	1312	1320	1298	0	28	0	--	--	33	--	--	71	8.0
Middle	2.15	3.46	4.20	1.37	1548	715	215	0	0	0	--	--	39	--	--	65	6.5
	1.93	2.25	2.77	2.05	1085	223	424	0	2	0	--	--	30	--	--	77	11.4
East	2.79	2.86	1.56	1.98	1616	620	515	3	0	0	--	--	29	--	--	70	5.4
	2.64	3.57	1.06	1.13	1610	340	425	7	1	0	--	--	33	--	--	84	10.4
Pine-grass:																	
West	1.74	1.42	3.29	2.35	589	181	327	92	40	12	--	--	28	--	--	55	9.7
	1.80	1.70	1.24	3.18	519	283	442	65	55	19	--	--	31	--	--	63	9.9
Middle	2.14	.74	1.29	3.38	640	42	228	80	21	11	--	--	41	--	--	79	11.9
	1.26	1.51	1.43	2.50	313	207	255	116	67	21	--	--	34	--	--	74	4.7
East	2.40	.61	6.94	1.38	373	1279	184	128	24	14	--	--	25	--	--	37	18.2
	3.19	.97	2.84	1.30	313	182	79	88	24	8	--	--	26	--	--	56	16.2
Grass:																	
West	1.10	2.93	2.43	1.56	203	111	190	136	91	22	--	--	21	--	--	72	8.3
	2.45	1.64	2.88	1.88	109	508	208	204	95	11	--	--	16	--	--	53	8.0
Middle	2.29	1.67	1.91	2.19	230	98	119	276	112	16	--	--	31	--	--	63	9.1
	2.52	2.21	1.23	1.44	111	89	120	214	58	13	--	--	22	--	--	70	9.1
East	3.71	1.56	1.99	1.59	172	143	247	244	38	8	--	--	23	--	--	83	7.0
	2.74	1.93	1.79	1.62	268	237	79	184	29	18	--	--	23	--	--	74	11.8

	Noncapillary pores, 0-3 in. (Percent)	Infiltration, f_c (Inches/hour)
Grassland	18.7	1.15
Pine-grass	21.2	1.78
Pine-litter	26.9	2.50

The strongest statistical correlation was obtained by using the soil layer with the least amount of noncapillary pore space. Minimum noncapillary pore space occurred in the second inch on 34 out of 54 plots. The third inch of soil had the least large pore space in 18 samples, and the first inch in two samples. The soil layer with the least noncapillary porosity, i.e., the first inch on two plots, the second inch on 34 plots, and the third inch on 18 plots, provided the highest correlation (0.581) with f_c infiltration and accounted for one-third of the variation in infiltration.

Table 3.--Summary of porosity and infiltration by cover type in 1946

Item[1]	Soil depth	Cover type			Least significant difference (1-99 odds)
		Pine-litter	Pine-grass	Grass	
	Inches				
Infiltration rate[2] (Inches/hour)	--	2.50	1.78	1.15	0.65
Bulk density (Gm./cc.)	0-1	1.16	1.19	1.24	.07
	1-2	1.40	1.52	1.46	
	2-3	1.42	1.51	1.48	
Capillary pore volume (percent)	0-1	20.50	23.90	25.20	3.40
	1-2	20.80	23.60	27.00	
	2-3	18.40	21.80	25.20	
Noncapillary pore volume (percent)	0-1	33.20	28.40	25.10	3.20
	1-2	23.30	17.20	14.80	
	2-3	24.30	17.90	16.20	

[1] Pastures 1, 2, and 3; other pastures not sampled.
[2] Averaged from table 2.

1952 Results

As in the 1946 studies, the relationship between porosity and cover type coincided with that between infiltration and cover type:

	Noncapillary pores, 0-2 in. (Percent)	Infiltration, f_c (Inches/hour)
Grassland	19.8	1.59
Pine-grass	26.1	1.96
Pine-litter	30.9	2.07

The strongest statistical correlation was obtained between noncapillary pores and infiltration in the pine-grass type, 0.615, significant to the 1 percent level. In the grassland the correlation was 0.377 (significant to the 5 percent level), while in the pine-litter type no correlation was found. Apparently, in this latter type large pore space did not limit infiltration.

The results of the laboratory measurements made in 1952 of noncapillary pore volume taken at the 0-2 inch depth are listed in table 2. In the laboratory method used to determine noncapillary pore volume, it is a simple matter to take readings at tensions up to 100 cm. The relation between selected soil moisture tensions from 0 to 100 centimeters and soil-moisture content by volume for the upper 2 inches of soil is given in figure 10.

