THESIS

HYDROLOGIC SIGNIFICANCE OF STAND DENSITY VARIATIONS IN ALBERTA LODGEPOLE PINE (*Pinus contorta* Dougl. (Moench) Voss var. *latifolia* Engelm.) FORESTS

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY Walter William Jeffrey

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ABSTRACT OF THESIS

HYDROLOGIC SIGNIFICANCE OF STAND DENSITY VARIATIONS IN ALBERTA LODGEPOLE PINE (*Pinus contorta* Dougl. (Moench) Voss var. *latifolia* Engelm.) FORESTS

With twin objectives of (1) determining whether any hydrologic effect of thinning persisted 25 years after implementation, and (2) examining the hydrologic significance (if any) of variations in stand density, studies of snow accumulation, canopy interception of rainfall, and soil moisture, were undertaken in natural and previously thinned stands of lodgepole pine in west central Alberta. Secondary objectives dealt with precipitation redistribution within forest stands, the utility of trough gauges in throughfall estimation, and sample numbers required in soil moisture sampling. Snowpack was ephemeral, and no definitive results on snow accumulation were obtained.

There was no evidence that thinning, after 20 years, increased throughfall. Two natural stands with identical basal areas, but differing widely in stem numbers and mean DBH, had significantly different net precipitation. In explaining these differences, a number of crown variables were tested. Canopy density appeared most helpful. Stemflow was negligible.

None of three plots showed any greater or lesser variability in throughfall. Throughfall was greater at the crown perimeter than at other positions beneath crowns. In storms < 0.50 inches, throughfall beneath canopy gaps was greater than at the crown perimeter. In storms > 0.50 inches, this was reversed. Throughfall, as a function of distance from tree stems, was approximately 85 percent randomly distributed.

Trough gauges tended to undercatch. The relationship of mean throughfall (standard gauge) and mean throughfall (trough gauge) was very precise, however.

Highly significant differences in plot soil moisture contents were found, but differences in soil moisture change were not significant. Soil moisture change was concentrated in the surface soil layers. Little change took place at depths greater than eight feet, in spite of water being available there. No significant differences in evapotranspiration were found, no effect of thinning remaining after 25 years. Mean daily evapotranspiration rate in July to September inclusive, 1966 was 0.09 inches water.

Number of samples required to yield a precision of estimate of one percent soil moisture by volume was calculated. For soil moisture content, 40 samples were required. For soil moisture change, at least eight samples appeared necessary. To estimate total soil moisture change in the whole instrumented solum, consistently with the same precision required more than eight access tubes. Soil moisture variance was greatest in early season.

Wide variations in stand density do not necessarily signify any difference in ecosystem hydrology. Better measures of stand description for hydrologic purposes are desirable.

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Some data on canopy interception of rainfall were utilized by J. E. Osborne, graduate student, U.B.C. Faculty of Forestry, as part of his coursework program, and he helped in some of the statistical analyses of throughfall. The snow accumulation data are being published by the Department of Forestry and Rural Development, with C. R. Stanton as junior author.

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INTRODUCTION

Research in watershed management is relatively new in Canada. Interest in forest hydrology was late in developing, the outgrowth, no doubt, of a situation in which natural resources seemed for many years to be greater than any human capacity to exploit them, in a country of wide extent and sparse and scattered population.

It was not until 1960 (Jeffrey, 1967) that a program of watershed management research was begun in the Saskatchewan River headwaters, located in south and west central Alberta. The writer was privileged to be associated with this program of research from its beginning at that time, until he moved to his present position in mid 1966.

This research program, called the East Slopes (Alberta) Watershed Research Program, used as its basic plan a problem analysis carried out in 1961 (Jeffrey, 1961b). This plan foresaw the establishment of a number of experimental watersheds, in which cover manipulation experiments would be carried out, after an adequate base of knowledge had been built up through companion studies (Jeffrey, 1964b).

These experimental watersheds in course of time were set up and have been described elsewhere (Jeffrey, 1965a).

From the beginning, it was recognized that research dealing with lodgepole pine (*Pinus contorta* Dougl. (Moench) Voss var. *latifolia* Engelm.) forests would assume a pre-eminent position in the program of study. Lodgepole pine occupies large surfaces in Alberta, and is a major commercial species there. Its utilization for wood products has been inhibited by its characteristically rather low mean diameter. Recently, however, pulp mills have begun to be established in Alberta, and while this development, at the time the watershed research program was begun, was confined to the northern foothills in the Athabaska River drainage, it was considered inevitable that eventually pulp mill development would extend to the headwaters of the Saskatchewan River, where the major tree species to be utilized would be lodgepole pine. This prognosis has since been vindicated by plans to develop a pulp mill in the North Saskatchewan River foothills.

These economic considerations lent impetus and urgency to studies of the hydrology of lodgepole pine forests. An experimental watershed is, at time of writing, in process of instrumentation, following a difficult period of examining potential candidate basins (Jeffrey, 1965a), none of which for a time appeared to be suitable, a somewhat disconcerting situation which delayed development of a basin for more than two years.

Contemporaneous with the selection of a basin, the studies reported in this dissertation were begun. The first data collections were made in 1963.

While it was recognized that the widespread cutting of pulpwood which would accompany pulpmill development would require an eventual concentration of research into (1) maintenance of water quality after logging, and (2) improvement of water yield through manipulation of forest cover, other considerations at the time of study initiation in 1963 dictated an initial focus of attention upon topics somewhat ancillary to these major areas of concern.

Forest managers in Alberta had for some time been casting their eyes upon the dense sapling and pole-size lodgepole pine stands which are abundant in western Alberta, wishing that they could carry out thinning in them to concentrate growth upon fewer stems per acre. Natural stands, largely of fire origin, tend to high stand densities, which result in "stagnation" and poor incremental volumes in terms of merchantability (Smithers, 1962).

In the early 1960s, a means of effecting such thinnings on a modest scale presented itself in the form of a source of inexpensive prison labour, as part of a program of petty offender rehabilitation instituted by the Government of Alberta. In addition, certain supplementary monies became available through increased Federal resource development grants.

Having through these developments obtained a taste of the joys emanating from a more intensive silviculture, it is not unnatural that foresters involved in these management programs began to aspire to a more ambitious thinning program. It was perhaps equally natural that they should have recognized the water-yielding potentialities of the Saskatchewan River headwaters as pertinent to their hopes in this direction. The hydrologic consequences of thinning forest stands quickly became the object of a warm and sustained interest.

At that time, nothing whatsoever was known of the hydrology of lodgepole pine forests in western Alberta. No work of any sort had been done. The immediacy of the questions raised, and the actual implementation of thinning programs, along with the possibility that water yield considerations might come to be cited in partial justification of such programs, indicated an initial need for research into stand density as a parameter in the hydrology of Alberta lodgepole pine forests.

While work done elsewhere gave good reason to believe that partial cutting of lodgepole pine, if a sufficient density reduction were effected, would result in water yield increases immediately following cutting, nothing substantive was known of the durability of such water yield increases, i.e., of the time trends concerned. For this reason, it was accepted as a working hypothesis that sufficiently severe thinning on deep soils would result in reduced interception and evapotranspiration, immediately following cutting. The research capability available was therefore concentrated upon studying the influence of thinning on hydrology beyond the initial period following thinning. It was further considered that if an evaporative loss reduction did not persist for a period of 20 years (or one-fifth of a 100 year rotation) after thinning was carried out, it was of limited economic value. For these reasons, research was confined to stands which had been thinned at least 20 years prior to study initiation. A number of such stands were available in convenient locations of the Alberta Rockies.

It was furthermore recognised that, by initiating study along these lines, it was possible to investigate the rather more basic question of stand density effects *per se*. Though stands had been artificially thinned, full response to thinning had been attained at the time studies were begun. Thus, it was possible to study, not only the long-term effects of thinning, but also the influence of varying stand density.

The parameters chosen for study were (1) snow accumulation, (2) canopy interception of rainfall, and (3) soil moisture, and (inferentially) evapotranspiration.

The objectives central to these studies may be stated as:

(1) to determine the effect of thinning in lodgepole pine forests upon evaporative losses, for time periods extending beyond the period immediately following thinning, and

(2) to investigate the influence of varying stand density upon snow accumulation, canopy interception of rainfall, and soil moisture, in lodgepole pine forests.

Since regional forest hydrology research was just beginning in the area, certain other objectives were incorporated into the study. These are listed below:

(3) to determine required sample numbers for soil moisture sampling using neutron probe equipment, as an aid in further soil moisture studies, and a guide for the instrumentation of experimental watersheds,

(4) to determine whether locally-produced inexpensive trough gauges might usefully be utilized in interception studies to establish approximate rainfall interception values for Alberta forest types.

A fifth objective was added later, in response to outside suggestion. It was:

(5) to evaluate precipitation redistribution at the ground surface in lodgepole pine stands.

In these ways, it was hoped that some insight might be obtained into significant facets of forest hydrology problems in Alberta.

Of these objectives, it may be noted that today, five years after study was begun, no definitive answer has elsewhere been produced for the questions inherent in objectives (1), (2), (3) and (5).

Chapter II

REVIEW OF LITERATURE

In this review of literature only major points of concern will be considered, in keeping with the aim of a concise treatment. Accordingly, only the most important literature items are cited. This thesis, concerning as it does, three major components of forest hydrology, namely snow accumulation, canopy interception of rainfall, and evapotranspiration, embraces a considerable portion of the interest spectrum of watershed management. The literature dealing with the topics listed is voluminous, and any attempt at exhaustive treatment would be foredoomed to failure.

Texts dealing with the older literature are Kittredge (1948) and Colman (1953). More recently, a review was also made by Penman (1963). The Russian literature, which does not always agree with results from other areas, was summarized by Molchanov (1963). By and large, the results of the studies cited by Molchanov (1963), where they disagree with western findings, are somewhat difficult to substantiate and the methods used in study are not always clear (cf. comments by Penman, 1963). This situation is troublesome, and it means that the research work done in the U.S.S.R. is not completely susceptible to objective appraisal. For this reason, intense scrutiny of Molchanov (1963) is not a rewarding exercise. In the interests of brevity, little further reference is made to this body of variable information.

This thesis deals uniquely with lodgepole pine stands in Alberta. A brief look at the silvics of lodgepole pine, to establish a base for further study, is not untoward.

AUTECOLOGY OF LODGEPOLE PINE

The autecology of lodgepole pine was recently reviewed by Fowells (1965) in his monographic treatment "Silvics of forest trees of the United States." The date of the monograph is somewhat misleading, however, the most recent citations for lodgepole pine being for the year 1961.

Lodgepole pine extends from the Yukon and Northwest Territories of Canada, south to northern Mexico. By a coincidence, the writer helped (Jeffrey, 1961a, 1964a) to set its presently accepted northern limit within the Northwest Territories. The species is a common pioneer after burning, having a heliophytic habit and serotinous cones.

The species is characterized by a tendency to overstocking resulting from too-prolific regeneration. Densities of 175,000 stems per acre at age eight years, and of 44,000 stems per acre at age 22 years have been recorded, in Colorado and Montana respectively. This overstocking inevitably results in stagnation of the stands affected. The density of stand greatly affects merchantable stand volume.

Though individuals as old as 600 years, and stands of 400 years, have been encountered, lodgepole pine is generally considered overmature at stand ages of 200 years.

Subsequent to the Fowell (1965) citations, information has been contributed by Ackerman (1962a, b), Armit (1966), Dahms (1963), Day and Duffy (1963), Lotan (1964), Prochnau (1963) and Tackle (1964).

ALBERTA LODGEPOLE PINE

The status of known information concerning lodgepole pine in Alberta was reviewed by Smithers (1962), who dealt with the literature up to 1960. Since then, further information was presented by Ackerman (1962a, b) and Day and Duffy (1963).

Horton (1956) recognised four phytogeographic divisions within the lodgepole pine forests of the province. The Rocky Mountains lodgepole pine forest lies in the subalpine division of Horton's (1956) classification.

At the Kananaskis Forest Experiment Station, where this dissertation research was undertaken, the average dates (10 year average, 1938 to 1948) for different phenological events are as follows:

(1) Pollen dissemination begins	June 14
(2) Pollen dissemination ends	July 1
(3) Buds bursting	May 10
(4) Leaves fully flushed	June 13
(5) Diameter growth begins	May 15
(6) Diameter growth ends	July 24
(7) Height growth begins	May 2
(8) Height growth ends	August 13

This information comes from Horton (1954). From this source it would appear that physiological activity usually begins at the Kananaskis Forest Experiment Station in late-April, but may commence as early as mid-April.

Smithers (1962) described crown shape of Alberta lodgepole pine as being dependent on density. High density stands (10,000 stems per acre, at age 90 years) had sparsely tufted crowns. Medium density (1,000 to 3,000 stems per acre) has long narrow crowns, while low density stands (100 to 600 stems per acre) had triangular crowns. He also stated the crowns of subalpine lodgepole pine to be typically long and narrow with fine, upswept branches.

Horton (1957) examined lodgepole pine root systems in detail. He found a great deal of variability, but concluded that tap-rooting was prevalent, that maximum lateral root extension occurred fairly early in stand development, and that mature trees had heart-shaped root systems which resulted from the development of sinkers from the base of the lateral roots. He found roots penetrating to a maximum depth of 12 feet.

Because of the effect of high stand densities upon height and diameter growth and upon stand volumes, it is difficult to generalize about lodgepole pine stand mensurational characteristics in subalpine Alberta. Smithers (1957) stated that maximum basal area of fully stocked stands was attained at age 60 years. For dry sites, maximum basal area per acre was assessed as about 90 feet^2, for moist sites about 200 feet^2. However, the conclusion of basal area culmination at the early age of 60 years was dependent upon the methodology employed in the study, and cannot be regarded as proven.

Smithers (1956), working with 90 year old stands, concluded that basal area was not dependent upon stocking for ranges of 800 to 3,000 stems per acre. This was extended by another study to a range of 230 to 5,000 stems per acre (Smithers, 1962).

No yield table data for lodgepole pine stands in subalpine Alberta are available.

STAND DENSITY AND SNOW ACCUMULATION

The interrelationships of stand density and snow accumulation have received considerable attention in forest hydrology, an attention which has been made the more difficult by the problems attendant upon finding a reliable base against which to judge snow accumulation within forest stands.

In study of net rainfall beneath stands it is possible to measure rainfall in nearby clearings. Though this measurement has been the object of criticism, it has achieved a reasonable level of acceptability, and while subject to error, it is usually judged to be sufficiently closely approximate to precipitation above the stand to be an acceptable measure.

In the case of snow accumulation, however, openings in the forest "overcatch" in terms of snow accumulation, and cannot be used as a base of comparison. The source of this overcatch is not fully known. In a lucid exposition of the alternative possibilities, Hoover (1962), in a statement which has been quoted verbatim by both Jeffrey (1965b) and Miller (1966), has asked:

1. Is the excess in the opening a result of evaporation of snow from tree crowns?
2. Was intercepted snow merely blown, or shaken off, into the opening?
3. Did the wind eddies due to the surrounding tree crowns cause excess snow deposition in the opening?

Whatever the answer, the phenomenon necessitates that snow accumulation within stands can be studied only as index values affording comparison between stand types and densities in relative terms only, and not as absolute quantities, from which snowfall interception may be deduced.

In addition to the original paper of Hoover (1962), recent reviews of snow accumulation in forest stands have been made by Jeffrey (1965b) and, in a most comprehensive treatment, by Miller (1966).

Miller (1966) points out the difficulties inherent in generalizations concerning snow accumulation - forest type relationships. Since the topic is so complex, and since the experimental results reported in this thesis, as will be seen later, were not sufficient to warrant detailed treatment of this topic, no such review will be undertaken here.

Studies of snow accumulation in lodgepole pine stands have been reported by Niederhof and Dunford (1942), Wilm and Dunford (1948), Goodell (1952), and Miner and Trappe (1957). These authors reported greater accumulation of snow in small openings than beneath the forest stand itself.

Wilm and Dunford (1948) and Goodell (1952) concluded that cutting treatments which reduced basal area per acre resulted in increased snow accumulation.

STAND DENSITY AND CANOPY INTERCEPTION OF RAINFALL

Recent comprehensive reviews of canopy interception of rainfall have been made by Penman (1963) and Zinke (1967). Penman (1963) concentrated his attention upon extra-North American experience, while Zinke (1967), uniquely considered work in the United States. Together, these two papers give excellent overall coverage of work done in rainfall interception and document the great amount of work which has been done on this topic.

Present consideration deals with two central topics, (1) canopy interception - stand density interactions, and (2) canopy interception of rainfall in lodgepole pine stands.

Zinke (1967) summarized the results of his review of rainfall interception work in North America. The first 16 points of his summary are pertinent to consideration here and are quoted verbatim below:

> To summarize the results of the American interception studies presented here, one can hardly do better than to refer to the summaries made by Horton (1919), and later Kittredge (1948). The following are still the main points:
>
> 1. Interception represents a loss of precipitation which would otherwise reach the soil.
> 2. This loss through the evaporation process can be subdivided into the loss from interception storage and evaporation during the storm.
> 3. Interception loss can for most practical purposes be expressed as a function of precipitation per storm.
> 4. The interception storage for trees varies from 0.02 to 0.36 in.
> 5. Interception storage is greater for trees in forests than for isolated trees.
> 6. Interception evaporative loss during storms is less in forests than for isolated trees.
> 7. Percent interception loss is greater for storms with small amounts of precipitation, ranging from 100 percent to about 25 percent as an average constant rate for most trees.
> 8. Most hardwood trees have a similar interception loss during the growing season.
> 9. Stemflow is a relatively small percentage of from 1 to 5 percent of total precipitation, being zero in small storms.
> 10. The interception loss from needle-leaved trees is greater than from broad-leaved trees, both as regards interception storage and evaporation during rain.
>
> These conclusions by Horton (1919) have been largely borne out by the results reviewed in this paper. The American research has, since Horton's study, gone on to establish information on snow interception, throughfall variation in the forest, interception amounts in various other forest types in North America, and to refine and question some of the aspects of the interception process.

Thus Kittredge (1948) was able to add a few more findings to those of Horton's in his review of the subject in 1948:

11. Interception losses may be large in regions of high evaporation and are usually low in regions where they are compensated by fog or cloud drip.
12. Interception losses vary with forest conditions; well stocked stands intercept more than understocked; stands at ages between canopy closure and culmination of the current annual increment intercept more than those younger or older.
13. Interception losses vary with species and forest types because of thickness and density of foliage and crowns. Hence tolerant species intercept more than intolerant, climax more than pre-climax.

Additional conclusions have been arrived at in the review by Helvey and Patric (1965):

14. Throughfall measurements in hardwood stands are very similar over a wide range of canopy conditions.
15. Canopy interception loss in mature hardwood forests can be estimated from throughfall measurements alone for all practical purposes.
16. Moisture loss if considered as an interception loss is highly variable because of variations in water-storage capacity of the litter.

In the above summary, attention is directed particularly to points 12 and 13, which deal specifically with canopy density effects.

In presentations contemporaneous with that of Zinke (1967), Leyton, Reynolds and Thompson (1967), Delfs (1967) and Rogerson (1967) considered the question of stand density and rainfall interception.

Leyton _et al_. (1967), working with Norway spruce subjected to stand thinning practices, concluded:

> Overall, our results to date indicate reduction in interception loss due to thinning of the order of 10 percent, substantially less than the percentage reduction in basal area (approximately 20 percent).

Delfs (1967), dealing again with Norway spruce, came to a somewhat different conclusion, to-wit:

> The effect of spacing on interception determines the possibility of influencing water discharge by thinnings and group fellings. Measurements in the Harz area show clearly that a light opening of the canopy does not reduce interception. For example, the interception was 30 percent in a dense spruce pole stand, 31 percent in a light-thinned stand, and 22 percent in a small opening. This result for the opening was unexpected but can be explained by the action of wind which prevents all of the rainfall from reaching the ground of the opening. A large proportion of the rain is driven across the opening and intercepted by the crowns at the windward edge. Even an opening of 30m diameter, equal to the tree height, in a mature spruce stand had a mean annual interception of 20 percent. The long tree-crowns at the wind-exposed side of the opening received a larger amount of rain and consequently had relatively lower interception values. Openings must be at least twice the tree-length in diameter if the whole amount of rain should reach the ground in part of the area.

The results obtained by Rogerson (1967) were the most definitive of the three considerations quoted, and utilized a somewhat larger experiment and a more comprehensive statistical treatment. Working with loblolly pine, artificially thinned to a number of preselected stand density levels, Rogerson (1967) tested the relationship of a number of stand and storm variables to throughfall.

He concluded that estimates of throughfall based on rainfall and basal area were most practical. Throughfall was related to rainfall and to the product of rainfall and basal area. This relationship accounted for more of the variation than any other of 511 equations tested.

For the mean storm size of 0.65 inches, throughfall in stands of 40 feet^2 basal area was estimated to be 0.594 inches, while that for stands of 190 feet^2 basal area was 0.499 inches.

Roberson (1967) concluded:

> Throughfall estimates...correspond very closely with estimates other investigators have reported for specific

levels of basal area in shortleaf pine (Boggess, 1956) and red pine (Rogerson, 1960). This suggests that the equation may be applicable to other species than loblolly, and possibly to other areas.

The equation referred to was:

$$Y = 0.980X_1 - 0.00097X_{10} - 0.0184 \text{ ---------------------(1)}$$

where Y = throughfall

X_1 = rainfall (gross precipitation)

X_{10} = basal area x rainfall (X_1)

The impression derived from these results (Leyton et al., 1967; Delfs, 1967; Rogerson, 1967) is one of variation in throughfall and interception with stand characteristics, including stand density, with the suggestion that thinning reduces rainfall interception, with this reduction being more or less proportional to the residual basal area after thinning.

Rainfall interception in lodgepole pine stands has previously been studied by Niederhof and Wilm (1943) and Goodell (1952). These results are cited by Zinke (1967).

Goodell (1952) thinned second growth lodgepole pine stands having a basal area of 90 feet^2 per acre to post-thinning levels of 43 feet^2 and 36 feet^2. He concluded that an increase in throughfall of summer rainfall of 13.3 percent and 17.7 percent resulted from these treatments in the two years immediately following thinning being undertaken.

Niederhof and Wilm (1943) studied mature lodgepole pine stands in Colorado, the same venue as Goodell (1952). Niederhof and Wilm (1943) did not cite basal area levels for their study. However, these were provided by Kittredge (1948).

Stands having basal areas of 159 feet per acre were thinned to different levels of basal area, varying from 96 feet^2 to 40 feet^2 per acre. The study concluded that net precipitation was materially increased by cutting. Kittredge (1948) interpreted results of the study as follows:

> Both the interception storage and the evaporation factor decrease with the decrease in density of the residual stand although not in direct proportion to that decrease. (cf. Leyton *et al.*, 1967)

The regression equation derived by Niederhof and Wilm (1943) for a mature lodgepole pine stand of 159 feet^2 basal area per acre was:

$$Y = 0.8046X - 0.0290 \qquad (2)$$

where Y = net precipitation

X = gross precipitation.

For a stand of 96 feet^2 basal area per acre, the regression was:

$$Y = 0.8677X - 0.0149 \qquad (3)$$

Two stands, each with 65 feet^2 basal area per acre yielded regressions of:

$$Y = 0.9055X - 0.0131 \qquad (4)$$

and $$Y = 0.8933X - 0.0074 \qquad (5)$$

Equations (4) and (5), while similar, are not identical, and suggest that basal area is not an ideal measure of stand variability.

All of the studies quoted (Leyton *et al.*, 1967; Delfs, 1967; Rogerson, 1967; Niederhof and Wilm, 1943; Goodell, 1952) dealt with stands immediately following application of a thinning procedure. It would be expected that these results would be modified by canopy recovery following thinning. However, no research appears to have been carried out into the duration of the effects of thinning upon throughfall in forest stands, or of relating this to the severity of the original thinning.

Basal area has commonly been used to characterize stand density variations. The majority opinion of the literature appears to hold that basal area changes and variations are related to variation in throughfall and rainfall interception in forest stands having constant species composition.

STAND DENSITY, EVAPOTRANSPIRATION AND SOIL MOISTURE

In common with the topic of canopy interception of rainfall, the question of evapotranspiration in forests has been the subject of a voluminous literature. Only the interactions of stand density with evapotranspiration will be considered here.

Fortunately, a recent review by Douglass (1967) is available. One can do no better than to quote Douglass' (1967) consideration of "effects of varying stand density" in its entirety. Only the figures referred to by Douglass (1967) have been omitted:

> Vegetative density, by modifying the area of transpiring surface, net radiation, interception, wind patterns and turbulence, and root distribution, affects evapotranspiration rates from forest stands (my italics). Bay and Boelter (1963), Bethlahmy (1962), Della-Bianca and Dils (1960), Douglass (1960), McClurkin (1961), Moyle and Zahner (1954), Tarrant (1957), Zahner (1958), and Zahner and Whitmore (1960) studied effects of basal area reductions by logging, thinning, or other silvicultural treatments. In many cases, failure to sample the entire root depth and inability to account for drainage loss prevent direct comparison of evapotranspiration rates, but a tendency is clear - reducing stand density reduces evapotranspiration, and the greater the density reduction, the greater the evapotranspiration reduction (my italics). Under some climatic regimens, small density reductions may not be great enough to affect seasonal

or annual evapotranspiration savings. Zahner (1955, 1958) and Bay and Boelter (1963) observed that small density reduction on study plots in Arkansas and northern Minnesota was not severe enough to affect seasonal moisture deficits even though treatments changed evapotranspiration rates.

Evapotranspiration savings obtained by reducing stand density can be attributed partly to changes in root distribution and interception losses. Roots of fully stocked stands are approximately evenly distributed horizontally (Coile, 1937; Patric et al., 1965). When trees or groups of trees are removed, the uniform pattern of rooting is interrupted; roots are concentrated near trees and few roots occur in openings. Figure 3 illustrates an extreme example of variation in moisture distribution in the surface 8 ft. of soil beneath a loblolly pine plantation thinned from a 6-ft. by 6-ft. to an 18-by 18-ft. spacing. Rainfall and moisture changes during the 1959 growing season (Fig. 4) show continuing growing-season moisture accretion to, and some drainage through, the 4- to 8 ft. profile of the thinned stand. The large storms of May, July and August-September barely penetrated to 5 ft. in the adjacent unthinned stand, and water did not drain from the profile. Zahner and Whitmore (1960) found that a similar treatment in a 9-year-old loblolly plantation (thinning to a spacing of approximately 21 by 21 ft.) produced an unequal distribution of roots in the top 2 ft. of soil which lasted 5 years.

Effects of reducing stand densities on net evapotranspiration savings on a monthly, seasonal, and annual basis are best shown in unit watershed studies where deep seepage or bypass at the weir do not occur or are constant during calibration and treatment periods. In such studies, Reinhart et al. (1963) found that a commercial clearcut and a diameter limit cut which removed 86 and 59 percent, respectively, of the board-foot volume of hardwood stands in mountains of West Virginia resulted in increased growing season streamflow (evapotranspiration savings), but had no significant effect on dormant season flow. An extensive selection cut (removing 31 percent of board-foot volume) significantly increased growing-season flow (reduced evapotranspiration) but did not increase annual flow significantly. An intensive selection (removing 20 percent of board-foot volume) did not significantly alter seasonal or annual streamflow. Goodell (1958) also reports streamflow increases from a 40 percent reduction in basal area by timber cuttings in Colorado, but Rich (1959) found that removing 36 percent of the basal area of a mixed conifer stand in Arizona by logging and timber stand improvement work did not increase streamflow significantly. Hewlett and Hibbert (1961) report that a cove hardwood and a riparian cut in the Southern Appalachians did not increase annual flow, whereas other cuttings that removed 22 to 100 percent of stand

> basal area significantly increased annual water yield. Much of the increase came during the growing season, and the increases obtained by cutting northfacing watersheds were roughly related to the basal area removed. Large basal area reductions gave yield increases all through the year, but yield increases from small basal area reductions tended to be restricted to the season during which evapotranspiration savings actually occurred.
>
> The accuracy of the equation for predicting streamflow response limits the accuracy of estimating evapotranspiration. In some cases, density reductions may produce evapotranspiration reductions which are too small to detect. Also, timing of the evapotranspiration reduction cannot be judged from water yield data because of the lag between rainfall occurrence and reappearance as streamflow. In the dormant season, for example, an increase in flow may originate from either a dormant-season evapotranspiration reduction or a growing-season evapotranspiration reduction which only appears in the dormant season because of this lag response.

In relation to the extensive quotation above, two points are worth noting. Firstly, virtually no consideration of time trends is made. In other words, the results refer to conditions immediately following logging and do not take into account vegetative response to thinning.

Secondly, the basal area reductions referred to do not sufficiently discriminate between removal of basal area by discrete clearcut blocks, and reduction of density by selective cutting within stands. Obviously, no equivalence need necessarily be expected between removal of the same amount of basal area by these two methods.

Douglass (1967) in his summary concluded:

> Stand density and reductions in stand density cause evapotranspiration to vary. Experience has shown that when less than 20 percent of the basal area of well-stocked forest stands is cut, usually neither growing nor dormant season evapotranspiration...is changed significantly.

Noteworthy in the above statement is the evident equating, in the first sentence, of "stand density" and "reductions in stand density." While it may seem reasonable, at least immediately following a cutting, to expect decreased evapotranspiration following a "reduction in stand density" it is by no means so clear that differences in stand density _per se_ would necessarily show a similar trend.

In addition to the review by Douglass (1967), a review of forest treatment effects on water yield has been made by Hibbert (1967). This latter paper, while excellent, adds little to the conclusions already cited, covering many of the same studies.

It is, in conclusion, worthwhile to cite certain items of the conclusions derived by Goodell (1967), to-wit:

> With partial removal of forest, the pattern of removal should be of significance even though some empirical studies have not found this to be so (Hewlett and Hibbert, 1961; Goodell, 1959). Other studies do offer qualitative confirmation (Anderson and Gleason, 1960; Reinhart _et al._, 1963). Partial cutting to produce a spatially uniform stand should be less effective than one leaving an equivalent residual volume spatially variable in density. The uniform stand should give maximum interception of both water and radiant energy and maximum flow of soil water to transpiring surfaces. Stand reduction by partial clearing should minimize each of these parameters. The differences to be expected in soil moisture and snowpack evaporation are not evident; they would probably be small. With respect to transpiration reduction, the dimensions of clearing should be such that early root invasion from boundary trees is not a major factor. Clearings that are too small in relation to tree height or potential root spread may have little, if any, effect on transpiration losses; only interception losses may be significantly influenced. Neither the canopy absorption of radiation nor the availability of soil water to plant surfaces may be affected. Similar results may follow a uniform thinning that leaves trees too close together. Aspect and slope of terrain and sun elevation will influence these relationships.

and later:

> Forest cutting must be severe enough with respect to size of clearing in partial clearcutting or space between stems in selection cutting so that persistent discontinuities are produced in the canopy surface and for the root network.

Soil moisture studies in lodgepole pine forests have been reported by Wilm and Dunford (1948) and by Goodell (1952).

Wilm and Dunford (1948) found that the effect of partial cutting on autumn soil moisture deficits was relatively small, but greater in wet years than in dry years.

Goodell (1952) concluded also that his thinning treatments did not affect soil moisture levels. He attributed this lack of difference to interception of precipitation by logging slash, resulting in equal net precipitation reaching the soil in thinned and unthinned stands.

Both Wilm and Dunford (1948) and Goodell (1952) concluded from their rather comprehensive studies that partial cutting in lodgepole pine stands in Colorado should result in increased water yield. Wilm and Dunford (1948) also considered that such water yield increases should be maintained for considerable periods after cutting.

Molchanov (1963), in his review of experience in forest hydrology in the U.S.S.R., stated that improvement cutting of stands resulted in decreased evapotranspiration, provided stands were cleared to a "closeness of 0.8 - 0.7" (term not defined). However, when stands were thinned to a "closeness of 0.5" or less, development of herbaceous vegetation resulted in an upward trend in moisture consumption. He presented data indicating reduced evapotranspiration in thinned stands for seven years after thinning took place. In another study, evapotranspiration reductions of 70 mm (12.3 percent of control evapotranspiration) were indicated for a period of four years following improvement cutting. In individual years, evapotranspiration savings amounted to as much as 150 mm.

SUMMARY

This review of literature has elucidated the following salient points:

(1) Lodgepole pine demonstrates a considerable range in stand density. Dense stands are very common, particularly following fire. High stand density often results in "stagnation."

(2) In Alberta, maximum basal area per acre in lodgepole pine stands is 200 feet^2 on moist sites and 90 feet^2 on dry sites. Basal area is not dependent on stocking for ranges of 230 to 5,000 stems per acre.

(3) Lodgepole pine root systems may extend to a depth of 12 feet.

(4) At the Kananaskis Forest Experiment Station, physiological activity of lodgepole pine usually begins in late-April.

(5) Studies carried out elsewhere in lodgepole pine stands indicate that selective cutting results in increased snow accumulation.

(6) More snow accumulates in small openings in lodgepole pine stands, than beneath the canopy itself. This is in accord with results obtained in other forest types.

(7) Previously published values for rainfall interception storage range from 0.02 to 0.36 inches water, for North American forest types.

(8) Stand density affects canopy interception of rainfall, well stocked stands intercepting more rainfall. The thickness and density of foliage and crowns are considered to be primary variables.

(9) Thinning reduces rainfall interception though not in direct proportion to the basal area removed.

(10) There appears to be a relationship between specific levels of basal area and the amount of throughfall, at least in southern pine stands.

(11) Storm size and basal area have been shown to account for most of the variation in throughfall in tests made with loblolly pine.

(12) Beneath small gaps in the canopy throughfall is less than gross precipitation.

(13) Interception studies in lodgepole pine forests indicate that thinning increases throughfall.

(14) Basal area of residual stands following thinning has been used as a measure of stand density for throughfall comparison purposes in lodgepole pine. Studies have shown decreasing throughfall with increasing basal area.

(15) Vegetative density affects evapotranspiration rates from forest stands, by modifying transpiring surface area, net radiation, interception, wind patterns and turbulence, and root distribution.

(16) Reducing stand density reduces evapotranspiration, the greater the density reduction, the greater the evapotranspiration reduction.

(17) The literature is sometimes vague concerning the effects of stand density reductions and the influence of stand density levels *per se*.

(18) Partial cutting may logically be expected to be less effective in reducing evapotranspiration than removal of an identical basal area in block clearcuttings.

(19) Partial cutting to be effective must produce persistent discontinuities in the canopy surface and the root network.

(20) Studies of partial cutting in lodgepole pine forests have shown that autumn soil moisture deficits were not greatly affected. The effects, however, were greater in wet than in dry years.

(21) Previous research concluded that partial cutting in lodgepole pine stands increased water yield.

(22) The most comprehensive research done in lodgepole pine partial cutting also concluded that water yield increases from such cutting should be maintained for considerable periods after cutting.

(23) Other than some work done in the U.S.S.R., there has been no study of hydrologic time trends following partial cutting. The Russian work showed evapotranspiration savings persisting for at least seven years, the duration of the study.

Chapter III

METHODS OF STUDY

GENERAL DESCRIPTION OF STUDY AREA

Location

The studies reported herein were carried out on the Kananaskis Forest Experiment Station, which is located west-southwest of Calgary, Alberta at a distance of approximately 50 miles from that city. The experiment station is operated by the Department of Forestry and Rural Development of the Government of Canada as a centre for forest research in the subalpine region (Rowe, 1959). It is accordingly a small enclave of federal land in the midst of the provincially-owned and managed forest lands of Alberta.

The location of the experiment station is shown in Figure 1. Station headquarters are located at latitude 51° 02', longitude 115° 03', elevation 4560 feet M.S.L.

Climate

Climatic records have been kept at the Kananaskis Forest Experiment Station headquarters since 1939. These records have been summarized by McKay, Curry and Mann (1963). Data for precipitation, temperature, wind, and sunshine are available. Summaries of selected data are shown in Table 1.

The climate of the Kananaskis Forest Experiment Station may be characterized as that of a broad, intermountain valley. Certainly it

Figure 1. Topographic map showing the geographical location of the Kananaskis Forest Experiment Station.

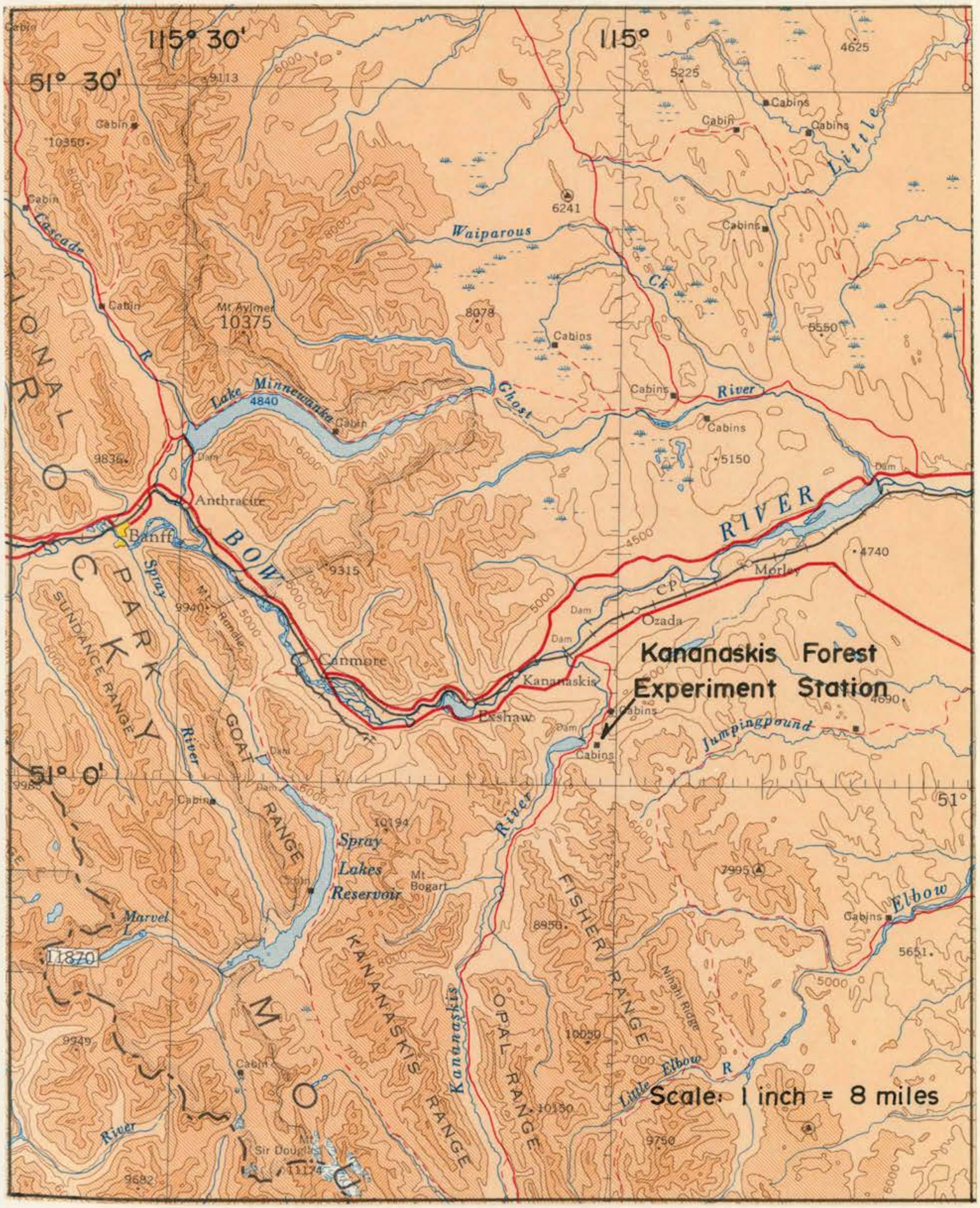

115° 30'
115°
51° 30'
51° 0'
51°
Kananaskis Forest
Experiment Station
Scale: 1 inch = 8 miles
BOW RIVER
Lake Minnewanka
4840
Waiparous
Ghost River
Cascade R
Mt Aylmer
10375
Banff
Anthracite
Canmore
Kananaskis
Exshaw
Ozada
Morley
Jumpingpound
Spray River
Spray Lakes Reservoir
Mt Bogart
GOAT RANGE
SUNDANCE RANGE
KANANASKIS RANGE
OPAL RANGE
FISHER RANGE
Kananaskis River
Elbow
Little Elbow R
Marvel L
Sir Douglas
PARK
Cabins
6241
8078
9315
10194
7995
5150
4740
5550
4625
5225
9113
10350
9836
9940
8950
10050
10150
9750
9949
9682
11870
11174
5651
4690

Table 1. Climatic data for the Kananaskis Forest Experiment Station Headquarters

	MONTH													
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	n
MEAN PRECIPITATION IN INCHES														
RAIN	0.0	0.0	0.0	0.4	2.3	4.2	2.6	2.8	2.0	0.5	0.1	0.0	14.9	21
SNOW	0.9	1.5	1.6	1.9	0.8	0.2	0.0	0.0	0.1	1.0	1.0	1.0	10.0	21
BOTH	0.9	1.5	1.6	2.3	3.1	4.4	2.6	2.9	2.1	1.5	1.1	1.0	25.2	21
DAYS WITH 0.01 PRECIPITATION	6	8	8	8	4	14	10	12	9	7	6	5	97	21
DAYS WITH 0.1 SNOW	6	8	8	4	0	0	0		1	4	5	5	49	
HEAVIEST 24-HR PRECIPITATION IN INCHES														
2.3-YEAR RETURN PERIOD	0.4	0.5	0.5	0.8	1.1	1.3	0.9	1.1	0.6	0.6	0.4	0.4	1.8	21
10-YEAR RETURN PERIOD	0.7	0.9	0.9	1.5	1.8	2.3	1.8	2.1	1.1	1.0	0.9	0.8	2.5	21
30-YEAR RETURN PERIOD	0.9	1.2	1.2	2.0	2.3	3.0	3.3	2.9	1.4	1.3	1.1	1.0	3.1	21
HEAVIEST	0.8	1.3	1.8	1.9	2.1	2.9	1.8	2.6	2.2	1.2	1.0	1.3	2.9	21
YEAR	43	48	45	40	46	51	44	41	40	51	42	56	51	

n = number of years of record

continued

Table 1. (Continued) Climatic data for the Kananaskis Forest Experiment Station Headquarters

	MONTH													
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	n
MONTH-END SNOW DEPTH IN INCHES														
2.3-YEAR RETURN PERIOD	0	0	0											21
10-YEAR RETURN PERIOD	3	12	12											21
30-YEAR RETURN PERIOD	11	14	14											21
HEAVIEST	6	15	18	2.0	0	-	0	0	0	5.0	3.0	8.0		21
YEAR	51	51	46	60	-	-	-	-	-	39	50	46		
MEAN TEMPERATURE IN DEGREES F.														
DAILY	15	19	24	36	46	51	58	56	49	41	27	23	37	21
DAILY MAXIMUM	27	31	36	47	58	63	72	70	62	53	38	34	49	21
DAILY MINIMUM	4	6	13	24	32	39	43	42	36	29	17	12	25	21
MONTHLY MAXIMUM	48	50	54	65	75	78	86	84	79	70	58	53		21
MONTHLY MINIMUM	-26	-25	-17	5	20	29	33	32	24	11	9	-15		21
EXTREME TEMPERATURES IN DEGREES F.														
MAXIMUM	58	60	64	75	82	88	93	92	85	80	66	61	93	21
YEAR	42	54	60	52	58	41	41	40	50	43	41	39	41	
MINIMUM	-50	-42	-41	-24	-7	23	23	29	15	-8	-32	-36	-50	21
YEAR	50	47	51	54	54	42	50	57	41	51	55	56	60	

n = number of years of record

continued

Table 1. (Continued) Climatic data for the Kananaskis Forest Experiment Station Headquarters

WIND	MONTH													
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR	n
MEAN SPEED mph	6	6	6	6	6	6	5	5	6	7	7	8	6	11
MEAN MAXIMUM ONE-HOUR WIND	34	27	26	25	21	20	19	18	22	30	32	31	25	11
MAXIMUM ONE-HOUR WIND	43	32	31	35	28	28	28	25	35	41	44	39	44	11
YEAR	59	57	56	60	57	56	47	58	59	39	39	57	39	11
DIRECTION	W	SW	SW	W	W	W	S	W	SW	W	SW	W		11
PEAK GUST mph														
PER CENT FREQUENCY FROM NOTED DIRECTIONS (May to Oct. 1939 - 1954)														
NORTH	10	11	15	13	9	8	7	8	7	5	6	6	8	11
NORTHEAST	2	8	5	3	8	10	9	10	9	7	4	4	7	11
EAST	7	6	6	7	11	12	11	11	11	6	4	4	7	11
SOUTHEAST	1	2	5	5	4	5	5	5	2	1	4	5	4	11
SOUTH	6	8	11	8	6	8	12	13	11	5	5	7	9	11
SOUTHWEST	31	25	26	25	17	26	29	27	26	21	39	37	31	11
WEST	27	27	14	25	35	22	19	17	25	41	24	26	22	11
NORTHWEST	4	2	9	8	7	6	5	5	6	11	6	5	6	11
CALM	12	11	9	6	3	3	3	4	3	3	8	6	6	11
AVERAGE SPEED FROM NOTED DIRECTIONS (mph) (1939 - 54)														
NORTH					4	3	4	4	3	3				15
NORTHEAST					5	4	5	5	4	5				15
EAST					4	4	4	4	4	3				15
SOUTHEAST					4	5	4	4	4	3				15
SOUTH					4	4	5	4	5	4				15
SOUTHWEST					7	7	7	6	6	8				15
WEST					7	6	5	5	5	8				15
NORTHWEST					6	6	6	6	6	7				15

n = number of years of record

continued

Table 1. (Continued) Climatic data for the Kananaskis Forest Experiment Station Headquarters

MONTHLY AVERAGE SUNSHINE (Note: Only 1 or 2 years of record Oct. through to May)													n
DURATION IN HOURS	69	138	159	246	201	236	311	254	163	121	71	61	5
PER CENT OF POSSIBLE	26	50	43	59	42	48	64	57	43	37	27	25	5
DURATION FOR HOUR ENDING 0500						14	13						5
0600				3	20	41	60	15					5
0700				32	38	55	78	58	3				5
0800			10	62	43	58	81	68	32				5
0900		7	42	73	46	61	81	70	57	19			5
1000	12	51	58	77	48	64	80	73	59	47	13		5
1100	34	63	62	78	47	62	82	73	58	52	34	35	5
1200	43	70	65	72	54	60	78	72	62	58	40	46	5
1300	45	78	63	77	57	59	73	68	63	59	37	46	5
1400	42	72	56	71	52	60	69	66	61	57	39	40	5
1500	37	78	62	68	53	54	65	65	59	53	45	27	5
1600	8	61	55	66	49	50	62	66	49	38	28	2	5
1700		14	39	65	54	51	62	60	38	11			5
1800			2	59	48	49	61	53	6				5
1900				21	33	40	58	29					5
2000					5	11	14						5

n = number of years of record

cannot be described as a typically subalpine climate. Where the station headquarters are located is in the transitional zone between the montane and subalpine forest regions (Rowe, 1959). Certain portions of the experiment station lie within the subalpine zone proper, and experience cooler temperatures and higher winter precipitation. However, the studies reported were carried out at the lower elevations of the experiment station; the climatic records presented are believed to be generally representative of the study areas concerned.