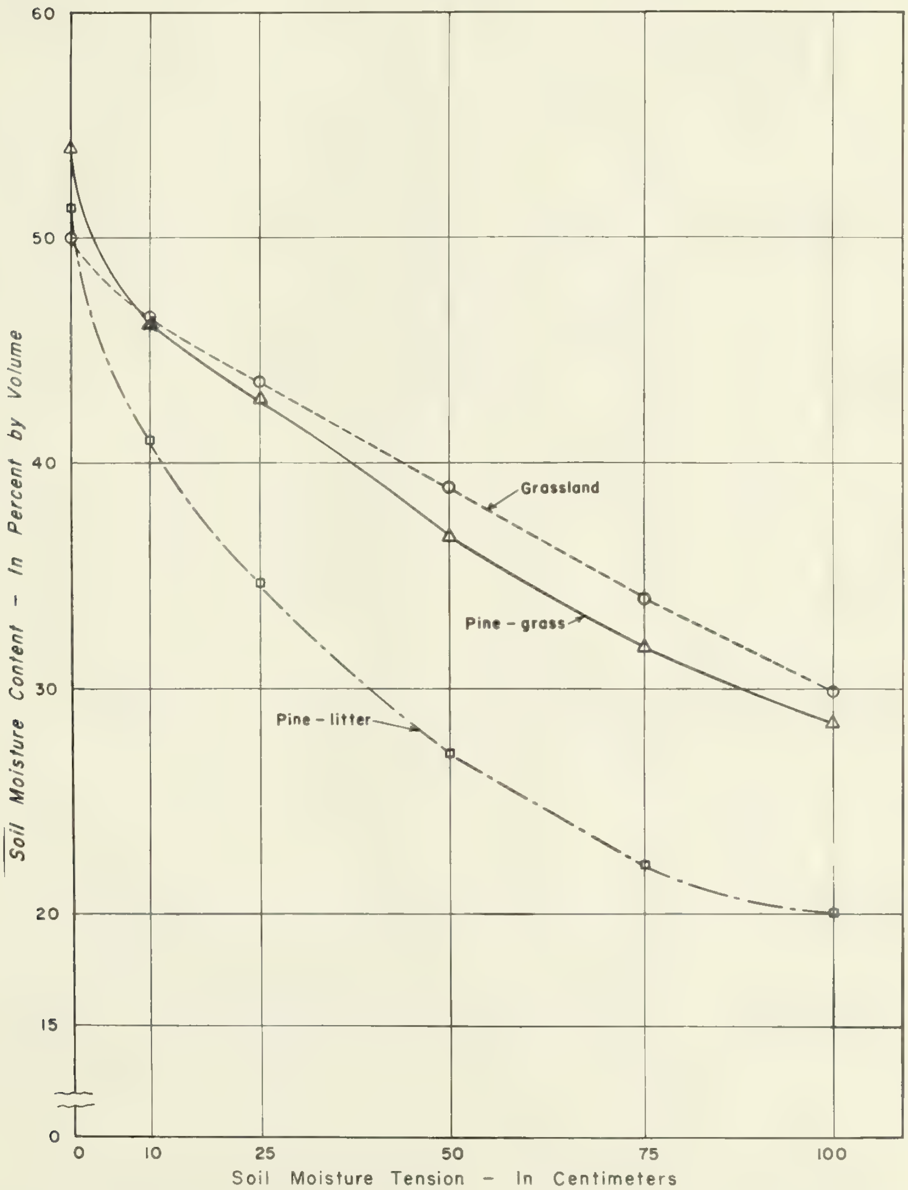

Figure 10.--Soil moisture tension curves for average cover type conditions (0-2 inches soil depth, 1952).

Surface soil under pine-litter cover lost the greatest quantity of water and that in grassland the least for tensions between 0 and 100 centimeters. (A separate analysis indicated that soil cores drained to somewhere between 4 cm. and 6 cm. of tension would more nearly approximate field saturation than 0 cm. of tension.) This indicates a higher noncapillary pore volume in the pine-litter than in the grassland.

1954 Results

In 1954, noncapillary porosity averaged higher in the exclosures than in the adjacent grazed pasture area (data from table 5):

	Large pores (Percent)	Infiltration rate (Inches/hour)
Grassland:		
Inside exclosures	24.2	3.26
Outside exclosures	14.8	1.24
Pine-grass:		
Inside exclosures	20.3	2.60
Outside exclosures	17.6	1.83

The effect of cattle exclusion on pore sizes is illustrated in figure 11. The average moisture tension curves for the surface 2 inches of soil for combined pine-grass and grassland are given for exclosures and the adjacent grazed areas. By 1954, the soil space occupied by large pores was less outside than inside the exclosures, but there was no difference in the smaller sized pores. The lower amount of large pore space in the surface 2 inches of soil surrounding exclosures is attributed to soil compaction caused by cattle trampling. This indicates that cattle trampling affects only the large pore space.

At 0 cm. tension, the mean soil moisture content by volume for the combined cover types was 55.3 percent for plots inside exclosures and 50.9 percent for those outside (fig. 11). The difference was significant at the 5-percent level, indicating that there were more large pores in the surface soil inside than outside exclosures. Differences were less at 25 cm. tension and not significant. At this tension, soil moisture content was 45.3 percent for the inside plots and 43.9 percent for the outside.

Variations in large pore volume account for part of the difference between f_c infiltration inside and outside plots.

RELATION OF INFILTRATION TO SOIL TEXTURE

Soil texture was found to be related to infiltration by cover types in 1946 and in 1954, but not in 1952 (table 4). Sand content (as a percent of the soil fraction passing a 2 mm. screen) was the best indicator of the influence of texture on infiltration. Infiltration increased with an increase in sand content. Such a relation is expected since soil space occupied by large pores is partially dependent on the sand. Large pores and sand, when related to infiltration were of about the same magnitude, indicating that either one could be used to predict infiltration.

Percent sand and percent noncapillary pores in the 0- to 2-inch soil layer were related in the pine-grass in 1946 (see table 2) and in 1954 (table 5); and were related in the grassland in 1952 (see table 2).

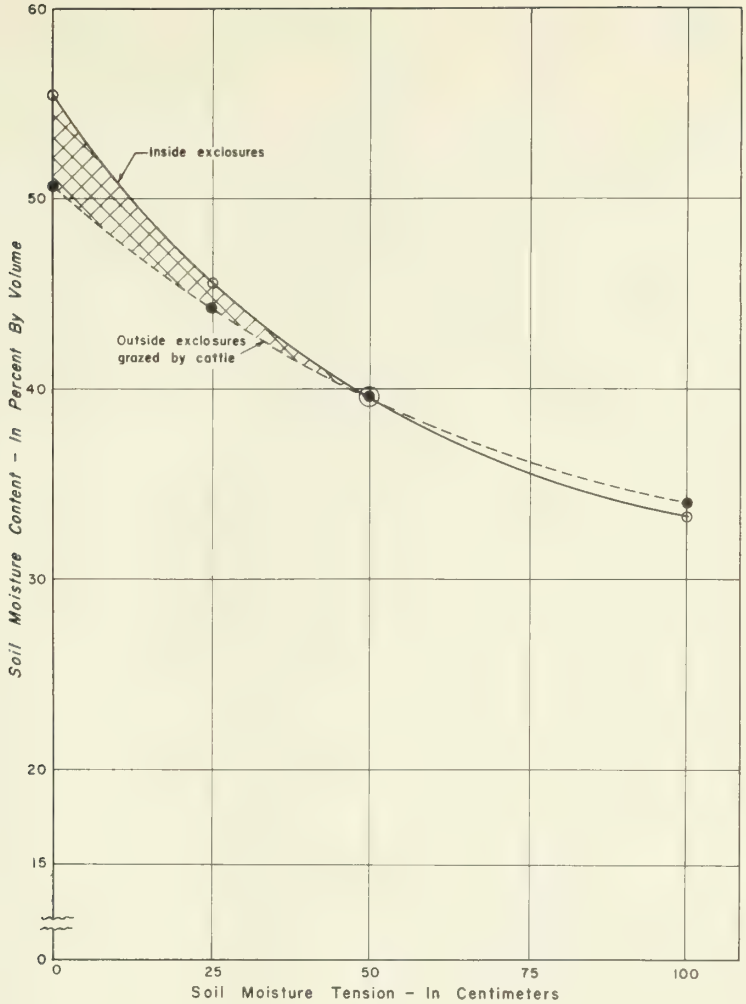

Figure 11.--Soil-moisture tension curves for average pine-grass and grassland, inside and outside exclosures (0-2 inches soil depth, 1954).

Table 4.--Correlation coefficients between f_c infiltration and sand, for three grazed cover types by years

Year	Soil depth	Cover type	Plots	Correlation coefficient: f_c infiltration and percent sand
	Inches		No.	
1946	2-3	Grassland	12	0.552*
		Pine-grass	14	.800**
		Pine-litter	14	.522*
1952	0-2	Grassland	36	.150
		Pine-grass	36	-.082
		Pine-litter	36	.138
1954	0-2	Grassland	8	.645*
		Pine-grass	16	.440*

**Significant to 1 percent level. *Significant to 5 percent level.

Percent noncapillary pores was chosen as the variable to predict infiltration because it appeared to be a more sensitive indicator of changes in soil structure.

Table 5.--Basic data, measurements inside and outside of cattle exclosures, Manitou range pastures

Cover type	f_c infiltration					Dead organic material					Noncapillary pores (0-2 in.)		Sand (0-2 in.)	
	1941	1947		1954		1941	1947		1954		1954		1954	
	In[1]	In	Out[2]	In	Out	In	In	Out	In	Out	In	Out	In	Out
	Inches/hour					Grams per plot					Percent			
						PASTURE 1								
Pine-grass	1.31	2.70	2.43	2.35	1.34	291	112	660	136	162	19	16	74	75
	1.64	4.65	3.05	2.40	.46	253	1,855	606	248	154	23	14	79	70
Grass	2.49	1.53	1.08	1.23	.81	285	102	146	211	39	22	14	42	51
	2.20	3.15	.91	2.15	.80	250	222	142	117	19	30	12	59	61
						PASTURE 2								
Pine-grass	1.97	2.03	2.30	4.90	1.66	327	210	391	514	174	30	15	42	63
	1.96	2.47	2.19	4.17	.94	562	268	345	440	287	22	13	68	45
Grass	1.48	1.41	.69	5.38	1.33	96	6	3	283	98	28	10	48	70
	1.51	2.85	1.14	2.38	1.35	120	24	55	220	189	18	17	55	61
						PASTURE 3								
Pine-grass	1.95	3.94	1.10	3.36	2.53	496	649	1,075	312	284	25	17	71	59
	1.01	2.61	1.87	3.50	2.28	273	58	225	299	136	16	19	61	88
Grass	1.47	1.80	.98	2.72	1.32	168	25	10	148	38	19	11	59	63
	1.90	1.22	1.25	3.27	1.35	223	221	30	155	98	25	20	46	64
						PASTURE 4								
Pine-grass	1.66	1.87	1.05	2.19	1.38	202	127	41	130	95	16	23	68	75
	1.18	4.42	.75	3.63	.71	209	32	31	75	77	24	10	53	53
	--	--	--	2.13	1.89	--	--	--	298	340	18	22	71	70
	--	--	--	2.56	2.56	--	--	--	228	23	28	17	72	78
Grass	1.75	1.72	.61	--	--	178	6	6	--	--	--	--	--	--
	2.38	5.57	2.16	--	--	161	119	216	--	--	--	--	--	--
						PASTURE 5								
Pine-grass	1.64	3.00	.91	.94	1.30	442	180	315	241	80	9	12	65	54
	1.73	1.49	.42	1.53	2.48	240	464	294	185	333	25	24	69	70
	--	--	--	1.66	1.41	--	--	--	157	101	10	31	74	72
	--	--	--	2.12	3.95	--	--	--	127	419	23	19	70	77
Grass	1.44	.76	.58	--	--	72	80	8	--	--	--	--	--	--
	1.66	1.69	1.36	--	--	116	33	8	--	--	--	--	--	--
						PASTURE 6								
Pine-grass	1.62	3.03	1.00	2.30	2.97	427	1,166	359	192	282	18	17	75	69
	1.45	2.72	2.62	1.94	1.41	317	169	67	141	135	19	12	74	70
Grass	2.75	2.01	1.97	4.93	1.86	161	31	109	51	56	29	15	77	78
	2.38	3.58	.71	3.99	1.07	324	96	9	144	88	23	19	78	76