Noteworthy in the climate is the rather low mean annual precipitation (25.2 inches) and in particular the very low mean winter (November to April inclusive) precipitation (8.4 inches). Also of interest is the occurrence of extremely wide temperature fluctuations during the winter months (Table 1). Ranges of over 100° F between extreme maximum temperatures and extreme minimum temperatures are shown for January, February, March and December. These temperature ranges are an expression of a highly developed "Chinook" (Foehn) wind phenomenon, which is also apparent in the wind speed and frequency data of Table 1.

Chinook winds contribute to overwinter wastage of the snowpack at the lower elevations of the Kananaskis Forest Experiment Station. For long periods during the average winter the ground surface is free of snow at the experiment station headquarters.

Physiography

The physiography of the experiment station is mountainous. From the broad, glaciated valley bottom (Fig. 1) where the studies were carried out, steep mountain chains rise up on either side to heights of 8,000 to 10,000 feet. These mountains have the sawtoothed appearance typically associated with young cordillera. An example of the physiography of a small valley, subsidiary to the Kananaskis River valley on the southern edge of the experiment station, is given in the published work dealing with the Marmot Creek Experimental Basin (Jeffrey, 1964b, 1965a).

The geology of the Kananaskis River valley is highly variable. Bedrock consists of a thick series of sedimentary strata, rather simply folded. Rocks range in age from late Paleozoic to early Cretaceous. Represented are dolomite, dolomitic sandstone, coal measures, conglomerate and limestone (Crockford, 1949).

Pleistocene and recent deposits overlie bedrock. The whole lower valley has been glaciated and a typical U-shaped valley profile is found.

Soils

Crossley (1951) described the soils of the Kananaskis Forest Experiment Station. Alluvial soils occupy the valley bottoms while occasional chernozems are associated with "meadows." Rendzinas are occupied by trembling aspen (Populus tremuloides Michx.) and balsam poplar (Populus balsamifera L.) groves.

The main soil types are podzolic and brunisolic, developed upon materials of variable calcium carbonate content, most of which are glacially deposited. These podzolic and brunisolic soils support a forest cover of lodgepole pine and Engelmann spruce (Picea engelmannii Parry.)

Vegetation

The predominant forest tree species on the experiment station is lodgepole pine. Lesser areas, which have escaped burning in the past, are occupied by spruce (Horton, 1959). Spruce tends to occupy moist alluvial bottom lands or upper slopes, the lower and mid slopes being covered with lodgepole pine, of which a variety of age and stand conditions is present.

Forest research work done on the Kananaskis Forest Experiment Station has been reported by Crossley (1955, 1956), Smithers (1956, 1957), Horton (1958, 1959), Ackerman (1957) and Ackerman and Johnson (1962).

STUDY DESIGN

The studies were carried out on the Kananaskis Forest Experiment Station, at low (4560 to 4750 feet M.S.L.) elevations of the Kananaskis River valley. Studies were made of:

(a) snow accumulation,

(b) canopy interception of rainfall,

(c) soil moisture accretion and depletion during the growing season.

A variety of lodgepole pine stand conditions was sampled in each study.

Snow Accumulation

Description of Study Plots

Three areas were selected for documentation of snow accumulation in different lodgepole pine stand conditions. Area #1 was located close to the Kananaskis Forest Experiment Station headquarters at an elevation of 4560 feet M.S.L. Areas #2 and #3 were distant from the experiment station headquarters 4.8 and 5.0 miles to the south, respectively. Elevations were 4750 feet M.S.L. in the case of Area #2 and 4700 feet M.S.L. in Area #3. The soil moisture studies reported were carried out in Area #1, the canopy interception studies in Area #2 and #3.

In Area #1, four stand conditions were selected. Stand data for these four conditions are shown in Table 2. Three of these conditions (1.1, 1.2, 1.3) had previously been thinned. Thinning had been carried out in 1939-40, so that it may safely be assumed that full canopy response to thinning had been achieved prior to the study being instituted. The fourth stand condition (1.4) had not been thinned.

In Area #2, four stand conditions and two small clearings (150 feet x 150 feet) were studied. Stand data for the conditions sampled are shown in Table 3. Two stand conditions (2.1, 2.4) had been thinned in 1941. Again, total canopy response to thinning can be assumed to have occurred prior to the institution of study. Two other stand conditions (2.2, 2.3) were unthinned, and the remaining two conditions sampled (2.5, 2.6) were clearings.

In Area #3, two conditions were investigated, an unthinned dense stand (3.1) and a small clearing (3.2). The stand carried 4600 live stems per acre, having a mean DBH of 2.5 inches, a mean height of 27 feet, and a basal area of 145 $feet^2$ per acre. This stand included within its boundaries canopy interception Plot 3.

Measurements were taken in the centre of homogeneous forest blocks, so that measurement points were surrounded by fairly large "buffer" areas of similar stand condition.

Table 2. Stand data for four stand conditions in Area #1

STAND CONDITION	DESCRIPTION	INCLUDES	APPROX. NO. LIVE STEMS/ACRE	BASAL AREA/ ACRE feet^2	MEAN DBH inches	MEAN HEIGHT feet
1.1	thinned	soil moisture plot #1	700	155	6.0	46
1.2	heavily thinned	soil moisture plot #2	500	110	6.0	41
1.3	heavily thinned	soil moisture plot #3	470	110	5.6	39
1.4	unthinned	soil moisture plot #4	1620	190	4.4	41

Table 3. Stand data for six conditions in Area #2

CONDITION	DESCRIPTION	INCLUDES	APPROX. NO. LIVE STEMS/ACRE	BASAL AREA/ ACRE feet^2	MEAN DBH inches	MEAN HEIGHT DOMINANT STEMS feet
2.1	Thinned	Interception Plot #1	625	155	6.5	54
2.2	Unthinned	Interception Plot #2	1725	141	3.7	38
2.3	Unthinned		1380	170	4.4	43
2.4	Thinned		1190	150	4.6	45
2.5	Clearing					
2.6	Clearing					

Areas #1 and #3 were on almost completely level terrain. Area #2 was very slightly sloping with a northerly aspect.

Methods of Measurement

The method used consisted of periodic measurements of the snowpack at marked snow course points throughout the winters of 1963-64 and 1964-65. Light snowfall in 1965-66 rendered sampling impractical. One measurement only was taken in January, 1966 following an unusually heavy snowfall.

Snow course points, varying from 10 to 25 in number, were located in each area. In open stands locations close to tree boles were avoided. In dense stands, canopy conditions were relatively homogeneous and no decisions of this type were required. In these cases, sample points were located along a straight line.

Snowpack measurements were made using a standard Federal (U.S.D.A.-S.C.S.) snow tube. Weighings were made with a Chatillon hide scale graduated in ounces, and allowing interpolation to one-half ounce. Direct field measurements were made of snow depth and water equivalent. Where samplings yielded weights of less than one-half ounce, these were recorded as a trace.

Methods of Analysis

Snow accumulation data were not collected by random sampling. No analysis could be made statistically of these data.

Canopy Interception of Rainfall

Description of Study Plots

Three plots were selected for canopy interception studies in different lodgepole pine stand conditions. Another two plots were studied in mixed lodgepole pine - Engelmann spruce - alpine fir (Abies lasiocarpa (Hook.) Nutt.) stands in the vicinity of Marmot Creek basin. The two plots last mentioned are not considered in this report, other than in the resume provided in Appendix A.

Two of the canopy interception plots in lodgepole pine stands were placed in Area #2. Plot 1 was located in Area 2.1, Plot 2 in Area 2.2. The third canopy interception plot was located in Area 3.1.

Stand conditions in the three interception plots are shown in Table 4. All stands had the typical regular stand structure associated with Alberta stands of lodgepole pine originating from a fire history. Plot locations are shown in Figure 2, while photographs of Plot 1 are presented as Figures 3 and 4, of Plot 2 as Figures 5 and 6, and of Plot 3 as Figures 7 and 8.

Table 4 shows that while mean total height, number of stems per acre and mean DBH were quite different among the three plots, basal area per plot was not greatly different, ranging only from 140 to 155 feet^2 per acre. This fact was not appreciated until after studies had begun. It would have been desirable to have a greater range of basal areas. The study of interception therefore necessarily had to consider stand density in terms of numbers of trees per acre rather than in terms of basal area. While the original objectives could not be fulfilled, nevertheless the study was still of interest, for if basal area which,

Figure 2. Location of canopy interception Plots 1, 2 and 3, and of two raingauges used to measure gross precipitation.

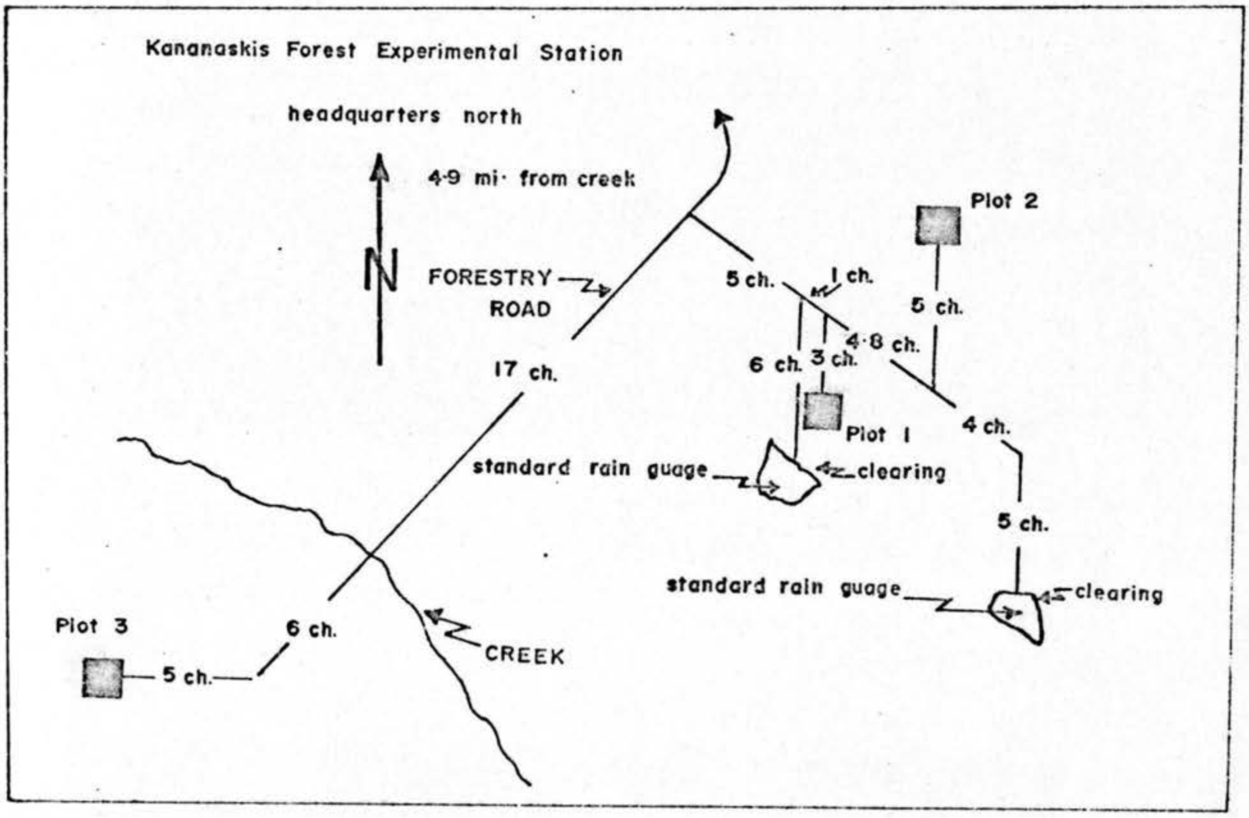

Kananaskis Forest Experimental Station
headquarters north
4·9 mi· from creek
N
FORESTRY ROAD
17 ch.
5 ch.
1 ch.
6 ch.
3 ch.
4·8 ch.
Plot 2
5 ch.
Plot 1
4 ch.
standard rain guage
clearing
5 ch.
standard rain guage
clearing
Plot 3
6 ch.
5 ch.
CREEK

Figure 3. Ground view of interception Plot 1.

Figure 4. Canopy closure on interception Plot 1.

Figure 5. Ground view of interception Plot 2.

Figure 6. Canopy closure on interception Plot 2.

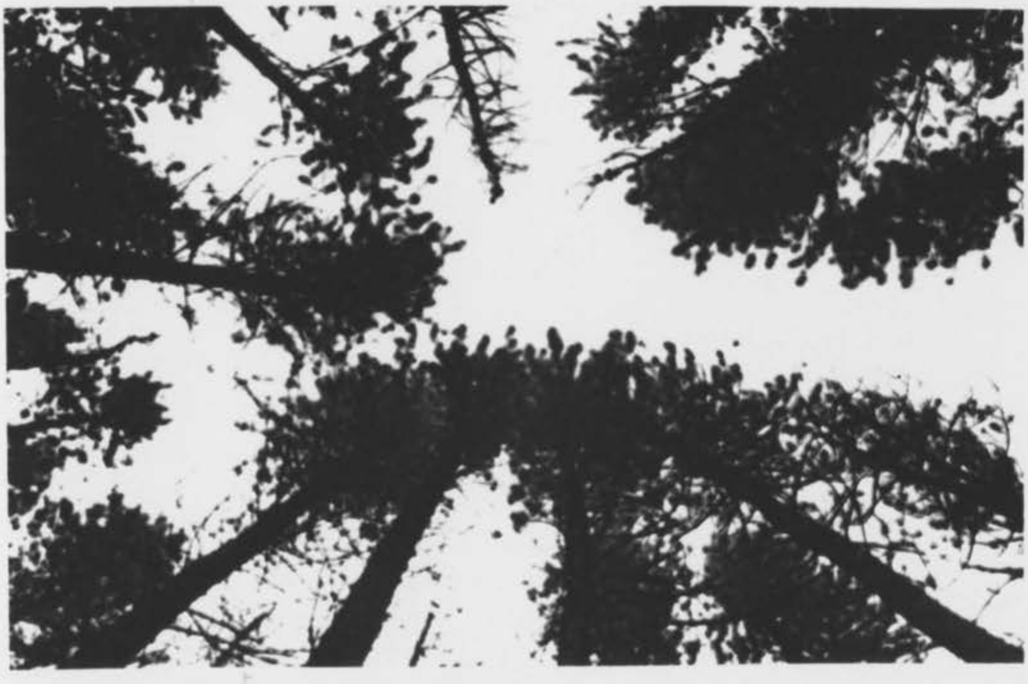


Figure 7. Ground view of interception Plot 3.

Figure 8. Canopy closure on interception Plot 3.

Table 4. Stand characteristics in canopy interception Plots 1, 2 and 3

PLOT	BASAL AREA PER ACRE $feet^2$		NO. OF STEMS PER ACRE		DBH (all species)	TREE MEAN HEIGHT (lodgepole pine)	CROWN MEAN LENGTH (lodgepole pine)		AGE (lodgepole pine)
	lP	wS	lP	wS	inches	feet	feet	% of total height	years
1	144	11	549	78	6.7	53.5	16.7	31.2	91
	Total = 155		Total = 627						
2	138	2	1681	48	3.8	39.9	14.6	36.6	88
	Total = 140		Total = 1729						
3	130	12	4260	296	2.5	26.8	12.0	44.8	84
	Total = 142		Total = 4556						

lP = lodgepole pine

wS = white spruce (*Picea glauca* (Moench) Voss).

as shown earlier, is regularly used to describe stand density, is valid for this purpose in forest hydrology, then it could be expected that no significant differences in canopy interception of rainfall would be found among the plots.

Plots were 100 feet x 100 feet and were located in the centre of stands surrounded by "buffer" areas of similar stand conditions.

Methods of Measurement

Within each plot 100 randomly located points were marked by numbered aluminum stakes. These points were used as the sampling points for standard Meteorological Branch Canada raingauges. This raingauge has an orifice area of 10 inches^2, stands 10½ inches high, and should be exposed at an orifice height of 12 inches above ground level. Thin circular wood blocks were attached to the base of each raingauge to raise the gauges to the recommended orifice height, and to aid in seating the gauges with orifices horizontal. Since terrain was level, or almost level, in all three plots, little difficulty was experienced in levelling gauge orifices, though some care was required. A standard raingauge is shown in Figure 9.

Due to fiscal considerations, five gauges per plot were used initially. This was increased, after part of one summer season had elapsed, to 10 raingauges per plot. Raingauges were located randomly within the 100 marked sampling points in each plot, and re-randomized after each measurable (0.01 inch) precipitation event, according to the "roving raingauge" technique of Wilm (1943).

In addition to standard raingauges, five trough gauges were located randomly in each plot. In Plots 1 and 2 these trough gauges

Figure 9. Trough gauge, 3 feet x 3 feet x 12 inches, in interception Plot 1. The polythene sheeting prevents rainfall other than that collected in the trough from entering the collecting vessels.

Meteorological Branch Canada standard raingauge also appears in right foreground.


1-1
1-1
Esso

Figure 10. Trough gauge, 9 feet x 1 foot x 4 inches, in interception Plot 3.


5-1
5-1

Figure 11. Stemflow instrumentation in interception Plot 1.

were 3 feet x 3 feet in horizontal dimensions with sides 12 inches in height.

In Plot 3, trough gauges were 9 feet x 1 foot, with sides 4 inches in height. These long troughs were used because stand density was such as to preclude the use of the square troughs utilized in the other two plots. Measurement of water collected was by weighing, using a Chatillon hide scale. The floors of the trough gauges were set one to two feet above ground level and the whole gauge was slightly inclined to facilitate drainage into collecting vessels. Trough gauge slopes varied from 4° to 8° (mean 6°) in Plot 1, from 5° to 7° (mean 6°) in Plot 2, and from 3° to 6° (mean 5°) in Plot 3.

The two types of trough gauges are shown in Figures 9 and 10.

Five trees each in Plots 1 and 2 were instrumented for stemflow measurement, using split plastic pipe as described by Thompson (1964). A representative stemflow installation is shown in Figure 11. Measurement of stemflow was by weighing.

Gross precipitation was measured by two standard raingauges located in the centres of the clearings shown in Figure 2. Clearings were approximately 150 feet x 150 feet in dimensions, or almost three tree heights (surrounding stand) in cross-section.

Instrumentation was emplaced in Plots 1 and 2 in early summer 1963, and in Plot 3 in mid-summer 1963. Data were collected during summers 1963 and 1964. Plots were checked each day and any rainfall occurring during the previous 24 hours measured. Where appropriate, two consecutive daily readings were added together, if they represented the result of a single continuous storm. In Plots 1 and 2, 21 storms were measured in 1963, and 25 storms in 1964. In Plot 3, 14 storms were measured in 1963, and 25 storms in 1964.

Methods of Analysis

Regression analyses were made of stemflow and throughfall data, both from standard gauges and trough gauges. Covariance testing of differences between regressions was carried out where applicable.

Soil Moisture Accretion and Depletion

Description of Study Plots

Five plots were selected for soil moisture studies in different lodgepole pine stand conditions. All five of these plots were in Area #1, close (within 700 yards) to the Kananaskis Forest Experiment Station headquarters. Locations of the plots are shown in Figure 12.

Stand conditions in the five soil moisture plots are shown in Table 5. Plots 1, 2, 3, which lay respectively within Areas 1.1, 1.2 and 1.3 of the snow accumulation study, had been thinned in 1939-40. Plot 4, which lay within snow accumulation Area 1.4, had not been thinned. Plot 5 was also in an unthinned stand. All stands were regular in structure. In Plot 5, there was a definite development of two-storied structure, with lodgepole pine occupying the overstorey and white spruce the understorey.

It is worthwhile to consider the variations shown by Table 5. Plots 1 and 2 were 85 years old, whereas Plots 3, 4 and 5 were 63 to 70 years of age. While stand differences of this magnitude have not been considered, in the western literature, to be influential upon evapotranspiration rates, the difference in stand ages may be regarded

Table 5. Stand characteristics in soil moisture Plots 1, 2, 3, 4 and 5

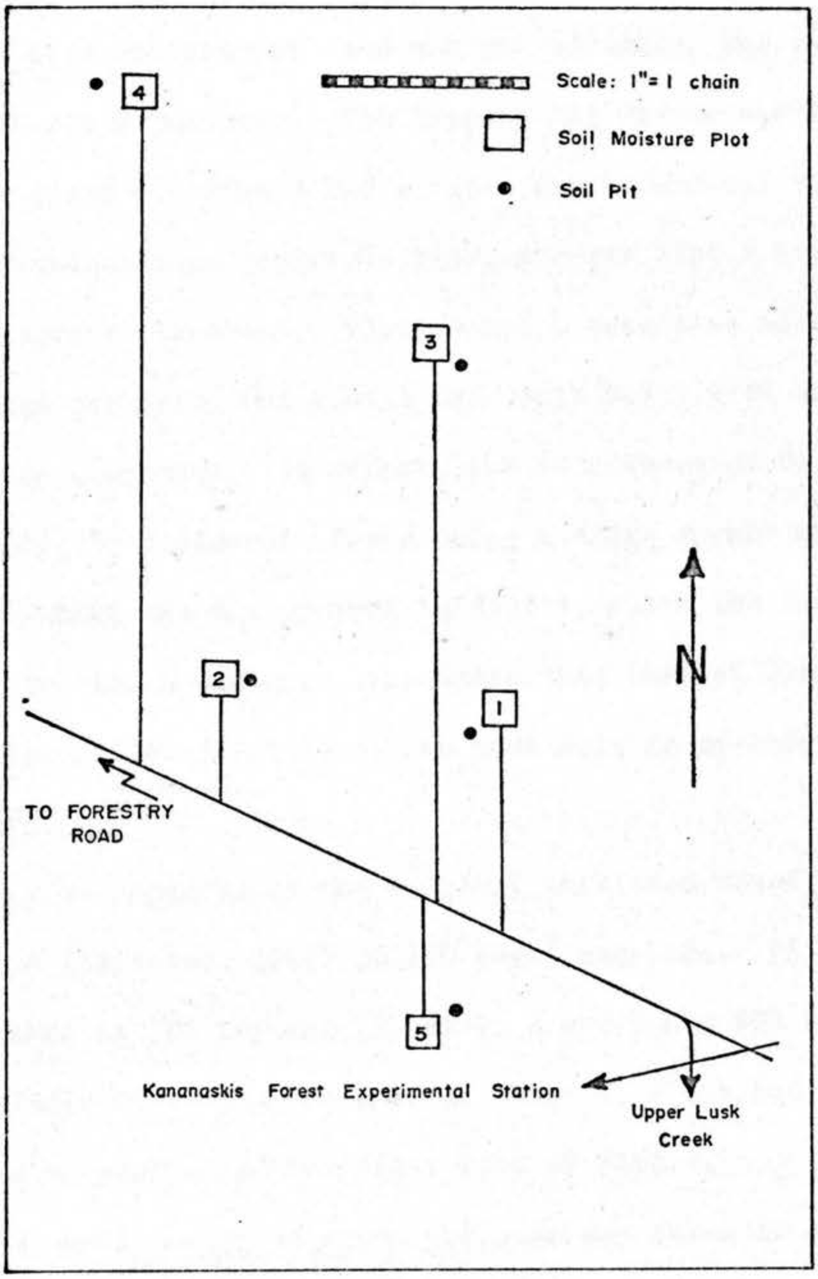
PLOT	BASAL AREA PER ACRE feet²		NO. OF STEMS PER ACRE		DBH (all species)		TREE HEIGHT (all species)		CROWN LENGTH (all species)		AGE (all species)	
					mean	range	mean	range	mean	%age of total tree ht.	mean	range
	lP	wS	lP	wS	inches	inches	feet	feet	feet	%	years	years
1	153	-	697	-	5.95	0.6-10.6	45.6	7.0-66.0	17.1	40.2	84	70-94
2	108	-	505	-	5.98	1.3-8.1	41.5	10.0-51.0	17.0	45.5	85	71-94
3	94	14	279	192	5.57 (7.06)[1]	0.6-11.5	32.1 (39.3)[1]	9.0-53.0	25.1	70.2	63	53-72
	Total = 108		Total = 471									
4	190	-	1620	-	4.39	0.9-8.0	41.3	14.0-57.5	13.2	31.7	68	32-77
5	131	42	645	975	4.00 (5.62)[1]	0.6-10.4	28.0 (42.4)[1]	6.0-65.0	13.8	50.1	70	36-96
	Total = 173		Total = 1620									

[1] Values for lodgepole pine alone

lP lodgepole pine

wS white spruce

Figure 12. Diagram showing contiguity of soil moisture Plots 1, 2, 3, 4 and 5, and of adjacent soil pits. Plots were located 700 yards north of the Kananaskis Forest Experiment Station headquarters, shown in Figure 1.


Scale: 1"= 1 chain
Soil Moisture Plot
Soil Pit
4
3
2
1
5
N
TO FORESTRY ROAD
Kananaskis Forest Experimental Station
Upper Lusk Creek

as a confounding effect. However, the major stand density variation was among Plot 3 and Plots 4 and 5. These plots were of similar age, and therefore there was no confounding effect of age in comparison between them.

The range in basal area between plots was large (108 $feet^2$ to 190 $feet^2$). The same was true of stem numbers per acre, the variation being 471 to 1620 stems per acre. The largest difference was between Plot 3 and Plots 4 and 5. Plot 2 had a basal area identical to Plot 3, but was composed uniquely of lodgepole pine, whereas Plot 3 had an important white spruce component. Plots 4 and 5 were also identical, in number of stems per acre, but Plot 5 had lower basal area and a large white spruce component. In effect, the structures of Plots 4 and 5 were essentially different, there being a white spruce understorey in Plot 5 which was not present in Plot 4, while the lodgepole pine overstorey in Plot 5 was much less dense than that of Plot 4. There was no major difference between the mean heights of lodgepole pine of any plots.

Plot 4 may be regarded as the original unthinned stand, having a high basal area (Smithers, 1962) of 190 $feet^2$ per acre. If Plot 4 basal area is taken as 100 percent, Plots 1, 2 and 3 had 80, 57 and 57 percent respectively of Plot 4 basal area. Plot 5, which had not been thinned, carried 91 percent of the basal area of Plot 4.

If Plot 4 and 5 number of stems per acre are taken as 100 percent, Plots 1, 2 and 3, the thinned plots, had respectively 43, 31 and 29 percent of the standing live trees carried by Plots 4 and 5.

These values show the radical nature of some of the thinning treatments carried out. A wide range in stand densities was present, to allow comparison of stand density - soil moisture interactions.

Photographs of ground and canopy conditions on the five plots are given in Figures 13 to 22 inclusive. Particular attention is drawn to Plot 3 photographs (Figs. 17 and 18) which document the occurrence of persistent discontinuities in canopy in 1967, 27 years after the thinning was carried out.

Vegetation on all five plots was essentially similar. The main difference between plots was in the relative luxuriance of the shrub layer. These differences are believed to be attributable to the relative amounts of light reaching the forest floor in the different plots. Plots 2 and 3 had lower canopy densities than the other three plots, as can be inferred from the stem number data in Table 5.

In Plot 1, there was a moderately dense low shrub layer composed of Shepherdia canadensis, with Rosa acicularis as a concomitant species.

In Plot 2, the shrub layer was both higher and denser. A moderately dense high shrub layer of Alnus crispa, with some Salix sp. intermixed, was present. A dense to moderately dense shrub layer, in which Shepherdia canadensis was dominant, with Rosa acicularis as a concomitant species, occurred beneath this high shrub layer.

In Plot 3, a moderately dense high shrub layer was again present. In this case, the dominant species was Populus tremuloides, with Salix sp. and Picea glauca as concomitants. A dense to moderately dense shrub layer occurred beneath the high shrub layer. The dominant species of this layer was again Populus tremuloides with Salix sp., Picea

Figure 13. Ground view of soil moisture Plot 1.

Figure 14. Canopy closure on soil moisture Plot 1.

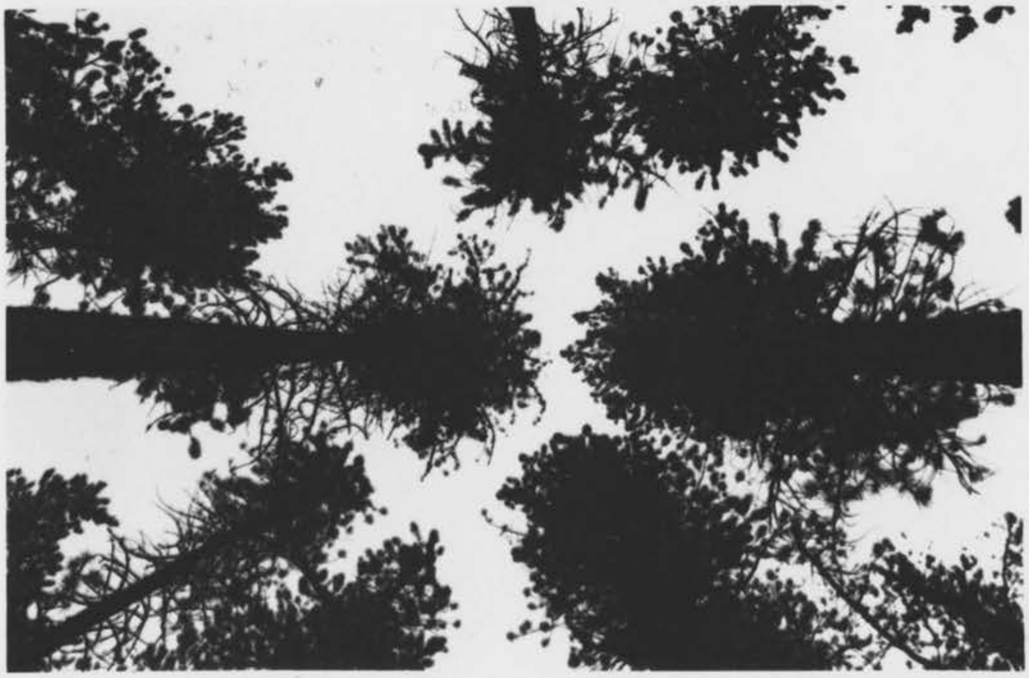


Figure 15. Ground view of soil moisture Plot 2.

Figure 16. Canopy closure on soil moisture Plot 2.

Figure 17. Ground view of soil moisture Plot 3.

Figure 18. Canopy closure on soil moisture Plot 3.

Figure 19. Ground view of soil moisture Plot 4.

Figure 20. Canopy closure on soil moisture Plot 4.

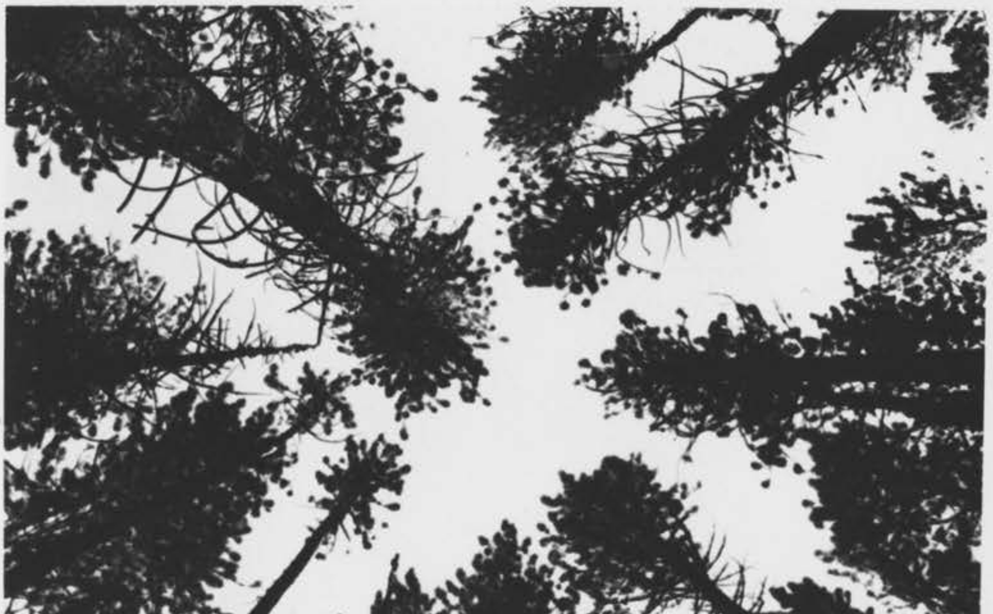
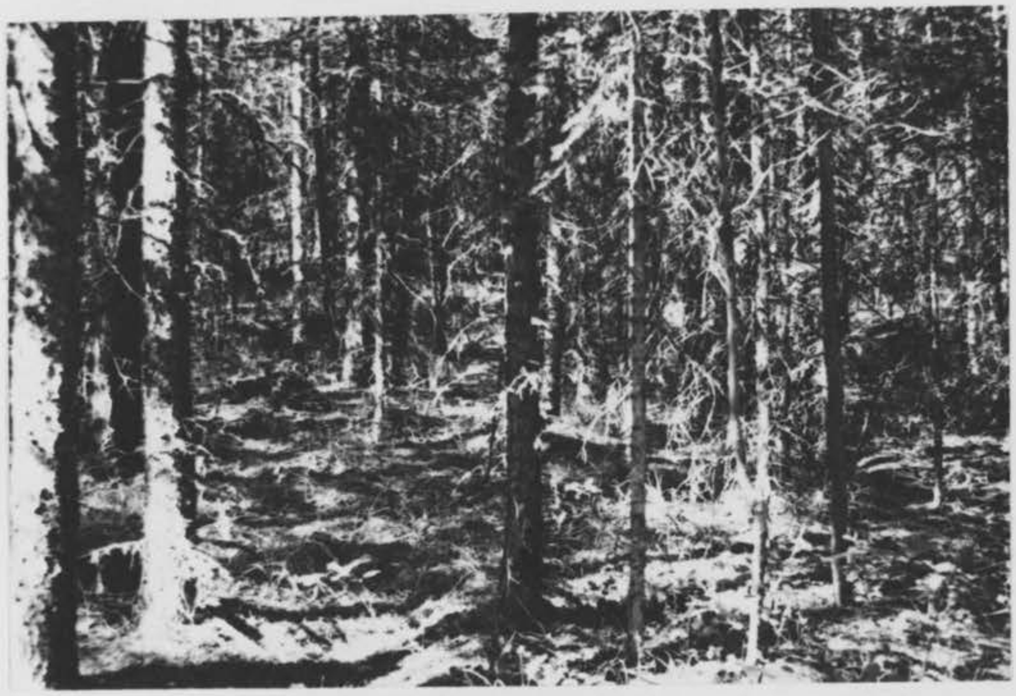


Figure 21. Ground view of soil moisture Plot 5.

Figure 22. Canopy closure on soil moisture Plot 5.



glauca and Shepherdia canadensis as concomitants, the latter species having sufficient representation to be classed as codominant.

In Plots 4 and 5, there was no high shrub layer and the shrub layer was sparse, Shepherdia canadensis and Rosa acicularis being the main component species.

The herb layer on all plots was well developed. However, its composition was such that considerable variation in the physiognomy of the vegetation was apparent.

In Plots 1, 2 and 3 grasses and tall herbs were dominant, and the herb layer luxuriant. Dominant species were Epilobium angustifolium, Calamagrostis rubescens, and Linnaea borealis var. americana. Concomitant species included Elymus innovatus, Aster sp., Casteleja sp., Cornus canadensis, Vicia americana, Lathyrus ochroleucos, Arnica cordifolia, Spirea lucida, Galium boreale, Fragaria glauca, Vaccinium sp. and Zygadenus elegans.

In Plots 4 and 5, the herb layer was much less luxuriant. Dominant species were Linnaea borealis var. americana and Calamagrostis rubescens with scattered representation of Elymus innovatus, Aster sp., Lathyrus ochroleucos, Pyrola spp., Epilobium angustifolium and Spirea lucida.

There was no bryophyte layer present in Plots 1, 2 and 3. In Plots 4 and 5, on the other hand, there was a well developed, though discontinuous, bryophyte layer which covered about half the ground surface area. The species of this layer were Hylocomium splendens and Pleurozium schreberi, with scattered representation of Ptilium crista-castrensis and Peltigera aphthosa.

From these vegetational differences, it is believed that Plots 4 and 5 may be regarded as basically distinct from the other three plots. Since no pedological (Table 6) or physiographic difference is present to explain this variation in ground cover, it is attributed to the effects of canopy density and light transmission to the forest floor.

The nomenclature of vascular plants follows Moss (1959), that of the bryophytes Bird (1962).

The surficial material of Area #1 was a lacustrine sand deposited during the glacial melt period, presumably as a result of local ice damming. The soil profiles were classifiable in the Canadian soil survey system (National Soil Survey Committee of Canada, 1965) as Arenic Podzo-Regosols. A photograph of a soil profile is given in Figure 23. The National Soil Survey Committee of Canada (1965) describe the Podzo Regosol Great Group as follows:

> Well and imperfectly drained soils that have light colored eluvial horizons (Ae) more than 1 inch thick and weak illuvial horizons (B) containing insufficient accumulations of sesquioxides, clay or organic matter to meet the requirements of the Podzolic Order. The parent material of these soils is coarse or moderately coarse in texture. Organic surface horizons (L-H) are usually present in the virgin soils but seldom exceed a few inches in thickness. Weak or thin Ah horizons may also be present.
>
> These soils have developed under forest or pine grass-forest vegetative cover. They were formerly classified as Gray Forested soils in the Podzolic Order. The description given in the N.S.S.C. 1963 report, however, applies chiefly to the Cutanic Podzo Regosol Subgroup.

They describe Arenic Podzo Regosols as:

> Podzo Regosols with free iron and aluminum as the main accumulation products in the B horizon but less than that required for the Podzol Great Group. That is, the oxalate extractable Δ(Fe + Al) is less than 0.8 percent.

Figure 23. Arenic Podzo Regosol near Plot 3.

These soils strongly resemble Podzols in appearance except the B horizons are usually lower in chroma. Also they usually have less acidic sola and higher base saturation than the Podzols. These Podzo Regosols have only been found on sands having a low amount of weatherable minerals. They occur in many parts of Canada.

The lacustrine sand material varied in depth from plot to plot. Minimum depth of lacustrine sand material at access tube locations was:

Plot 1 --------------4 feet

Plot 2 --------------3 feet

Plot 3 --------------8 feet

Plot 4 --------------7 feet

Plot 5 -------------14 feet

Beneath the lacustrine sand material occurred compacted gravel and till materials (Appendix B). These were sometimes so highly compacted as to be almost impossible to remove with shovel and pick. It was often very difficult to make any penetration of these materials with a shovel point, even to a depth of one inch.

The range in different parameters of the lacustrine sand material is given in Table 6.

Individual descriptions of the soils at the five plot locations are listed in Appendix B. These descriptions follow the format of the U. S. Department of Agriculture, Soil Survey Staff (1951), rather than that of the Canadian system.

Some discussion of the data presented in Table 6 is worthwhile. The area was chosen for study on the basis of the following considerations:

(1) A suitable variety of stand conditions and thinning treatments was available.

Table 6. Variation in soil characteristics in soil moisture Plots 1, 2, 3, 4 and 5

CHARACTERISTIC	PLOT 1	PLOT 2	PLOT 3	PLOT 4	PLOT 5
1. TOTAL DEPTH, SURFICIAL MANTLE (FEET)	4	3	8	7	14
2. DEPTH - L, F, H LAYERS (INCHES)	2	3	1	1	2
3. DEPTH - A_1 HORIZON (INCHES)	2	ABSENT	1	2	2
4. DEPTH - A_2 HORIZON (INCHES)	2	1	1	1	ABSENT
5. DEPTH - A_3 HORIZON (INCHES)	2	2	1	ABSENT	ABSENT
6. DEPTH - AB HORIZON (INCHES)	ABSENT	ABSENT	ABSENT	3	2
7. DEPTH - B_1 HORIZON (INCHES)	1	1	2	ABSENT	ABSENT
8. DEPTH - B_2 HORIZON (INCHES)	9	3	4	6	4
9. DEPTH - B_3 HORIZON (INCHES)	ABSENT	ABSENT	ABSENT	3	6
10. TOTAL DEPTH - A + B HORIZONS (INCHES)	16	7	9	15	14

continued

Table 6. (Continued) Variation in soil characteristics in soil moisture Plots 1, 2, 3, 4 and 5

CHARACTERISTIC	PLOT 1	PLOT 2	PLOT 3	PLOT 4	PLOT 5
11. TEXTURE - A HORIZONS	LOAMY SAND - SANDY LOAM	SANDY LOAM	LOAMY SAND - SANDY LOAM	SANDY LOAM	SANDY LOAM
12. TEXTURE - B HORIZONS	SAND - SANDY LOAM	SANDY LOAM	SANDY LOAM	SANDY LOAM	SAND - SANDY LOAM
13. TEXTURE - C HORIZON	SANDY LOAM	LOAMY SAND	SANDY LOAM	SANDY LOAM	SANDY LOAM
14. pH - A HORIZONS	6.8	6.2	6.5	6.4	6.2
15. pH - B HORIZONS	7.6	7.6	7.3	7.3	6.8
16. pH - C HORIZONS	8.2	8.0	8.2	7.8	8.2
17. DRY COLOUR (MUNSELL) - A HORIZONS	10 YR 7/3	10 YR 7/3	10 YR 4/3	10 YR 6/4	10 YR 6/4
18. DRY COLOUR (MUNSELL) - B HORIZONS	10 YR 6/2	10 YR 6/2	10 YR 4/3 - 5/2	10 YR 4/4 - 6/2	10 YR 5/4
19. DRY COLOUR (MUNSELL) - C HORIZONS	10 YR 7/1	10 YR 7/1	10 YR 6/2	10 YR 6/1	10 YR 6/1
20. FIELD CAPACITY - A HORIZONS (% H_2O BY WEIGHT)	15.90	18.41	16.60	15.57	26.29
21. FIELD CAPACITY - B HORIZONS (% H_2O BY WEIGHT)	14.78	11.98	18.58	13.15	14.73
22. FIELD CAPACITY - C HORIZON (% H_2) BY WEIGHT)	10.74	12.77	11.84	10.41	7.61

continued

Table 6. (Continued) Variation in soil characteristics in soil moisture Plots 1, 2, 3, 4 and 5

CHARACTERISTIC	PLOT 1	PLOT 2	PLOT 3	PLOT 4	PLOT 5
23. WILTING POINT - A HORIZONS (% H_2O BY WEIGHT)	5.77	8.03	7.01	5.51	15.69
24. WILTING POINT - B HORIZONS (% H_2O BY WEIGHT)	7.86	5.94	10.74	7.25	7.76
25. WILTING POINT - C HORIZONS (% H_2O BY WEIGHT)	5.26	6.24	5.84	6.48	3.79
26. BULK DENSITY - A HORIZONS (gm/cm^3)	1.27	1.45	1.42	1.24	1.24
27. BULK DENSITY - B HORIZONS (gms/cm^3)	1.32	1.27	1.44	1.23	1.05
28. BULK DENSITY - C HORIZONS (gms/cm^3)	1.34	1.30	1.46	1.43	1.43
29. TOTAL H_2O STORAGE[1] - UPPER 3 FEET (INCHES)	3.37	3.20	2.32	2.19	2.24
30. TOTAL H_2O STORAGE[1] - UPPER 4 FEET (INCHES)	4.03	-	2.77	2.62	2.83
31. TOTAL H_2O STORAGE[1] - UPPER 7 FEET (INCHES)	-	-	6.97	5.20	5.07
32. TOTAL H_2O STORAGE[1] - UPPER 8 FEET (INCHES)	-	-	8.34	-	5.57
33. TOTAL H_2O STORAGE[1] - UPPER 14 FEET (INCHES)	-	-	-	-	9.59

1 Field capacity minus wilting point

(2) The lacustrine sand material was stone free, allowing easy and reliable installation of access tubes.