[1] In = Inside exclosures, not grazed. [2] Out = Outside exclosures, grazed.

RELATION OF INFILTRATION TO SOIL MOISTURE

Initial soil moisture content before the wet run was obtained in 1946 and 1954. Analyses of these data showed there was no relation between the soil moisture content of prewetted soil just prior to the wet run and infiltration rates measured during the run. Apparently, the influence of moisture content of prewetted soils is masked by other soil and vegetation properties.

RELATION OF INFILTRATION TO DRY AND WET SURFACE SOIL

In contrast, there is a significant relationship between infiltration rates on dry and wet surface soil. In 1952 infiltration rates were measured on dry and prewetted surface soils on the same plots (table 6). Regression equations derived from these data were:

for pine-litter $Y = 0.85X + 0.46$
for pine-grass $Y = 0.71X + 0.75$
for grassland $Y = 1.00X + 0.41$

where

Y = the estimated infiltration rate (f_c) on dry soil in inches per hour,
X = the infiltration rate (f_c) on wet soil in inches per hour.

The high correlation of infiltration rates on dry and wet surface soil is shown by these data:

	Standard error of b	Standard error of regression equation	Correlation coefficient r
Pine-litter	0.19**	0.36	0.922**
Pine-grass	.31*	.45	.772**
Grassland	.13**	.36	.793**

(*Significant at 1 to 19 odds; ** Significant at 1 to 99 odds)

In the grassland type, infiltration under dry soil conditions was 0.4 inch higher than under wet surface soil conditions. In the other two vegetation types, the regression equations show that f_c infiltration on dry surface soil was higher than that on prewetted soil up to 2.6 inches per hour on pine-grass and 3.0 inches per hour on pine-litter. For rates exceeding 3 inches per hour, wetted surface soils had higher infiltration rates than when dry.

INFILTRATION RATES AS INFLUENCED BY PROTECTION FROM GRAZING

Infiltration tests were obtained at random but stratified by cover types in each exclosure in 1941. Paired infiltration measurements of inside and outside exclosures were not made at that time. The 24 infiltration measurements taken within the fenced exclosures were compared with the 108 observations randomized over the 1,700-acre pasture area in 1941 to determine whether the infiltration rates found within the exclosures were the same as those measured in the pastures. There was no significant difference between the rates measured within the exclosures and those of the pastures.

Thus, the infiltration rates of the three cover types obtained in 1941 within the exclosures were representative of the overall pasture conditions. Differences in infiltration between inside and outside exclosures in subsequent years would be the result of protection from grazing.

Table 6.--Infiltration rates for 1952 on dry and prewetted surface soils, Manitou range pastures

Cover type and strata	Pasture 1		Pasture 2		Pasture 3		Pasture 4		Pasture 5		Pasture 6	
	Dry	Wet[1]	Dry	Wet[1]	Dry	Wet[1]	Dry	Wet[1]	Dry	Wet[1]	Dry	Wet[1]
	Inches per hour											
Pine litter:												
West	1.61	1.44	1.31	1.13	1.18	1.07	1.60	0.88	3.21	3.23	1.88	1.77
	1.11	1.28	2.55	1.95	2.08	1.72	1.82	1.76	2.51	2.69	3.84	3.87
Middle	2.89	2.92	3.06	3.36	1.04	.85	3.60	3.47	4.13	3.64	1.65	1.37
	3.86	4.29	1.53	1.94	3.41	3.56	1.29	1.15	2.63	2.52	2.52	2.05
East	2.88	3.52	.96	.68	1.32	1.17	2.57	2.06	1.78	1.54	2.65	1.98
	1.50	1.66	1.32	1.06	2.19	2.34	1.74	1.40	3.46	1.98	1.42	1.13
Pine-grass:												
West	2.44	1.98	2.63	3.17	2.73	2.10	2.31	1.51	2.23	1.85	2.07	2.35
	1.81	1.31	1.88	1.69	2.60	1.96	2.96	2.52	1.46	1.28	2.99	3.18
Middle	2.30	1.74	1.21	1.17	1.38	1.66	2.51	2.63	1.65	2.18	4.03	3.38
	1.92	1.30	3.00	3.18	3.15	3.94	2.41	1.95	1.07	1.62	2.66	2.50
East	1.51	1.56	1.51	1.29	1.02	.63	1.48	1.23	1.74	1.72	2.99	1.38
	1.80	1.37	1.34	1.99	1.88	1.21	2.06	1.48	2.80	3.16	1.24	1.30
Grass:												
West	1.57	.97	1.91	1.38	2.23	1.63	1.55	1.01	2.26	1.91	1.51	1.56
	1.92	1.57	2.68	2.16	2.03	1.96	1.61	1.51	2.03	1.64	1.88	1.88
Middle	1.27	1.20	1.76	1.24	2.97	2.66	1.23	1.29	1.89	1.30	2.25	2.19
	1.14	1.22	2.43	2.00	1.66	1.60	2.04	1.49	1.67	1.31	2.36	1.44
East	2.17	1.71	3.77	2.88	1.33	.60	2.17	1.89	1.63	1.14	1.77	1.59
	1.82	1.10	2.58	1.63	2.83	2.10	1.45	1.29	1.62	1.56	3.20	1.62

[1] Data taken from table 2.

Infiltration measurements in 1947 and 1954 were made inside and outside the exclosures for the pine-grass and grassland types (fig. 12). The pine-litter type was not measured because of its generally high infiltration rate. The f_c infiltration means due to protection from grazing were:

Year	Exclosures		
	Grassland	Pine-grass	Combined
	(Inches per hour)		
1941	1.95	1.59	1.77
1947	2.27	2.91	2.59
1954	3.26	2.60	[1] 2.82

[1] 16 plots in pine-grass; 8 plots in grassland

Since measurements by cover type in exclosures were representative of the pasture area in 1941, it is indicated by the changes in f_c infiltration due to protection from grazing, that the pastures would have likewise improved had they been protected.

Preliminary analyses of 1947 and 1954 comparisons between inside and outside exclosures indicated that insufficient observations prevented full statistical evaluation of results. Variations between the plots within the exclosures and within those outside also tended to nullify a rigorous statistical analysis. A summary of f_c infiltration between inside and outside the exclosures appears in table 7.

Figure 12.--Fenced exclosure in grassland in heavily grazed pasture. The extreme difference in ground cover conditions between inside (right) and outside (left) exclosures by 1954 is shown by inset photos.

Table 7.--Mean f_c infiltration for plots inside and outside exclosures in the range pastures (from table 5)

Item	Pine-grass		Grassland		Combined	
	1947	1954	1947	1954	1947	1954
	Inches per hour					
Lightly grazed:						
Pasture 2						
Inside exclosure	2.25	4.54	2.13	3.88	2.19	4.21
Outside exclosure	2.25	1.30	.92	1.34	1.58	1.32
Pasture 5						
Inside exclosure	2.25	1.56	1.23	--	1.74	1.56
Outside exclosure	.67	2.29	.97	--	.82	2.29
Moderately grazed:						
Pasture 3						
Inside exclosure	3.28	3.43	1.51	3.00	2.39	3.21
Outside exclosure	1.49	2.41	1.12	1.34	1.30	1.87
Pasture 6						
Inside exclosure	2.88	2.12	2.80	4.46	2.84	3.29
Outside exclosure	1.81	2.19	1.34	1.47	1.58	1.83
Heavily grazed:						
Pasture 1						
Inside exclosure	3.68	2.38	2.34	1.69	3.01	2.03
Outside exclosure	2.74	.90	1.00	.81	1.87	.85
Pasture 4						
Inside exclosure	3.15	2.63	3.65	--	3.40	2.63
Outside exclosure	.90	1.64	1.39	--	1.14	1.64

Table 7 shows that with three exceptions out of 22 comparisons, the f_c infiltration was higher inside the exclosures than outside for both the pine-grass and grassland in 1947 and 1954. Combining the observations (table 7) for the two cover types for each of the years more clearly brings out what might be expected when measuring f_c infiltration inside and outside exclosures. There is some justification for combining observations in that the exclosures were only $2\frac{1}{2}$ acres in size (5 chains × 5 chains), thus it was somewhat difficult in all instances to separate the two cover types in such a small area. The combination of cover types would appear to give a more adequte index to f_c infiltration within the exclosures than the individual cover types. Similar difficulties occurred in locating plots outside the exclosures.

DISCUSSION OF INFILTRATION RATES AS INFLUENCED BY CATTLE GRAZING

The large variation in infiltration from spot to spot within each pasture before the start of the experiment prevented full evaluation of the effect of cattle grazing on infiltration on an overall pasture basis. The 1,700-acre pasture was too large and the soil-vegetation conditions too varied to allow taking an adequate number of samples with the infiltrometer in any one season.

The design of the study called for the random location of infiltration plots by three strata and by three cover types within each pasture (page 13). In this design it was assumed that the location of plots within a single stratum and cover type would represent similar soil and vegetation conditions from year to year as the study progressed. This assumption did not prove valid since differences from plot to plot in the same stratum and cover type varied greatly during a single year as well as from year to year and between pastures treated alike. Individual plot vegetation and soil conditions often varied to the extent that grazing effects were masked by inherent plot characteristics. Possibly, this difficulty might have been overcome by doubling the number of samples (infiltrometer plots) in each pasture.