(3) The soils appeared on the basis of profile characteristics (Appendix B) to be remarkably homogeneous for forest soils.

It is in relation to the third factor listed, that subsequent analyses showed the assumption to be not entirely correct.

Variation in the depth of A and B horizons was not originally considered to be a serious disadvantage. This was borne out by laboratory study. The values presented in Appendix B demonstrate that there was little difference in field capacity and wilting point values for the 12 to 24 inches soil depth on Plots 3, 4 and 5 which had total depths of A + B horizon of seven to 15 inches. There was, however, a large difference in the 12 to 24 inches soil depth soil moisture constants between Plots 1 and 2 and Plots 3, 4 and 5 (Appendix B). This was a function of the actual water holding capacities of the A and B horizon materials on the different plots, and of different bulk densities (Table 6). The bulk density values were kindly supplied by Canada Department of Forestry and Rural Development.

A wider replication of bulk density samples would have allowed a more exact appraisal to be made of soil moisture constants in terms of percent moisture by weight and actual water storage. However, it should be noted that in Plots 1 and 3, where adequate replication was obtained through additional sampling, bulk densities showed considerable variation between the two plots (Table 6), so that this factor is not thought to have been too influential.

Bulk density samples could not be obtained in deep soil layers. Therefore one mean bulk density value had perforce to be used for the whole C horizon. By anticipating somewhat, it may be noted that measurement of soil moisture contents in the C horizon indicated that soil moisture varied approximately as values calculated from pressure apparatus and bulk density determinations would indicate. Again, the bulk density determination factor is believed to be of relatively small influence.

As noted, there was considerable variation in the water-holding capacity of A and B horizons on the different plots. This was also true of C horizons. The net result was that considerable variation was found in total water storage in equivalent depths of soil in the different plots (Table 6).

For the uppermost seven feet of soil, Plot 3 had 6.97 inches total water storage (field capacity minus wilting point), compared to 5.20 inches in Plot 4, and 5.07 inches in Plot 5. Subsequent measurement confirmed large differences. This meant that the amount of water available for transpiration was not identical in the equivalent depths of the different plots. Since the most interesting comparison was between Plots 3 and 4 (Table 5), which showed the largest stand variations, this was unfortunate and represented a confounding factor.

Methods of Measurement

In establishing the values presented in Table 6, methods used were as follows:

(1) pH - Beckmann glass electrode pH meter (Peech, 1965);

(2) field capacity - pressure membrane apparatus at 1/3 bar pressure (Richards, 1965);

(3) permanent wilting point - pressure membrane apparatus at 15 bar pressure (Richards, 1965);

(4) soil texture - hydrometer method (Day, 1965);

(5) bulk density - core sampler (Blake, 1965).

In the light of considerations which will be introduced later, it is worthwhile to stress that the 1/3 bar and 15 bar moisture contents ("field capacity" and "wilting point") were obtained in the following manner.

Two random locations were selected in each plot, and soil samples collected by auger in each of the upper (A and B) soil horizons, as well as in each 12 inch depth increment in the C horizon.

These samples were subjected to the pressure apparatus tests in the laboratory of the Soil Science Department at the University of British Columbia. Two replicates of each sample, to give a total of four values for each horizon or depth increment, were used. The tests were carried out by approved technique in a controlled temperature room. Especial care was taken to ensure scrupulous exactitude in all steps in the measurement sequence. This was due to the fact that a previous set of values for 15 bar and 1/3 bar moisture contents, which had kindly been supplied by the Alberta Regional Laboratory of the Department of Forestry and Rural Development, showed unexpected values, which were deemed to require verification. For this reason, especial care was taken to obtain reliable results, and it is believed that the values presented in Table 6 and in Appendix B meet that requirement.

The plots for soil moisture measurement were 50 feet x 50 feet in size, in the centre of the stand, with an adequate surround of similar stand conditions. Within each plot, 10 locations were randomly chosen in the case of Plots 1 to 4 inclusive, while six locations were selected in Plot 5.

At each location, aluminum access tubes were installed using a "Perrin" soil auger. Tubes were carefully backfilled to avoid the creation of voids around the access tubes. Sealing of the tubes and their general maintenance procedures followed the recommendations of U. S. Department of Agriculture, Forest Service (1962).

The soil moisture measurement system consisted of a Troxler neutron probe Model 104 (2.72 mc RaBe, 4.14 x 10^4 n/sec.) and a Troxler Model 200 B scaler. Operation of the probe followed the manufacturer's instructions and the recommendations of U. S. Department of Agriculture, Forest Service (1962). Readings were taken at 12 inch depth intervals, beginning at six inches depth below the soil surface. Counting time was two minutes, following the recommendation of Merriam and Knoerr (1961). Readings were taken at varying intervals, with one week intervals being the ideal objective. However, logistical considerations sometimes extended the interval between readings to two weeks or longer. The Troxler system in operation is shown in Figure 24.

Access tubes were installed in mid-summer, 1963 in Plots 1 to 4 inclusive, and in Plot 5 during fall, 1963. Readings were taken during 1963, 1964, 1965 and 1966 in Plots 1 to 4 inclusive, and during 1964 to 1966 inclusive in Plot 5.

Considerable difficulty was experienced with instrumentation in mid-summer, 1964 and in early summer, 1965. This difficulty resulted in interrupted scheduling of data collection.

Figure 24. Troxler neutron probe in position with S-4 shield atop access tube and Model 200B scaler in operation.

Methods of Analysis

Analysis of variance methods were applied to measurements of (1) soil moisture content, (2) soil moisture change, and (3) evapotranspiration (as calculated from soil moisture change).

Calibration of Neutron Probe

Operation of neutron probe equipment in forest areas may present special problems, not encountered to the same degree in agricultural lands. One of these is the difficulty experienced in operating surface neutron-scattering equipment. Minor irregularities in the forest floor, and the typically undulating micro-relief of the surface beneath forest stands, along with accumulations of organic material, make surface neutron-scattering equipment impractical in most forested situations. The surface detector does not function properly if placed on top of the undisturbed organic (L, F and H) layers. If the organic material is removed around access tube locations to allow surface neutron scattering equipment to be placed directly on top of mineral soil, serious difficulties are encountered.

Removal of the organic layer interferes with an ecosystem-component of considerable significance in forest hydrology. Interception of precipitation by litter at access tube locations is eliminated and soil moisture recharge conditions at variance with those on the remainder of the study plot are created. In addition, removal of the L, F and H layers tends to create "wells" around the access tubes, into which drainage of water may take place, resulting in atypical soil moisture conditions at sampling points. Additional depression storage may also be created.

For these reasons, it was believed more acceptable to use the depth (Troxler Model 104) neutron probe for soil moisture measurements at all depths, including the surface foot. An attempt was made, accordingly, during the probe calibration procedure, to develop a special empirical calibration for the surface foot of soil in the study area. This section presents the results of that attempt.

Procedure

The procedure used was essentially that recommended by Van Bavel, Nixon and Hauser (1963), by Canadian National Committee, International Hydrologic Decade (1966), and by King (1967).

Soil was taken from the C horizon (parent material) of the soil pit near Plot 3 (Figure 12). Soil texture was sandy loam (8% clay, 15% silt, 77% sand). A cubic steel tank 40 inches in side dimension was filled with this soil, the soil tamped in evenly, and a sealed access tube installed in the exact centre of the soil mass. The probe was lowered in the access tube until it was positioned in the exact geometric centre of the soil mass. A 10 minute count was then taken.

The probe was then removed and the soil excavated until the new upper soil surface was exaftly six inches above the previous geometric centre of the soil mass. The probe was lowered to its exact previous position and another 10 minute count taken.

Twenty minute standard counts were taken immediately prior and immediately subsequent to readings being made in the soil mass.

Using a core sampler, 10 soil cores were removed from the volume of soil encompassed by a four inch radius from the access tube, and six inches above and six inches below the original geometric centre of the soil mass. The total soil volume removed by the 10 core samples was 688 cm^3. Core samples were then used to establish, through drying and weighing, the percent moisture by weight and the bulk density. From these values, percent moisture by volume was calculated.

Each replication of this procedure furnished a count ratio at 20 inches depth (exact geometric centre), a count ratio at six inches depth, a percent moisture by volume and a bulk density.

Between readings, the soil was removed from the tank, mixed thoroughly, after sprinkling with water if appropriate, replaced in the tank, tamped evenly, and another replication procedure begun. The procedure was repeated a total of 21 times.

Results of Calibration

The values obtained in the calibration procedure are shown in Table 7.

There was a high correlation between count ratios obtained at 20 inches depth (X_1) and at six inches depth (X_2).

The relationship between X_1 and X_2 is curvilinear and is expressed by the equation:

$$X_2 = -7.308 + 0.756X_1 + 0.0037X_1^2 \qquad (6)$$

for which the coefficient of correlation (r) is 0.996, with 18 degrees of freedom.

The resultant curve obtained from equation (6), and plotted values of X_1 and X_2, are shown in Figure 25.

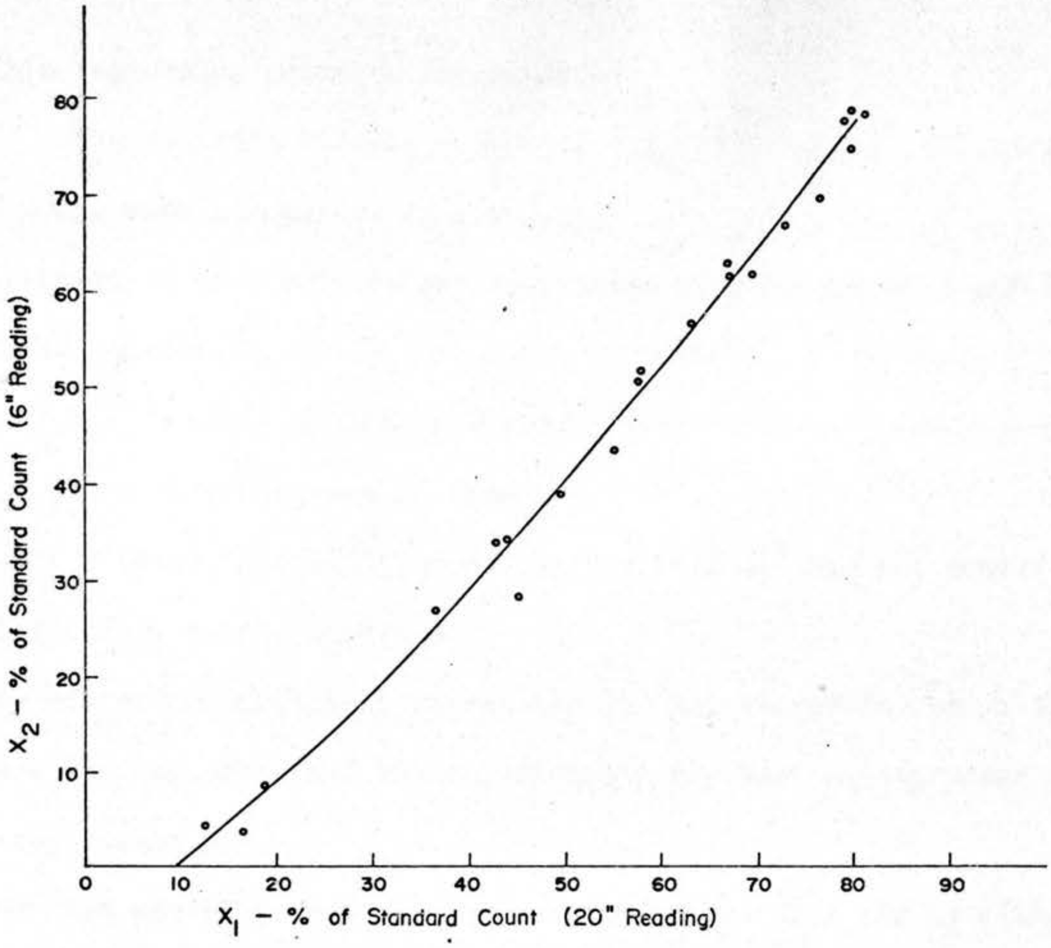
A linear regression was calculated expressing percent moisture by volume as a function of count ratio for values of Y and X_1 (Table 7).

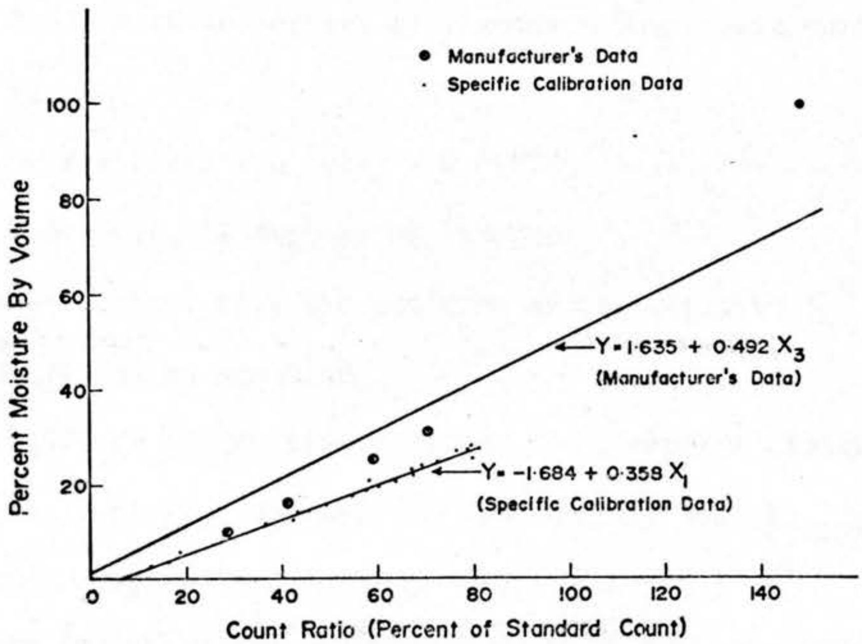
Table 7. Values obtained by neutron probe calibration procedure

PROBE AT 20" COUNT RATIO (% OF STANDARD COUNT) X_1	PROBE AT 6" COUNT RATIO (% OF STANDARD COUNT) X_2	%AGE OF H_2O BY VOLUME % Y	BULK DENSITY gms/cm^3
42.77	33.90	12.76	1.58
12.46	4.24	2.67	1.52
79.02	77.37	27.04	1.70
79.69	78.75	27.59	1.75
81.22	78.37	26.99	1.73
76.40	69.45	26.46	1.77
79.42	74.33	25.01	1.75
72.43	66.71	24.57	1.76
69.22	61.68	23.62	1.78
67.59	61.65	21.81	1.75
66.82	62.97	22.18	1.74
58.07	51.42	20.27	1.73
63.52	56.67	20.56	1.77
57.95	50.47	18.94	1.71
55.24	43.54	17.71	1.73
49.27	39.00	15.92	1.71
45.25	28.23	14.37	1.70
43.77	33.98	13.93	1.70
36.47	26.49	11.77	1.59
18.87	8.52	5.54	1.64
16.20	4.08	3.92	1.59

Figure 25. Relationship between count ratios (X_1, X_2) with the probe at 20" depth (X_1) and at 6" depth (X_2).

Figure 26. Manufacturer's calibration as expressed by equation (11) and individual calibration as expressed by equation (7).


X2 - % of Standard Count (6" Reading)
X1 - % of Standard Count (20" Reading)


Manufacturer's Data
Specific Calibration Data
Y = 1·635 + 0·492 X3
(Manufacturer's Data)
Y = -1·684 + 0·358 X1
(Specific Calibration Data)
Percent Moisture By Volume
Count Ratio (Percent of Standard Count)

This regression produced the equation:

$$Y = -1.684 + 0.358X_1 \text{ ------------------------------------ } (7)$$

with r = 0.996 with 19 degrees of freedom.

Calculation of a curvilinear regression from values of Y and X_1 produced the equation:

$$Y = -1.654 + 0.356X_1 + 0.0002X_1^2 \text{ ---------------------- } (8)$$

with r = 0.996 with 18 degrees of freedom.

Table 8 shows that addition of the variable X_1^2 did not contribute significantly to the equation.

The use of a curvilinear regression did not therefore result in an increase in precision, and the relationship may best be expressed as a linear regression.

The same procedure was carried out for values of Y and X_2 (Table 7). The linear equation produced was:

$$Y = 3.067 + 0.315X_2 \text{ ------------------------------------ } (9)$$

with r = 0.991 with 19 degrees of freedom. The curvilinear equation produced was:

$$Y = 1.963 + 0.393X_2 - 0.0009X_2^2 \text{ ---------------------- } (10)$$

with r = 0.993 with 18 degrees of freedom.

Table 8 shows that the addition of the variable X_2^2 contributed significantly to the equation.

The use of a curvilinear regression therefore resulted in an increase in precision, and the relationship may best be expressed as a curvilinear regression.

From the above regression analyses, it was determined that equations (7) and (10) gave the best results for the "deep" (20 inches depth) and "shallow" (6 inches depth) conditions respectively.

Table 8. Variance ratios associated with quadratic equations (8) and (10)

INDEPENDENT VARIABLE	REGRESSION COEFFICIENT	STANDARD DEVIATION	VARIANCE RATIO
X_1	0.3561	0.0347	105.290
X_1^2	0.00002	0.00035	0.002
X_2	0.3928	0.0339	134.590
X_2^2	-0.00091	0.00039	5.574[1]

1 Significant at p = 0.05

Table 9. Manufacturer's calibration data for neutron probe

COUNT RATIO % OF STANDARD COUNT	% H_2O BY VOLUME %
X_3	Y
0.36	0.0 (probe in air)
28.63	10.6
41.51	16.3
59.11	24.9
71.00	30.3
149.41	100.0 (probe in water)

To compare equation (7) with the manufacturer's calibration curve (Figure 26), the original probe calibration data were obtained from the manufacturer. These data are shown in Table 9. A linear regression was calculated, expressing percent moisture as a function of count ratio, and utilizing all six points of Table 9.

This calculation yielded the equation:

$$Y = 1.635 + 0.4922X_3 \text{ -------------------------------- } (11)$$

with $r = 0.979$ with 4 degrees of freedom. Utilization of the four central points of Table 3, i.e., omitting the values for air and water, is perhaps more realistic. This yields the equation:

$$Y = -2.700 + 0.462X_3 \text{ --------------------------------- } (12)$$

with $r = 0.999$ with 2 degrees of freedom.

The manufacturer's calibration as expressed by equation (11), is shown in Figure 26, along with the calibration curve obtained by the specific calibration procedure outlined above, as expressed by equation (7).

Statistical comparison was made between equations (7) and (11), according to the procedure outlined by Freese (1964). The two equations were significantly different ($p = 0.01$). This is true also of equations (11) and (12).

In the calibration data (Table 7) it is seen that data for low values of percent moisture by volume were sparse. Three sets of data only were obtained for moisture percentages by volume of less than 12 percent, and no data were available for moisture percentages by volume of less than three percent. For this reason, less confidence can be placed in equation (7) and equation (10) at low moisture contents than is justified at moisture contents greater than 12 percent by volume.

The early calibration curves produced (e.g. Van Bavel, 1958) invariably showed calibration curves passing through the origin. Van Bavel et al. (1963), however, presented a curve which did not, but which had a small negative intercept (Van Bavel, Nielsen and Davidson, 1961). More recently, Koshi (1966) again illustrated a calibration curve passing through the origin.

It was, therefore, believed desirable to establish in the cases of equation (7) and equation (10) whether it was statistically permissible to condition these equations to pass through the origin, using procedure as set out by Freese (1964).

Equation (7) was recalculated, with the restriction imposed that there be no constant term ($b_0 = 0$), to yield the equation:

$$Y = 0.3316X_1 \text{ -- } (13)$$

with $r = 0.996$ with 18 degrees of freedom.

Statistical testing of equation (13) in relation to equation (7), according to the method shown by Freese (1964), demonstrated that it was permissible to condition the relationship to pass through the origin.

The same procedure was applied to equation (5), to yield the new equation:

$$Y = 0.4789X_2 - 0.00174X_2^2 \text{ ------------------------------ } (14)$$

with $r = 0.990$ with 17 degrees of freedom.

Again, statistical testing of equation (14) in relation to equation (10) demonstrated that it was permissible to condition the relationship to pass through the origin.

Accordingly, the calibration procedure carried out resulted in equation (13) being used for the transformation of all count ratios into percent moisture by volume at depths greater than one foot, and equation (14) for this transformation in the surface foot of soil.

The calibration curve expressed by equation (13) is shown in Figure 27, the surface calibration curve expressed by equation (14) in Figure 28.

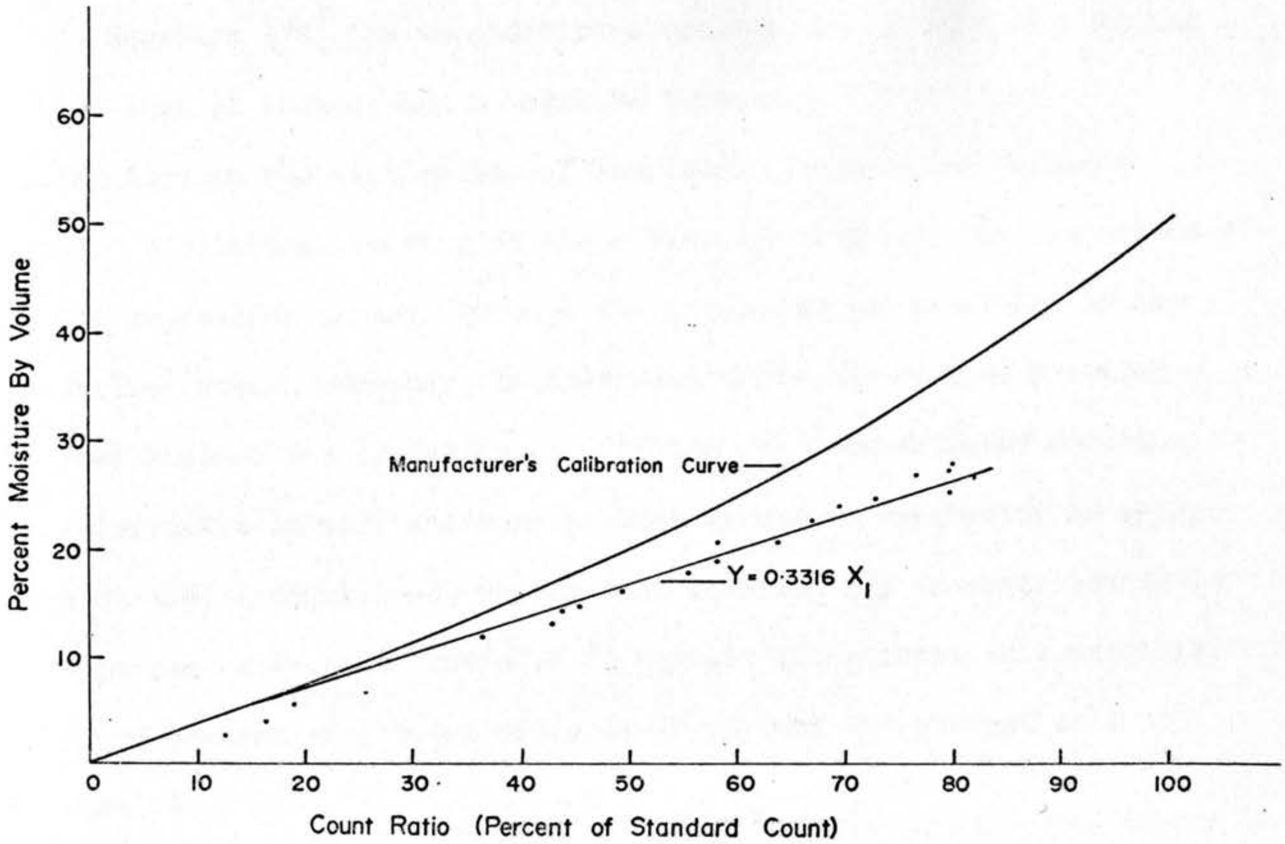
Discussion

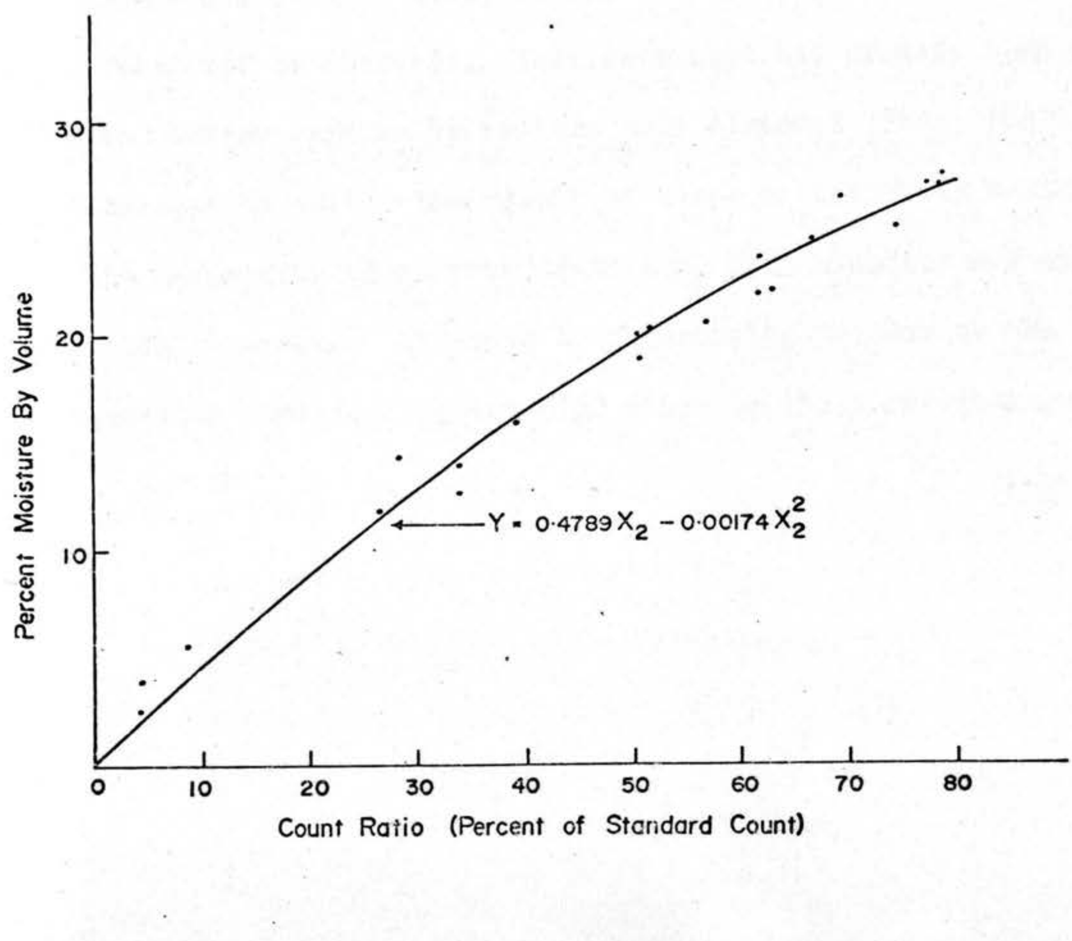
The results presented immediately above tend to encourage the view that an approximate, empirical calibration can be made, which will allow soil moisture estimates to be obtained, at least in certain soil types, in the surface foot of soil using depth probe equipment, thus obviating the difficulties encountered in the use of surface detector systems in forest conditions.

The equations obtained are precise. Examination of the actual point data in Figure 28 suggests, as would be expected, that precision is greater at higher soil moisture contents. The relatively high positive intercept in the unconditioned equation (10) can be attributed to loss of neutrons across the soil surface at low moisture contents. As such, it represents an inaccuracy in calibration. Statistical testing determined that it was permissible to condition the regression to pass through the origin, to obtain conditioned equation (14) as the final calibration for the surface foot of soil. In this instance, conditioning of the equation to pass through the origin results in improved accuracy. There are valid physical reasons for using the conditioning procedure and it seems entirely acceptable.

Figure 27. Manufacturer's calibration curve, as supplied with equipment, and individual specific calibration curve, as expressed by equation (13).

Figure 28. Individual specific calibration curve for the surface foot of soil, as expressed by equation (14).


Percent Moisture By Volume
Manufacturer's Calibration Curve
Y = 0·3316 X1
Count Ratio (Percent of Standard Count)


Percent Moisture By Volume
Y = 0·4789 X2 − 0·00174 X2²
Count Ratio (Percent of Standard Count)

Equation (7), the unconditioned calibration equation for depths greater than 12 inches, had a negative intercept. This shows a similar form to the calibration of Van Bavel, Nielsen and Davidson (1961). Statistical testing of these data again showed that conditioning the regression to pass through the origin was permissible, in the statistical sense. However, in this case there may be more pressing physical reasons for preferring to utilize the unconditioned equation. (The difference in soil moisture percent by volume estimation in using equation (13) (conditioned) rather than equation (7) (unconditioned) is -0.43 percent at a count ratio of 80 percent (27 percent soil moisture) and +0.63 percent at a count ratio of 40 percent (13 percent soil moisture)).

These data suggest that more attention might be paid to the question of statistical conditioning of calibration equations where a small intercept is obtained. This intercept has usually been attributed to neutron capture by certain soil elements (King, 1967). Where the intercept is small, the result of these calculations would suggest that the assumption of neutron capture by soil elements may not be statistically proven. It would be interesting to examine the results of regression conditioning tests on other calibration equations.

Chapter IV

RESULTS AND DISCUSSION

SNOW ACCUMULATION

Results of snowpack measurements in 1963, 1964 and 1966 can be considered separately for each of Areas #1, 2 and 3. In all areas, results are disappointing because of the ephemeral nature of the snowpack, demonstrated in Figures 29, 30, 31, 34 and 35.

Area #1

The results of measurements in Area #1 are shown in Figure 29, and in Figures 30 and 31 which also show accumulated snowfall measured at the synoptic weather station of the Kananaskis Forest Experiment Station, 700 yards distant from Area #1.

While total snowfall at the synoptic weather station in winter 1963 was approximately 6½ inches water equivalent, and almost 5 inches water equivalent in winter 1964, total snowpack in one of the four subareas of Area #1 ever reached depths exceeding six inches snow in these two winters, or water equivalents of much more than one inch. Furthermore, for long periods (Figs. 29, 30, 31) there was no snowpack whatsoever upon the ground.

It was assumed that falling snow, accumulated on the forest floor, was removed by the action of recurrent Chinook winds. Examination of air temperature records at the synoptic weather station tends to support that assumption (Figs. 32, 33). Daily maximum air temperature

Figure 29. Snow accumulation (inches) in four forest stands of Area #1 in winter 1963, winter 1964 and in January, 1966.

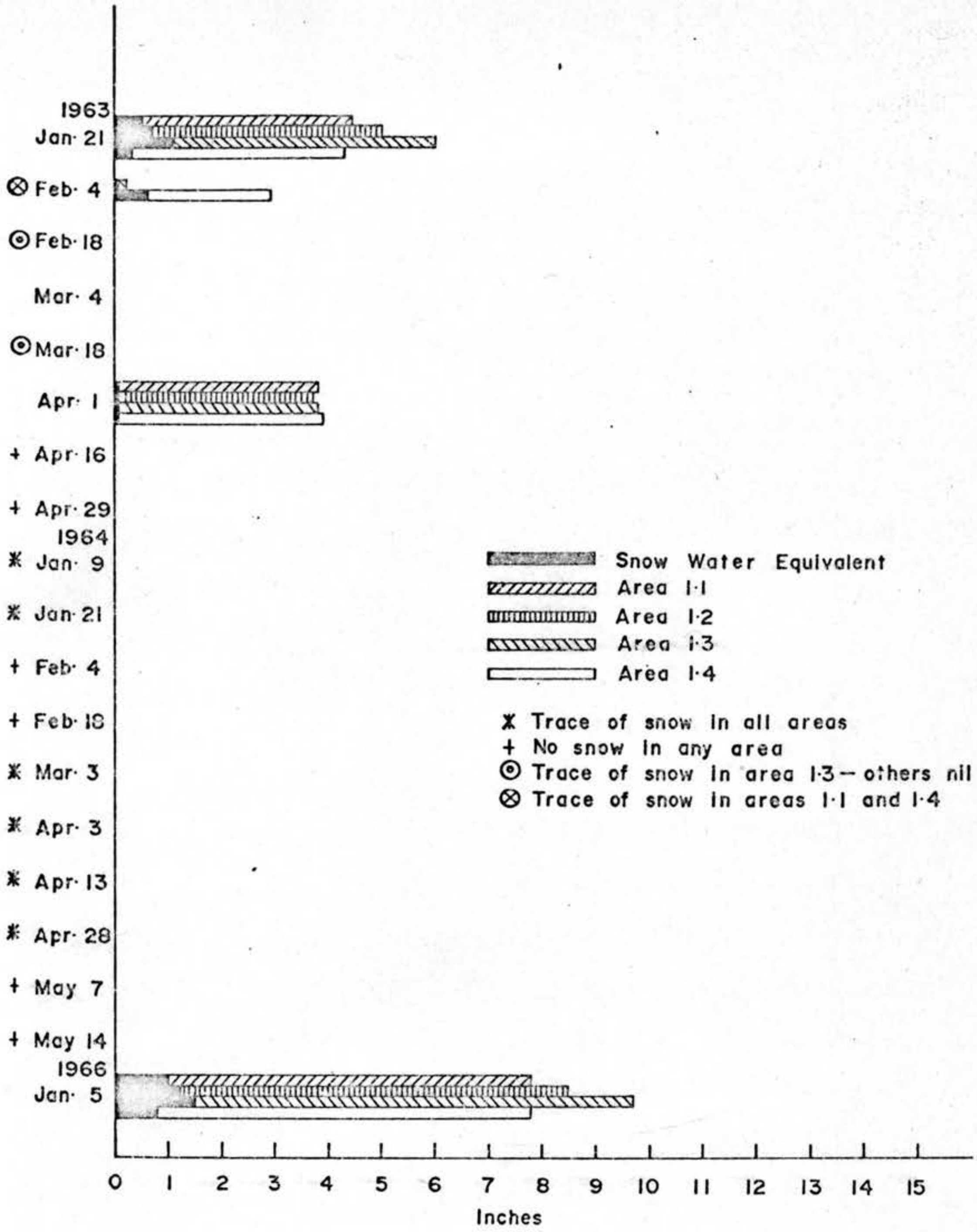

1963
Jan· 21
⊗ Feb· 4
⊙ Feb· 18
Mar· 4
⊙ Mar· 18
Apr· 1
+ Apr· 16
+ Apr· 29
1964
✱ Jan· 9
✱ Jan· 21
+ Feb· 4
+ Feb· 18
✱ Mar· 3
✱ Apr· 3
✱ Apr· 13
✱ Apr· 28
+ May 7
+ May 14
1966
Jan· 5
Snow Water Equivalent
Area 1·1
Area 1·2
Area 1·3
Area 1·4
✱ Trace of snow in all areas
+ No snow in any area
⊙ Trace of snow in area 1·3 – others nil
⊗ Trace of snow in areas 1·1 and 1·4
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Inches

Figure 30. Total accumulated snowfall measured at the Kananaskis Forest Experiment Station synoptic weather station, in January to April inclusive 1963, in comparison to values obtained by periodic measurement in Area 1.3.

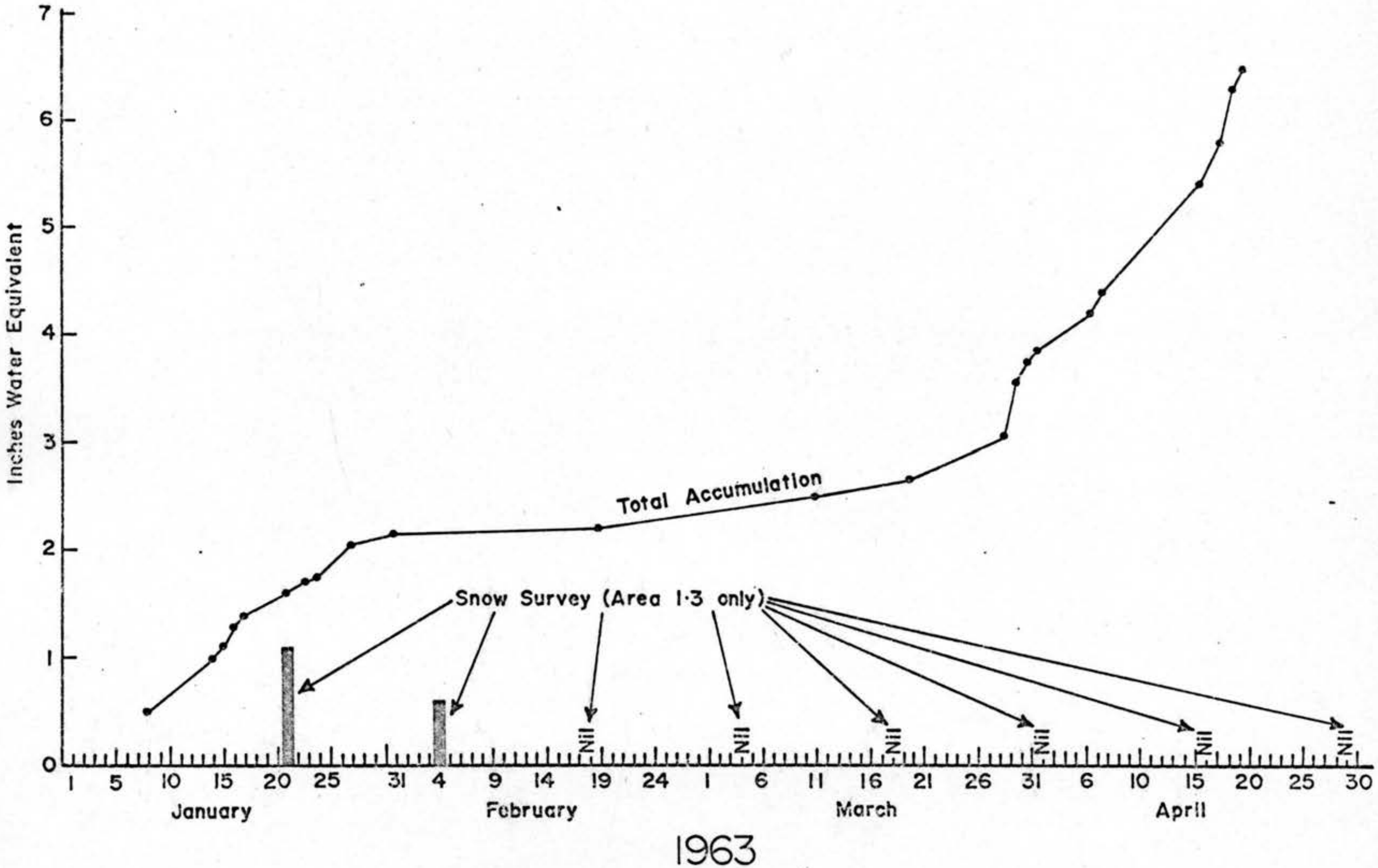
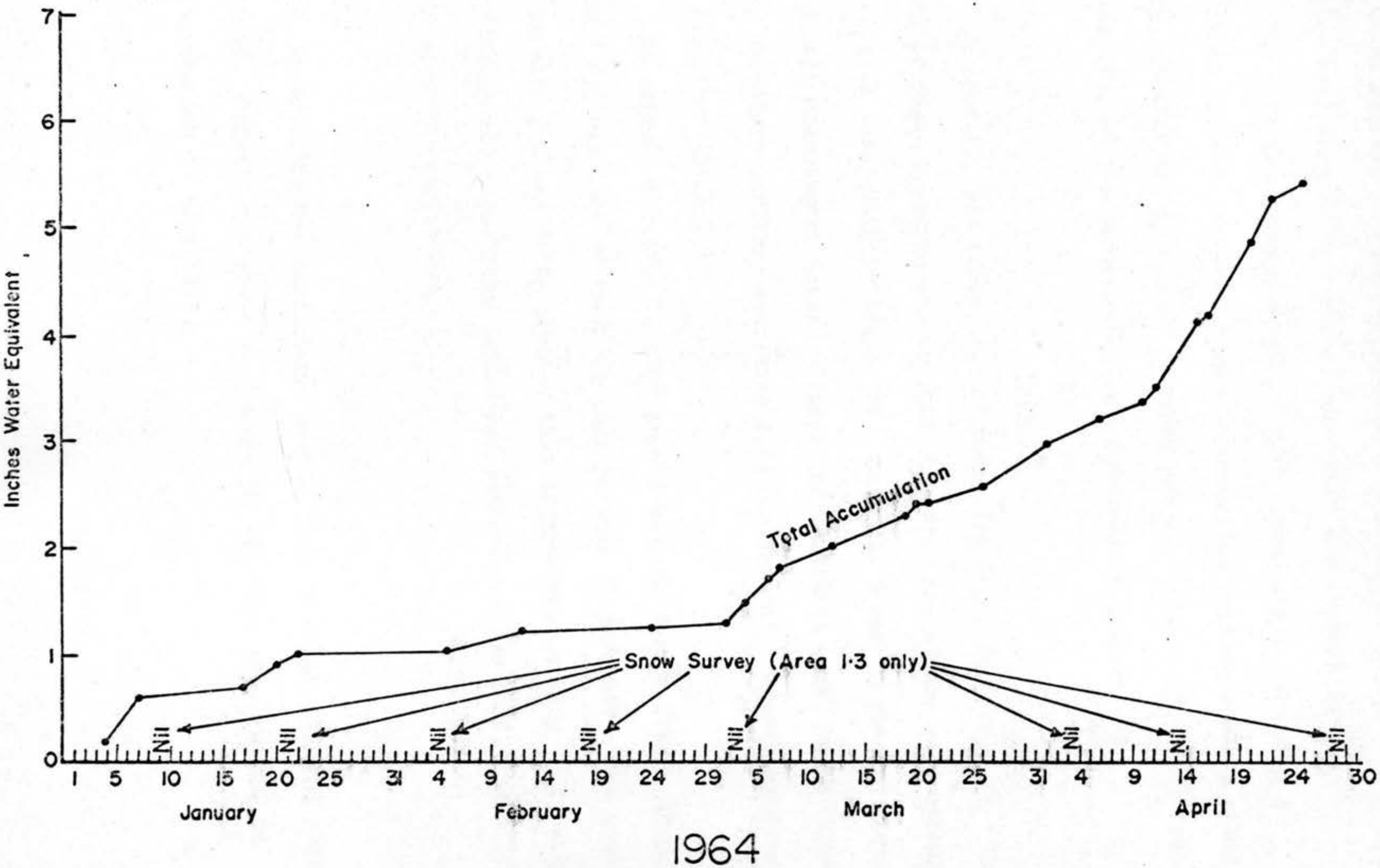

Inches Water Equivalent
Total Accumulation
Snow Survey (Area 1·3 only)
Nil
January
February
March
April
1963

Figure 31. Total accumulated snowfall measured at the Kananaskis Forest Experiment Station in January to April inclusive, 1964 in comparison to measurements obtained in Area 1.3.


Inches Water Equivalent
0
1
2
3
4
5
6
7
Total Accumulation
Snow Survey (Area 1·3 only)
Nil
Nil
Nil
Nil
Nil
Nil
Nil
Nil
1 5 10 15 20 25 31 4 9 14 19 24 29 5 10 15 20 25 31 4 9 14 19 24 30
January
February
March
April
1964

of 45 to 65 degrees F. were not uncommon, and provide evidence of advective heat surplus to occasion snow melt and evaporation.

The sole measurement taken in 1966, immediately following a major storm, showed increasing snow accumulation with decreasing stand density, as measured by number of stems per acre (Table 2). This trend was also true of the January 21, 1963 measurement (Figure 29).

Area #2

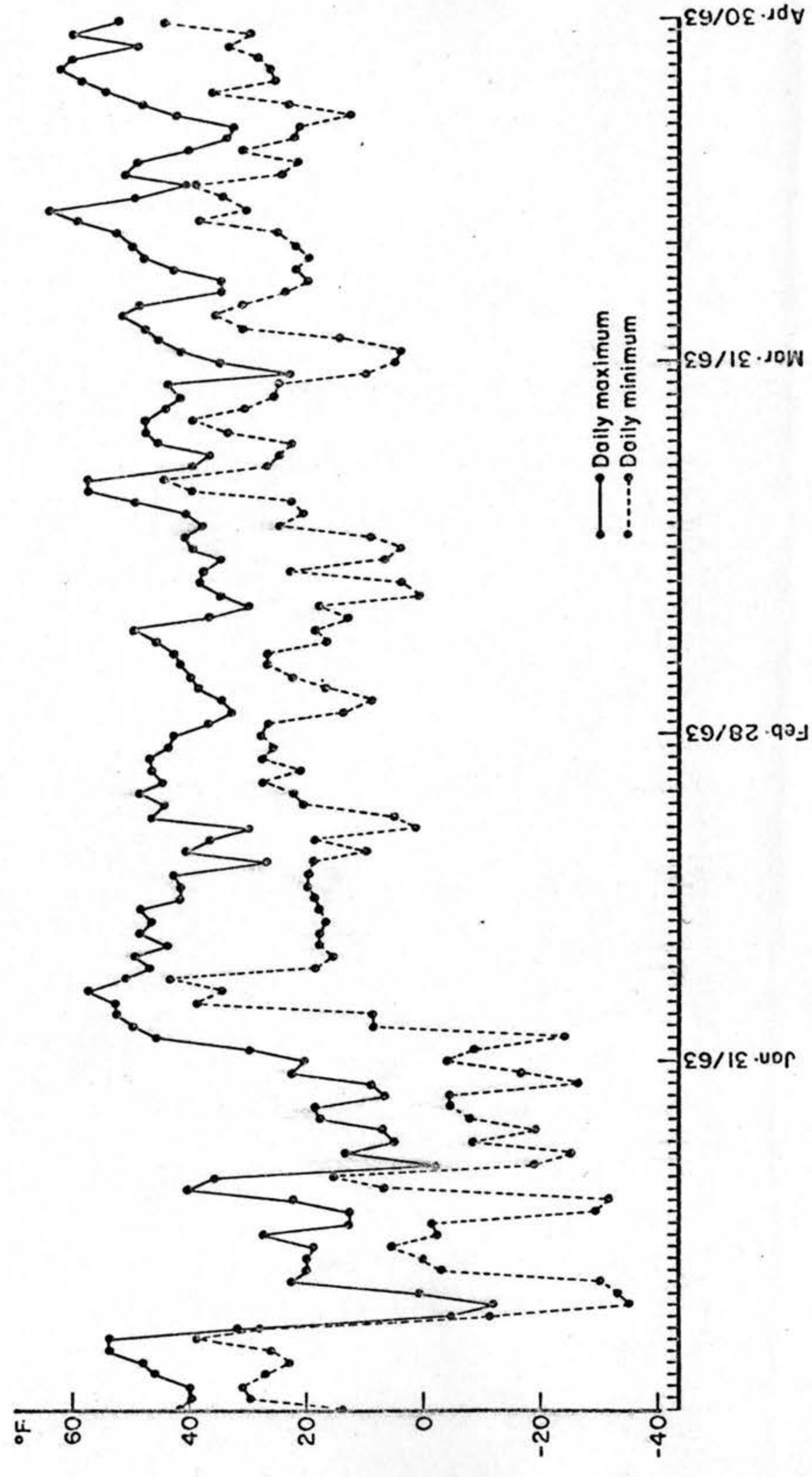
In Area #2, six areas, two of them clearings, were studied. The results of these measurements in 1963 and 1964, and of the sole measurement in 1966, are shown in Figure 34. Snow was found in the two clearings on all measurement dates. Though the clearings were, to all appearances, extremely similar, one (Area 2.6) consistently trapped more snow than the other (Area 2.5).

In common with Area #1, the ground beneath forest stands (Areas 2.1 to 2.4), was bare of snow for long periods (Figure 34). The snowpack in Area 2.2 was often greater than in the other stands (2.1, 2.3, 2.4), though all three other areas had fewer stems per acre (Table 3), albeit greater basal areas.

Area #3

In Area #3, two conditions, one of these a small clearing, were examined. Results are shown in Figure 35, and were very similar to those obtained in Area #2.

Figure 32. Daily maximum and daily minimum air temperatures measured at the synoptic weather station of the Kananaskis Forest Experiment Station in January to April, 1963.


°F.
60
40
20
0
-20
-40
Jan·31/63
Feb·28/63
Mar·31/63
Apr·30/63
Daily maximum
Daily minimum

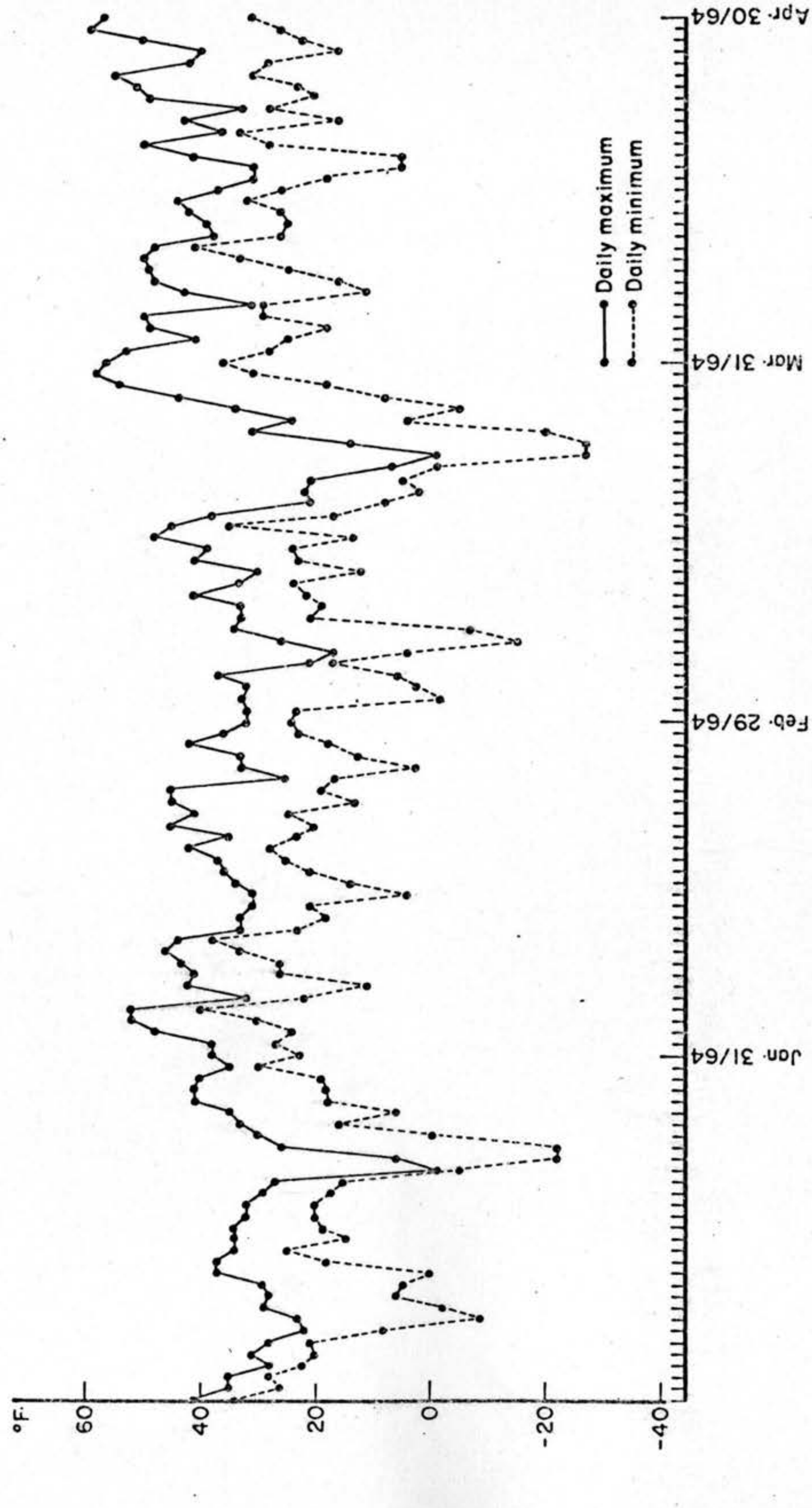

Daily maximum
Daily minimum
Apr. 30/64
Mar. 31/64
Feb. 29/64
Jan. 31/64
°F.
60
40
20
0
-20
-40

Figure 34. Snow accumulation (inches) in six sub-areas of Area #2, in January to April (inclusive) 1963, January to April (inclusive) 1964 and on January 5, 1966.

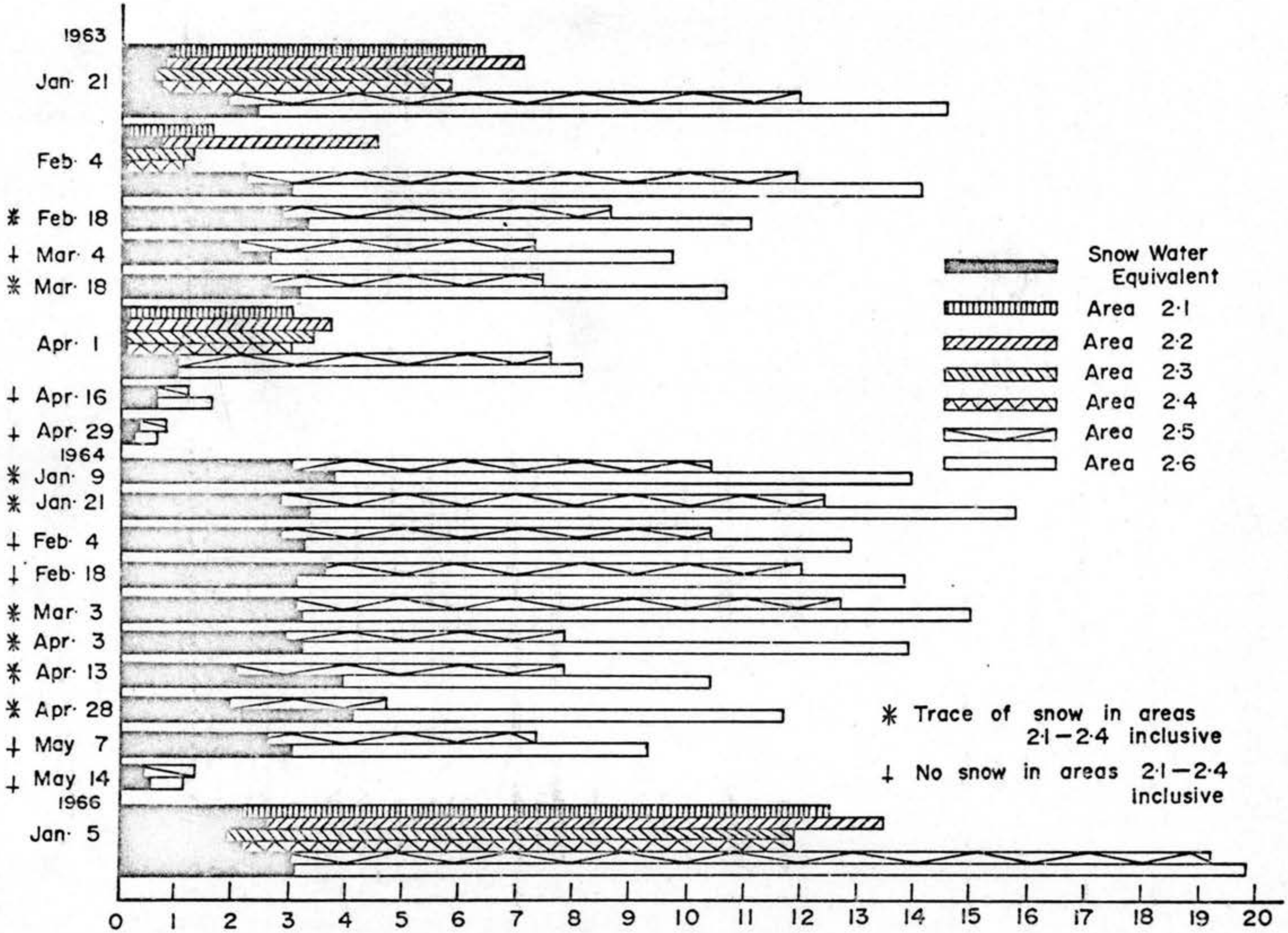
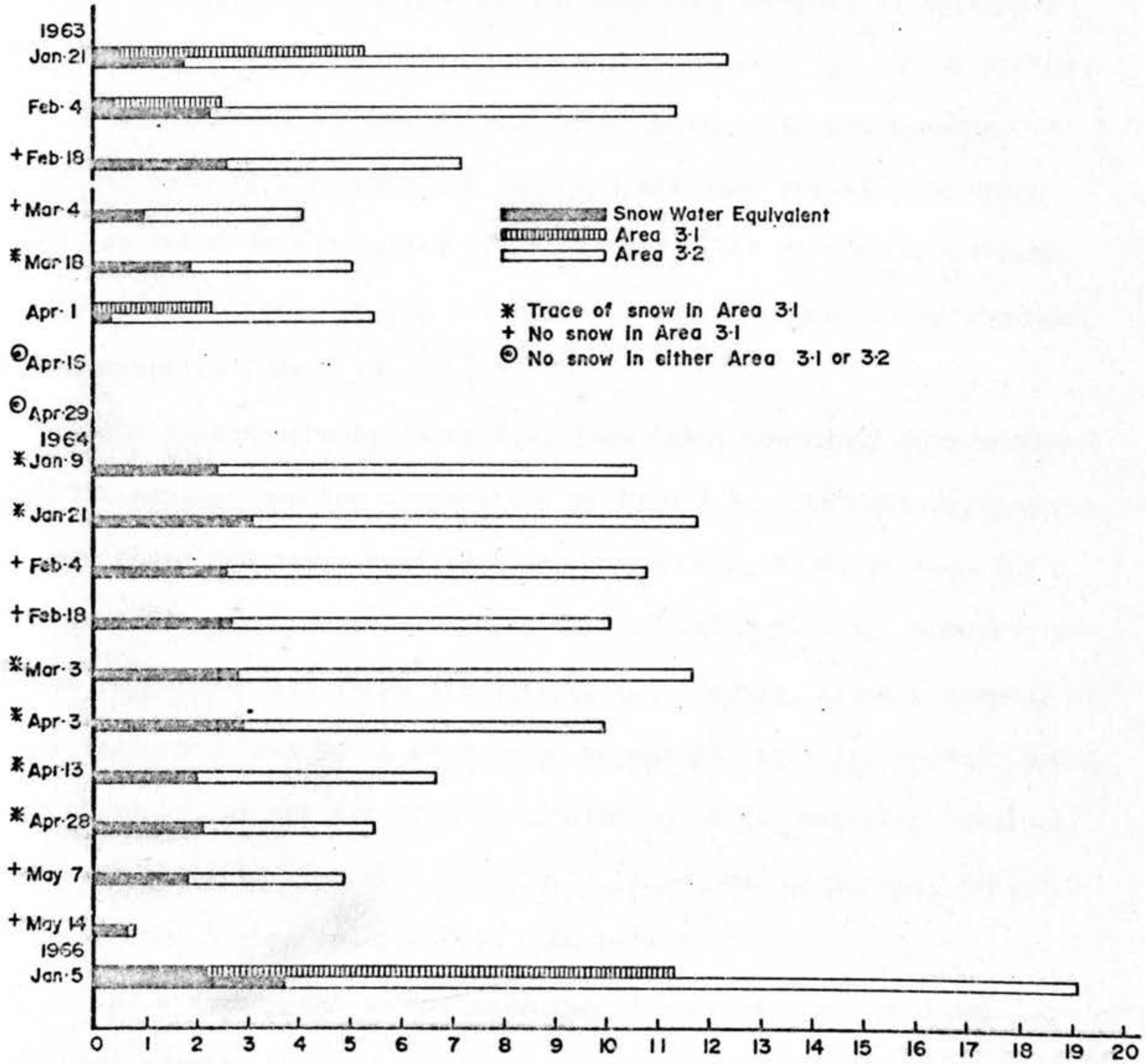

1963
Jan· 21
Feb· 4
Feb· 18
Mar· 4
Mar· 18
Apr· 1
Apr· 16
Apr· 29
1964
Jan· 9
Jan· 21
Feb· 4
Feb· 18
Mar· 3
Apr· 3
Apr· 13
Apr· 28
May 7
May 14
1966
Jan· 5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Snow Water Equivalent
Area 2·1
Area 2·2
Area 2·3
Area 2·4
Area 2·5
Area 2·6
* Trace of snow in areas 2·1 – 2·4 inclusive
No snow in areas 2·1 – 2·4 inclusive

Figure 35. Snow accumulation (inches) in Area #3, during winter 1963 and winter 1964, and on January 5, 1966.


1963
Jan·21
Feb·4
+Feb·18
+Mar·4
*Mar·18
Apr·1
⊙Apr·15
⊙Apr·29
1964
*Jan·9
*Jan·21
+Feb·4
+Feb·18
*Mar·3
*Apr·3
*Apr·13
*Apr·28
+May 7
+May 14
1966
Jan·5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Snow Water Equivalent
Area 3·1
Area 3·2
* Trace of snow in Area 3·1
+ No snow in Area 3·1
⊙ No snow in either Area 3·1 or 3·2

Discussion

The preceding results are of interest in their documentary character. They show that within the forest, at the elevations concerned, in this region of the Rocky Mountains, snowpack is ephemeral and that it fluctuates widely in its magnitude over the winter months.

The increase in snow accumulation in small forest openings is in accord with results obtained in lodgepole pine forests, in other areas, as noted in the review of literature. The difference in snow accumulation between opening and adjacent forest cannot be interpreted as interception loss.

One forest opening (Area 2.6) invariably contained more snowpack than the similar opening represented by Area 2.5. The main differences between these two areas were that the surrounding trees on Area 2.5 were less dense and somewhat taller than around Area 2.6. However, it is not suggested that these are determining factors, since a complex of other influences may be at work, e.g. topographically-influenced, local wind currents, or the aerodynamic smoothness of the canopies involved. There was a slight elevation difference in the two clearings, Area 2.6 being 40 feet higher in elevation than Area 2.5.

These data point to the need for further research in the following areas:

(1) The disposition of snow during snowpack fluctuations during winter; the portion evaporated and that going to soil moisture recharge as melt waters.

(2) The contribution to soil moisture recharge as a result of snow melting and dripping from the forest canopy, and the magnitude of snow interception losses.

(3) The management implications of small openings and strips in lodgepole pine stands in this elevational zone.

In conclusion, it is difficult, because of the paucity of data, to make any reliable generalizations concerning snow accumulation and stand density. A general trend of greater snow accumulation in stands with less basal area (Area #2) or with fewer stems per acre (Area #1) can be considered as suggested, though not confirmed, by the results obtained.

CANOPY INTERCEPTION OF RAINFALL

Canopy interception studies dealt with the following topics:

(1) Throughfall, as measured by standard gauges, in the three plots.

(2) Stemflow, as a component of net precipitation.

(3) Throughfall variation within plots.

(4) Trough gauge performance, as compared to standard gauges, in throughfall estimation.

These topics are considered separately on the pages which follow.

Throughfall - Differences Between Plots

Three plots were studied. Plot 1 had been thinned in 1941; Plot 2 was its unthinned counterpart. Plot 3 was an unthinned dense stand of low height and low mean DBH.

Only measurements taken by standard raingauges are considered under this heading. Trough gauge data receive later treatment.

Results of Original Studies

In the period of 1963, during which measurements were taken, 21 storms were experienced having total gross precipitation of 10.11 inches. In the 1964 period, 25 storms were measured, having total gross precipitation of 4.77 inches.

The basic statistics of gross precipitation for each plot are given in Table 10 for 1963 and Table 11 for 1964. During 1963, Plot 1 was the first to be instrumented, followed by Plot 2, with Plot 3 being set up later in the season. Readings in Plot 1 began on June 16, 1963 and terminated on August 25, 1963. In 1964, readings began on June 12, 1964 and terminated on September 18, 1964.

A summary of 1963 plus 1964 gross precipitation is contained in Table 12. The frequency distribution of storms in 1963 and 1964 by storm size classes is given in Table 13.

Table 13 shows that very few storms exceeded 1.00 inch, while over 50 percent of the storms measured had a gross precipitation of 0.20 inches or less. Values of throughfall, interception and gauge variation on all three plots in both years are given in Table 14. Differences between the two gauges located in the clearings shown in Figure 2, and used to measure gross precipitation, occurred occasionally but were not significant. Mean values of the five to 10 gauges within each plot are given as throughfall in Table 14. Also included is the value for each storm of the throughfall gauge having the highest reading. This value exceeded gross precipitation in approximately 30 percent of the storms measured.

Table 10. Basic statistics of 1963 precipitation used for analysis, showing number of storms, total gross precipitation, mean, maximum, minimum precipitation per storm, standard deviation and coefficient of variation percent

	PLOT NUMBER		
	1	2	3
No. of storms	21	21	14
Total gross precipitation (inches)	10.11	10.11	5.04
Mean precipitation (inches)	0.48	0.48	0.36
Maximum precipitation (inches)	2.40	2.40	2.30
Minimum precipitation (inches)	0.01	0.01	0.01
Standard deviation	0.74	0.74	0.59
Coefficient of variation (%)	154	154	165

Table 11. Basic statistics of 1964 precipitation used for analysis, showing number of storms, total gross precipitation, mean, maximum, minimum precipitation per storm, standard deviation and coefficient of variation percent.

	PLOT NUMBER		
	1	2	3
No. of storms	25	25	25
Total gross precipitation (inches)	4.77	4.77	4.77
Mean precipitation (inches)	0.19	0.19	0.19
Maximum precipitation (inches)	0.74	0.74	0.74
Minimum precipitation (inches)	0.01	0.01	0.01
Standard deviation	0.18	0.18	0.18
Coefficient of variation (%)	95	95	95

Table 12. Basic statistics of 1963 + 1964 precipitation used for analysis, showing number of storms, total gross precipitation, mean, maximum, minimum precipitation per storm, standard deviation, and coefficient of variation percent.

	PLOT NUMBER		
	1	2	3
No. of storms	46	46	39
Total gross precipitation (inches)	14.88	14.88	9.81
Mean precipitation (inches)	0.32	0.32	0.24
Maximum precipitation (inches)	2.40	2.40	2.30
Minimum precipitation (inches)	0.01	0.01	0.01
Standard deviation	0.53	0.53	0.38
Coefficient of variation (%)	164	164	158

Table 13 Frequency distribution of storm size in 1963 and 1964 in Plots 1, 2 and 3.

PLOT NUMBER	1				2				3			
YEAR	1963		1964		1963		1964		1963		1964	
STORM SIZE (inches)	n	%	n	%	n	%	n	%	n	%	n	%
0.01-0.10	6	29	10	40	6	29	10	40	5	36	10	40
0.11-0.20	5	24	6	24	5	24	6	24	3	21	6	24
0.21-0.30	4	19	4	16	4	19	4	16	2	14	4	16
0.31-0.40	1	5	2	8	1	5	2	8	1	7	2	8
0.41-0.50	-	-	1	4	-	-	1	4	-	-	1	4
0.51-0.60	1	5	1	4	1	5	1	4	1	7	1	4
0.61-0.70	1	5	-	-	1	5	-	-	1	7	-	-
0.71-0.80	-	-	1	4	-	-	1	4	-	-	1	4
0.81-0.90	-	-	-	-	-	-	-	-	-	-	-	-
0.91-1.00	-	-	-	-	-	-	-	-	-	-	-	-
1.00-1.25	-	-	-	-	-	-	-	-	-	-	-	-
1.26-1.50	-	-	-	-	-	-	-	-	-	-	-	-
1.51-1.75	-	-	-	-	-	-	-	-	-	-	-	-
1.76-2.00	1	5	-	-	1	5	-	-	-	-	-	-
2.01-2.25	-	-	-	-	-	-	-	-	-	-	-	-
2.26-2.50	2	10	-	-	2	10	-	-	1	7	-	-
TOTAL	21		25		21		25		14		25	
TOTAL %		100		100		100		100		100		100

Table 14 Gross precipitation, mean throughfall, maximum throughfall and interception for storms during 1963 and 1964 at Plots 1, 2 and 3.

			PLOT NUMBER								
			1			2			3		
Storm No.	GP^1	GP^2	M3 Thfl	4 Thfl	5 Int	M Thfl	X Thfl	Int	M Thfl	X Thfl	Int.
1	0.11	0.11	0.07	0.09	0.04	0.07	0.13	0.04	-	-	-
2	0.04	0.04	0.02	0.03	0.02	0.02	0.03	0.02	-	-	-
3	2.40	2.40	2.18	2.82	0.22	2.04	2.47	0.36	-	-	-
4	1.87	1.87	1.18	1.37	0.69	1.71	2.20	0.16	-	-	-
5	0.12	0.12	0.09	0.12	0.03	0.09	0.11	0.03	-	-	-
6	0.28	0.28	0.24	0.30	0.04	0.22	0.32	0.06	-	-	-
7	0.25	0.25	0.20	0.24	0.05	0.22	0.33	0.03	-	-	-
8	0.18	0.18	0.10	0.16	0.08	0.09	0.17	0.09	0.08	0.10	0.10
9	0.23	0.22	0.12	0.14	0.10	0.16	0.26	0.06	0.09	0.13	0.13
10	0.11	0.11	0.06	0.07	0.05	0.05	0.08	0.06	0.09	0.10	0.02
11	0.54	0.56	0.47	0.58	0.09	0.37	0.49	0.19	0.54	0.61	0.02
12	0.07	0.07	0.02	0.03	0.05	0.03	0.04	0.04	0.02	0.02	0.05
13	2.34	2.30	2.14	2.95	0.16	2.28	3.06	0.02	1.83	2.30	0.47
14	0.69	0.69	0.56	0.75	0.13	0.57	0.81	0.12	0.56	0.80	0.13
15	0.06	0.06	0.02	0.03	0.04	0.03	0.06	0.03	0.02	0.04	0.04
16	0.03	0.03	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02
17	0.07	0.08	0.03	0.05	0.05	0.03	0.05	0.05	0.04	0.07	0.04
18	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01
19	0.13	0.14	0.09	0.15	0.05	0.10	0.16	0.04	0.11	0.15	0.03

Table 14 Gross precipitation, mean throughfall, maximum throughfall and interception for storms during 1963 and 1964 at Plots 1, 2 and 3.- continued.

Plot Number			1			2			3		
Storm No.	GP[1]	GP[2]	M[3] Thfl	[4] Thfl	[5] Int	M Thfl	X Thfl	Int	M Thfl	X Thfl	Int
20	0.32	0.31	0.20	0.33	0.11	0.19	0.28	0.12	0.17	0.21	0.14
21	0.28	0.28	0.23	0.29	0.05	0.22	0.28	0.06	0.18	0.26	0.10
22	0.22	0.22	0.11	0.20	0.11	0.16	0.25	0.06	0.14	0.20	0.08
23	0.18	0.18	0.13	0.17	0.05	0.13	0.18	0.05	0.15	0.20	0.03
24	0.23	0.23	0.17	0.21	0.06	0.16	0.27	0.07	0.09	0.14	0.14
25	0.30	0.30	0.06	0.10	0.24	0.19	0.25	0.11	0.19	0.28	0.11
26	0.41	0.41	0.47	0.63	0.06	0.38	0.74	0.03	0.32	0.50	0.09
27	0.33	0.33	0.24	0.33	0.09	0.25	0.30	0.08	0.23	0.32	0.10
28	0.00	0.01	0.03	0.04	0.02	0.02	0.03	0.01	0.00	0.00	0.01
29	0.12	0.13	0.08	0.11	0.05	0.09	0.12	0.04	0.08	0.13	0.05
30	0.37	0.37	0.21	0.27	0.16	0.28	0.47	0.09	0.26	0.77	0.11
31	0.06	0.06	0.01	0.02	0.05	0.03	0.06	0.03	0.02	0.04	0.04
32	0.12	0.12	0.06	0.07	0.06	0.05	0.10	0.07	0.06	0.10	0.06
33	0.06	0.06	0.01	0.02	0.05	0.02	0.04	0.04	0.03	0.12	0.03
34	0.08	0.08	0.05	0.06	0.03	0.05	0.07	0.03	0.06	0.09	0.02
35	0.20	0.20	0.10	0.20	0.10	0.09	0.18	0.11	0.11	0.23	0.09
36	0.02	0.02	0.00	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.01
37	0.20	0.20	0.10	0.19	0.10	0.14	0.23	0.06	0.10	0.15	0.10
38	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01
39	0.04	0.03	0.01	0.02	0,02	0.03	0.05	0.00	0.01	0.02	0.01
40	0.21	0.21	0.12	0.16	0.09	0.13	0.19	0.08	0.11	0.16	0.10
41	0.08	0.08	0.03	0.06	0.05	0.03	0.07	0.05	0.04	0.07	0.04

Table 14 Gross precipitation, mean throughfall, maximum throughfall and interception for storms during 1963 and 1964 at Plots 1, 2 and 3 - continued.

Plot Number			1			2			3		
Storm No.	GP[1]	GP[2]	M[3] Thfl	[4] Thfl	[5] Int	M Thfl	X Thfl	Int	M Thfl	X Thfl	Int.
42	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
43	0.04	0.04	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.05	0.02
44	0.55	0.55	0.37	0.48	0.18	0.40	0.46	0.15	0.33	0.41	0.22
45	0.18	0.18	0.11	0.14	0.07	0.11	0.15	0.07	0.09	0.12	0.09
46	0.69	0.74	0.78	1.11	0.04	0.72	1.18	0.02	0.66	0.87	0.08

[1]GP = Gross precipitation in first standard gauge (inches)

[2]GP = Mean gross precipitation (inches) (two standard gauges).

[3]M Thfl = Mean throughfall (inches)

[4]X Thfl = Maximum throughfall (inches) as maximum standard gauge value recorded for given storm.

[5]Int = Interception (inches), determined as mean gross precipitation minus mean throughfall.

Results of interception and interception percent for 1963 and 1964, plus the two seasons combined are given in Table 15. Interception was calculated as:

$$\frac{\text{Sum gross precipitation - sum throughfall}}{\text{Sum gross precipitation}} \times 100$$

This is the conventional method, though an alternative method (mean of sum of interception divided by gross precipitation, for each storm) has been proposed by Kittredge, Loughead and Mazurak (1941). This second method yields consistently higher results than the method above.

Table 15 shows markedly higher interception percent values for 1964 than for 1963. This is the result of the different disposition of precipitation during the two years (Tables 10, 11, 13), there being a much higher proportion of small storms during 1964. It has been conventional in the literature to express interception as a total seasonal or monthly value. The discrepancy between 1963 and 1964 results shows the dangers inherent in this procedure.

Storms for 1963 and 1964 were classified as shown in Table 16. Within each storm class, for each plot separately, individual storm interception percent values were determined and averages for each class computed. Results for 1963, 1964 and 1963/4 combined are given in Table 16. It is evident that the number of storms measured was not sufficiently large for meaningful average values to be obtained for individual storm classes. Accordingly, the results expressed in Table 16 are not further considered.

Simple linear regression equations of mean throughfall per storm on gross precipitation were calculated in each plot for each year

Table 15 Gross precipitation, throughfall, interception and interception percent for each Plot for 1963/1964 and 1963/4 combined.

	PLOT NUMBER		
	1	2	3
		1963	
Gross precipitation	10.11	10.11	5.04
Throughfall	8.03	8.50	3.74
Interception	2.08	1.61	1.30
Interception % 1	20.6	15.9	25.8
		1964	
Gross precipitation	4.77	4.77	4.77
Throughfall	3.27	3.50	3.12
Interception	1.50	1.27	1.65
Interception % 1	31.4	26.6	34.6
	1963 & 1964		
Gross precipitation	14.88	14.88	9.81
Throughfall	11.30	12.00	6.86
Interception	3.58	2.88	2.95
Interception % 1	24.1	19.3	30.1

1 $\frac{\text{Sum gross precipitation - Sum net precipitation}}{\text{Sum gross precipitation}} \times 100$

Table 16 Interception percent by storm class of Plots 1, 2 and 3 for 1963, 1964 and 1963/4 combined.

Storm class (inches)	PLOT 1			PLOT 2			PLOT 3		
	No. Storms	GP[1]	Inter-ception %	No. Storms	GP[1]	Inter-ception %	No. Storms	GP[1]	Inter-ception %
				1963					
0.01-0.10	6	0.05	65.5	6	0.05	58.6	5	0.05	64.0
0.11-0.20	5	0.13	37.9	5	0.13	39.4	3	0.14	34.9
0.21-0.40	5	0.27	26.1	5	0.27	24.6	3	0.27	45.7
0.51-0.75	2	0.63	17.6	2	0.63	24.8	2	0.63	12.0
1.00 +	3	2.19	16.3	3	2.19	8.2	1	2.30	20.4
				1964					
0.01-0.10	10	0.04	57.5	10	0.04	45.0	10	0.04	47.5
0.11-0.20	6	0.16	42.6	6	0.16	39.6	6	0.16	41.6
0.21-0.30	4	0.24	52.1	4	0.24	33.3	4	0.24	44.8
0.31-0.50	3	0.37	17.1	3	0.37	18.0	3	0.37	27.0
0.51-0.75	2	0.65	10.9	2	0.65	13.2	2	0.65	23.3
				1963 & 1964					
0.01-0.10	16	0.04	60.9	16	0.04	50.7	15	0.04	53.8
0.11-0.20	11	0.15	40.7	11	0.15	39.5	9	0.16	39.6
0.21-0.30	8	0.25	37.2	8	0.25	26.6	6	0.24	45.2
0.31-0.50	4	0.36	21.1	4	0.36	22.5	4	0.36	31.2
0.51-0.75	4	0.64	14.2	4	0.64	18.9	4	0.64	17.7
1.00 +	3	2.19	16.3	3	2.19	8.2	1	2.30	20.4

[1] GP = Mean gross precipitation (per storm)

separately. These results are given in Table 17. Combining data from storms in 1963 and 1964 similar regression equations were computed for each plot. Covariance analysis showed this to be permissible. Combined seasons results are given in Table 18 and graphically presented in Figure 36. Individual storm values around Plot 1 are shown in Figure 37, as an example of storm size distribution.

In addition to the basic statistics of each linear equation, the initial storage capacity was computed and is given in Tables 17 and 18. Determination of initial storage capacity was by the technique employed by Wilm and Niederhof (1941) and does not allow for the curvilinearity proposed by Rutter (1963). The interception values of Plot 1 were plotted over gross precipitation as shown in Figures 38 with no obvious curvilinear portion. Lack of clarity for the light storms due to their large number was overcome as shown in Figure 39 with an expanded scale. In both Figures 38 and 39 there was no obvious trend of curvilinearity, and the linear relationship was used throughout.

Discussion and Supplementary Tests

The regression equations (21), (22) and (23) presented in Table 18 indicate that throughfall is greatest in Plot 2, and least in Plot 3 (Figure 36). Thus, if the stand in Plot 1 prior to thinning was the same as that which subsequently developed into the stand studied in Plot 2, it can only be assumed that, 23 years after the thinning, no effect of thinning on throughfall persisted. Furthermore, one is tempted to conclude that canopy response to thinning was such that throughfall at the time of study had actually been reduced as a result of thinning.

Table 17. Simple linear regression equations of throughfall (Y) on gross precipitation (X) in Plots 1, 2 & 3 for 1963 and 1964 with basic statistics and computed initial storage.

Plot	Year	No. Storms	Regression constant	Regression coefficient	Regression No.	SE_E [a]	r [b]	$r^2\%$	Initial storage
1	1963	21	-0.0346	0.8661	(15)	0.108	0.987	97.4	0.042
	1964	25	-0.0432	0.9140	(16)	0.066	0.931	86.6	0.047
2	1963	21	-0.0376	0.8991	(17)	0.040	0.998	99.6	0.042
	1964	25	-0.0280	0.8866	(18)	0.034	0.979	95.8	0.032
3	1963	14	-0.0169	0.8108	(19)	0.048	0.995	99.1	0.021
	1964	25	-0.0237	0.7826	(20)	0.035	0.973	94.6	0.030

a. SE_E = standard error of estimate

b. r^b = simple correlation coefficient, and

c. $r^2\%$ = coefficient of determination percentage

Table 18. Simple linear regression equations of throughfall (Y) on gross precipitation (X) in Plots 1, 2 & 3 for 1963/4 combined with basic statistics and computed initial storage.

Plot	No. Storms	Regression constant	Regression coefficient	Regression No.	SE_E	r	r^2%	Initial storage (inches)
1	46	-0.0352	0.8689	(21)	0.086	0.983	96.7	0.040
2	46	-0.0328	0.8965	(22)	0.037	0.997	99.4	0.037
3	39	-0.0245	0.8101	(23)	0.039	0.992	98.5	0.030

Figure 36. Simple linear regression equations of throughfall (Y) on gross precipitation (X) in Plots 1, 2 and 3 for 1963/64 combined.

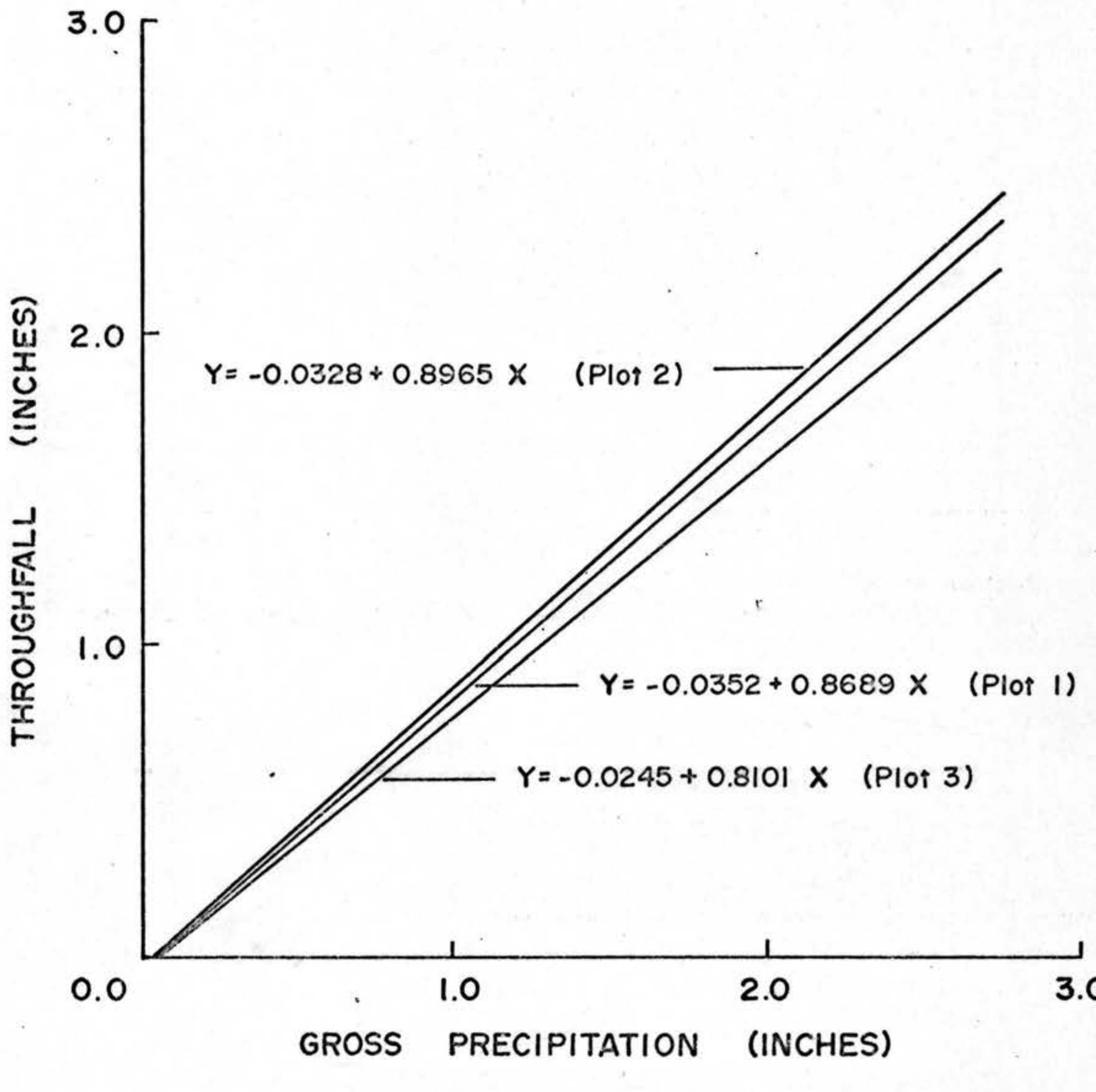

3.0
2.0
1.0
0.0
THROUGHFALL (INCHES)
Y= -0.0328 + 0.8965 X (Plot 2)
Y= -0.0352 + 0.8689 X (Plot 1)
Y= -0.0245 + 0.8101 X (Plot 3)
1.0
2.0
3.0
GROSS PRECIPITATION (INCHES)

Figure 37. Simple linear regression equation of throughfall (Y) on gross precipitation (X) in Plot 1 for 1963/64 combined, showing individual storm data.