Grazing effect on f_c infiltration might have been more pronounced had subsequent plots been located in the vicinity of the 1941 plots. Inherent variations between yearly plot locations would have been minimized. Livestock grazing over a range pasture is not uniform and may vary from heavy to no use. Such a pattern often persists for a period of years; continuing plots in the same vicinity would give a measure of changes in infiltration associated with grazing use.

Figure 13 illustrates the large variation in infiltration for the three cover types, both within and between the six pastures for the years of measurement.

Another difficulty encountered was that pastures showed different infiltration rates even under uniform treatment such as in the exclosures. In general, there was a recovery or increase in infiltration rates in pine-grass and grassland in the exclosures. Infiltration rates were not measured in the pine-litter type in exclosures. The mean pasture infiltration rates were about the same at the beginning of the study as they were at the end (fig. 14). Thus, the main effect of cattle grazing was preventing an increase or recovery in infiltration rates.

On the basis of the preceding discussion, future studies of the influence of different degrees of livestock grazing on infiltration should consider:

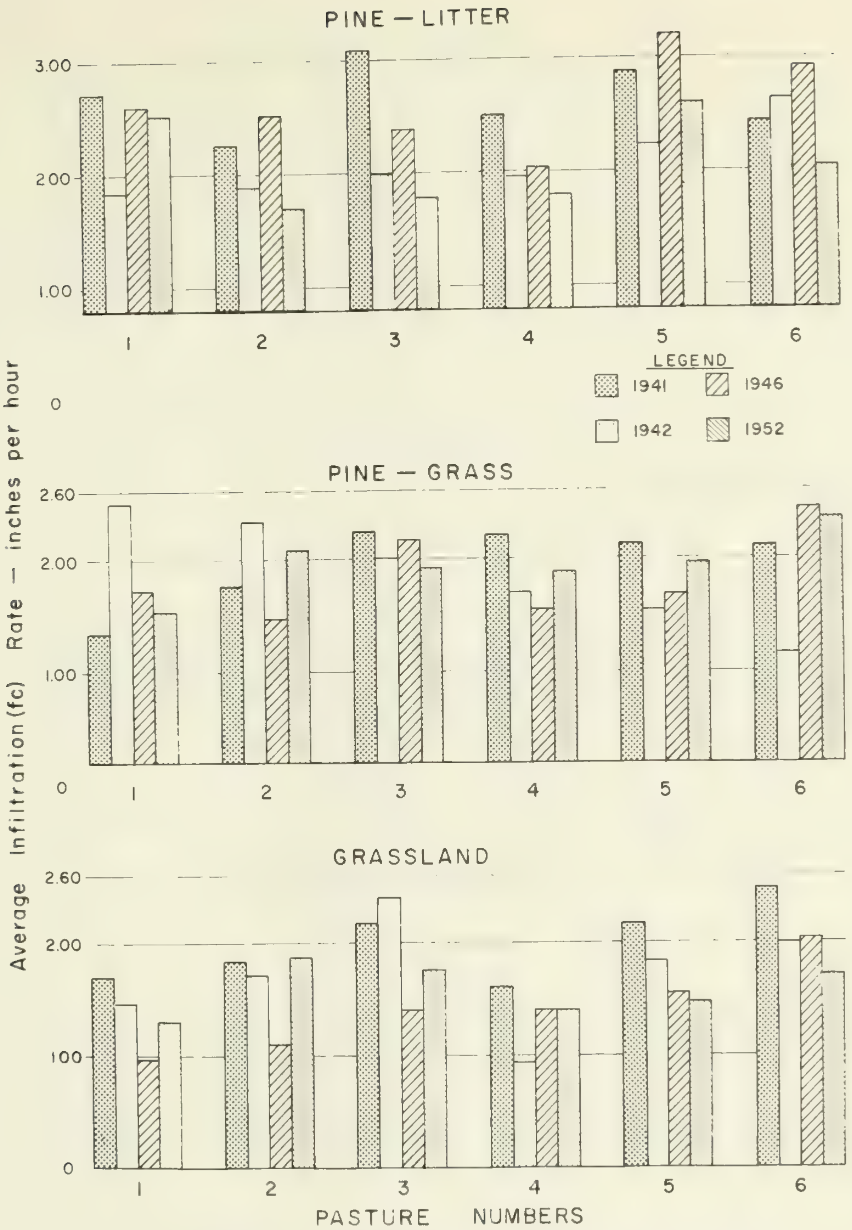

Figure 13. --Mean infiltration (f_c) rates by pastures and cover types, 1941-52.

1. Allowing experimental range areas to recover their infiltration values through protection until the rates are fairly uniform.