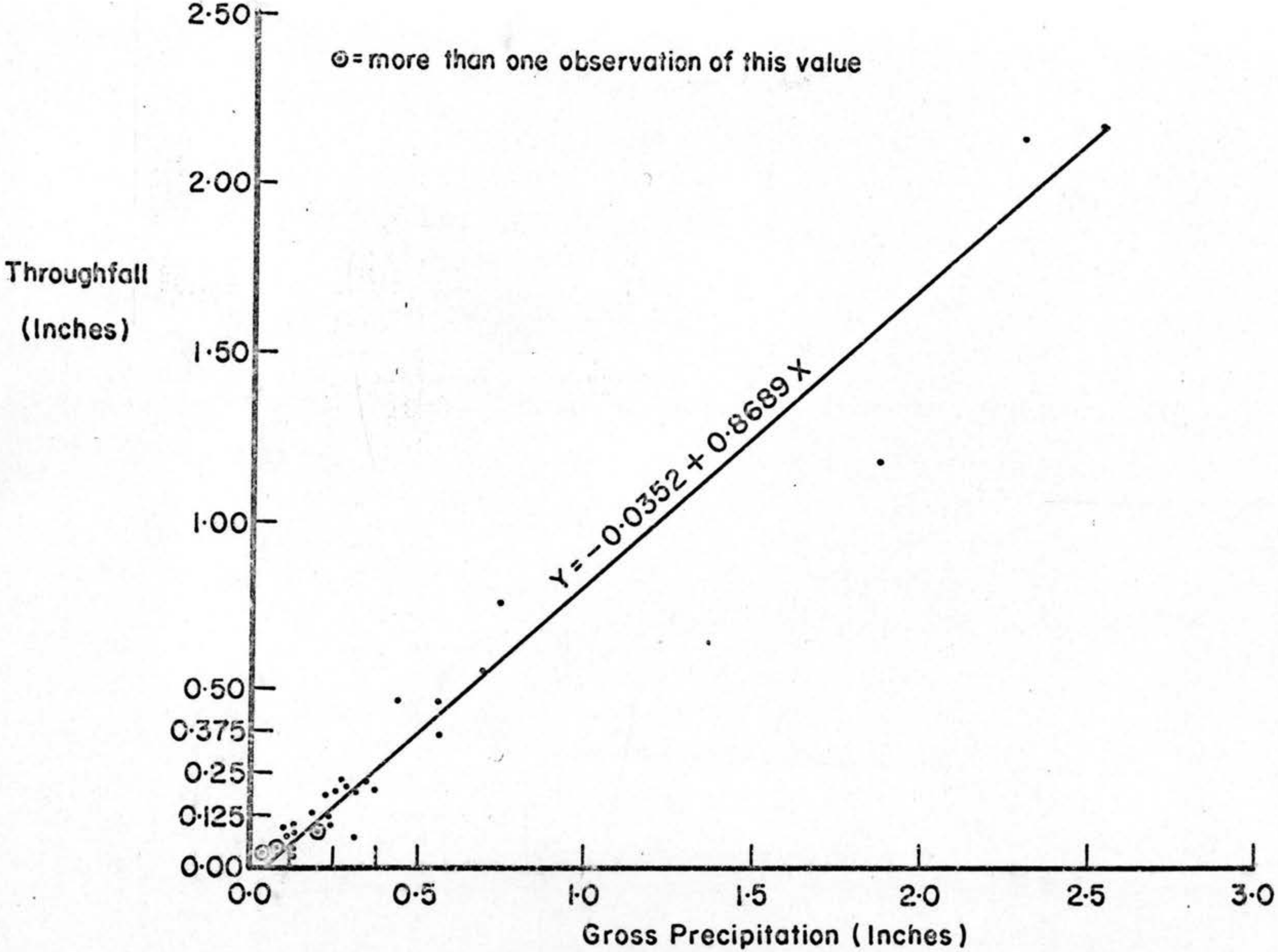
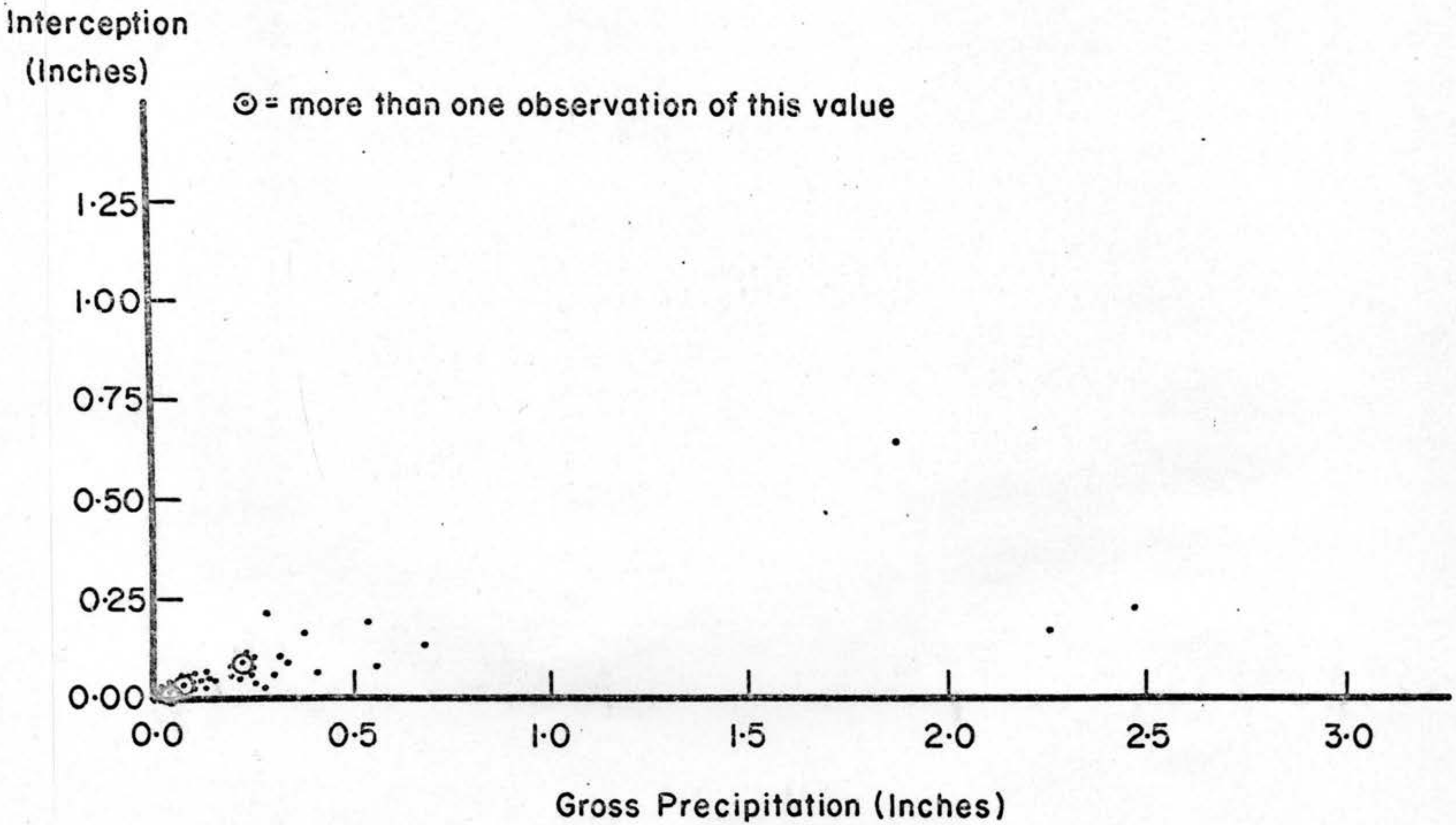
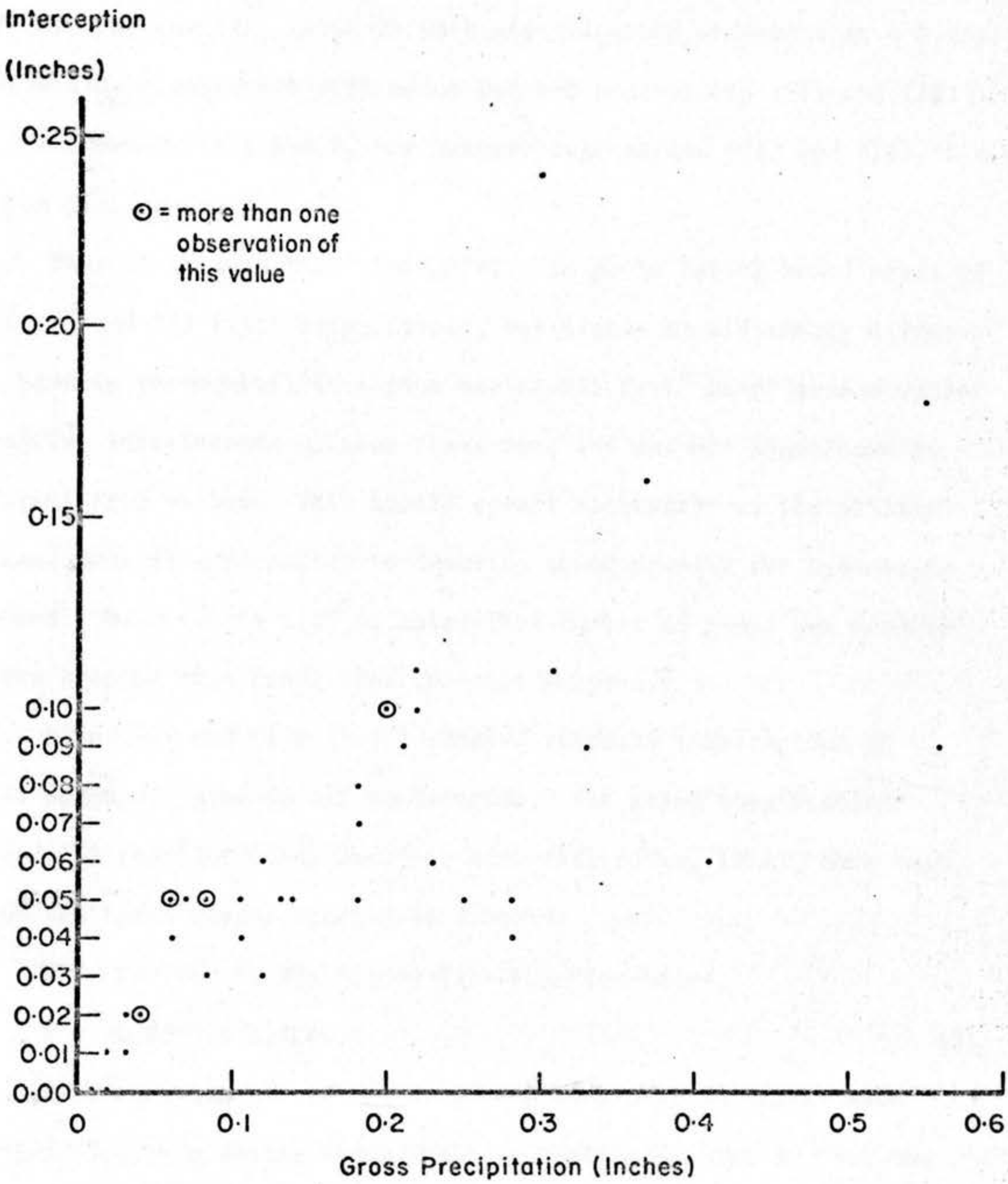

⊙ = more than one observation of this value
Throughfall (Inches)
2·50
2·00
1·50
1·00
0·50
0·375
0·25
0·125
0·00
0·0
0·5
1·0
1·5
2·0
2·5
3·0
Gross Precipitation (Inches)
Y = −0·0352 + 0·8689 X

Figure 38. Relationship between interception and gross precipitation in Plot 1 for 1963-64 combined showing individual storm values.



Interception
(Inches)
⊙ = more than one observation of this value
1·25
1·00
0·75
0·50
0·25
0·00
0·0
0·5
1·0
1·5
2·0
2·5
3·0
Gross Precipitation (Inches)

Figure 39. Relationship between interception and gross precipitation in Plot 1 for 1963/64 combined showing individual storms, but omitting storms of more than 0.60 inches.


Interception
(Inches)
0·25
0·20
0·15
0·10
0·09
0·08
0·07
0·06
0·05
0·04
0·03
0·02
0·01
0·00
⊙ = more than one observation of this value
0
0·1
0·2
0·3
0·4
0·5
0·6
Gross Precipitation (Inches)

Covariance analysis to test difference between regression (21), (22) and (23) was carried out. This analysis showed that regressions (22) (Plot 2) and (23) (Plot 3) were significantly different ($p = 0.01$). There was no significant difference between regressions (21) and (22), i.e., between Plots 1 and 2, nor between regressions (21) and (23), i.e., between Plots 1 and 3.

Thus it is seen that throughfall, in plots having basal areas of 140 $feet^2$ and 142 $feet^2$ respectively, was highly significantly different, whereas throughfall in a plot having 155 $feet^2$ basal area occupied a position intermediate between these two, and was not significantly different from either. This surely speaks eloquently of the utility of basal area as a parameter to describe stand density for hydrologic purposes. However, it will be noted that number of stems per acre is no more helpful than basal area for this purpose.

Niederhof and Wilm (1943) studied rainfall interception in mature lodgepole pine forest in Colorado. The stand they studied carried 159 $feet^2$ of basal area per acre (Kittredge, 1948), more than any of the three stands studied in Alberta.

They arrived at the throughfall equation below:

$$Y = -0.0290 + 0.8046\ X \qquad (2)$$

This equation it will be noted, is virtually identical with equation (23), expressing throughfall in 1963/64 in Plot 3. Yet the stand of Niederhof and Wilm (1943) was entirely different from Plot 3, having 300 to 400 trees per acre larger than 3.5 inches DBH (Wilm and Dunford, 1948), whereas Plot 3 had over 4500 stems per acre, with a mean DBH of 2.0 inches.

Horton (1919) derived the equation:

$$GP - E = NP + LS$$

where GP = gross precipitation,

E = evaporation during a storm,

NP = net precipitation (throughfall),

LS = leaf storage.

Direct measurement of GP and NP are possible and leaf storage (LS) can be computed.

One distinct problem with the equation above is the necessity that gross precipitation and net precipitation are comparable. They both should be precise measurements. Within the experiment described above, gross precipitation was measured at ground level with standard gauges which were located in large openings. The gauges were relatively close to the plots and thus comparable with conditions experienced within the plots. The very small differences between the two outside gauges in both locations are seen in Table 14. Ideally, the validity of the measurements of these gauges should be checked by comparing them with over-canopy gauges and standard ground level gauges set on both the windward and leeward sides of the plots. Wicht (1941) found a definite "exposure" effect on his outside gauge but Rowe and Hendrix (1951) found a negligible difference between ground level gauges and canopy gauges.

Leaf storage, or initial storage values, were given in Table 17 for the two seasons studied. There appears to be no regular relationship between leaf storage and plot basal area or number of stems. Values of leaf storage reported here generally exceed those given by Niederhof and Wilm (1943), but gross precipitation in Alberta was higher than that in Colorado. Storage capacities were summarised by Zinke (1967) for a variety of conifers. The overall results for 1963/64 given in Table 18 are higher than those previously published for lodgepole pine.

The variation in initial storage values given in Table 17 is due to a variety of factors which cannot be separated easily. Between the two seasons there is a difference in total precipitation and storm size frequency (Table 10, 11, 13). Why values should be higher for the 1963 season when rainfall was heavier is unknown. The difficulties experienced in attempting to correlate water storage and leaf surface area have been described by Grah and Wilson (1944).

Zinke (1967) summarised techniques used to determine net precipitation and pointed out that there were usually insufficient sampling points used. Within this study there were 5 or 10 gauges. Some results quoted by Zinke (1967) indicated 15 gauges would have been desirable in order to obtain a 5 percent standard error of estimate, but even more may be required with the light precipitation commonly experienced within the experimental area. The large variation in storm size (Tables 13, 14, 15) rendered an accurate measurement of throughfall difficult, especially when a few large storms were recorded. During 1963, three large storm events (more than one inch of rain) occurred (Table 14) and these caused the large standard deviation in Table 10 compared with Table 11.

Some of the problems of standard gauges and locations within plots are revealed in Table 14. Rainfall intercepted in at least one gauge commonly exceeded gross precipitation. On occasions, however, the mean of five or 10 gauges exceeded gross precipitation and there was "negative interception." In Plot 1 this occurred in storms number 26, 28 and 46. Excesses are possible balanced by abnormally low values such as storms 4 and 25 in Table 14. This large variation, however, affects the determination of interception percent. This would help explain some of the anomalies in Table 16. Although the trend of interception values in this table is correct, they do not approach the regular sequence reported by Penman (1963).

Following scrutiny of the regression equations obtained in Plots 1, 2 and 3, as presented in Table 18, it became obvious that throughfall in the three plots did not follow any neat relationship with basal area per unit area, as postulated by Wilm and Dunford (1948), Kittredge (1948) and Rogerson (1967), among others. Attention was therefore given to the possibility of measuring other variables which might account for the differences in throughfall between the three plots.

Zinke's (1967) review suggested the possibility of canopy density being a pertinent factor. In each of the 100 points on each plot, it was noted, by measurement in 1967, whether the sampling point lay beneath, or between, tree crowns. Sampling points were randomly located; the estimate obtained therefore was believed to be reliable. These measurements showed canopy density on the three plots to be, as follows:

Plot 1	Plot 2	Plot 3
62%	65%	89%

Since only three plots were examined, the utilization of canopy density in a regression model was considered to be unjustified and was not attempted. Inspection shows, however, that the discrepancy between the throughfall estimate for Plot 3 and those for Plots 1 and 2 is approximately consistent with the values of canopy density obtained above, though it is somewhat in disagreement with the results of co-variance analysis.

Miller (1959) suggested stem density (Σ DBH) to be well correlated with transmission of insolation in lodgepole pine stands. Plot stem densities were calculated, to yield the results below:

Plot 1	Plot 2	Plot 3
941 inches	1512 inches	2296 inches

With only three plots, interpretation of stem density into a regression model could not be attempted. However, by inspection it is seen that, while the stem density value for Plot 3 may be helpful in understanding the low throughfall experienced there, the relative stem density values for Plots 1 and 2 are in opposition to the throughfall estimates obtained for those two plots.

Delfs (1967) considered stand age and crown length to be variables which helped determine throughfall amounts, in intensively managed stands of European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*) in Germany.

In the three lodgepole pine plots of this study, stand age was virtually identical (Table 4), so that this parameter may be ignored. However, crown length data were available on all three plots. The average crown length (mean of 30 lodgepole pine trees per plot) in the three plots was (Table 4), as follows:

Plot 1	Plot 2	Plot 3
16.7 feet	14.6 feet	12.0 feet

It is obvious from these values that crown length is not helpful in explaining the observed differences between plots.

During 1967, for 20 sample trees in each plot, crown width was measured, along with DBH and total height. If one assumes that crown projectional area (CPA) is a true circle, then it may be calculated from crown width. Similarly, if crown form is assumed to be paraboloid, then from crown width and crown length, the volume of space occupied by tree crowns (CV) and the area of the outer surface of tree crowns (CS) may also be calculated. The assumptions listed, of course, are obviously not wholly justified. However, they are arithmetically necessary and conventionally utilized by biometricians dealing with tree crown parameters.

Based upon these assumptions, crown volume (CV) and crown surface (CS) were calculated for each sample tree in each plot. From these calculated values and measured DBH data, linear regressions of crown volume (CV) and crown surface (CS) on DBH were calculated, according to the models.

(1) CV ($feet^3$) = a + b. DBH (inches)

(2) CS ($feet^3$) = a + b. DBH (inches)

The results of these regressions are shown in Table 19. Similar regressions were calculated with basal area as the independent variable. These resulted in slightly higher coefficient of determination values. These regression data are not included.

Table 19 shows that fairly precise equations expressing crown volume (CV) and crown surface (CS) as a function of DBH, were obtained. However, the slopes (Table 19) of the regression lines are practically vertical and for prediction purposes the equations are worthless. It was therefore impossible to estimate total crown volume and total crown surface from the DBH distribution, as was originally intended. A

Table 19. Regression analyses of crown volume (CV) and crown surfaces (CS) on DBH in Plots 1, 2 and 3.

Plot	Dependent variable	Regression constant	Regression coefficient	Regression No.	SE_E	r	$r^2\%$
1	CV	-272.19	91.05	(24)	130.958	0.745	55.5
	CS	- 46.86	46.92	(25)	90.365	0.640	41.0
2	CV	- 84.24	35.32	(26)	26.527	0.837	70.1
	CS	- 45.19	31.30	(27)	28.192	0.787	62.0
3	CV	- 62.36	33.05	(28)	24.602	0.860	74.0
	CS	- 53.62	37.34	(29)	23.886	0.891	79.4

<u>White spruce</u>

All Plots combined

CV	-742.65	272.54	(30)	489.469	0.745	55.6
CS	-232.45	123.71	(31)	202.290	0.775	60.1

calculation of sorts using mean DBH for individual stands, can be carried out but it, too, is a valueless estimate.

As a result of these equations, this line of enquiry had perforce to be abandoned.

Numerous investigators have calculated linear regressions expressing crown width (CW) as a function of DBH, according to the general model:

$$CW\ (feet) = a + b.\ DBH\ (inches)$$

The most recent example of the use of this model is the work of Bonnor (1964), using data from five stands at the Kananaskis Forest Experiment Station.

Using the data from the 20 lodgepole pine sample trees in each plot, and from the 23 white spruce sample trees, the following regressions were calculated:

<u>Lodgepole Pine</u>

<u>Plot 1</u>

$$CW = 2.576 + 0.588\ DBH \tag{32}$$

with $r = 0.814$, with 18 degrees of freedom.

<u>Plot 2</u>

$$CW = 0.820 \div 0.683\ DBH \tag{33}$$

with $r = 0.759$, with 18 degrees of freedom.

<u>Plot 3</u>

$$CW = 0.671 + 0.712\ DBH \tag{34}$$

with $r = 0.809$, with 18 degrees of freedom.

White Spruce

All Plots

$$CW = 3.903 + 0.657\ DBH \tag{35}$$

with r = 0.569, with 21 degrees of freedom.

The above regression values for lodgepole pine (equations (32), (33), (34)) do not support the tentative conclusions of Bonnor (1964) that stand density need not be considered as a variable in working with DBH and crown width relationships. However, this is not central to the present study.

From the regressions obtained, total crown projectional area (CPA) was calculated for each of the three plots, to yield the results below:

Plot 1	Plot 2	Plot 3
4767 feet^2	3669 feet^2	4505 feet^2

It is evident from inspection of the values that crown projectional area (CPA) does not serve to explain the differences found between plots.

The total crown circumference in linear feet also can be calculated from crown width estimates and plot stand tables. Such calculation of crown circumference per plot yielded the following values:

Plot 1	Plot 2	Plot 3
2904 feet	4160 feet	7341 feet

Crown circumference might be a pertinent variable since throughfall has been found to be heaviest in the zone of the crown near its perimeter. This was confirmed, as will be shown later, by the present study. However, if this were a pre-eminent factor, one could expect in that case to find higher values of throughfall in Plot 3, which had very much more crown circumference than the other two plots. The actual results (Figure 36) are exactly the opposite, so that one must conclude that crown circumference is not a pertinent variable.

No further tests and calculations of canopy characteristics could be made from the data either available, or capable of being obtained in 1967.

The results may be summarized as follows:

(1) In explaining the differences in throughfall between plots, basal area is of no value. This contradicts the conclusions of, among others, Rogerson (1967) and Kittredge (1948) based upon Wilm and Dunford (1948). Both of these other studies were based upon thinnings carried out just prior to measurements being made. It may be true that for such conditions, before crown response to thinning takes place, basal area is a useful variable to express stand density. However, it is worthwhile to bear in mind the conclusion of Wallis (1965) who, on examining the shortcomings of multiple regression analysis, found that a precise equation could be found which fitted the data but did not necessarily explain the relationship between the variables. Rothacher (1963) also considered basal area to be a poor estimator of intercepting canopy surface.

(2) Canopy density estimates, though three plots were too few for statistical testing, seemed in general agreement with the differences in interception between plots, inasmuch as Plot 3 which had the highest canopy interception also had a considerably higher canopy density than the other two plots. Rothacher (1963) and Skau (1964) considered canopy density to be the most reliable stand parameter for explanation of throughfall variation. Stem density was a less useful estimator.

(3) Crown length and age of stand, suggested by Delfs (1967) as pertinent variables, could not be used as explanatory parameters to

explain differences in throughfall. The ordination of crown length was the opposite in trend to the ordination of throughfall.

(4) Meaningful estimates of crown volume and crown surface could not be attained mensurationally by the approaches attempted with the data available. Slope of regression lines suggests that it is impossible to predict crown volume and surface from basal area or DBH.

(5) Neither total crown projectional area nor total crown circumference served to help explain differences in throughfall.

Stemflow Measurements

Stemflow was recorded in 1963 and 1964 on five sample trees per plot in Plot 1 and 2. Sizes of trees used are given in Tables 20 and 21. An analysis of correlation between stemflow and tree DBH revealed a complete absence of any relationship (r = 0.03). Values given in Tables 20 and 21 indicate the variability of stemflow. Within Table 20 are stemflow values (volume of water collected in cubic inches) for the storms of 1963 and 1964 from the trees in Plot 1. For each storm's gross precipitation (GP) the volume (cubic inches) of water of a raingauge with an aperture equivalent to the breast-height cross-sectional area of the sample tree has also been included. Values actually recorded which exceed the breast-height "raingauge" equivalent are underlined. Comparable values from the trees in Plot 2 are given in Table 21.

To test the relationship of stemflow with storm size the values for stemflow on two additional plots in Marmot Creek basin (Plots 4 and 5) were included with the values of Plots 1 and 2. Mean stemflow from the five sample trees in each plot was plotted over gross precipitation and mean throughfall (standard gauges). There was a total of 37 observations. Basic statistics are given in Table 22, with the correlation

Table 20 Stemflow (V.S-f) (inches^3) and breast-height surface-area equivalent[1] (V.dbh) for each sample tree and storm (GP) in Plot 1 during 1963 and 1964

	Sample Tree (DBH) - inches									
	4.4		6.6		7.5		7.6		9.3	
GP (inches)	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}
2.40	199.0	36.5	692.0	81.1	980.0	106.1	572.0	109.0	263.0	1663.0
2.34	232.0	35.6	312.0	79.9	628.5	103.5	556.0	106.2	237.3	158.9
1.87	98.7	28.4	309.5	64.0	375.0	82.8	259.0	84.9	166.2	127.1
0.69	8.6	10.5	72.7	23.6	32.8	30.5	20.5	31.3	10.4	46.8
0.69	32.8	10.5	50.1	23.6	46.6	30.5	46.6	31.3	19.1	46.8
0.55	1.7	8.4	1.7	18.8	3.6	24.4	-	-	5.2	37.4
0.54	17.3	8.2	8.6	18.5	72.7	23.9	12.1	24.5	15.6	36.6
0.41	32.8	6.2	20.8	14.0	32.8	18.1	10.4	18.6	6.9	27.8
0.37	8.6	5.6	5.2	12.7	15.6	16.4	6.9	16.8	6.9	23.1

1 The olume in cubic inches which would have been intercepted from the given storm by a raingauge whose aperture is equivalent to the sample tree breast-height cross-sectional area.

Table 20 Stemflow (V.S-f) (inches^3) and breast-height surface-area equivalent[1] (V.dbh) for each sample tree and storm (GP) in Plot 1 during 1963 and 1964. - continued.

	Sample Tree (DBH) - inches									
	4.4		6.6		7.5		7.6		9.3	
GP (inches)	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}
0.33	3.6	5.0	-	-	3.6	14.6	-	-	3.6	22.4
0.30	-	-	-	-	1.7	13.3	-	-	1.7	20.4
0.23	3.6	3.5	3.6	7.9	5.2	10.2	1.7	10.4	5.2	15.6

Table 21 Stemflow (V.S-f) (inches^3) and breast-height surface-area equivalent[1] (V.dbh) for each sample tree and storm (GP) in Plot 2 during 1963 and 1964

	Sample Tree DBH - inches									
	4.3		4.4		4.5		6.1		6.9	
GP	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}	V.S-f in.^{3}	V.dbh in.^{3}
2.40	358.5	34.8	22.5	36.5	169.9	38.2	446.8	70.1	514.5	89.8
2.34	208.0	33.9	305.0	35.6	114.3	37.2	121.2	68.3	284.0	87.5
1.87	401.5	27.1	766.5	28.4	539.0	29.7	445.0	54.6	890.0	69.9
0.69	32.8	10.0	64.0	10.5	10.4	11.0	1.7	20.2	6.9	25.8
0.69	55.4	10.0	6.9	10.5	24.2	11.0	58.9	20.2	105.7	25.8
0.54	20.8	7.8	64.0	8.2	8.6	8.6	1.7	15.8	5.2	20.2
0.41	10.4	5.9	93.5	6.2	27.7	6.5	1.7	12.0	12.1	15.3
0.33	3.6	4.8	-	-	-	-	-	-	-	-
0.30	3.6	4.3	1.7	4.6	-	-	1.7	8.8	1.7	11.2
0.23	3.6	3.4	1.7	3.5	5.2	3.7	1.7	6.7	3.6	8.1

1 The volume in cubic inches which would have been intercepted from the given storm by a raingauge whose aperture was equivalent to the sample tree breast-height cross-sectional area.

matrix in Table 23. Regression equations of mean stemflow on gross precipitation and mean throughfall are shown in Table 24. Figure 40 shows regression (36) (Table 24) and plotted stemflow values for Plot 1.

Based upon the stems per acre values in Table 4 and presuming there is no relationship between stemflow and tree breast-height-diameter, the first equation (36) in Table 24 can be used to predict total stemflow for any storm within each plot. Thus in Plot 1 with 627 stems per acre, each of which will collect (on average) a certain stem-flow from a specific storm, for a hypothetical storm of 3.00 inches a stemflow value of 16.36 lbs. or 453.0 cubic inches of water per tree can be computed. If each tree "collected" this amount, total volume collected by all trees (per acre) in Plot 1 would be:

$$453.0 \times 627 \text{ cubic inches,}$$

this volume over an acre surface area. Therefore, the depth of water in inches would be:

$$\frac{453.0 \times 627}{4840 \times 9 \times 144} = 0.045 \text{ inches}$$

Similarly, for Plot 2 with 1729 stems per acre, the value would be:

$$\frac{453.0 \times 1729}{4840 \times 9 \times 144} = 0.125 \text{ inches}$$

These values are for a 3.00 inch storm (exceeding any value recorded) yet the percentage of gross precipitation returned to the soil as stemflow would be:

$$\frac{0.045}{3.00} \times 100 \text{ or } 1.5\% \text{ in Plot 1, and}$$

$$\frac{0.125}{3.00} \times 100 \text{ or } 4.2\% \text{ in Plot 2.}$$

Table 22 Basic statistics of stemflow data from four plots combined for both 1963 and 1964 (stemflow values in pounds weight).

Variable	Mean	Standard deviation	Minimum	Maximum	Coefficient of variation %
Stemflow	4.261	7.32	0.062	36.062	171.8
Mean stemflow[1]	4.252	5.86	0.025	21.962	137.9
Tree breast-height diameter (inches)	7.50	2.77	4.30	14.80	37.0

[1]Mean of five instrumented trees on each plot.

Table 23 Simple correlation matrix between gross precipitation (GP), mean throughfall (THFL), stemflow (S-f), and mean stemflow (MS-f).

	GP	THFL	S-f	MS-f
GP	1.000			
THFL	0.978	1.000		
S-f	0.645	0.626	1.000	
MS-f	0.808	0.784	0.799	1.000

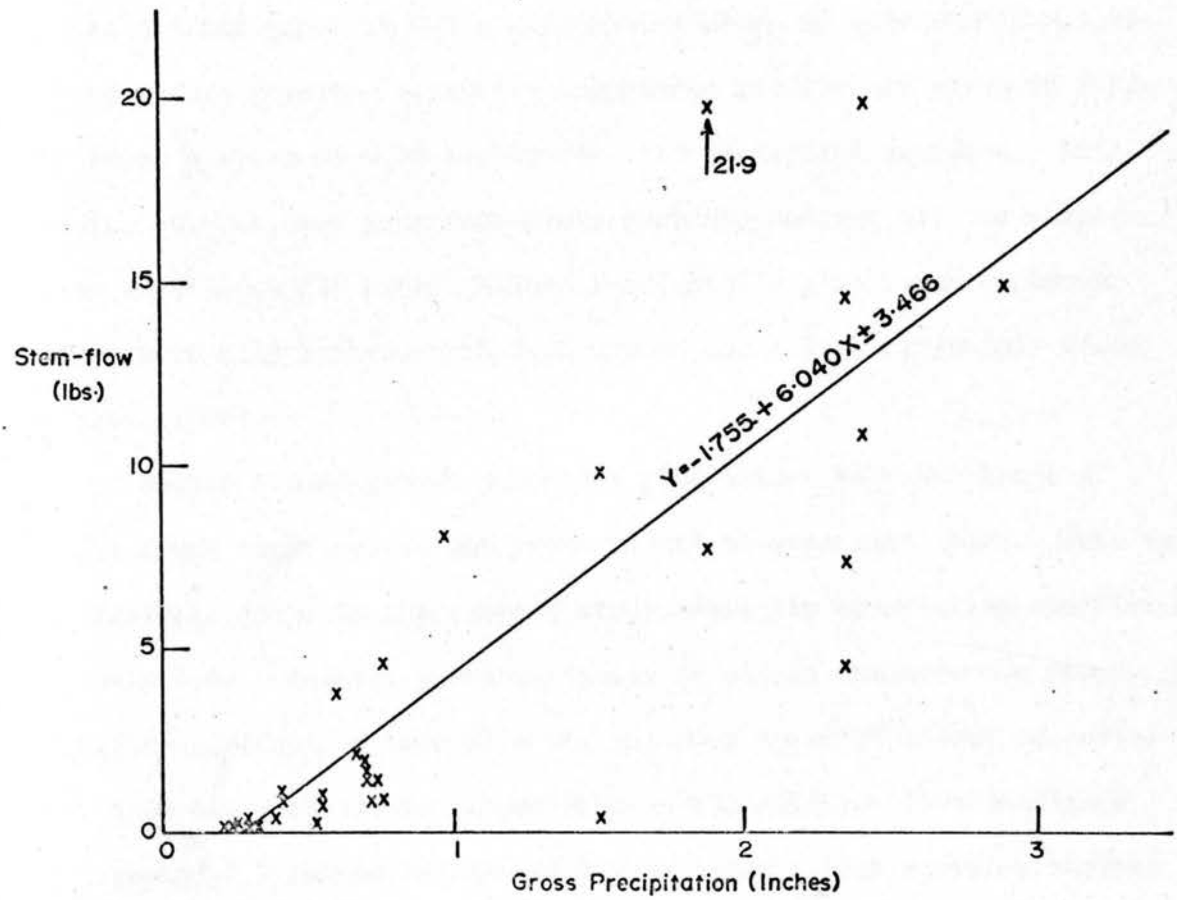
At p = 0.01, significant 'r' for 37 observations = 0.510

Table 24. Simple linear regression equations of mean stemflow (pounds weight) on gross precipitation (GP) and mean throughfall (THFL) (precipitation in inches depth)

REGRESSION CONSTANT	REGRESSION COEFFICIENT	REGRESSION NO.	SE_E	r	r^2 %	I.S.
-1.755	6.040 GP	(36)	3.466	0.808	65.3	0.291
-0.935	6.069 THFL	(37)	3.653	0.784	61.4	0.154

I.S. = Initial storage before stemflow measurable

Figure 40. Simple linear regression of stemflow (lbs.) on gross precipitation.


Stem-flow
(lbs.)
20
15
10
5
0
21·9
Y=-1·755+6·040X±3·466
0
1
2
3
Gross Precipitation (Inches)

Although several assumptions have been made above, it is apparent that very little precipitation was passed to the soil as stemflow in these stands, even from very heavy storms.

Studies by Wilm and Niederhof (1941) and Wilm and Dunford (1948) reported stemflow to be of little importance in lodgepole pine stands. In the earlier paper it was stated that a storm of 0.30 inches was required before stemflow started. Comparable results are given in Table 24, where a storm of 0.29 inches resulted in initial stemflow. This result, however, was from four plots combined and not all the sample trees were lodgepole pine. Values for loblolly pine given by Hoover (1953) were 0.10 inches, with 0.30 inches for alligator juniper cited by Skau (1964).

Within second-growth ponderosa pine stands Rowe and Hendrix (1951) found stemflow was not proportional to stem size (DBH). This was conclusively found in the current study where the correlation coefficient was only 0.03. Results given in Tables 20 and 21 indicate the non-significant effect of tree size and the more apparent effect of individual tree characteristics or position in the canopy. Thus in Plot 1 the stem of 7.5 inches DBH invariably recorded a high stemflow whereas the flow down the largest tree (9.3 inches DBH) was frequently smaller than that down the smallest tree (Table 20). Whether crown shape, i.e. ascending branches, or position of the stem of 7.5 inches DBH was determinant, is not known, but it was apparently not absolute size which determined stemflow. Similar effects could be noted in the other plots. In Table 21 the flow down the stem 4.4 inches DBH was frequently more than down the stem 6.1 inches DBH.

In Tables 20 and 21, the amount which would be collected in a raingauge whose intercepting area was equivalent to the stem cross-sectional area has been included. Individual trees varied in their yield of stemflow in relation to storm size, but generally the storm had to be more than 0.40 inches for the yield to exceed the "stem area equivalent" value. Kittredge _et al_. (1941) noted the variation of certain trees in their yield of stemflow and the effects of their location within the canopy.

Although tree size had a non-significant effect upon stemflow there was a positive effect of storm size. This is readily apparent in Tables 20 and 21. Correlation coefficients between stemflow, mean stemflow, net precipitation and gross precipitation given in Table 23 were all highly significant, though not very high. Coefficients of determination (r^2) given in Table 24 indicate other factors besides storm size must account for approximately 35 percent of the variation in stemflow. Tree characteristics and canopy position again suggest themselves as being pertinent.

The percentage of gross precipitation which is intercepted by the canopy and then passes to the soil as stemflow is important. If this value is high the overall interception may become quite small, as found by Hoover (1953). Kittredge _et al_. (1941) found stemflow on average accounted for 1.4 percent of gross precipitation in storms of 0.73 inches and 2.4 percent in storms of 1.42 inches. Individual trees showed values up to 9.0 percent in the heaviest storms. Values for a variety of species over a complete season were given by Ovington (1954).

Only 10 out of 46 storms during 1963/64 produced stemflow in Plot 1. This was comparable to the 9 out of 43 reported by Wilm and Dunford

(1948). Their gross precipitation was 11.3 inches for all 43 storms whereas Plot 1 in the present study received 14.8 inches. Wilm and Dunford (1948) assumed an average crown width of 10 feet and found stemflow per tree only amounted to 0.01 inches of water for the entire 43 storms.

Following the determination, already noted, that there was no meaningful correlation between stemflow and DBH, an attempt was made to test the correlation between stemflow volume and crown variables of instrumented trees. During 1967, data on crown length and crown width of trees instrumented for stemflow measurement in Plots 1 and 2 were secured for analysis.

Utilizing stemflow volume in cubic inches as the dependent variable, linear regressions were calculated with the following individual independent variables, (1) crown length (CL), (2) crown width (CW), (3) crown surface area (CS), (4) crown volume (CV), (5) crown projectional area (CPA).

The correlation coefficients associated with these regressions are shown in Table 25. Data for 1963 and 1964 were combined. None of the variables tested showed any significant correlation.

A further test, which converted stemflow to inches depth over the crown projectional area, was made using the same crown parameters. The results were the same. No parameter showed any marked correlation with stemflow.

Throughfall Variation Within Plots

In the evaluation of "within-stand" throughfall variation, the first step is to assess the overall variation within each stand for the

Table 25. Correlation coefficients (r) obtained in linear regression analysis of stemflow volume per storm on various parameters of crown characteristics.

INDEPENDENT VARIABLES TESTED

CL^1	CW^2	CS^3	CV^4	CPA^5
		Plot I		
0.030	0.099	0.015	0.029	0.092
		Plot 2		
0.127	0.049	0.157	0.149	0.061

1CL = crown length

2CW = crown width

3CS = crown surface area

4CV = crown volume

5CPA = crown projectional area

various storm size classes. Two measures of variation are available: (1) standard deviation, and (2) coefficient of variation.

Standard deviations and coefficients of variation were calculated for seven storm size classes in Plots 1, 2 and 3, 1963 and 1964 data being combined.

The results of these calculations are presented in Table 26.

On all three plots, trends were similar. Standard deviation increased progressively with increasing gross precipitation. Coefficient of variation decreased progressively with greater storm size. From comparison of standard deviations, one would conclude that variation increased with higher precipitation amounts. From coefficients of variation one would be tempted to believe that variation decreased in larger storms. This illustrates one of the major weaknesses and dangers of the coefficient of variation statistic, namely its sensitivity to an increase in size of mean value. From the data in Table 26, it is seen that variation increased as storm size increased.

For comparison of "within-stand" variation between plots, both the standard deviation and the coefficient of variation may be used, provided one examines each storm size class separately. From such a comparison, there is no reason to conclude that any one plot demonstrated any higher or lower variability than any of the other two plots.

The relationship between interception and soil moisture distribution was recently examined by Eschner (1967), who summarized the findings of the relevant literature.

Since the research of Hoppe (1896), it has been noted that throughfall tended to increase with increasing distance from the tree stem. For

Table 26 Variation in throughfall (1963 and 1964 combined) in Plots 1, 2 and 3 for seven storm size class.

Storm class (inches-gross precipitation)	Number of observ-ations	Mean throughfall (inches)	Standard deviation (inches)	Coefficient of variation (percent)	Range (inches)
		Plot 1			
0.01 - 0.05	65	0.0114	0.0101	89.03	0.00 - 0.03
0.06 - 0.10	63	0.0248	0.0174	70.27	0.00 - 0.06
0.11 - 0.25	150	0.1082	0.0514	47.50	0.00 - 0.24
0.26 - 0.50	60	0.2355	0.1370	58.17	0.05 - 0.63
0.51 - 0.75	25	0.6288	0.1895	30.13	0.35 - 1.11
0.76 - 1.00	0	-	-	-	-
1.01 +	20	1.8885	0.5741	30.40	0.99 - 2.95
		Plot 2			
0.01 - 0.05	85	0.0151	0.0112	74.33	0.00 - 0.05
0.06 - 0.10	83	0.0357	0.0180	50.35	0.00 - 0.10
0.11 - 0.25	149	0.1182	0.0589	49.84	0.02 - 0.33
0.26 - 0.50	65	0.2474	0.1045	42.24	0.09 - 0.74
0.51 - 0.75	25	0.5884	0.2124	36.10	0.23 - 1.18
0.76 - 1.00	0	-	-	-	-
1.01 +	18	1.9539	0.4275	21.88	1.11 - 3.06

Table 26 Variation in throughfall (1963 and 1964 combined) in Plots 1, 2 and 3 for seven storm size class - continued.

Storm class (inches-gross precipitation)	Number of observ-ations	Mean throughfall (inches)	standard deviation (inches)	Coefficient of variation (percent)	Range (inches)
		Plot 3			
0.01 - 0.05	84	0.0131	0.0160	122.03	0.00 - 0.07
0.06 - 0.10	65	0.0331	0.0223	67.37	0.00 - 0.12
0.11 - 0.25	135	0.0985	0.0477	48.43	0.01 - 0.23
0.26 - 0.50	49	0.2300	0.0857	37.27	0.07 - 0.50
0.51 - 0.75	14	0.6336	0.1525	24.08	0.31 - 0.87
0.76 - 1.00	0	-	-	-	-
1.01 +	5	1.8300	0.3838	20.97	1.26 - 2.30

pine species, data have been obtained by Hoppe (1896) and Kittredge *et al.* (1941).

While Wilm and Collett (1940) noted a similar relationship with snow accumulation in lodgepole pine stands, no studies appear to have been made to test the relationship for throughfall of rain, in relation to lodgepole pine. The present study offered an opportunity to make such a test upon sound statistical grounds.

Each interception plot contained 100 randomly selected sampling points, within which gauges were rerandomized after each measurable precipitation event.

At each of these points, in each sample plot, the following measurements were made:

1. Distance to nearest tree.
2. DBH of nearest tree.
3. Distances to each of nearest three trees.
4. DBH of each of nearest three trees.

In addition, each sampling point was classified according to the following code:

Position	Description
1A	Beneath tree crown, within 1 foot of tree stem.
1B	Beneath tree crown, distant more than 1 foot from tree stem.
2	Beneath edge of tree crown perimeter.
3	In gap, between tree crowns.

These measurements allowed tests to be made of the systematic variation of throughfall in the three lodgepole pine stands studied.

By making a conventional separation of precipitation events into six storm size classes (Table 27), and within each storm class on each plot, obtaining a mean value of throughfall, expressed as a percentage of gross precipitation, for each of the four gauge positions listed above, it was possible to make a first approximation of systematic throughfall variation, if any.

The results of this first test in Plots 1, 2 and 3 are shown in Tables 27, 28 and 29 respectively. These results are worthy of examination. They demonstrate quite well the increasing percentage throughfall as storm size increases. This relationship of increasing throughfall percentage with greater storm size is true of all gauge positions and all plots, wherever a sufficient number of observations was obtaine (n > 10). A few anomalies were found, e.g., Plot 1, Position 3, Storm class 0.76 inches +, but in these cases n < 10 and the unexpected results must be considered as a function of inadequate sampling.

Comparison of Positions 1A and 1B is best carried out in Plot 3 where, because of a larger number of stems per acre, more samples were obtained in Position 1A. In Plot 3, no substantial difference in percentage throughfall can be discerned between the two positions (Table 29). Insufficient samples were obtained in Position 1A on Plot 1 (Table 27) to allow any comparison to be made. In Plot 2 (Table 28), there again were generally insufficient samples, though the data in this case tend to suggest that throughfall percentages may be less in Position 1A than in Position 1B in this stand condition. However, only in one case, storm class 0.11 to 0.25 inches, was the sample size large enough to allow a true comparison (Table 28). In this case, the difference (Position 1A, n = 14, THFL = 0.065 inches, GP = 0.168 inches; Position 1B, n = 18, THFL = 0.113 inches, GP = 0.169 inches) is fairly large.