2. Establishing sufficient samples (plots) to minimize plot variation and to provide adequate statistical control.

3. Remeasuring plots in the vicinity of the original plot location.

4. Restricting sampling to grassland cover types and other key grazing types or areas.

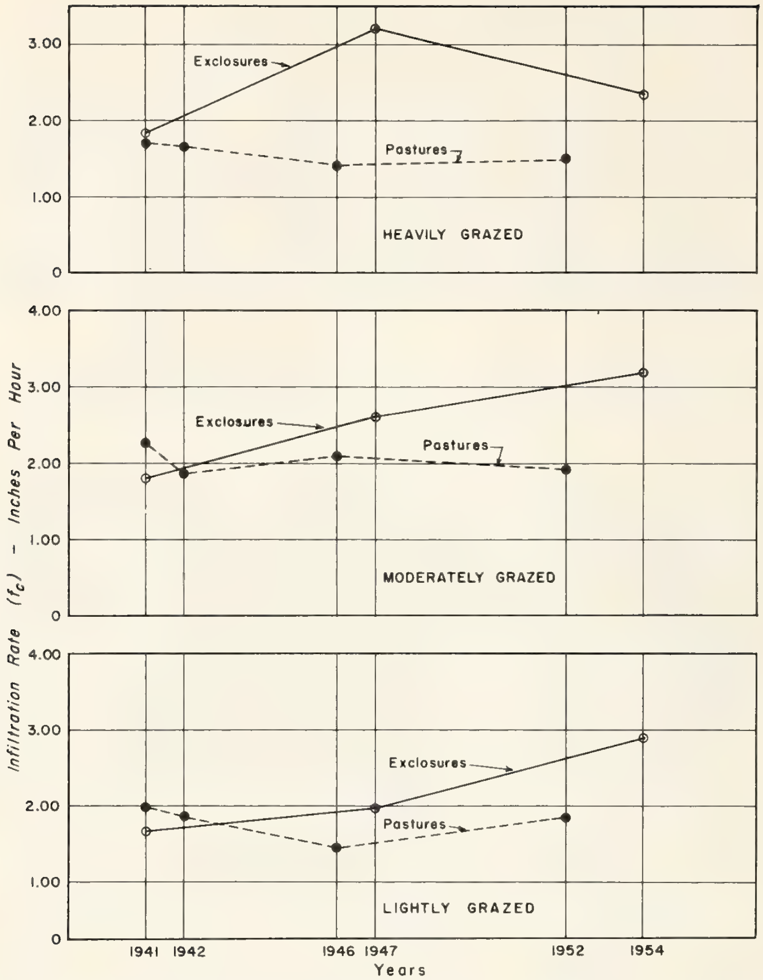

Figure 14.--Comparison of infiltration trends in exclosures with those in pastures for the combined pine-grass and grassland types.

PREDICTING INFILTRATION RATES FROM VEGETATION AND SOIL PROPERTIES IN PINE-GRASS AND GRASSLAND COVER TYPES

Thus far, it has been shown that a number of vegetation and soil properties were related to infiltration. Certain factors were more strongly correlated, while others were related only in certain years.

A prediction formula to have any worth must utilize factors that not only affect the process of infiltration, but do so rather strongly. Such factors should be associated with infiltration, regardless of the season, year, cover type, or other conditions. In this study, it was found that the air-dry weight of dead organic material expressed in grams per plot and the percent of noncapillary space in the upper layers of surface soil exerted an appreciable effect on infiltration.

This is illustrated by the 1946 data consisting of 54 plots in the three cover types (see table 2). When dead organic material in grams per plot (X_1) and the minimum percent of noncapillary pore space (by 1-inch layers) in the surface 3 inches of soil (X_2) are related to f_c infiltration (Y), the multiple correlation coefficient is 0.745, highly significant.

The regression equation developed for the 54 observations was:

$$Y = 0.0026 X_1 + 0.038 X_2 + 0.362$$

with a standard error of estimate of $\pm$ 0.75 inch per hour. These two factors accounted for 55 percent of the variation between infiltrometer plots.

In order to develop and test a formula, it is necessary to have an adequate number of observations. Dead organic material in grams per plot was obtained in all years except 1942, so a large sample was available. Noncapillary pore space measurements were taken in three pastures in 1946, six pastures in 1952, and both inside and outside exclosures in 1954. However, methods employed for determining soil porosity differed by years and the same soil layers were not sampled each year. In order to utilize all soil pore space measurements the 1946 data for the 0-1 and 1-2 inch depths were combined. This gave comparable noncapillary pore space, for the 3 years, that could be used to develop a prediction formula. In so doing, some sacrifice in the accuracy of the prediction resulted, since measurements of minimum noncapillary pore space were not available for 1952 and 1954.

Since infiltration rates under pine-litter were always high, there is no need for estimating these rates for watershed evaluation purposes. Thus, infiltration rates obtained on the two cover types, i.e., grassland and pine-grass types that produced most of the herbage and would be most subject to grazing were considered in developing the prediction equation.

Statistical tests were made to determine whether the regressions between infiltration, noncapillary pore space, and dead organic material for pine-grass and grassland were operating in a similar manner. It was found that there were no real differences between individual cover type regressions so the data were pooled.

The following regression equation was developed from the 1946 and 1952 observations:

$$Y = 0.00243 X_1 + 0.0460 X_2 + 0.28$$

where

Y = f_c infiltration rate in inches per hour,
X_1 = grams of dead organic material per plot (2.5 square feet),
X_2 = noncapillary pore volume in percent of total volume.

The standard error of this regression is $\pm$ 0.61 inch per hour with a multiple correlation of 0.602. This prediction formula is not sufficiently accurate for estimating infiltration on individual plots, but there is no need for such a measurement. An average infiltration rate for a given site or area of similar soil-vegetation characteristics is the only useful measurement.