Table 27 Variation in throughfall in Plot 1, as determined by storm size and gauge position (1963 + 1964 combined)

STORM CLASS Inches	No. of observ-ations	Mean THFL[1] inches	Mean [2] GP inches	THFL/ GP percentage
		POSITION 1 A		
0.01 - 0.05	1	0.010	0.030	33.33
0.06 - 0.10	3	0.020	0,067	30.15
0.11 - 0.25	8	0.094	0.186	50.82
0.26 - 0.50	1	0.350	0.410	85.36
0.51 - 0.75	0	0.000	0.000	0.000
0.76 +	1	2.300	2.300	100.00
		POSITION 1 B		
0.01 - 0.05	11	0.006	0.031	19.69
0.06 - 0.10	18	0.009	0.069	12.40
0.11 - 0.25	40	0.093	0.180	52.00
0.26 - 0.50	15	0.212	0.333	61.20
0.51 - 0.75	7	0.739	0.719	102.07
0.76 +	4	1.977	2.197	89.00
		POSITION 2		
0.01 - 0.05	19	0.011	0.028	36.40
0.06 - 0.10	17	0.028	0.072	37.22
0.11 - 0.25	47	0.116	0.178	63.85
0.26 - 0.50	18	0.215	0.327	64.12
0.51 - 0.75	10	0.589	0.666	88.14
0.76 +	6	2.233	2.238	98.96
		POSITION 3		
0.01 - 0.05	34	0.013	0.029	41.17
0.06 - 0.10	25	0.035	0.070	48.73
0.11 - 0.25	55	0.115	0.168	67.68
0.26 - 0.50	26	0.259	0.318	79.27
0.51 - 0.75	8	0.582	0.676	85.58
0.76 +	9	1.573	2.159	71.92

1. THFL = throughfall

2. GP = gross precipitation

Table 28 Variation in throughfall in Plot 2 as determined by storm size and gauge position (1963 + 1964 combined)

Storm Class inches	No. of observ-ations	Mean THFL 1 inches	Mean 2 GP inches	THFL/ GP percentage
		POSITION 1 A		
0.01 - 0.05	8	0.009	0.030	27.08
0.06 - 0.10	9	0.024	0.072	33.46
0.11 - 0.25	14	0.065	0.168	38.47
0.26 - 0.50	5	0.208	0.360	56.91
0.51 - 075	2	0.355	0.625	56.49
0.76 +	3	2.317	2.313	100.16
		POSITION 1 B		
0.01 - 0.05	5	0.008	0.036	26.66
0.06 - 0.10	9	0.040	0.070	56.15
0.11 - 0.25	18	0.113	0.169	64.60
0.26 - 0.50	5	0.346	0.382	91.52
0.51 - 0.75	2	0.505	0.690	73.18
0.76 +	0	0.000	0.000	0.000
		POSITION 2		
0.01 - 0.05	50	0.015	0.031	47.63
0.06 - 0.10	40	0.034	0.069	48.63
0.11 - 0.25	62	0.121	0.174	68.11
0.26 - 0.50	34	0.247	0.313	77.19
0.51 - 0.75	10	0.706	0.689	101.19
0.76 +	6	2.152	2.235	96.99
		POSITION 3		
0.01 - 0.05	22	0.020	0.033	58.78
0.06 - 0.10	25	0.040	0.070	58.47
0.11 - 0.25	55	0.130	0.171	74.80
0.26 - 0.50	21	0.234	0.321	72.78
0.51 - 0.75	11	0.539	0.689	77.56
0.76 +	9	1.701	2.111	80.95

1 = throughfall

2 = Gross precipitation

Table 29 Variation in throughfall in Plot 3 as determined by storm size andggauge position (1963 + 1964 combined)

STORM CLASS Inches	No. of observ-ations	Mean THFL 1 inches	Mean 2 GP inches	THFL/ GP Percentage
		POSITION 1 A		
0.01 - 0.05	33	0.005	0.029	15.00
0.06 - 0.10	10	0.025	0.068	35.77
0.11 - 0.25	32	0.082	0.178	46.81
0.26 - 0.50	8	0.167	0.324	50.95
0.51 - 0.75	5	0.594	0.730	80.87
0.76 +	1	1.700	2.300	73.91
		POSITION 1 B		
0.01 - 0.05	16	0.004	0.027	10.62
0.06 - 0.10	14	0.030	0.068	43.75
0.11 - 0.25	17	0.081	0.165	49.53
0.26- 0.50	5	0.176	0.326	52.43
0.51 - 0.75	3	0.680	0.723	94.50
0.76 +	0	0.000	0.000	0.00
		POSITION 2		
0.01 - 0.05	23	0.025	0.029	80.29
0.06 - 0.10	35	0.035	0.071	49.25
0.11 - 0.25	70	0.104	0.172	59.89
0.26 - 0.50	28	0.245	0.341	71.77
0.51 - 0.75	4	0.675	0.727	92.73
0.76 +	3	2.063	2.300	89.71
		POSITION 3		
0.01 - 0.05	12	0.026	0.030	83.19
0.06 - 0.10	6	0.040	0.070	54.16
0.11 - 0.25	16	0.126	0.183	70.68
0.26 - 0.50	8	0.272	0.331	81.08
0.51 - 0.75	2	0.580	0.715	80.87
0.76 +	1	1.260	2.300	54.78

1 = throughfall

2 = Gross precipitation

In general, the results obtained do not tend to substantiate the hypothesized effect of greater canopy density near the tree stem resulting in greater canopy interception close to the tree bole, as derived by the review made by Eschner (1967). Similarly, no effect of "branch stub drip" in the annular area around the tree stem, such as noted by Leonard (1961), Voigt (1960) and Rutter (1963), can be substantiated by these data.

Comparison of data from Positions 1B and 2, allows testing of the hypothesis that "the zone of maximum throughfall is just within the perimeter of the crown" (Eschner, 1967; based upon Leyton and Carlisle, 1959 and Delfs, 1958).

In Plot 1 (Table 27), percentage throughfall values were consistently greater for Position 2 than for Position 1B, in the four storm classes in which a sufficient sample (n > 10) was obtained for both gauge positions. Plot 2 results (Table 28) are indecisive because of small sample sizes in Position 1B. In Plot 3 (Table 29), the results obtained support the conclusions derived for Plot 1. In all plots (Tables 27, 28, 29) it is interesting to note the very high frequency of samples occurring beneath crown edges.

From the data obtained, the hypothesis of greatest throughfall at the crown edge would appear to be supported.

Comparison of data from Positions 2 and 3 allows the catch in gaps between crowns to be evaluated. In Plot 1, the percentage throughfall in gaps was greater than in Positions 2 and 1B for all storms with sufficient sample sizes, i.e. up to 0.50 inches. In Plot 2 (Table 28), this again was largely true, though for storm class 0.25 to 0.50 inches the results were inconclusive. In Plot 3, due to dense canopy, few readings in gaps were obtained. Where sufficient samples were available the trend obtained was similar to Plots 1 and 2.

It is worthwhile, however, to examine the data for the larger storms, even though the sample was unavoidably small. In Plots 1 and 2, for storms greater than 0.50 inches, the percentage throughfall was invariably greater in Position 2 than in Position 3 (Tables 27, 28).

These results from Plots 1 and 2 are thought to be an expression of rainfall interception by crowns adjacent to openings at angles of rainfall incidence other than 90 degrees, and of a drip concentration effect at the crown edge. It is noteworthy that in gaps, percentage throughfall never reached 100 percent in any plot, thus demonstrating the effects of adjacent crowns interacting with rainfall angles (cf. Delfs, 1967).

From these analyses, the following tentative conclusions are suggested for lodgepole pine stands:

1. In all cases, regardless of gauge position, percentage throughfall increased as storm size became greater.
2. No evidence was found of either increased or decreased throughfall in the annular zone within one foot radius of the tree stem.
3. In all cases, the data suggest that throughfall percentage was appreciably higher at the crown edge than in other positions beneath the crown.
4. Throughfall in gaps between crowns never reached 100 percent of gross precipitation.
5. In storms of 0.50 inches or less, more throughfall was experienced in gaps than in any other position, including crown perimeters.

6. In storms greater than 0.50 inches, throughfall appeared to be greater at crown perimeters than in gaps.
7. The effect of crowns adjacent to gaps and of rainfall angles shallower than 90° is considered to account for conclusions listed under (4) and (6) above, with the added influence of drip concentration at crown perimeters postulated in the case of (6).

The conclusions just listed indicate a zone of greater throughfall at the crown edge than for the other areas of ground lying beneath tree crowns. It does not, however, indicate that there need be a relationship between throughfall and distance from the tree stem.

The existence of such organized variation in precipitation reaching the ground beneath forest stands has the stature of an accepted hydrologic fact, as shown in the review made by Eschner (1967). In most of the pertinent studies made, the effect of storm size has tended to confound the effect of distance from stem upon percentage throughfall. The data collected by standard gauges in this study and the availability of sampling point location data allowed statistical tests to be made of the relationship between percent throughfall and gauge position.

Data (1) distance to the nearest tree, and (2) mean distance to the nearest three trees, allowed two models to be tested. These are:

(1) $THFL/GP \times 100 = a + b.L_1$, where

$THFL$ = throughfall (inches)

GP = gross precipitation (inches)

L_1 = distance to nearest tree (feet)

(2) $THFL/GP \times 100 = a + b.L_3$, where

L_3 = mean distance to nearest three trees.

These models were tested in each of Plots 1, 2 and 3 for three storm classes. The first model, utilizing distance to the nearest tree (L_1), generally gave results better than the second.

The results of testing the first model, for 1963 and 1964 data combined, in the three plots are shown in Table 30. The results of testing the second model, which utilized mean distance to the nearest three trees, are shown in Appendix C.

Table 30 indicates that a relationship exists between percent throughfall and distance to the nearest stem, but that this relationship is not a strong one in lodgepole pine stands. Levels of significance ranged from $p = 0.005$ to "not significant." Where high levels of significance were obtained, coefficient of determination values were low, the highest obtained being $r^2 = 27.6\%$, and the lowest $r^2 = 2.1\%$.

While some equations were highly significant, the commonly low coefficient of correlation values lead to the conclusion that caution should be used in interpreting such a relationship. A sample plot of individual observations is given in Figure 41.

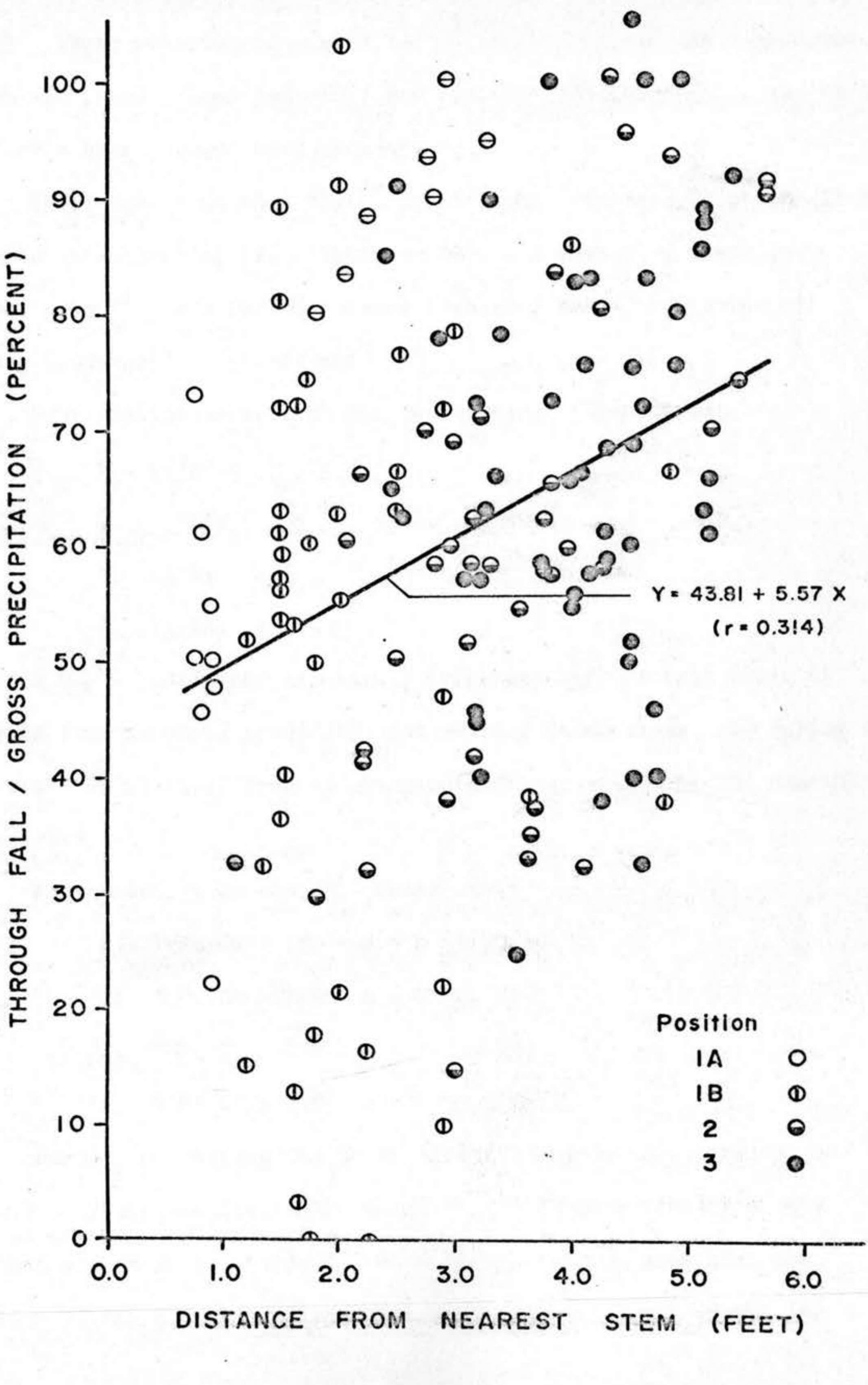
However, it is true that two factors intrude into these considerations. Firstly, data collected in gaps (Position 3) were included, so that the test was not confined to data collected beneath tree crowns. Secondly, no account was taken of variable crown width. A gauge three feet distant from a small tree might be beneath the crown perimeter, whereas another gauge an identical distance from a large tree might be midway between the stem and the crown perimeter.

The second of these factors was taken first into account. It is known that there is a strong correlation between crown width and diameter at breast height. In lodgepole pine these relationships have

Table 30 Regression equations showing the relationship between percent throughfall (Y), and (L_1) distance to nearest tree (X) for three storm class in Plots 1, 2 and 3, with all 1963 and 1964 data combined.

Storm class (inches)	No. of observ-ations	Regression equation	No. of equation	SE_E	r	r^2%	Level of Signif-icance
		PLOT 1					
0.06-0.10	63	Y=12.27+6.73X	(38)	21.36	0.376	14.1	0.005
0.11-0.25	150	Y=43.81+5.57X	(39)	21.67	0.314	9.9	0.005
0.26-0.50	60	Y=58.78+3.40X	(40)	34.29	0.144	2.1	N.S.
		PLOT 2					
0.06-0.10	83	Y=31.34+7.88X	(41)	20.52	0.470	22.1	0.005
0.11-0.25	149	Y=51.26+6.23X	(42)	22.59	0.332	11.0	0.005
0.26-0.50	65	Y=66.04+3.88X	(43)	25.01	0.169	2.8	N.S.
		PLOT 3					
0.06-0.10	65	Y=37.47+5.75X	(44)	30.83	0.144	2.1	N.S.
0.11-0.25	135	Y=40.23+10.62X	(45)	22.67	0.402	16.2	0.005
0.26-0.50	49	Y=47.68+11.31X	(46)	18.47	0.525	27.6	0.005

Figure 41. Individual observations from storms of 0.26 to 0.50 inches gross precipitation in Plot 1, and the regression line (39) obtained by analysis.


THROUGH FALL / GROSS PRECIPITATION (PERCENT)
0
10
20
30
40
50
60
70
80
90
100
0.0
1.0
2.0
3.0
4.0
5.0
6.0
DISTANCE FROM NEAREST STEM (FEET)
Y = 43.81 + 5.57 X
(r = 0.314)
Position
1A
1B
2
3

been demonstrated by a number of authors, the most recent being Bonnor (1964). These relationships were tested in these plots and high correlation was found. Equations (32) for Plot 1, (33) for Plot 2, and (34) for Plot 3 have already been presented.

These equations show that a proportional increase in crown width accompanies increasing DBH. Thus, a statistic combining distance to nearest tree (L_1) and DBH of nearest tree (D_1) takes the factor of varying crown width into account.

Four statistics were chosen for testing. These were:

1. L_1/D_1
2. L_1/BA_1
3. L_3/D_3
4. L_3/BA_3

in which BA_1 = basal area of nearest tree, and L_3/D_3 = mean ratio of distance from sampling point/DBH, for nearest three trees, and L_3/BA_3 = mean ratio of distance from sampling point/basal area, for the nearest three trees.

Four models were tested. These were:

1. $THFL/GP \times 100 = a + b\ (L_1/D_1)$
2. $THFL/GP \times 100 + a + b\ (L_1/BA_1)$
3. $THFL/GP \times 100 = a + b\ (L_3/D_3)$
4. $THFL/GP \times 100 = a + b\ (L_3/BA_3)$

Results of testing the first of these models are presented in Table 31. These results, when compared with those derived from the original simple model (Table 30) show rather conclusively that the addition of the DBH term to simulate crown width did not result in improvement of correlations, and in fact resulted in reduced "r" values in most cases.

Results obtained from the other three models tested were no better. These results are shown in Appendix C. None of these results serve to increase confidence that there is a well-established organized relationship between percent throughfall and distance from the stem, in lodgepole pine stands.

There still remains the fact that not all the data utilized in the above regression analyses were collected beneath tree crowns, since some of these came from "gap" (Position 3) situations. To test whether this had any effect, and to see whether an improved relationship was obtained by omitting Position 3 data, the same models were tested using Position 1A, 1B and 2 data only.

The results of testing the original model:

$$THFL/GP \times 100 = a + b.L_1$$

are shown in Table 32. Table 30 and Table 32 are directly comparable therefore, the sole difference being that all the data used in constructing the equations in Table 32 were collected beneath tree crowns, whereas some of those in the regressions of Table 30 came from "gap" situations.

The results using "beneath crown" data only are not greatly different from those using Position 3 data also. In most cases, the "r" values obtained were lower than those for the corresponding equations of Table 30.

The results of the model using mean distance to the nearest three trees, but omitting Position 3 data, are shown in Appendix C.

Table 31 Regression equations showing the relationship between percent throughfall (Y), and (X) ratio (L_1/D_1) of distance to nearest tree (L_1) : DBH of nearest tree (D_1) for three storm classes in Plots 1, 2 and 3, with all 1963 and 1964 data combined.

Storm class (inches)	No. of observations	Regression equation	Equation No.	SE_E	r	r^2%	Level of Significance
		PLOT 1					
0.06-0.10	63	Y=21.64+24.95X	(47)	22.41	0.233	5.4	0.100
0.11-0.25	150	Y=48.13+27.14X	(48)	22.15	0.242	5.9	0.005
0.26-0.50	60	Y=62.29+14.81X	(49)	34.45	0.107	1.1	N.S.
		PLOT 2					
0.06-0.10	83	Y=34.72+23.67X	(50)	20.98	0.430	18.5	0.005
0.11-0.25	149	Y=51.92+23.26X	(51)	22.20	0.375	14.1	0.005
0.26-0.50	65	Y=71.00+ 6.54X	(52)	25.25	0.102	1.0	N.S.
		PLOT 3					
0.06-0.10	65	Y=44.27+34.08X	(53)	31.12	0.042	0.1	N.S.
0.11-0.25	135	Y=42.76+21.97X	(54)	22.80	0.390	15.2	0.005
0.26-0.50	49	Y=50.21+27.14X	(55)	18.87	0.495	24.5	0.005

The data utilized for Table 32 equations were all collected beneath tree crowns at known distances from tree stems. As such, they are comparable to those used in constructing the regression equations of Reynolds and Leyton (1963), in which high correlation coefficients, very much higher than those obtained in the present study, were found in the relationship of throughfall and distance from stem, in a Norway spruce plantation. Reynolds and Leyton (1963), however, used throughfall for time periods of varying lengths, so that the effects of storm size were not apparent.

The plantation used by Reynolds and Leyton (1963) was young. Its mean height was 26 feet, the number of stems per acre about 2,000. It was, therefore, not dissimilar to Plot 2, and considerably less dense than Plot 3. The two situations, that of Reynolds and Leyton (1963) and that of the present study, in other words, are comparable. One must conclude that there is a considerably better organized relationship between Norway spruce throughfall and distance from stem than there exists in lodgepole pine.

The identical models using DBH and basal area to take into account variable crown spread were tested, omitting Position 3 data, to establish whether regressions were improved by confining analysis to data collected beneath the crown.

The results of this analysis using the simplest of these models:

$$THFL/GP \times 100 = a + b\ (L_1/D_1)$$

are shown in Table 33. Table 33 is therefore exactly comparable to Table 31, the sole difference being the omission of Position 3 data from the analyses resulting in the Table 33 regressions.

Table 32 Regression equations showing the relationship between percent throughfall (Y) and (L_1) distance to nearest tree (X) for three storm classes in Plots 1, 2 and 3, with 1963 and 1964 data combined, position three omitted.

Storm class (inches)	No. of observ-ations	Regression equation	Equation No.	SE_E	r	r^2%	Level of Signif-cance
		PLOT 1					
0.06-0.10	38	Y=20.83+1.52X	(56)	21.03	0.079	0.6	N.S.
0.11-0.25	95	Y=42.98+5.64X	(57)	23.11	0.284	8.0	0.010
0.26-0.50	34	Y=54.50+3.25X	(58)	33.58	0.140	1.9	N.S.
		PLOT 2					
0.06-0.10	58	Y=29.10+9.48X	(59)	21.19	0.384	14.7	0.005
0.11-0.25	94	Y=52.46+5.08X	(60)	23.40	0.210	4.4	0.050
0.26-0.50	44	Y=53.25+12.08X	(61)	26.72	0.331	10.9	0.050
		PLOT 3					
0.06-0.10	59	Y=38.01+ 5.17X	(62)	31.00	0.121	1.4	N.S.
0.11-0.25	119	Y=40.26+10.52X	(63)	22.72	0.358	12.8	0.005
0.26-0.50	41	Y=49.16+10.30X	(64)	19.05	0.429	18.4	0.010

Table 33 shows again that the addition of the DBH parameter to take into account varying crown width does not result in any general improvement of the correlation coefficient (Table 32 and Table 33). Again, also, "r" values tended to be smaller when Position 3 data were excluded from the analysis (Table 31 and Table 33).

The regression equations obtained from the other models tested and utilizing only Positions 1A, 1B and 2 data, are included in Appendix C.

Previous analyses, already discussed, have shown a zone of heavier throughfall near the crown perimeter. The analyses presently under discussion do little more than this. It is determinable that a rather weak relationship exists between throughfall percent and distance from stem. This relationship seems to apply to gaps between trees as well as for the ground beneath the crowns themselves.

While regression statistics were obtained which were highly significant, in general correlation coefficient values were not large and coefficient of determination percent seldom exceeds 15 percent. This cannot reliably be interpreted as any more than confirming that there is a zone of greater throughfall at the crown edge.

One can only conclude that the low "r" values and the wide "scatter" of the data (Figure 40) are the expression of a relatively open crown habit in lodgepole pine. From this one might deduce that organized distribution of precipitation which has been found in stands of some species cannot lightly be assumed to occur in all. It also suggests that rigorous, statistically sound sampling might show the organization of precipitation distribution to be less pronounced than has been thought.

Table 33 Regression equations showing the relationship between percent throughfall (Y) and (X) ratio (L_1/D_1) of distance to nearest tree (L_1) : DBH of nearest tree (D_1) for three storm classes in Plots 1, 2 and 3 with 1963 and 1964 data combined, position 3 omitted.

Storm class (inches)	No. of observ-ations	Regression equation	No. of equation	SE_E	r	r^2%	Level of signif-icance
		PLOT 1					
0.06-0.10	38	Y=32.76-18.56X	(65)	20.83	0.158	2.5	N.S.
0.11-0.25	95	Y=43.67+34.04X	(66)	23.23	0.266	7.1	0.010
0.26-0.50	34	Y=63.58-0.28X	(67)	33.92	0.001	0.0	N.S.
		PLOT 2					
0.06-0.10	58	Y=36.34+20.61X	(68)	21.90	0.300	9.0	0.025
0.11-0.25	94	Y=55.04+16.00X	(69)	23.44	0.202	4.1	0.050
0.26-0.50	44	Y=60.17+32.00X	(70)	26.86	0.316	10.0	0.050
		PLOT 3					
0.06-0.10	59	Y=47.83- 3.49X	(71)	31.20	0.042	0.1	N.S.
0.11-0.25	119	Y=41.93+22.63X	(72)	22.66	0.364	13.3	0.005
0.26-0.50	41	Y=52.94+22.08X	(73)	19.98	0.320	10.2	0.050

Certainly, on the basis of this study, one is tempted to conclude that variation in throughfall in lodgepole pine stands is to a large extent (approximately 85 percent) randomly distributed.

The remaining obvious source of variation in precipitation incident upon the forest floor, is stemflow. Eschner (1967) reviewed the literature on stemflow as a contribution to variation in soil moisture within stands. Authors who have dealt with pine species in this context are Hoover (1953) and Horton (1919).

The standard method of considering stemflow as a source of variation in soil moisture is to convert the stemflow volume to inches depth water over an annular area two feet greater in diameter than stem DBH.

This conversion was applied to the data presented earlier in Tables 20 and 21. Results of the conversion are shown in Table 34.

It is immediately evident that the conversion utilized does not change the impression obtained and recorded earlier, namely that stemflow was negligible. Stemflow depths were small, extremely small in comparison to the values quoted by other authors for other species.

Stemflow in lodgepole pine stands in Alberta does not make a major contribution to soil moisture variation within stands.

Trough Gauge Measurements of Throughfall

As stated earlier, five trough gauges were operated concurrently with standard gauge readings in all three plots. The gauges in Plot 3, 9 feet x 1 foot x 4 inches, were of different dimensions than those, 3 feet x 3 feet x 12 inches, in Plots 1 and 2.

Table 34 Total stemflow in 1963 and 1964 (combined) as inches depth of water over an area two feet greater in diameter than stem DBH.

		PLOT 1			
Tree DBH (inches	4.4	6.6	7.5	7.6	9.3
Total stemflow (1963 + 1964) (ins.^{3})	638.7	1476.2	2198.1	1485.2	741.1
Stemflow depth (inches)	0.258	0.526	0.784	0.502	0.231
		PLOT 2			
Tree DBH (inches)	4.3	4.4	4.5	6.1	6.9
Total stemflow (1963+1964) (ins.^{3})	1098.2	1325.8	899.3	1080.4	1823.7
Stemflow depth (inches)	0.447	0.536	0.362	0.396	0.640

Table 35 gives a comparison of standard and trough gauge data within each plot.

Simple correlation coefficient (r) matrices for each plot and year are given in Table 36, including relationships between mean gross precipitation and mean throughfall. The latter expression is presented as that measured by standard gauges (THFL(S)) and that measured by troughs (THFL(T)). Included in the table are the appropriate values of 'r' for the 1.0 percent significance level.

Linear regression equations of mean depth of water in trough gauges on mean gross precipitation are given in Table 37 with appropriate basic statistics. No regressions for 1963 and 1964 data combined are presented, since covariance analysis showed that this was not permissible in Plots 1 and 2, where significant differences between regression slopes were encountered. Comparisons between predicted throughfall from standard gauge data and trough gauge data are shown in Figures 42, 43 and 44.

A brief review by Reigner (1964) evaluated trough gauges and compared their results with those from conventional gauges. He noted the possible causes of loss from splashing when the trough was horizontally positioned. Results quoted by Reigner (1964) from trough gauges used under canopies were inconclusive but some evidence is presented here. There was a very significant correlation between net precipitation as determined by standard gauges and trough gauges but the latter tended to underestimate throughfall with increased storm size. This is apparent in Figures 42 and 43. The underestimate, presuming roving standard gauges record the true throughfall, of throughfall by trough gauges was quite appreciable in large storms. There were indications

Table 35. Annual mean, standard deviation (S.D.) and coefficient of variation percent (C.V.%) of throughfall (inches water) as determined by standard and trough gauges within each Plot.

		Gauge					
		Standard			Trough		
Plot	Year	Mean	S.D.	C.V.%	Mean	S.D.	C.V.%
1	1963	0.397	0.698	176	0.302	0.451	149
	1964	0.133	0.172	130	0.138	0.157	114
2	1963	0.318	0.569	179	0.250	0.375	150
	1964	0.173	0.192	111	0.166	0.158	95
3	1963	0.396	0.668	169	-	-	-
	1964	0.180	0.175	97	0.117	0.136	116

Table 36 Simple correlation coefficients between mean gross precipitation (GP), mean throughfall from standard gauges (THFL(S)) and mean throughfall from trough gauges (THFL(T)) for each plot and year, including value of correlation coefficient (r) at the 1.0 percent level of significance.

Plot	YEAR 1963				YEAR 1964			
1	G P	1.000			G P	1.000		
	THFL (S)	0.977	1.000		THFL (S)	0.932	1.000	
	THFL (T)	0.984	0.992	1.000	THFL (T)	0.941	0.986	1.000
		r = 0.665				r = 0.630		
2	G P	1.000			G P	1.000		
	THFL (S)	0.998	1.000		THFL (S)	0.959	1.000	
	THFL (T)	0.974	0.978	1.000	THFL (T)	0.982	0.979	1.000
		r = 0.693				r = 0.679		
3	Insufficient results for statistical analysis.				G P	1.000		
					THFL (S)	0.942	1.000	
					THFL (T)	0.982	0.983	1.000
						r = 0.630		

Table 37. Simple linear regression equations of throughfall (mean depth of water in troughs) on mean gross precipitation (GP) by years and plots, including basic statistics of equations.

Plot	Year	No. of storms	Regression constant	Regression coefficient	Regression No.	SE_E	r	r^2%
1	1963	21	0.0140	0.6500	(74)	0.089	0.984	96.8
	1964	25	-0.0219	0.8771	(75)	0.058	0.942	88.8
2	1963	21	0.0082	0.7133	(76)	0.141	0.968	93.7
	1964	25	-0.0199	0.8912	(77)	0.032	0.982	96.4
3	1963	insufficent data						
	1964	25	-0.0164	0.7864	(78)	0.027	0.983	96.7

that differences between the two estimates of throughfall were smaller during 1964 when there were no large storms (Figs. 42, 43, 44).

Standard error of estimate values for the regression equations using trough gauges, which are given in Table 37, were small and the equations precise.

The regression equations developed expressing mean trough gauge throughfall catch as a function of gross precipitation (Table 37) showed that there were serious discrepancies in mean throughfall as estimated by standard gauge, at least in the case of the 1963 data (Figs. 42 and 43). Trough gauges seriously underestimated the throughfall produced by large storms (> 0.75 inches gross precipitation).

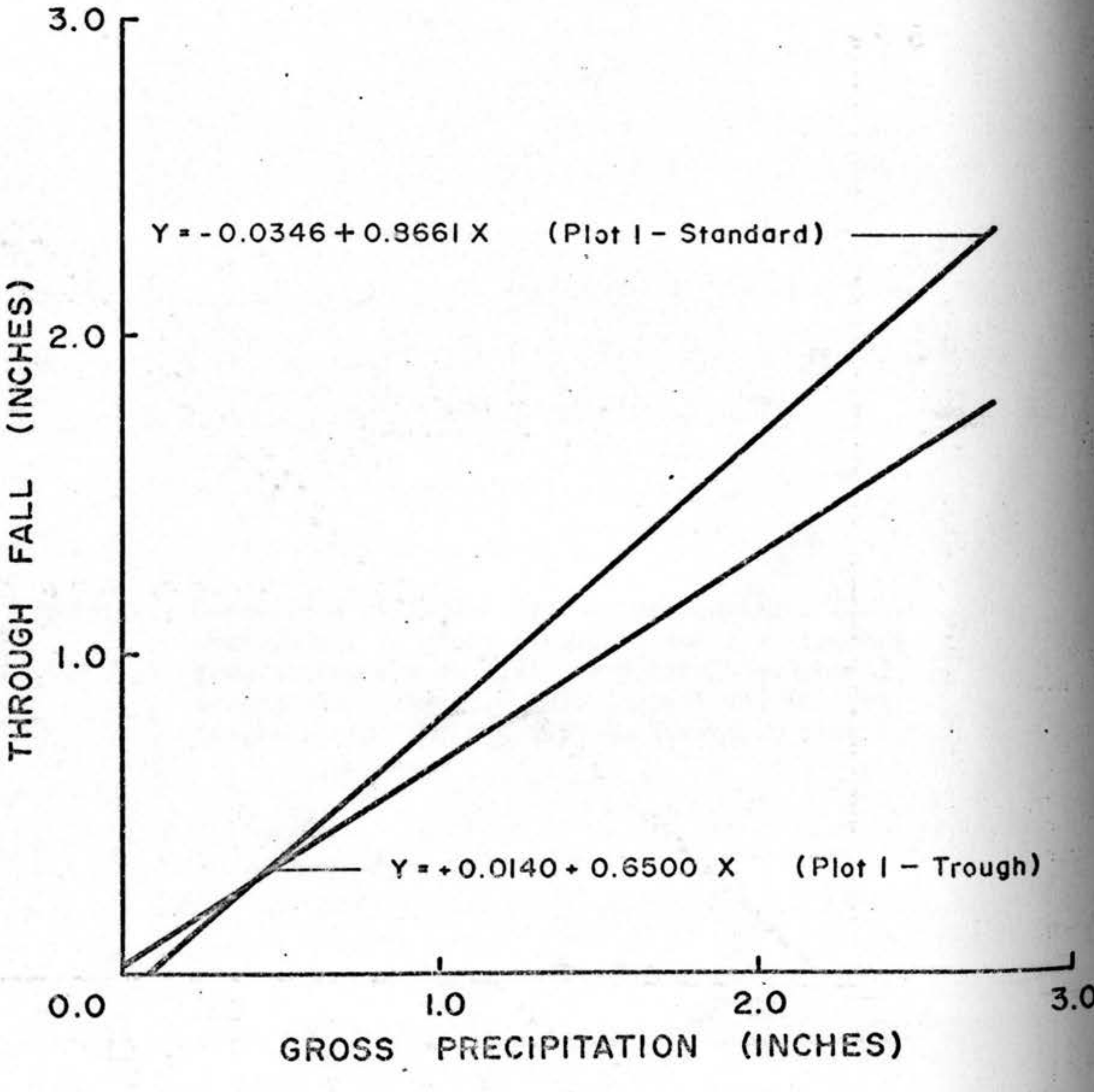
Where no large storms were encountered, as was the case in 1964 (Table 14), there was no appreciable difference in throughfall estimates by trough and standard gauges.

One has to conclude from this that the trough gauges tested did not function well in large storms, and in such storms their use resulted in a serious underestimate of throughfall. There was also a tendency for trough gauges somewhat to underestimate throughfall in all storms in Plot 1 (Fig. 42).

Trough gauges have been used in a number of interception studies and their use in this regard has not been criticized. Delfs (1958), Leyton and Carlisle (1959), Reynolds and Leyton (1963) and Leyton, Reynolds and Thompson (1967) all report on interception studies utilizing trough gauges.

Tests of trough gauges have shown them to compare well with other gauges (Storey and Hamilton, 1943; Hayes and Kittredge, 1949; Hamilton, 1954), and they have been described as aerodynamically efficient. It

Figure 42. Comparison of linear regression equations for throughfall on gross precipitation for standard gauges (regression (15)) and trough gauges (regression (74)) in 1963 (upper) and in 1964 (regressions (16) and (75)) (lower) in Plot 1.


3.0
2.0
1.0
0.0
THROUGH FALL (INCHES)
Y = -0.0346 + 0.8661 X (Plot I - Standard)
Y = +0.0140 + 0.6500 X (Plot I - Trough)
1.0
2.0
3.0
GROSS PRECIPITATION (INCHES)

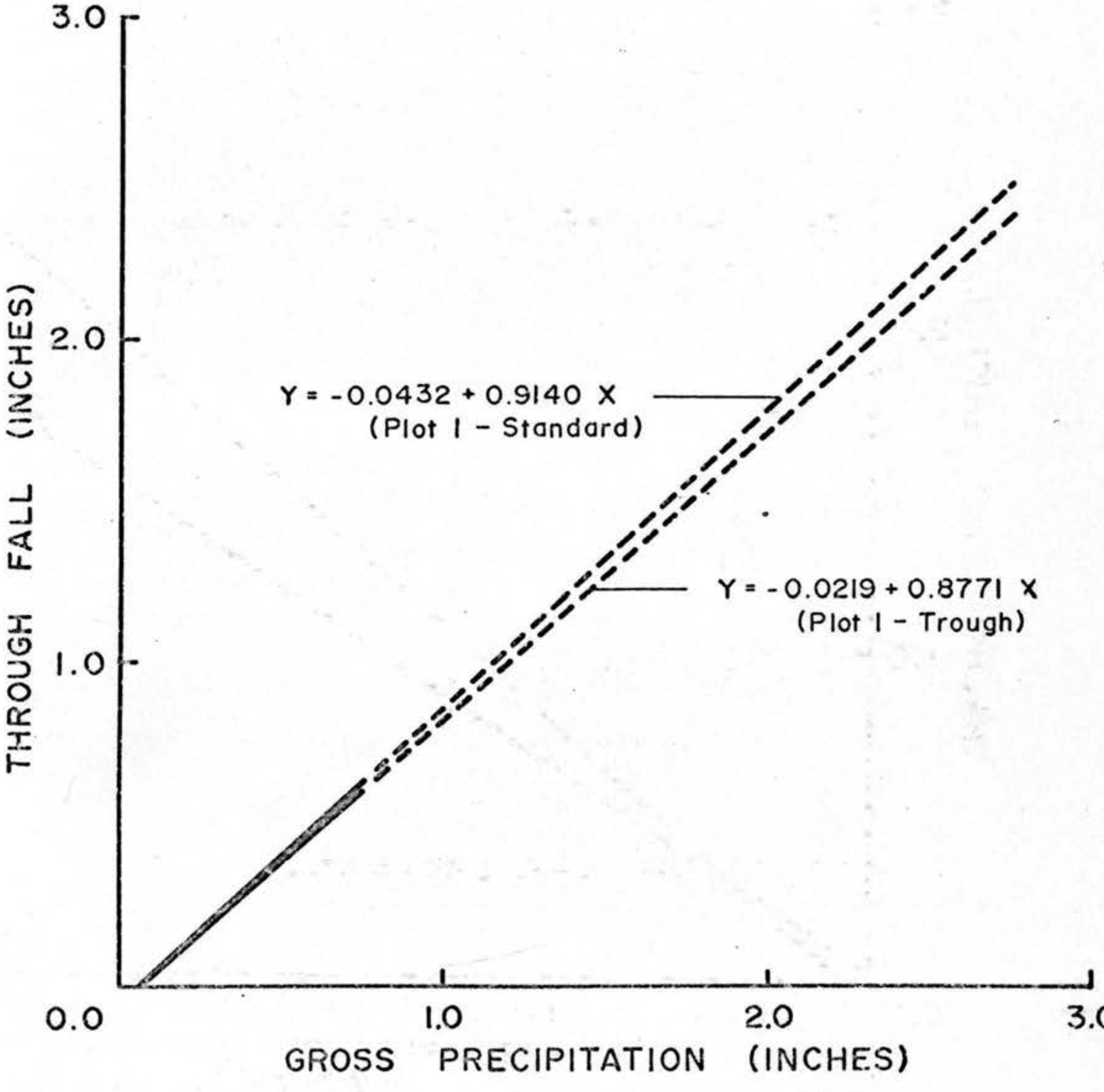
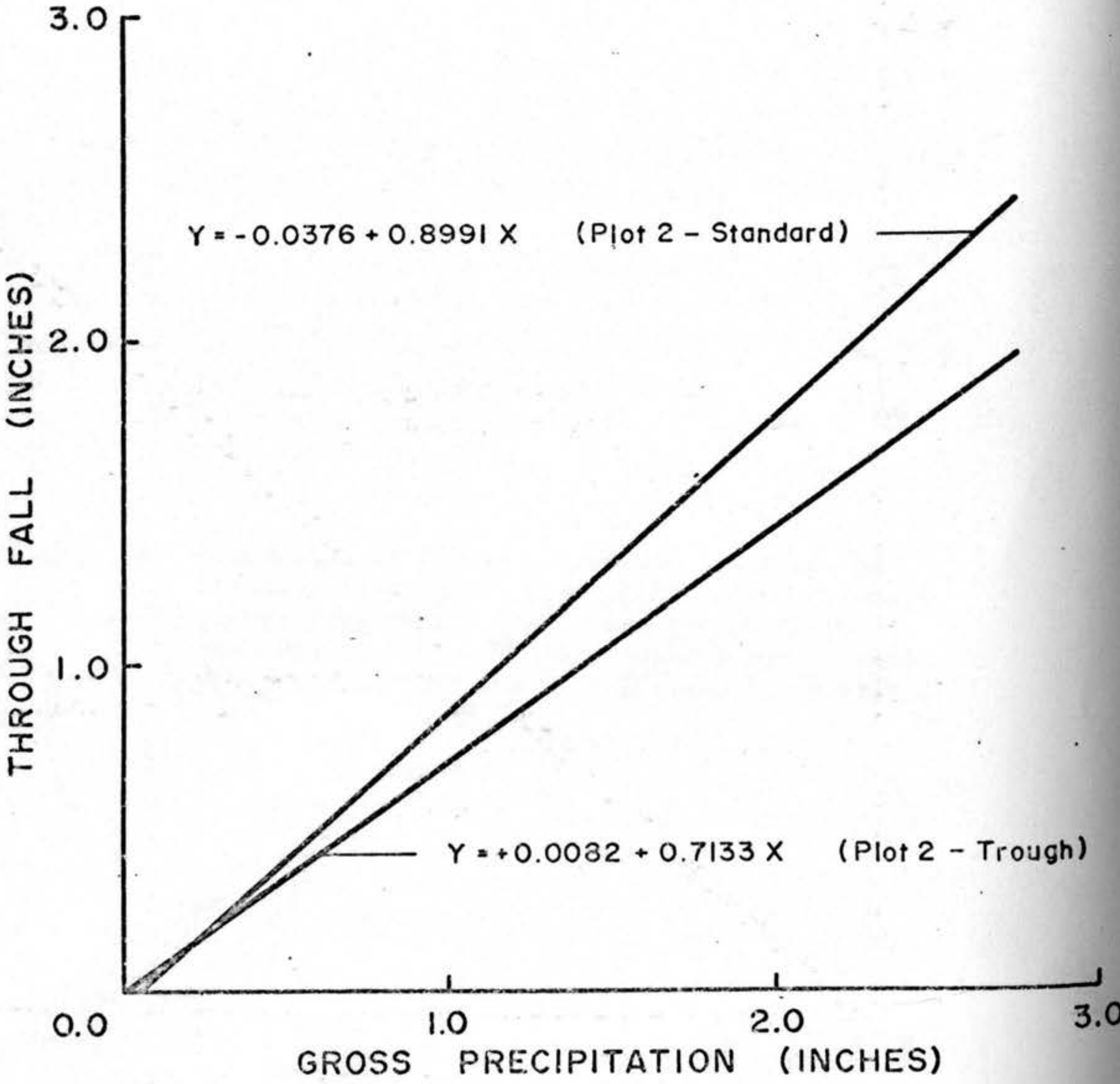

3.0
2.0
1.0
0.0
THROUGH FALL (INCHES)
Y = -0.0432 + 0.9140 X
(Plot I - Standard)
Y = -0.0219 + 0.8771 X
(Plot I - Trough)
1.0
2.0
3.0
GROSS PRECIPITATION (INCHES)

Figure 43. Comparison of linear regression equations of throughfall on gross precipitation for standard gauges (regression (17)) and trough gauges (regression (76)) in 1963 (upper) and in 1964 (regressions (19) and (77)) (lower), in Plot 2.



3.0
2.0
1.0
0.0
THROUGH FALL (INCHES)
Y = -0.0376 + 0.8991 X (Plot 2 - Standard)
Y = +0.0082 + 0.7133 X (Plot 2 - Trough)
1.0
2.0
3.0
GROSS PRECIPITATION (INCHES)

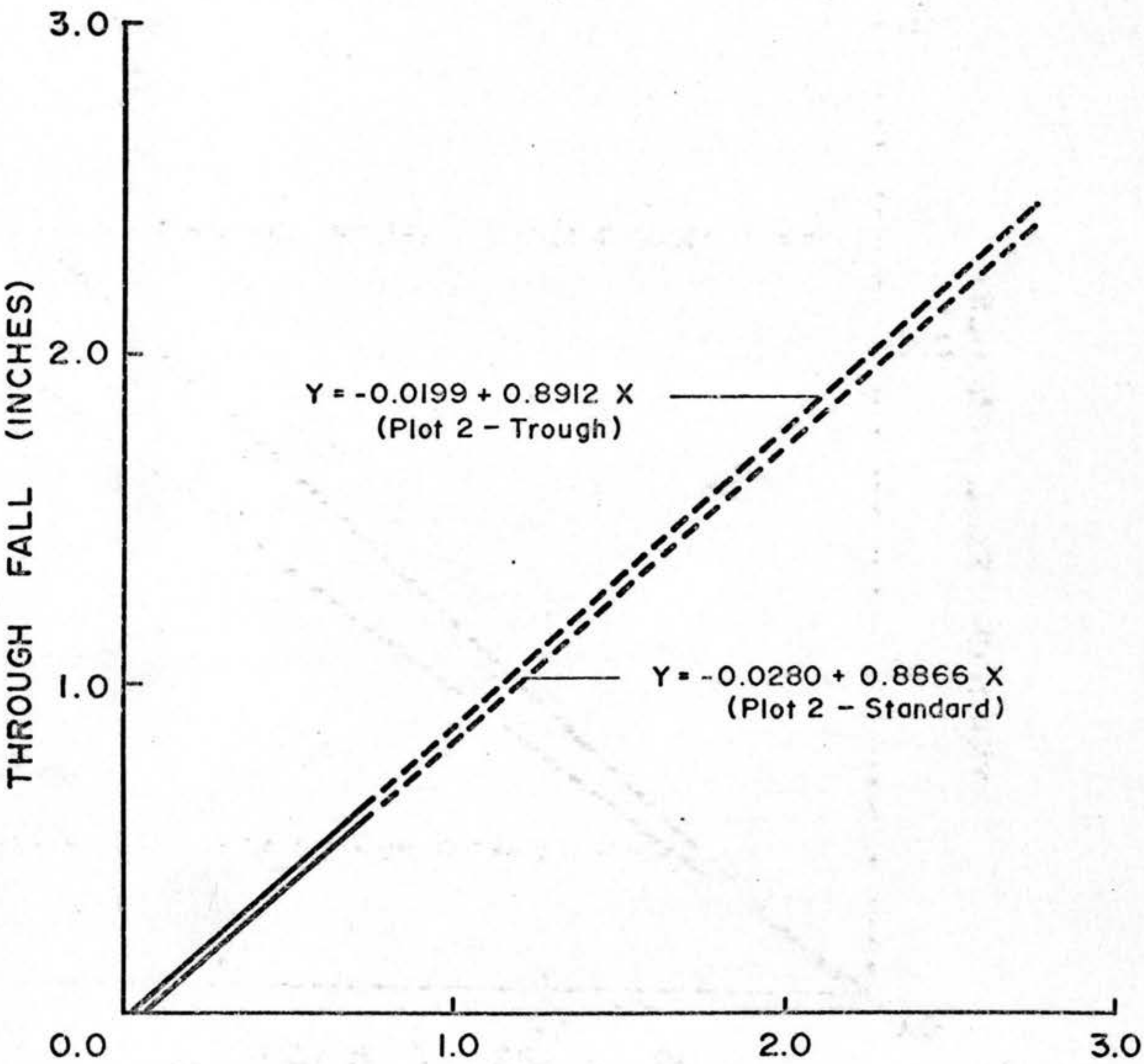
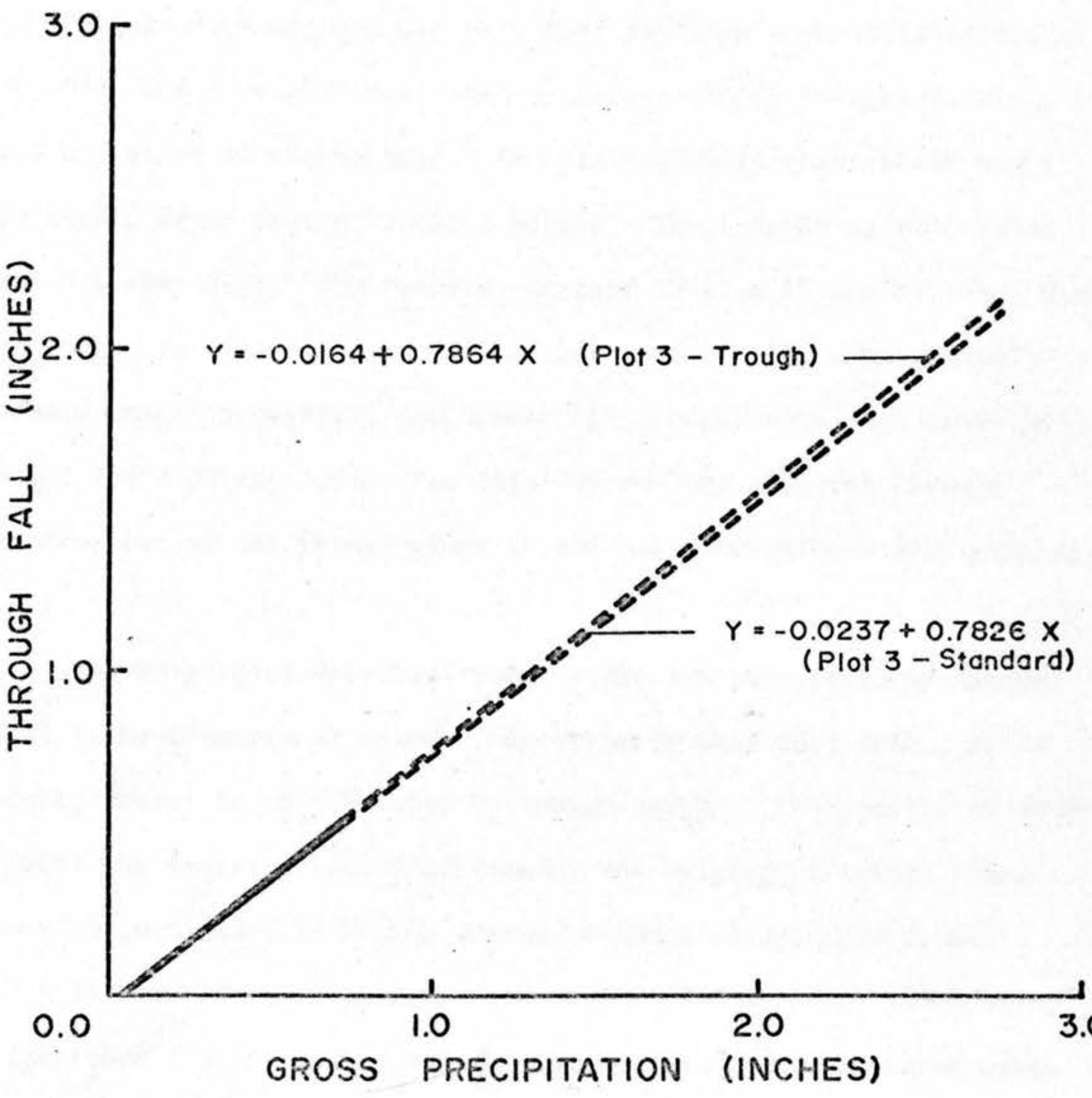

3.0
2.0
1.0
0.0
THROUGH FALL (INCHES)
Y = -0.0199 + 0.8912 X
(Plot 2 - Trough)
Y = -0.0280 + 0.8866 X
(Plot 2 - Standard)
1.0
2.0
3.0
GROSS PRECIPITATION (INCHES)

Figure 44. Comparison of linear regression equations of throughfall on gross precipitation for standard gauges (regression (20)) and trough gauges (regression (78)) in 1964 in Plot 3.


3.0
2.0
1.0
0.0
THROUGH FALL (INCHES)
Y = -0.0164 + 0.7864 X (Plot 3 - Trough)
Y = -0.0237 + 0.7826 X
(Plot 3 - Standard)
1.0
2.0
3.0
GROSS PRECIPITATION (INCHES)

is true, as pointed out by Reigner (1964), that these tests have applied to troughs of semi-circular cross-section only, and not to those of rectangular cross-section such as used in this study.

Splash from troughs has been considered as a possible source of loss which might result in an underestimate. These troughs in Plots 1 and 2 had sides 12 inches high. It seems unlikely that splash would have been a major factor in those gauges. The troughs in Plot 3 had sides 3 inches high. The results obtained (Tables 17 and 37) show that the troughs in Plot 3 during 1964 rather more closely approximated standard gauge throughfall catch than the troughs with high sides in Plots 1 and 2 during 1964. For this reason loss of catch through splashing out of the trough gauge is not believed to be a very pertinent factor.

The bulging of unbraced trough sides was considered by Reigner (1964) to be a source of error. Any error of this sort would, it is thought, result in an overcatch by trough gauges. The results of study indicate the reverse. For this reason, the bulging of trough sides cannot be considered to be the source of the discrepancies found.

In view of the departure from recommended practice in choosing a high-sided trough with a rectangular cross-section, the aerodynamic efficiency of the troughs was evaluated as a possible source of error, at the time the study was begun. At that time it was reasoned that, since summer rainfall in the area was not characteristically accompanied by high winds, these factors were not of major importance. Wind speeds in the summer months at the Kananaskis Forest Experiment Station may be appreciable, up to mean maximum one hour winds of 22 mph in summer (Table 1), but observation suggests that these maximum wind speeds occur in dry weather. It is true also that a large percentage of throughfall, particularly in dense stands, occurs as "drip" from the canopy, so that the vertical distance through which the drops fall before reaching a gauge is fairly short, in many cases a matter of a few feet only. Drop size, from "canopy drip" is furthermore characteristically large, so that this factor too tends to operate against the likelihood of drops developing a large horizontal component in their fall direction before they reach a gauge.

The most pertinent factor, however, was considered to be the wind speed within the stand. The reduction in wind speed within forest stands is well-known (Geiger, 1965). Data quoted by Geiger (1965) suggest that in wind speeds above the stand of 10 mph, the wind speed within the stand at the height of gauge orifice exposure (2 to 3 feet) would be no more than one-quarter of this value.

The combined effects of (1) a large part of throughfall occurring as canopy drip, (2) large drop size of canopy drip, and (3) wind speed reduction within stands, were considered when the study was begun as militating against any important aerodynamic effect of gauge shape. Underestimate of throughfall from trough gauges, coupled with the elimination of other possible sources of error, leads to the conclusion that this was not so, and that in fact there was some aerodynamic effect which results from gauge design. Unfortunately, no further evidence is available.

The performance of trough gauges in the few large storms encountered was poor. This is thought to be the result of the collecting system utilized (Figs. 9, 10) in which trough catch was channelled into two vessels through a T-coupling. Unless this coupling was exactly positioned, more of the trough catch was directed into one of the vessels, which might then overflow while the other remained unfilled. Though in the absence of further tests there is no means of checking this postulate, the underestimate of throughfall from troughs in large storms is not considered primarily to be a function of gauge performance.

If it is assumed that the throughfall estimate obtained by standard gauge techniques is the preferred estimate for canopy interception of rainfall studies, then it is worthwhile to establish whether trough gauge estimates can be converted to standard gauge estimates. The data collected allow such an attempt to be made.

The first model tested was the simplest one possible, namely:

THFL (S) = a + b.THFL (T), where

THFL (S) = mean throughfall for one storm, as caught by standard gauges, in inches

THFL (T) = mean throughfall for one storm, as caught by trough gauges, in inches.

The data for 1963 and 1964 were kept separate. The results of testing the above model are presented in Table 38.

Table 38 shows that precise estimates of mean standard gauge catch can be obtained from mean trough gauge catch. Standard errors of estimate were usually fairly small and the equations precise. However, while the equations for Plots 1 and 2 in 1963 were similar, and those for Plots 1, 2 and 3 in 1964 were similar, there was little similarity between the equations obtained for 1963 and those obtained for 1964. This was thought to result from the effect of the few large storms measured in 1963, for which the trough gauge estimates, as noted earlier, were poor.

In Table 38, the equation for Plot 3 in 1964 was more precise than those calculated for Plots 1 and 2 in 1964. Plot 3 utilized a long (9 feet), narrow (1 foot), low (4 inches) trough, in contrast to the square (3 feet x 3 feet), high (12 inches) troughs in Plots 1 and 2. The data suggest that the trough design utilized in Plot 3 gave superior performance, when evaluated against the results obtained by standard gauge sampling.

To test whether the effects of large storms was responsible for the discrepancy in results as obtained in 1963 and 1964 data, new regression analyses were made for Plots 1 and 2 utilizing the 1963 data. In these analyses, only storms with gross precipitation of 0.75 inches or less were utilized, the data for larger storms being omitted. The largest storm measured in 1964 was 0.74 inches. Therefore, the data used for the new 1963 analyses were completely comparable to those utilized in the 1964 analyses.

The results of the new 1963 analyses are shown in Table 39. The regression equations in Table 39 can be directly compared with the regression equations for 1964 in Table 38. Results show that there was little difference between regression equations for Plots 1 and 2 in 1963 and 1964, when only storms of 0.75 inches gross precipitation or less are taken into consideration. When the large storm data were omitted, there was a substantial reduction in the standard error of estimate.

Regressions (81) to (85) inclusive are shown in Figure 45. The regressions are seen to be closely similar, as was confirmed by covariance analysis, which showed no significant differences between them. This allowed the calculation of composite regression (94), presented later.

Table 38 Regression equations expressing mean throughfall in standard gauges (Y) as afunction of mean throughfall in trough gauges (X), for 1963 and 1964 data in Plots 1, 2 and 3.

Plot	Year	No.of storms	Regression equation	Regression No.	SE_E	r	r^2%
1	1963	21	Y= -0.048 + 1.428X	(79)	0.089	0.991	98.2
2	1963	21	Y= -0,058 + 1.488X	(80)	0.122	0.978	95.7
1	1964	25	Y= -0.0191 + 1.123X	(81)	0.034	0.982	96.6
2	1964	25	Y= -0.0139 + 1.091X	(82)	0.026	0.989	97.9
3	1964	25	Y= -0.0086 + 1.089X	(83)	0.009	0.996	99.2

Table 39 Regression equations, expressing mean throughfall in standard gauges (Y) as a function of mean throughfall in trough gauges (X), in Plots 1 and 2, utilizing 1963 storms having gross precipitation of 0.75 inches or less only.

Plot	Year	No.of storms	Regression equation	Regression No.	SE_E	r	r^2%
1	1963	18	Y= -0.0077 + 1.093X	(84)	0.023	0.990	98.0
2	1963	18	Y= -0.0080 + 1.049X	(85)	0.027	0.985	97.0

Reigner (1964) found, for his trough gauges located in the open, that the trough gauges underestimated rainfall. He utilized and tested a regression model which took into account the slope of the trough gauge.

The model he utilized was:

$Y = a + b_1X + b_2X.S$, where

Y = amount per storm, as measured in the standard gauge, in inches,

X = amount caught in any low trough, in inches,

S = slope of the low trough, in percent.

Results of this model were as follows:

$$Y = 0.011 + 1.073\ X - 0.00319\ X.S \qquad (86)$$

both variables being highly significant at the one percent level.

This work by Reigner (1964) suggested a line of enquiry to be followed in this study. A similar model was postulated and tested.

This model was:

$$\overline{THFL}\ (S) = a + b_1\ \overline{THFL}\ (T) + \frac{\Sigma(THFL\ \ (T).S)}{n}, \text{ where}$$

$\overline{THFL}$ (S) = mean throughfall in any storm, as measured by standard gauges, in inches,

$\overline{THFL}$ (T) = mean throughfall caught in any storm, as measured by trough gauges, in inches,

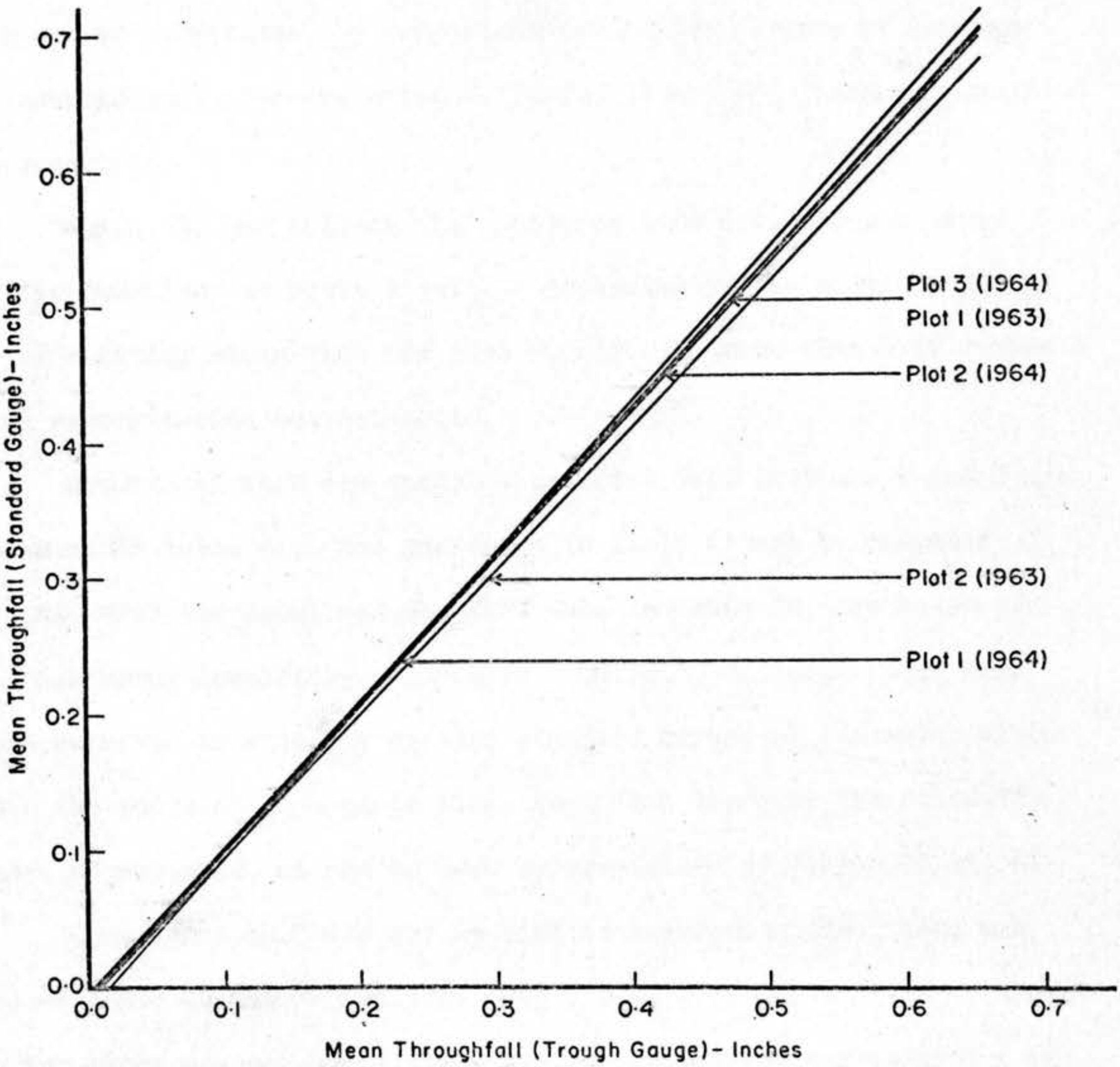
THFL (T) = throughfall caught in individual trough gauges, in inches,

S = slope of individual trough gauges, in degrees,

n = number of trough gauges.

The results of testing this model are shown in Table 40. These results show that mean throughfall in standard gauges can be expressed

Figure 45. Regression lines expressing the relationship of throughfall as measured by roving standard gauges, and throughfall in trough gauges, in Plots 1 and 2 in 1963 and 1964 and Plot 3 in 1964, storms of 0.75 inches gross precipitation or less only.


Mean Throughfall (Standard Gauge) - Inches
0·0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
Plot 3 (1964)
Plot 1 (1963)
Plot 2 (1964)
Plot 2 (1963)
Plot 1 (1964)
Mean Throughfall (Trough Gauge) - Inches

with improved precision from mean throughfall in trough gauges and trough gauge slope data. Addition of trough gauge slope data sometimes, though not always, improved the standard error of estimate. This can be ascertained by comparison of standard errors of estimate and coefficients of correlation in Tables 38 and 40, which are completely comparable.

Again, it was evident that 1963 and 1964 data did not yield similar equations in Plots 1 and 2. Accordingly, the previous procedure of omitting storm data for 1963 storms with more than 0.75 inches gross precipitation was attempted.

Results of this new analysis for 1963 data in Plots 1 and 2 are presented in Table 41. The equations in Table 41 can be compared directly with the equations for 1964 data in Table 40, the basis of analysis being completely comparable. Omission of large storm data again resulted in slightly smaller standard errors of estimate, while again the addition of a gauge slope term also improved the standard errors of estimate, as can be seen by comparison of Tables 39 and 41.

Covariance analysis was applied to regression (89), (90) and (91) of Table 40 and regressions (92) and (93) of Table 41 to determine whether there was any significant difference between regressions. Covariance analysis showed significant differences between regressions. It should be noted, however, that the appropriateness of applying covariance analysis to curvilinear regressions is open to debate.

The analysis of trough gauge results can be summarized as follows:

Table 40. Results of regression analyses expressing mean throughfall (standard gauge) as a function of mean throughfall (trough gauge) and trough gauge slope, for data collected in 1963 and 1964 separately.

Plot	Year	No. of storms	Regression equation[1]	Regression No.	SE_E	r	r^2%
1	1963	21	$Y=-0.0410-6.535X_1+1.399X_2$	(87)	0.066	0.995	99.8
2	1963	21	$Y=-0.428-24.414X_1+4.519X_2$	(88)	0.074	0.992	98.4
1	1964	25	$Y=-0.0029+9.9092_1-1.431X_2$	(89)	0.025	0.991	98.2
2	1964	25	$Y=-0.0137-0.804X_1+0.329X_2$	(90)	0.027	0.989	97.8
3	1964	25	$Y=-0.0057-1.612X_1+0.585X_2$	(91)	0.013	0.997	99.4

1. In regression equations:

$Y = \overline{THFL}(S)$; $X_1 = \overline{THFL}(T)$; $X_2 = \sum \overline{(THFL(T),S)}/n$.

(1) Trough gauge estimates of throughfall, based on five randomly but permanently sited trough gauges per plot, were not identical with throughfall estimates from roving standard gauges.

(2) Trough gauges tended to underestimate throughfall in comparison to standard gauges.

(3) Undercatch associated with trough gauge throughfall estimates, was most probably the result of an aerodynamic effect of the gauge design used. This is in spite of theoretical considerations which would lead to the belief that aerodynamical considerations, in the situation under study, were not of major importance, and of the fact that two gauge types were tested, one of which might be expected to be aerodynamically much more efficient than the other.

(4) Trough gauges gave poor results in large storms. This is believed to be a result of the collection system used and not of gauge performance.

(5) Of the two trough gauge types tested, there were indications that the long, narrow, low troughs gave results somewhat closer to, though not identical with, standard gauge results. These low troughs are, by coincidence, virtually identical to the type recommended by Reigner (1964).

(6) Mean standard gauge catch per storm can be estimated from mean trough gauge catch per storm with good precision.

(7) When only storms less or equal to 0.75 inches gross precipitation were considered, there was no significant difference in the relationship of mean standard gauge catch with mean trough gauge catch between years and plots.

Table 41. Regression equations expressing mean throughfall (standard gauge) as a function of mean throughfall (trough gauge) and gauge slope, omitting storms in 1963 with gross precipitation greater than 0.75 inches.

Plot	Year	No. of storms	Regression equations	Equation No.	SE_E	r	r^2%
1	1963	18	$Y=-0.0011+4.639X_1-0.635X_2$	(92)	0.021	0.992	98.4
2	1963	18	$Y=-0.0120+10.665X_1-1.681X_2$	(93)	0.025	0.988	97.6

(8) When years and plots are combined, this relationship is expressed as:

$$\overline{THFL}\ (S) = -0.012 + 1.093\ \overline{THFL}\ (T) \qquad (94)$$

with r = 0.988, with 1 and 106 degrees of freedom, and standard error of estimate = 0.025 inches.

(9) The addition of a gauge slope parameter to the prediction equation, as suggested by Reigner (1964), sometimes resulted in a lower standard error of estimate.

(10) Covariance analysis of the results of the regression model incorporating a gauge slope parameter showed that regressions for plots and years were significantly different. Covariance analysis may not, however, be appropriate.

(11) When years and plots are combined this expanded model yields the following equation:

$$\overline{THFL}\ (S) = -0.012 + 1.283\ \overline{THFL}\ (T) - 0.035\ \frac{\Sigma(THFL\ (T)\ .S)}{n} \qquad (95)$$

with r = 0.988, with 2 and 105 degrees of freedom and standard error of estimate = 0.025 inches.

(12) The main advantage of trough gauges is that, if they are successful, they avoid the manpower problems associated with standard gauge re-randomization. With the recent development of interest in forested experimental and representative basins in Canada (Jeffrey, 1967) there is an added interest in obtaining interception estimates for water balance studies, along the lines suggested by Zinke (1967). The results of this study suggest that trough gauges, randomly and permanently located, may be useful for this purpose, provided certain factors are taken into account.

(13) Where trough gauges are used for interception studies, the type of gauge used should be compared statistically with roving standard gauges, to obtain a conversion equation of the type given in (8) and (11) above. The results presented indicate that trough gauge catch cannot otherwise be precisely equated to standard gauge catch, since troughs tend to underestimate throughfall.

(14) In view of the possible savings of research labour inherent in a fixed trough gauge sampling system, further study of trough gauge accuracy in throughfall studies is warranted. At the same time, uncritical application of trough gauge sampling, even of approved trough gauge types with semi-circular cross-section, would appear somewhat questionable.

SOIL MOISTURE

Soil moisture studies dealt with the following topics:

(1) Soil moisture content.

(2) Soil moisture change.

(3) Evapotranspiration.

(4) Precision in soil moisture sampling.

These topics are considered separately on the pages which follow.

Five plots were studied. Of these, three (Plots 1, 2, 3) had been thinned in 1939-40. Plots 4 and 5 had not been thinned.

Readings were taken in 1963, 1964, 1965 and 1966.

Comparison of Soil Moisture Contents

The data on soil moisture content, in each depth zone of each plot, which will be presented in the few pages immediately following, may be anticipated here to make a comparison between soil moisture values obtained in the laboratory using pressure apparatus, and those obtained in the field using the calibrated neutron probe.

The comparisons to be made are between, firstly, 1/3 bar moisture content (field capacity) and the highest value obtained during the measurement sequence with the neutron probe, and secondly, between 15 bar moisture content (wilting point) and the lowest value obtained by the neutron probe.

Such comparisons have been made in tabular form. For convenience, the tabular presentations are placed in Appendix B. These comparisons show that there were frequently large discrepancies between the values obtained by the two methods. In the surface foot of soil, field values were always appreciably less than laboratory values. The field range for "field capacity" was 0.29 inches water to 0.93 inches water, and for "wilting point" 0.49 inches water to 0.95 inches water.

In the tables of Appendix B, only 1966 measurement values are shown. When data for all years were utilized, the field range in differences for "wilting point" did not change. The field range for "field capacity" became 0.19 inches water to 0.95 inches water.

In the 12 to 24 inches depth, the range in difference between methods for "field capacity" was +0.36 to -0.31 inches water, for "wilting point," nil to 0.44 inches water. For 24 to 36 inch depth, and 36 to 48 inch depth, differences were generally somewhat less than at shallower depths, but in a few cases were appreciable. At depths deeper than these, it could not safely be assumed that soils ever reached either field capacity or wilting point during the measurement periods.

As mentioned earlier, the laboratory determinations were made with scrupulous care. They are believed to be of a high order of reliability.

Discrepancies of this type are not unusual (cf. Tabler, 1965). However, when they are of the order shown above they become too large to be ignored, and they immediately might be interpreted as casting a considerable shadow upon the neutron probe calibration.

The magnitude of differences in the 0 to 12 inch depth, and at the 12 to 24 inch depth, showed that both shallow and deep neutron probe measurements were concerned. Thus both probe calibration equations (13) and (14) have to be considered.

The largest discrepancies between the two methods occurred in the first and second depth zones. At the deeper zones, discrepancies became smaller. This suggests that the characteristics of the A and B horizons played a role in the occurrence of discrepancies. It will be recalled that the material used for the probe calibration was C horizon material. It may be postulated that the calibration was accurate for the C horizon material but was not accurate for A and B horizons. The 12 to 24 inch depth zone, in Plots 2 and 3, was composed uniquely of C horizon material. Appendix B shows that large discrepancies were found in Plot 2 though not in Plot 3. The evidence is inconclusive, especially when it is noted that the second depth zone of Plot 5, which contained a B horizon, showed close correspondence between the two sets of values (Appendix B).

The conditioned probe calibration equations, as outlined earlier, were used for conversion of count ratios to percent moisture by volume. It should be ascertained whether selection of the conditioning procedure, which is arguable, was sufficient to account for the discrepancies noted.

Inspection showed that lowest field moisture contents corresponded approximately to count ratios of 10 percent. At such a count ratio the difference in soil moisture estimation was about 1.18 percent moisture by volume, or 0.14 inches water per 12 inches of soil depth, with the unconditioned equation (14) yielding the higher value. Obviously, the conditioned equation did not explain the "wilting point" discrepancies in the surface foot.

Highest soil moisture contents in the surface foot corresponded to an approximate count ratio of 40 percent. The difference in moisture estimation by equation (14) (conditioned) and equation (10) (unconditioned) for such a count ratio was -0.02 inches water per 12 inches soil depth, a completely negligible difference.

The differences in moisture estimation by conditioned (13) and unconditioned (7) equations for depths deeper than 12 inches, were even smaller than these.

It is evident that the selection of conditioned equations from calibration data did not explain the discrepancies encountered.

The four values obtained for 1/3 bar moisture content and 15 bar moisture content for each horizon and soil depth increment in some cases showed considerable variation. No obvious correspondence, however, was evident between this variability and the size of the difference between methods.

Other explanations suggest themselves. Bulk density values may be incorrect or unrepresentative. Plants may extract soil moisture at soil moisture tensions greater than 15 bars. These postulates cannot be tested. It is, in any case, true that the 1/3 bar and 15 bar moisture contents are regarded only as approximations.

The fact remains, however, that some evaluation has to be made of the meaning of the discrepancies encountered.

Earlier, in Table 6, total available soil water storage (1/3 bar moisture content minus 15 bar moisture content) was presented for various soil depths in each plot. Similar data from the highest and lowest neutron probe readings obtained can be collated from Appendix B.

These data are compared in Table 42 and a remarkable correspondence is immediately evident. From this correspondence it is suggested that the probe calibration was not accurate for the A and B soil horizons, presumably due to differences between these horizons and the C horizon parent material. It would appear, however, that the calibration used resulted in a rather constant underestimate. If true, this indicates that the slopes of the calibration equations were appropriate to the soils in question. Comparisons between plots can be made with relative confidence and comparisons of moisture change are in no way jeopardized.

The lack of correspondence between absolute moisture contents obtained by the two methods poses interesting problems for neutron probe research. It has not, apparently, been suggested that a separate calibration is required for the upper soil horizons, yet that is what these data tend to imply.

Throughout this section, attention is directed primarily to individual soil depths or to zones within the solum, rather than to "between-plot" comparisons of the whole instrumented depth overlying compacted gravel and till, which varied from three feet in Plot 2 to 14 feet in Plot 5. This preoccupation with individual depths of zones, may tend to obscure the fact that there was a very considerable difference in total soil moisture contents in the five plots.

For instance, in 1966 at the start of record, Plot 1 contained 6.1 inches soil moisture, Plot 2 - 5.2 inches, Plot 3 - 11.0 inches, Plot 4 - 8.5 inches, and Plot 5 - 12.6 inches. The variation is, of course, a function of varying soil depth and water holding capacity among the five plots.

The march of total soil moisture in the five plots is shown in Figure 46 for 1963, Figure 48 for 1964, Figure 50 for 1965, and Figure 52 for 1966. Particular attention is drawn to these graphical presentations, since they show total moisture content and total moisture change for all plots in a readily assimilable form. Thus, they complement the individual statistical analyses presented in later pages.

First Year of Record - 1963

Ten access tubes were installed in each of Plots 1 to 4 inclusive during July, 1963. The first readings in these tubes were taken on August 7, 1963. During 1963, with four plots in operation only, it required two days to take readings on all four plots.

Table 42 Total available water storage (inches) in the uppermost 12, 36 and 48 inches of soil in each plot, by two methods.

Soil depth (inches)	PLOT 1	2	3	4	5
	Pressure apparatus data[1]				
0-12	1.33	1.23	1.33	1.17	1.00
0-36	3.37	3.20	2.32	2.19	2.24
0-48	4.03	-	2.77	2.62	2.83
	Neutron probe data[2]				
0-12	1.53	1.52	1.32	1.26	0.88
0-36	3.21	3.27	2.76	2.73	2.20
0-48	3.87	-	3.21	3.51	2.92

1. Taken from Table 6 and Appendix B, 1/3 bar moisture content minus 15 bar moisture content.

2. Taken from Appendix B, highest neutron probe estimate minus lowest neutron probe estimate.

Six sets of readings were taken at approximately weekly intervals between August 7, 1963 and September 12, 1963. One further measurement was taken on October 25-27, 1963, to make a total of seven sets of measurements in all, during the year.

Soil moisture levels in each plot were plotted for comparison by individual depths (Figure 47). Rainfall during the period of record, graphically presented in Figure 47, totalled 3.51 inches, as measured at the synoptic weather station of the Kananaskis Forest Experiment Station headquarters, approximately 700 yards distant from the plots.

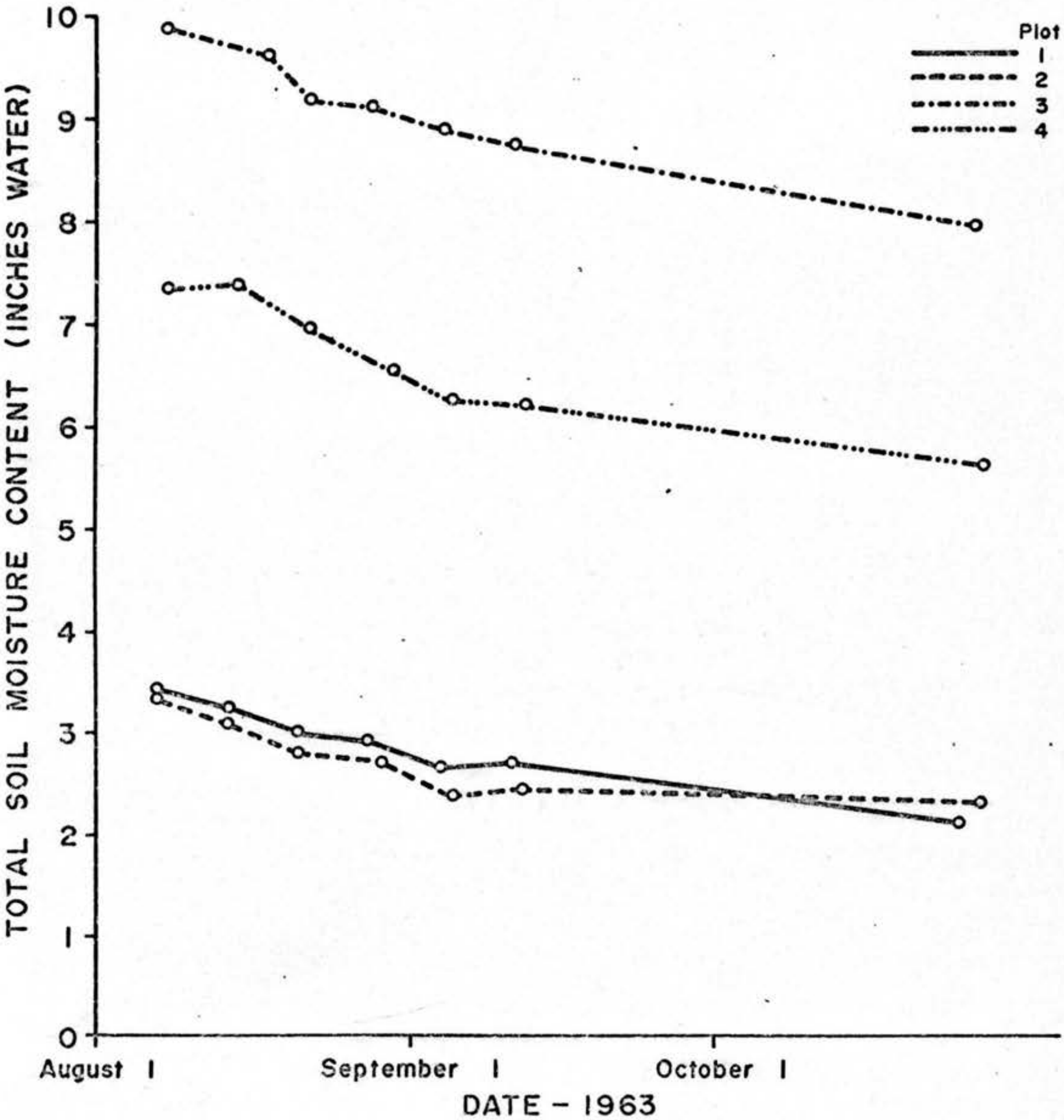
The general trend in soil moisture content was one of progressive decrease during the period, early August to late October, 1963. Thus, Plot 1 (total depth, four feet) had 4.13 inches total moisture stored on August 6 and 2.56 inches total moisture stored on October 25, while Plot 4 (total depth, seven feet) had 7.36 inches total moisture stored on August 8 and 5.66 inches total moisture stored on October 27.

In the uppermost 12 inches of soil, Plot 4 showed the highest moisture contents (Figure 47). The other three plots were not greatly different one from another. Soil moisture decreased until September 4-5, then increased slightly on September 11-12. No marked change was evident between these values and those obtained on October 25-27.

In the second foot (12 to 24 inches depth), Plot 2 had the highest moisture contents (Figure 47), followed by Plots 4, 1 and 3 in that order. Soil moisture levels decreased progressively at this depth throughout the period of record.

The third foot (depth, 24 to 36 inches) showed little difference in soil moisture levels between plots. Aside from a slight increase in

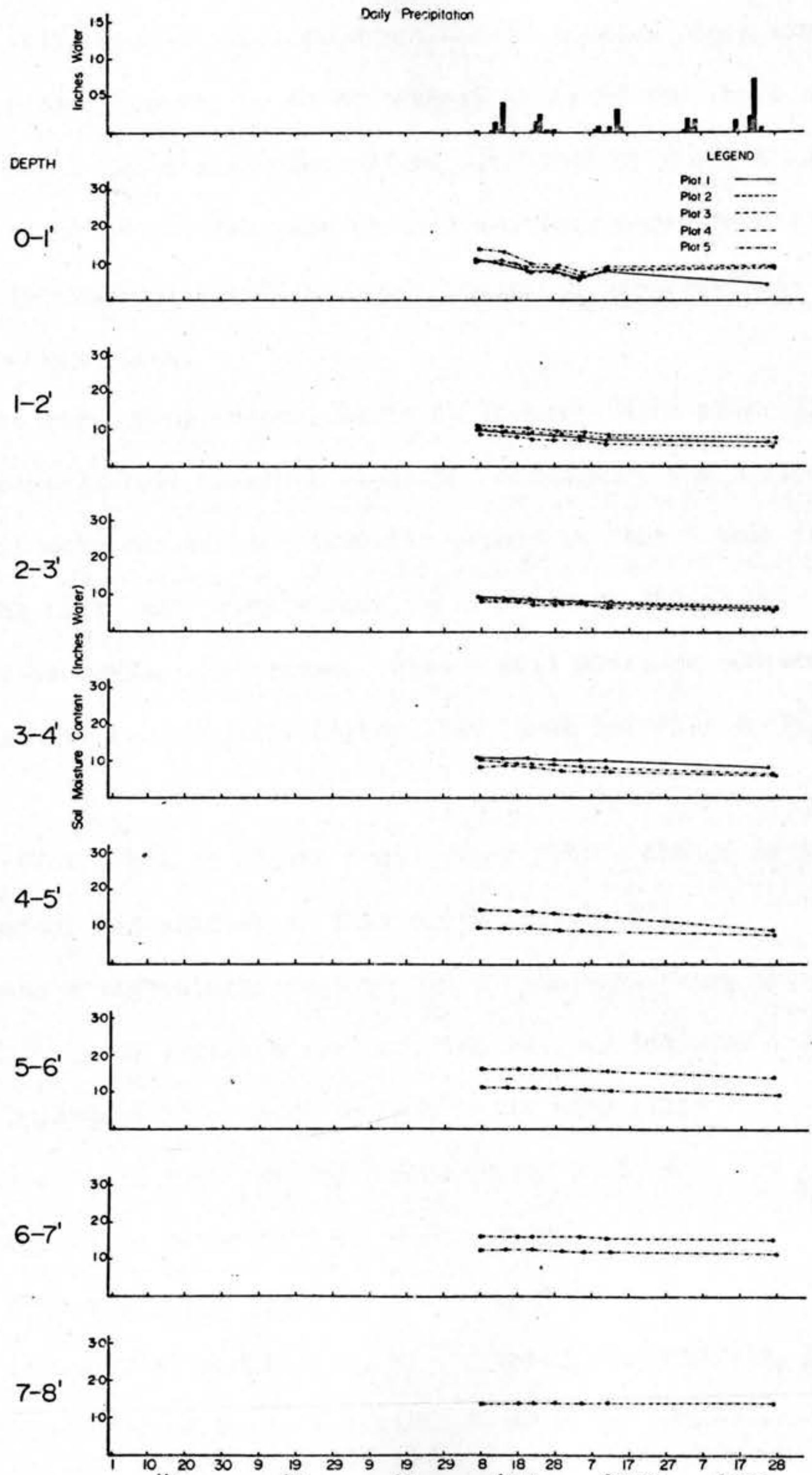
Figure 46. March of total soil moisture in Plots 1, 2, 3, and 4 in 1963. Moisture contents are for the whole instrumented solum (Plot 1 - 4 feet; Plot 2 - 3 feet; Plot 3 - 8 feet; Plot 4 - 7 feet; Plot 5 - 14 feet).



TOTAL SOIL MOISTURE CONTENT (INCHES WATER)
0
1
2
3
4
5
6
7
8
9
10
Plot
1
2
3
4
August 1
September 1
October 1
DATE - 1963

Figure 47. Soil moisture contents of individual depths, Plots 1 - 4 inclusive during 1963.

SOIL MOISTURE CONTENTS - PLOTS 1, 2, 3, 4, 5, - 1963



soil moisture in Plot 3 on September 4, a consistent steady decrease in soil moisture took place.

More difference in soil moisture levels between plots was found in the fourth foot (depth, 36 to 48 inches) where of the three plots (1, 3, 4), Plot 1 had the highest values, followed by Plots 3 and 4 in that order. A slight increase in soil moisture took place in Plot 4 on August 15; otherwise soil moisture decreased progressively at this depth on all plots.

In the fifth foot (depth, 48 to 60 inches), both plots (3, 4) showed progressive soil moisture depletion throughout the period of record. Soil moisture was considerably higher in Plot 3 than in Plot 4.

In the sixth and seventh feet, soil moisture showed only a slight decrease during the season. Plot 3 soil moisture contents at these depths were considerably higher than those for Plot 4 (Figure 47).

Only Plot 3 had an eighth foot. Very little change in soil moisture content was evident at this depth (Figure 47).

To make a statistical test of the differences noted above, separate analyses of variance were carried out, as follows:

1. Uppermost three feet of soil - all four plots
2. Uppermost four feet of soil - Plots 1, 3, 4
3. Uppermost seven feet of soil - Plots 3, 4
4. Uppermost eight feet of soil - Plot 3.

The analysis of variance table for the first analysis, the uppermost three feet of soil, is given in Table 43. Other analysis of variance tables are included in Appendix D.

The results of these analyses of variance are consistent. They show:

1. Highly significant differences between plots, periods (dates of measurement) and depths.

2. Highly significant interactions of plot x depth and period x depth.

3. Interactions, plot x period, and plot x period x depth, not significant.

Second Year of Record - 1964

The first sets of measurements in 1964 were taken on April 8, though it was not until April 27 to 30 that a full set of measurements was made on all plots simultaneously. Access tubes had been installed in Plot 5 during autumn, 1963 so that this plot was fully incorporated into the schedule of readings in 1964.

A great deal of trouble was experienced with instrumentation during 1964. Both probe and scaler gave problems which resulted in loss of regular record, and which culminated in both being returned to the supplier for repairs in July, 1964. As a result of these difficulties, readings in 1964 were somewhat sporadic and were terminated on July 10, no further measurements being possible for the balance of the year. During the period April 8 to July 10, seven sets of measurements were made on all plots with the exception of Plot 4, in which only six sets of readings were taken.

While the 1963 measurements showed soil moisture trends in late season (August to October), the 1964 readings showed early season soil moisture regime. As such, the 1963 and 1964 values are to a

Table 43. Analysis of variance: uppermost three feet of soil, 1963 soil moisture contents (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Variance ratio	Level of significance
Plot (B)	3	2.87	0.96	31.80	0.005
Period (P)[1]	6	10.45	1.74	57.88	0.005
Depth (D)	2	1.82	0.91	30.27	0.005
B x P	18	0.60	0.03	1.11	N.S.
B x D	6	2.56	0.43	14.18	0.005
P x D	12	3.20	0.27	8.87	0.005
B x P x D	36	0.99	0.03	0.92	N.S.
Error	756	22.75	0.03		
TOTAL	839	45.25			

1. Date of measurement.

certain degree complementary to each other. March of total soil moisture in the instrumented solum is shown in Figure 48.

Soil moisture contents were plotted graphically by individual depths for comparative purposes (Figure 49), along with rainfall during the period of record (8.29 inches total, April 8 to July 10, 1964).

In contrast to the soil moisture trend in 1963, when mid and late season values only were obtained, and during which the trend in the upper soil depths was generally downward throughout the period of record, soil moisture trends in 1964, where early season values were obtained, showed some fluctuation.