A covariance analysis showed no difference between the regression developed for the combination of the measurements for 1946 and 1952 and the measurements for 1954. These observations were then combined into a single revised formula:

$$Y = 0.00288 X_1 + 0.0374 X_2 + 0.43$$

where

Y = f_c infiltration rate in inches per hour,
X_1 = grams of dead organic material per plot (2.5 square feet),
X_2 = noncapillary pore volume in percent of total volume.

The above formula was very similar to the one developed for the 1946 and 1952 plot data. The multiple correlation was lowered slightly, to 0.595, but the standard error of estimate remained about the same; $\pm$ 0.61 versus $\pm$ 0.62 inch per hour.

Since the infiltration study on the Elk Ridge Allotment (Reid and Love, 1951) of the Roosevelt National Forest, west of Loveland, contained applicable noncapillary pore space and dead organic material as well as infiltration measurements, these data were inserted into the latter equation developed at Manitou. The reliability of this equation for predicting mean infiltration rates on the Elk Ridge Allotment is shown below:

Soil origin	Cover type	Mean f_c with infiltrometer	Probable range of true mean f_c with infiltrometer (1-19 odds)	Estimated mean f_c using dead organic material and noncapillary pores
		- - - (Inches per hour) - - -		
Granite-schist	Grassland	1.81	2.25 to 1.37	1.50
Granite-schist	Pine-grass	2.14	2.97 to 1.31	2.18
Schist	Grassland	1.63	2.14 to 1.12	1.52

Apparently, equally reliable measurements of mean infiltration for each vegetation-soil condition would have been obtained by using noncapillary pore space and dead organic material measurements instead of conducting the more elaborate infiltrometer tests.

The value of the derived prediction formula is apparent when it is realized the predictions were well within accepted experimental errors, even though soils were dissimilar, consisting of alluvial and residual material derived from bedrock varying from granite to schist. Moreoever, data used in developing the equation were obtained at considerable distance from the area providing the test data. Thus, this equation appears to have widespread usefulness. It can be used directly where an approximation of watershed conditions is desired or for delineating critical flood-source areas.

SUMMARY AND CONCLUSIONS

During the years 1941 through 1954, infiltration studies were conducted on six contiguous range pastures at the Manitou Experimental Forest. Other investigations were carried out on the Elk Ridge Allotment of the Roosevelt National Forest during 1950. Both areas are representative of the ponderosa pine-bunchgrass ranges of the Colorado Front Range.

During the course of the investigation, infiltrometer plots were located at random within the three cover types of pine-litter, pine-grass, and grassland. Infiltration was measured through the use of the Rocky Mountain infiltrometer, a portable "rainmaker" by applying rain at the rate of 4.0 to 5.0 inches per hour on a 2.5-square-foot plot for a 50-minute duration. Infiltrometer tests were made on plots prewetted 6 to 24 hours before the final wet run was conducted, except for the years 1952 and 1954, when rainfall was applied on dry soil for 50 minutes followed by tests on wet soil 15 to 22 hours later. Most of the analyses and results presented were based on infiltrometer tests on prewetted soils. However, the same basic relationships between infiltration rates were obtained whether infiltration rates on wet or dry surface soils were used. Information was collected on vegetation and soil properties that might in any way affect or be related to infiltration.

The main purpose of the present study was to isolate and evaluate vegetation and soil influences on infiltration on granitic derived soils of the ponderosa pine-bunchgrass range of the Colorado Front Range. To this end, the conclusions which follow meet this objective:

1. Infiltration varies with cover type on ponderosa pine ranges. These rates, for 1946 and 1952 averaged:

	Inches per hour
Pine-litter	2.37
Pine-grass	1.94
Grassland	1.50

2. Weight of dead organic material and the amount of noncapillary pores in the surface soil were the most important measured factors influencing infiltration rates of granitic alluvium soils occurring in the Manitou pastures.

3. Providing protection from cattle grazing resulted in an increase in infiltration rates from those measured at the start of the experiment in 1941. Rather rapid recovery of infiltration rates was observed on pine-grass, which showed most of the increase taking place in the first 6 years of protection. In the grassland, recovery of infiltration rates continued through 1954, or 13 years after the start of the experiment.

4. Infiltration rates in grassland and pine-grass can be estimated by measuring the quantity of dead organic material and noncapillary pores in the surface soil. In the Manitou pastures, 35 percent of the variation in infiltration rates (Y) between individual infiltrometer plots was accounted for by the two factors, grams of dead organic material per plot (X_1), and percent noncapillary pores (X_2). This regression equation:

$$Y = 0.00288 (X_1) + 0.0374 (X_2) + 0.43$$

best expressed this relationship. The standard error of regression is ± 0.62 inch per hour.

This formula cannot be used for estimating infiltration rates on a plot as small as 2.5 square feet. It is useful for estimating an average infiltration rate for a given site or local area. The developed regression equation is satisfactory for estimating infiltration rates for grassland parks and openings in the ponderosa pine ranges of Colorado.

5. There is a significant relationship between infiltration rates on dry and wet surface soil. The estimated infiltration rate on dry soil (Y) and the infiltration rate on prewetted soils (X) can be expressed as follows:

for pine-litter:	$Y = 0.85X + 0.46$
for pine-grass:	$Y = 0.71X + 0.75$
for grassland:	$Y = 1.00X + 0.41$

Standard errors for the regression equations are $\pm$ 0.36 (pine-litter); $\pm$ 0.45 (pine-grass); and $\pm$ 0.36 (grassland) in inch per hour.

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