In the first (uppermost) foot of soil, soil moisture decreased from late April to early June (Figure 49) then rose between June 3 to 5, and June 23 to 25. Thereafter a fairly pronounced decrease was detectable until the close of record on July 10. Highest values were obtained on Plot 2, and lowest on Plots 3 and 5 respectively.

In the second foot of soil, an increase in soil moisture was apparent until May 11 to 13, a decrease from then until June 3 to 5, an increase thereafter to June 23 to 25, and a decrease from those dates until the end of record. Changes in moisture content were of lesser magnitude than in the surface foot of soil. As in the surface foot, trends on all plots were similar. The ranking of values, from highest to lowest was Plot 2, Plot 1, Plot 4, Plot 3, Plot 5, the same order as in the first foot of soil.

In the third foot, differences were much less pronounced (Figure 49), and values were generally lower than in the uppermost two feet. Soil moisture, as in the second foot, increased up to May 11 to 13,

Figure 48. March of total soil moisture in Plots 1, 2, 3, 4 and 5 in 1964. Moisture contents are for the whole instrumented solum. (Plot 1 - 4 feet; Plot 2 - 3 feet; Plot 3 - 8 feet; Plot 4 - 7 feet; Plot 5 - 14 feet).

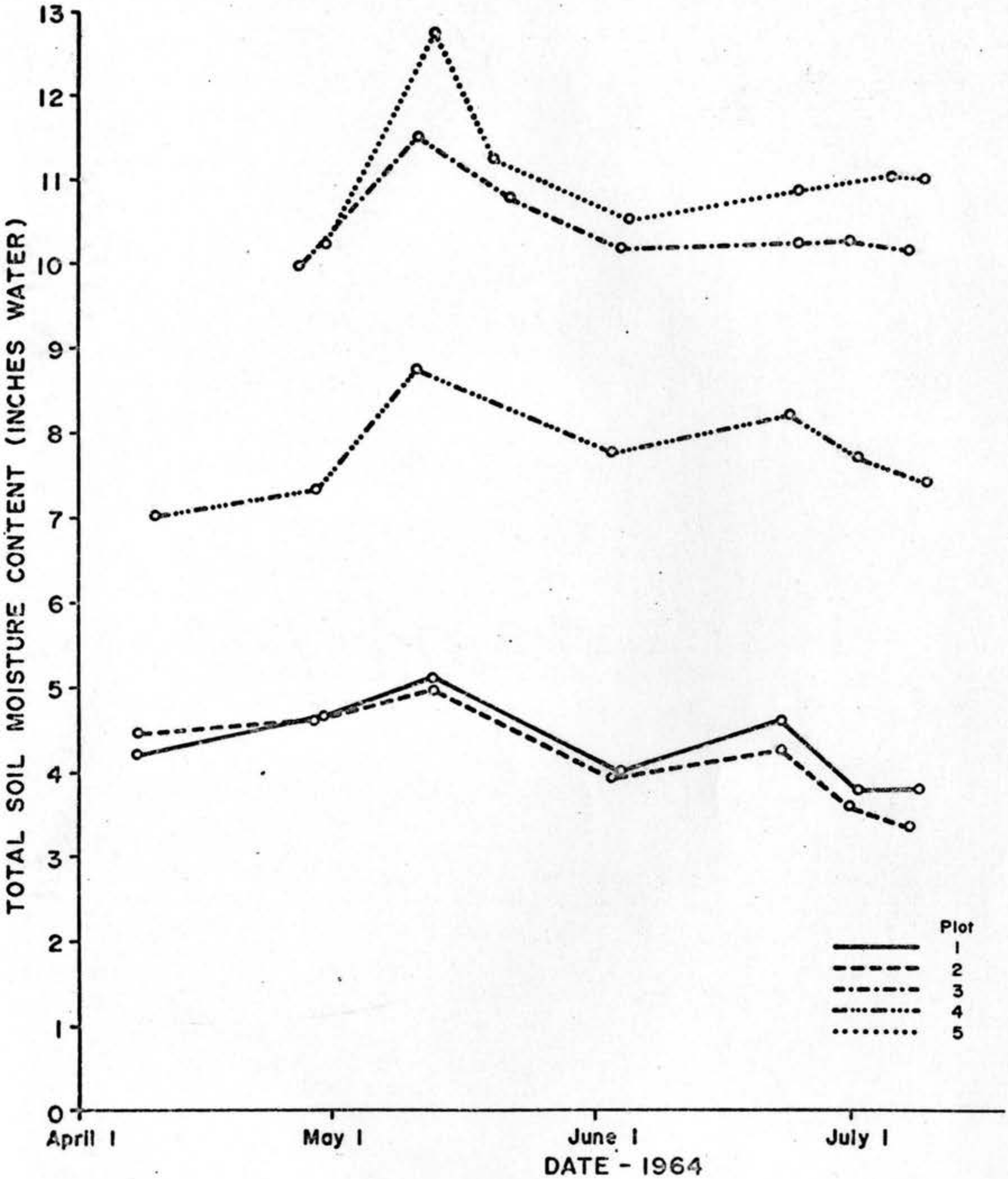
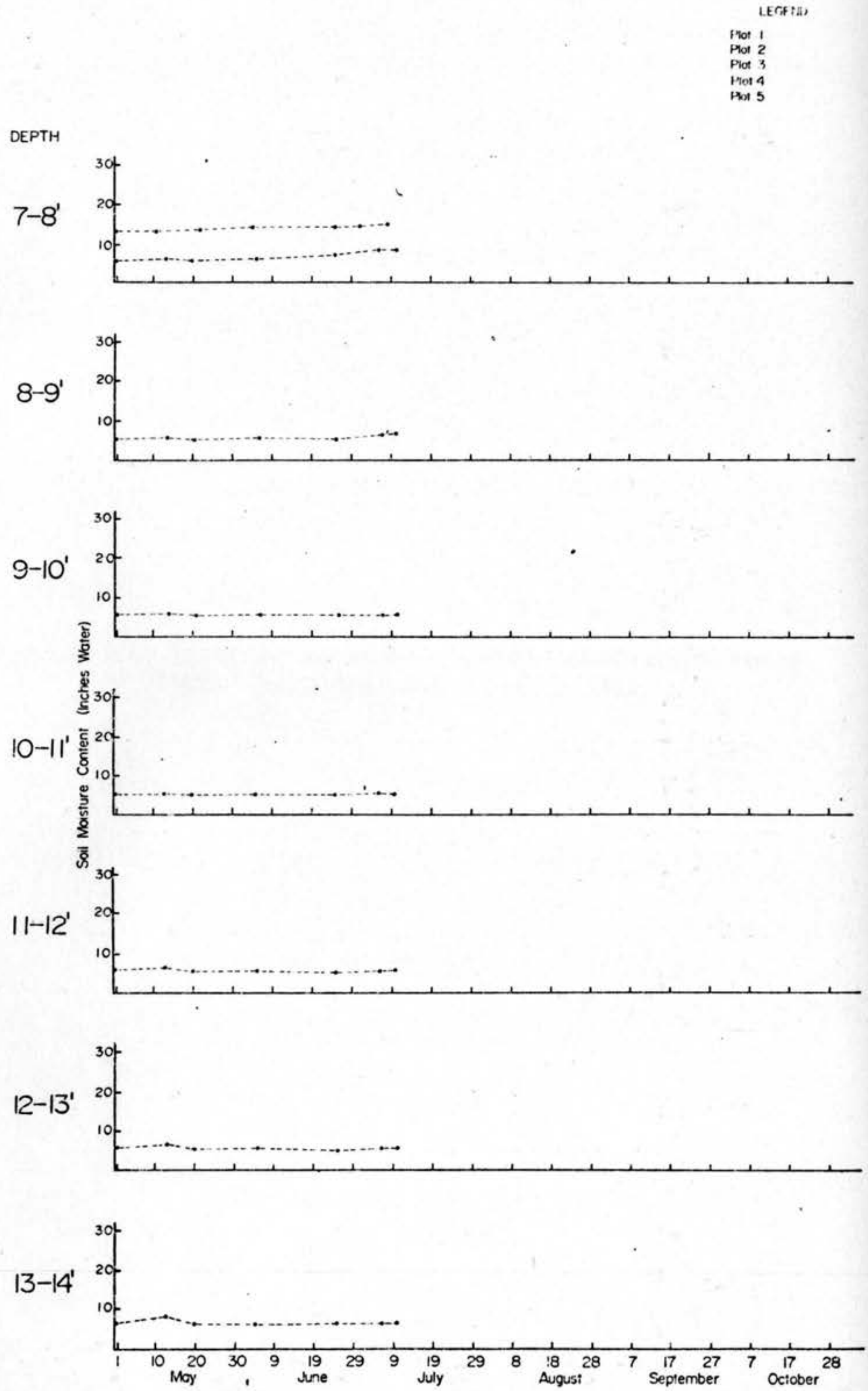
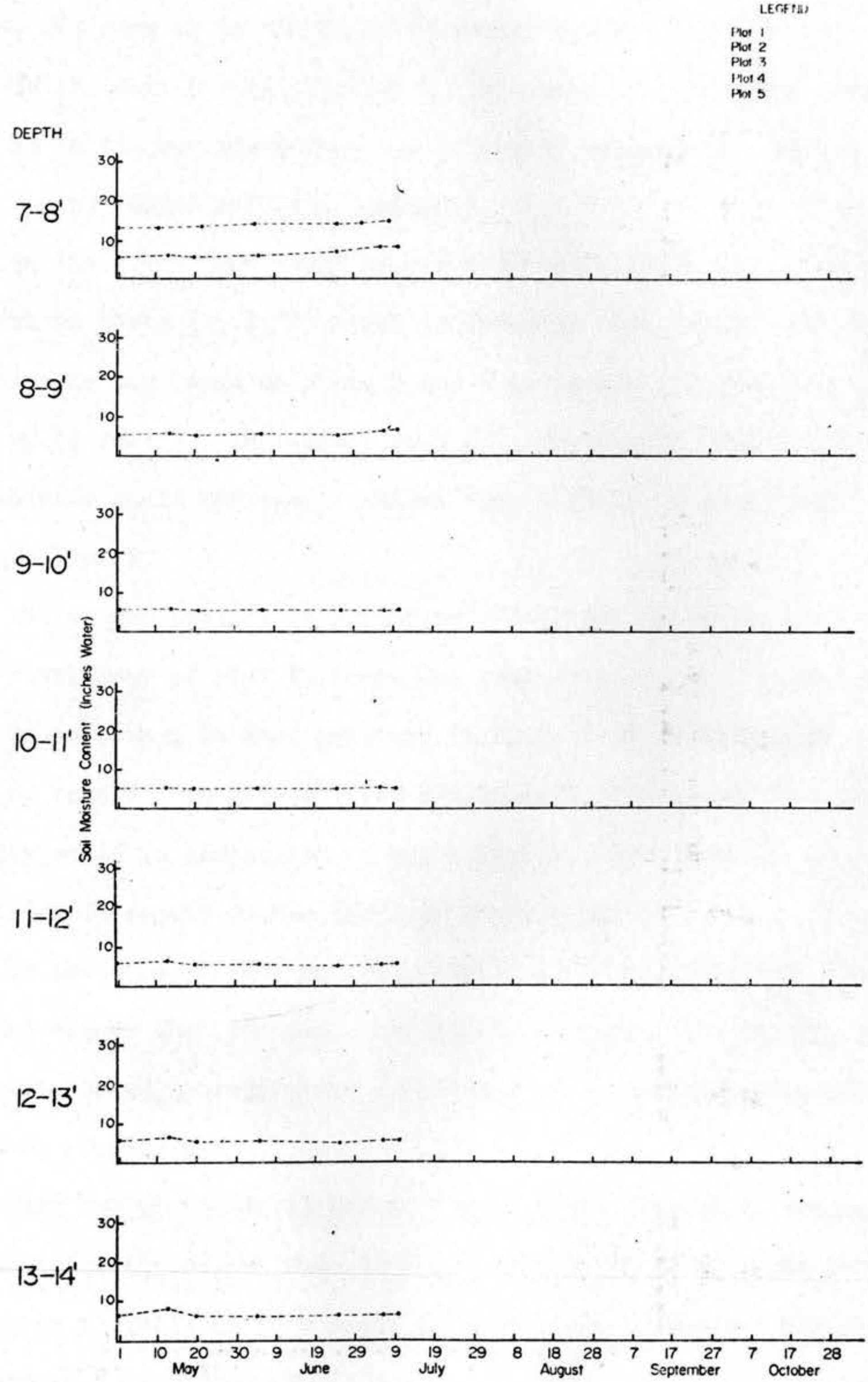

13
12
11
10
9
8
7
6
5
4
3
2
1
0
TOTAL SOIL MOISTURE CONTENT (INCHES WATER)
April 1
May 1
June 1
July 1
DATE - 1964
Plot
1
2
3
4
5

Figure 49. Soil moisture contents in individual depth zones of Plots 1 to 5 inclusive during 1964.

SOIL MOISTURE CONTENTS – PLOTS 1, 2, 3, 4, 5, – 1964
(Continued)



SOIL MOISTURE CONTENTS -- PLOTS 1, 2, 3, 4, 5, - 1964
(Continued)



and for the remainder of the period of record showed the same trend as did the second foot of soil. The ranking of soil moisture contents was also the same as in the 12 to 24 inches depth.

In the fourth foot, increasing soil moisture was again noted up to May 11 to 13, but thereafter was generally decreasing. Plot 4 showed lowest values and Plot 1 highest.

In the fifth foot, soil moisture contents increased initially in all three plots (3, 4, 5) which extended to this depth. Increased soil moisture was found on Plots 3 and 5 up to May 11 to 13, and on Plot 4 up to June 3. Thereafter soil moisture change tended to be a comparatively small decrease. Values were highest in Plot 3 and lowest in Plot 5.

While some periods of slight soil moisture depletion were noted in the sixth foot of Plot 3, there was generally either a slight increase or no change in soil moisture in Plots 4 and 5 throughout the period of record. In general, changes in soil moisture at this depth were very small in comparison to upper depths. Soil moisture contents in Plot 3 were almost double those of Plots 4 and 5.

In the seventh foot of soil, Plot 3 again had moisture contents very much higher than the other two plots. Changes were slight, and in general showed a progressive increase in soil moisture throughout the period of record.

Only two plots (3, 5) had an eighth foot. Plot 3 values again were substantially higher than those in Plot 5. Soil moisture tended to increase slightly at this depth on both plots throughout the period of record.

Below the eight-feet depth, only Plot 5 was represented. The general trend from eight feet to fourteen feet depth was for changes to be very slight, and to be positive.

To make a statistical test of the differences noted above, analyses of variance were carried out on the same plan as was used for the 1963 data, with the following additions:

1. In the analysis for the uppermost eight feet, two plots (3 and 5) were represented.

2. An analysis of variance was carried out for the uppermost fourteen feet. Only Plot 5 figured in this analysis.

The analysis of variance table for the uppermost three feet is given in Table 44. Other analysis of variance tables for 1964 are given in Appendix D.

The results of analysis of variance were in general very similar to those of the 1963 analyses.

1. Plots, periods and depths were always highly significantly different.

2. Interactions, plot x depth, and period x depth, were always highly significant.

3. Interactions, plot x period, and plot x period x depth, were generally not significant, but in some analyses (seven and eight feet) were significant.

The significance levels associated with the various components of variation in the different analyses are shown in Table 45.

Third Year of Record - 1965

In the early portion of 1965, instrumentation problems were again encountered. Accordingly, the first full set of readings could not be

Table 44. Analysis of variance: uppermost three feet of soil, 1964 soil moisture contents (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	4	14.81	3.703	84.59	0.005
Period (P)[1]	7	33.58	4.797	109.59	0.005
Depth (D)	2	51.74	25.868	590.96	0.005
B x P	23	*	*	*	
B x D	8	3.81	0.477	10.89	0.005
P x D	14	18.81	1.344	30.87	0.005
B x P x D	46	*	*	*	
Error	897	37.94	0.04		
Total	932	157.30			

* Best estimate is zero.

1 Date of measurement.

obtained until June 8 to 11, 1965. Measurements were taken on 13 different occasions between these dates and the end of October; two in June, four in July, and four in August, none in September, and two in October. The absence of data in September was again the result of instrumentation difficulties.

The summers and fall months of 1965 were considerably wetter than the long-term average, as is shown by the monthly precipitation values of Table 46. On some plots, higher soil moisture values were obtained during 1965 than in any of the other three years of record, in spite of the late start in readings.

While 1963 showed late season values, and 1964 early season data, the 1965 measurements gave the first opportunity to study soil moisture trends over a large portion of the summer and fall season. Due to the heavy precipitation experienced, considerable fluctuation in soil moisture occurred, particularly in the uppermost depths of the solum. The march of total soil moisture in all plots is shown in Figure 50.

First foot of soil showed a pattern of soil moisture accretion and depletion from early June to mid-August. Thereafter accretion took place until early September, followed by depletion from then until late October. During periods of high soil moisture there was considerable difference between plots. Differences were less when soil moisture had been depleted. Trends are shown in Figure 51. Plot 2 had highest soil moisture values, followed in order by Plots 1, 4, 3, and 5.

In the second foot (12 to 24 inches depth) of soil, differences in soil moisture content between plots tended to be relatively small. Moisture contents showed the same ranking as the uppermost foot, Plot

Table 45. Levels of significance associated with sources of variations in analyses of variance for three, four, seven, eight and fourteen uppermost feet of soil. 1964 soil moisture contents.

Source of variation	Three feet	Four feet	Seven feet	Eight feet	Fourteen feet
Plot (B)	0.005	0.005	0.005	0.005	not applicable
Period (P)	0.005	0.005	0.005	0.005	0.005
Depth (D)	0.005	0.005	0.005	0.005	0.005
B x P	-	N.S.	-	-	not applicable
B x D	0.005	0.005	0.005	0.005	not applicable
P x D	0.005	0.005	0.005	0.005	0.005
B x P x D	-	-	-	0.005	not applicable

Table 46. Comparison of monthly rainfall in summer and fall months of 1965 with long-term average for those months.

MONTH	MONTHLY PRECIPITATION (INCHES WATER)	
	LONG-TERM AVERAGE[1]	1965
June	4.4	6.17
July	2.6	2.80
August	2.9	4.14
September	2.1	4.59
October	1.5	0.99
TOTAL	13.5	18.69

1 Taken from McKay, Curry and Mann (1963).

1 being greatest and Plot 5 least. Soil moisture depletion was found at dates later than those determined for the uppermost foot. However, trends in the second foot of soil may be said to be essentially similar (though less marked) to those noted above for the first foot of soil (Figure 51).

The third foot showed very little difference in soil moisture content between plots. Trends were similar to those of the shallower soil depths, but less pronounced.

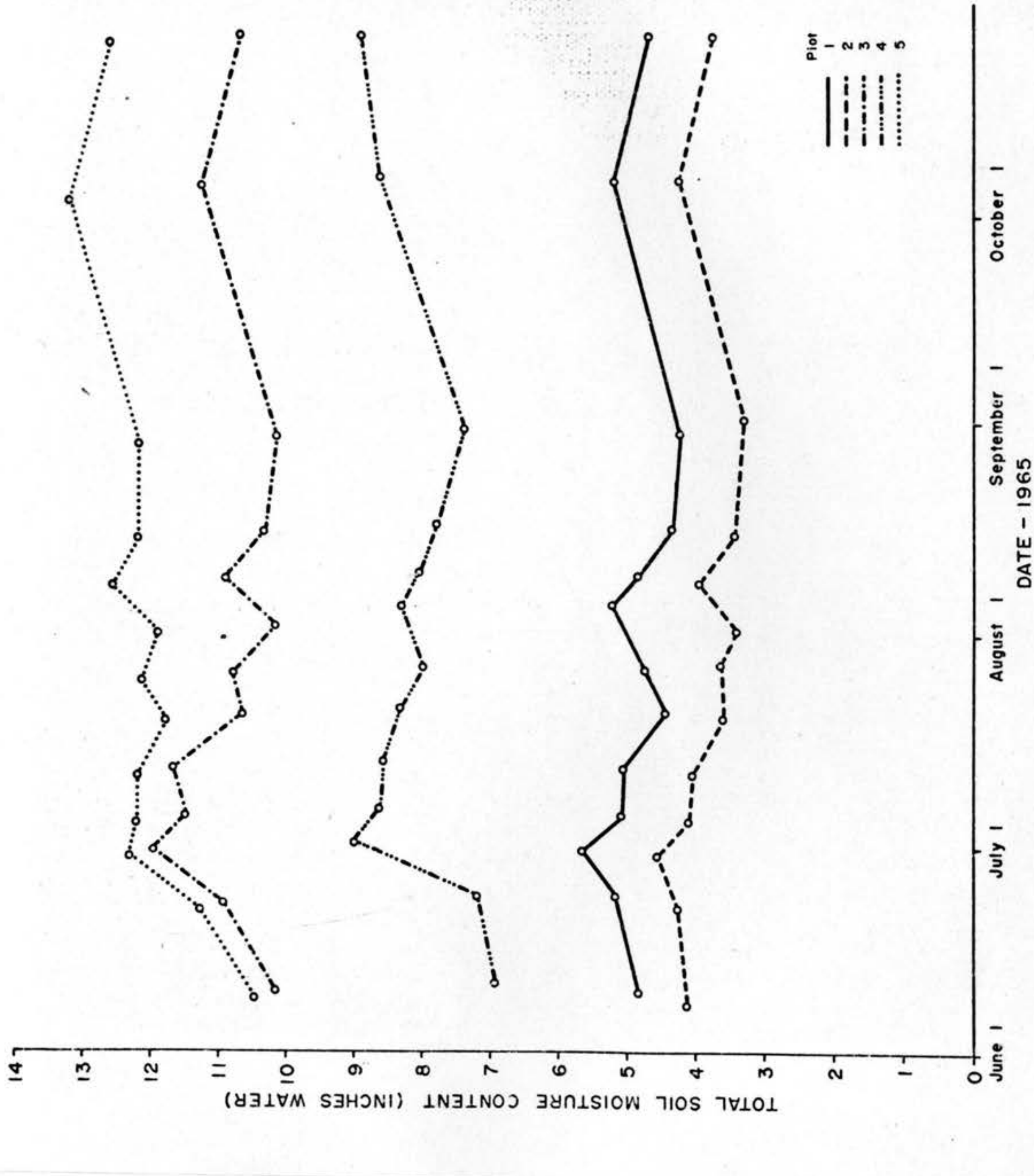
Greater differences between plots were found in the fourth foot. Plot 4 showed values lower than the other plots, which had soil moisture contents little different one from the others. A pattern of soil moisture accretion was noted to the end of June. Thereafter, a depletion pattern held until the end of August, followed by slight accretion during September, and slight depletion during October.

In the fifth foot of soil, Plot 3 had soil moisture contents considerably greater than Plots 4 and 5 (Figure 51). Trends were similar in all plots. Moisture accretion took place to end of June. Thereafter changes were slight.

The same pattern was found in the sixth foot of soil. In the seventh foot, Plot 5 had moisture contents considerably lower than Plots 3 and 4. Plot 5 showed a rather marked soil moisture accretion until early July, whereas Plot 3 demonstrated virtually no change in soil moisture content.

In the eighth foot of soil, Plot 3 again had values considerably greater than Plot 5. Accretion took place to mid-July. Thereafter there was little change.

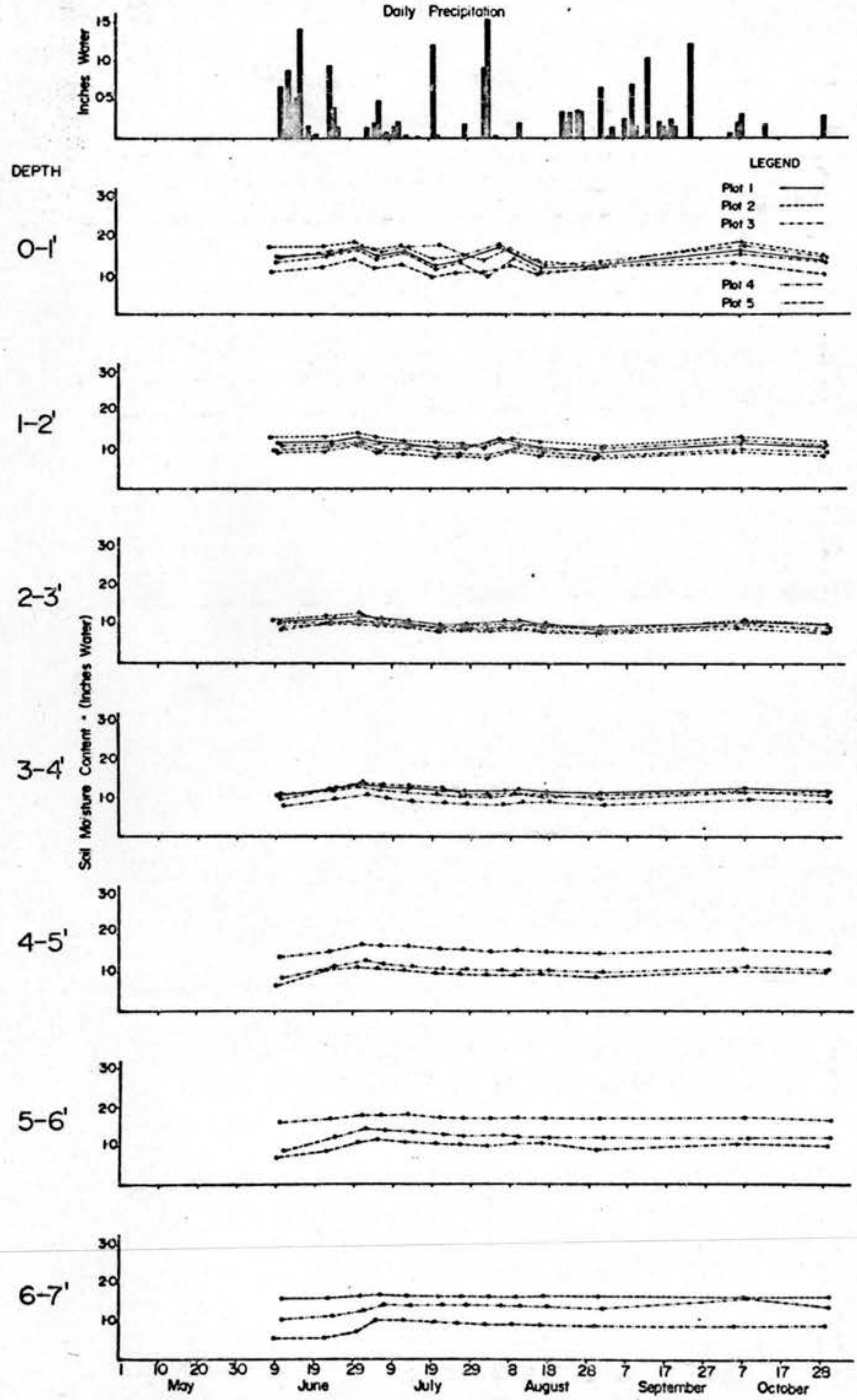
Figure 50. March of total soil moisture in Plots 1, 2, 3, 4 and 5 in 1965. Moisture contents are for the whole instrumented solum. (Plot 1 - 4 feet; Plot 2 - 3 feet; Plot 3 - 8 feet; Plot 4 - 7 feet; Plot 5 - 14 feet.)



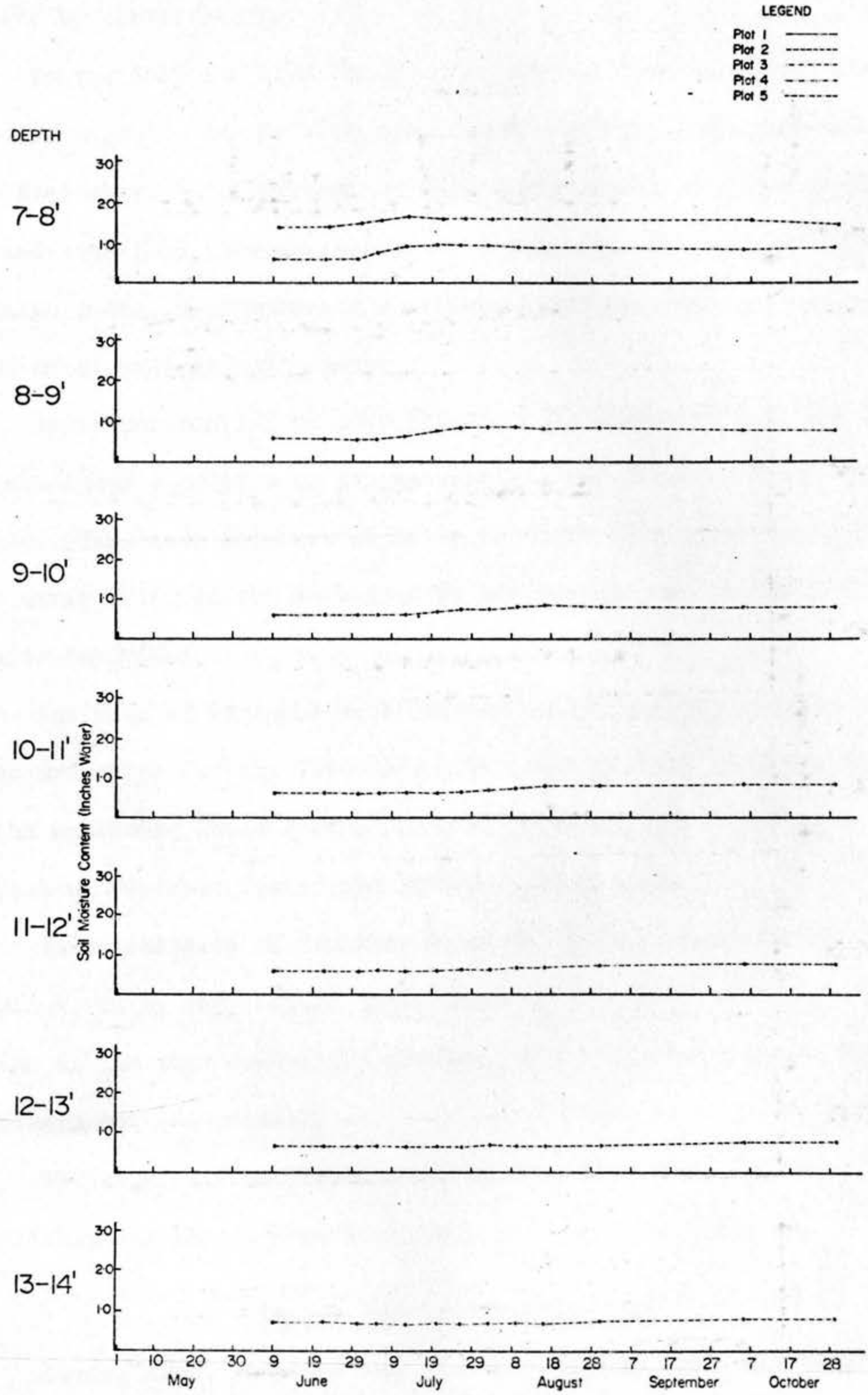
TOTAL SOIL MOISTURE CONTENT (INCHES WATER)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
June 1
July 1
August 1
September 1
October 1
DATE - 1965
Plot
1
2
3
4
5

Figure 51. Soil moisture contents in individual depths of Plots 1 to 5 inclusive during 1965.

SOIL MOISTURE CONTENTS - PLOTS 1, 2, 3, 4, 5, - 1965



SOIL MOISTURE CONTENTS – PLOTS 1, 2, 3, 4, 5, – 1965
(Continued)



Only Plot 5 had soil depths greater than eight feet. In the ninth foot, a period of soil moisture accretion ended in late July, followed by little change.

In the 10th and 11th feet, soil moisture accretion took place until mid-August. In the 12th foot, this accretion period extended to early September. Accretion of soil moisture also took place in the 13th and 14th foot, but was not great. Once accretion of soil moisture had taken place, soil moisture contents tended to remain constant at depths of eight feet and greater.

It is interesting to note (Figure 51), that soil moisture accretion continued in Plot 5 to progressively later dates as depth increased. Thus soil moisture at seven to eight feet depth increased up to early July, in the 10th foot to mid-August, and in the 21th foot to early September.

Analyses of variance were carried out in exactly the same manner as was described for the 1964 data. The analysis for variance table for the uppermost three feet of soil is given in Table 47. Other analysis of variance tables are included in Appendix D.

These analyses of variance show all sources of variation with one exception, to be very highly significant (p = 0.005). The one exception is the third order interaction, plot x period x depth, which was always not significant.

The significance levels associated with the various components of variation in the different analysis are shown in Table 48.

Fourth Year of Record - 1966

During 1966, readings began on May 11th to 12th, and continued to September 27 to 30, with the exception of Plot 5, where one additional reading was taken on October 11. Measurements were made 14 times on Plots 1 to 4 inclusive, and 15 times on Plot 5. Data were collected at weekly intervals during May and June, and approximately every two weeks thereafter.

Total precipitation during the period of record in 1966 was 12.27 inches. This was slightly less than the long-term average, since precipitation from beginning of May to end of September, 1966 was 13.1 inches, in comparison to the long-term average of 15.1 inches for the same period.

The lower precipitation, than that experienced in the same months of 1965, influenced soil moisture trends in 1966, as is seen by comparison of Figure 50 and Figure 52.

During 1966, in the first foot there were wide differences between plots in soil moisture contents at the start of record. By mid-August these differences had substantially decreased. The general trend was to progressive drying at this depth (Figure 53). The ranking of soil moisture contents was, in descending order, Plot 2, 1, 4, 3 and 5, the same ranking as determined in previous years of record. Some plots dried more than others at this depth (Figure 53).

In the second foot of soil, there was, in general, less difference in soil moisture contents between plots, than in the first foot. The general trend was one of soil moisture depletion. Periods of measured soil moisture accretion were infrequent. Again, Plot 2 showed the highest values.

The third foot showed only negligible differences between plots. A general drying trend was evident, though less pronounced than that established in the second foot.

Table 47. Analysis of variance: uppermost three feet of soil, 1965 soil moisture contents (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plots (B)	4	19.46	4.87	165.01	0.005
Periods (P)[1]	12	17.30	1.44	48.89	0.005
Depths (D)	2	87.12	43.56	1477.20	0.005
B x P	48	4.44	0.09	3.14	0.005
B x D	8	4.47	0.56	18.97	0.005
P x D	24	2.88	0.12	4.07	0.005
B x P x D	96	3.05	0.03	1.08	N.S.
Error	1590	46.89	0.03		
TOTAL	1784	185.61			

1. Date of measurement.

Table 48. Levels of significance associated with sources of variation in analysis of variance for uppermost three, four, seven, eight and fourteen feet of soil. 1965 soil moisture contents.

Source of variation	Three feet	Four Feet	Seven feet	Eight feet	Fourteen feet
Plot (B)	0.005	0.005	0.005	0.005	not applicable
Period (P)[1]	0.005	0.005	0.005	0.005	0.005
Depth (D)	0.005	0.005	0.005	0.005	0.005
B xP	0.005	0.005	0.005	0.005	not applicable
B x D	0.005	0.005	0.005	0.005	not applicable
P x D	0.005	0.005	0.005	0.005	0.005
B x P x D	N.S.	N.S.	N.S.	N.S.	not applicable

1. Date of measurement.

In the fourth foot, Plot 5 showed the lowest values as the beginning of record, but dried less than some of the other plots over the season (Figure 53). Plot 4 consistently had the lowest values, over the remainder of the period of record, while Plot 1 had consistently highest values. Soil moisture accretion took place up to early June. Thereafter, a depletion pattern was found.

In the fifth foot, Plot 3 values were appreciably higher than those of Plots 4 and 5. After soil moisture accretion ceased in mid-June, a general depletion trend set in.

The sixth foot demonstrated virtually no change over the season in Plot 3, in which values were found which were higher than in either of the other two plots. The pattern for the seventh foot was an identical one.

In the eighth foot, Plot 3 values were considerably greater than Plot 5 values. Little change in soil moisture took place.

At depths beyond eight feet, only Plot 5 was represented. Virtually no change in soil moisture content took place at depths between eight and fourteen feet in this plot.

The identical analysis of variance models, as used in 1964 and 1965, were tested for the 1966 data. The analysis of variance table for the uppermost three feet of soil is given in Table 49. Other analysis of variance tables are included in Appendix D.

These analysis of variance show all sources of variation to be highly significant. The third order interaction, plot x period x depth, was not significant in some analyses.

The significance levels associated with the various components of variation in the different analyses are shown in Table 50.

Figure 52. March of total soil moisture in Plots 1, 2, 3, 4 and 5 in 1966. Moisture contents are for the whole instrumented solum. (Plot 1 - 4 feet; Plot 2 - 3 feet; Plot 3 - 8 feet; Plot 4 - 7 feet; Plot 5 - 14 feet.)

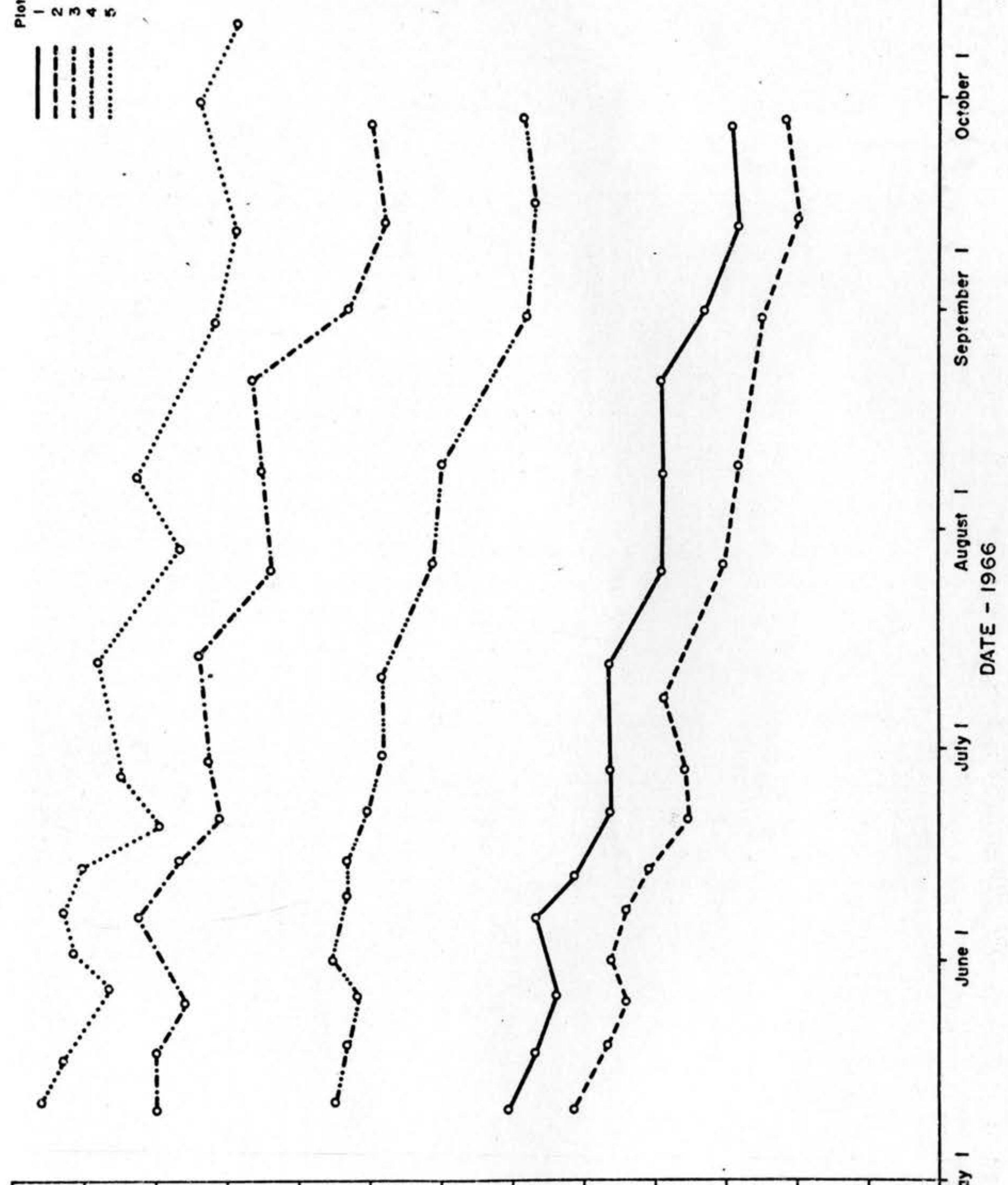
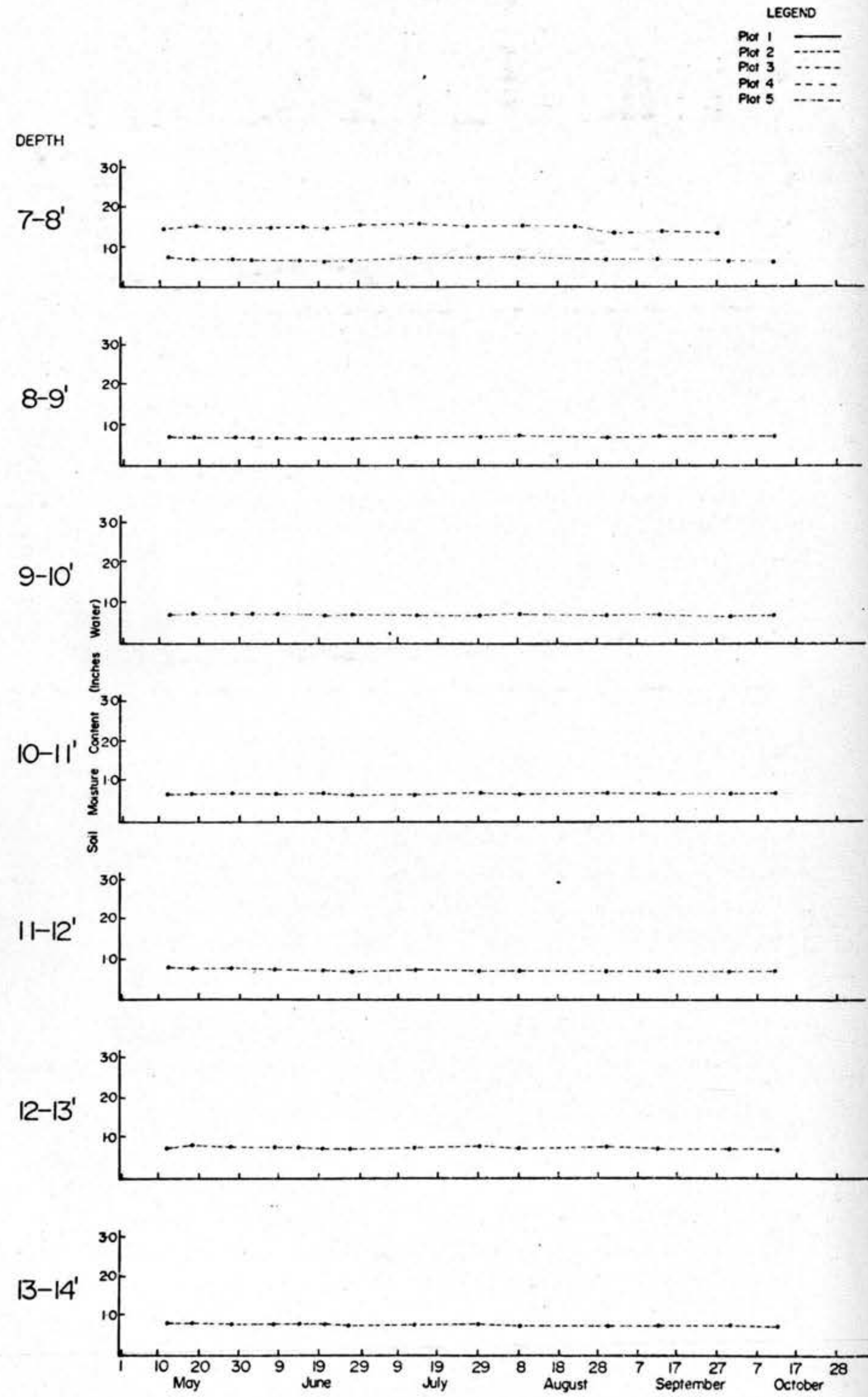

Plot
1
2
3
4
5
TOTAL SOIL MOISTURE CONTENT (INCHES WATER)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
May 1
June 1
July 1
August 1
September 1
October 1
DATE - 1966

Figure 53. Soil moisture contents in individual depths of Plots 1 to 5 inclusive during 1966.

SOIL MOISTURE CONTENTS – PLOTS 1, 2, 3, 4, 5, – 1966
(Continued)



SOIL MOISTURE CONTENTS - PLOTS 1, 2, 3, 4, 5, - 1966

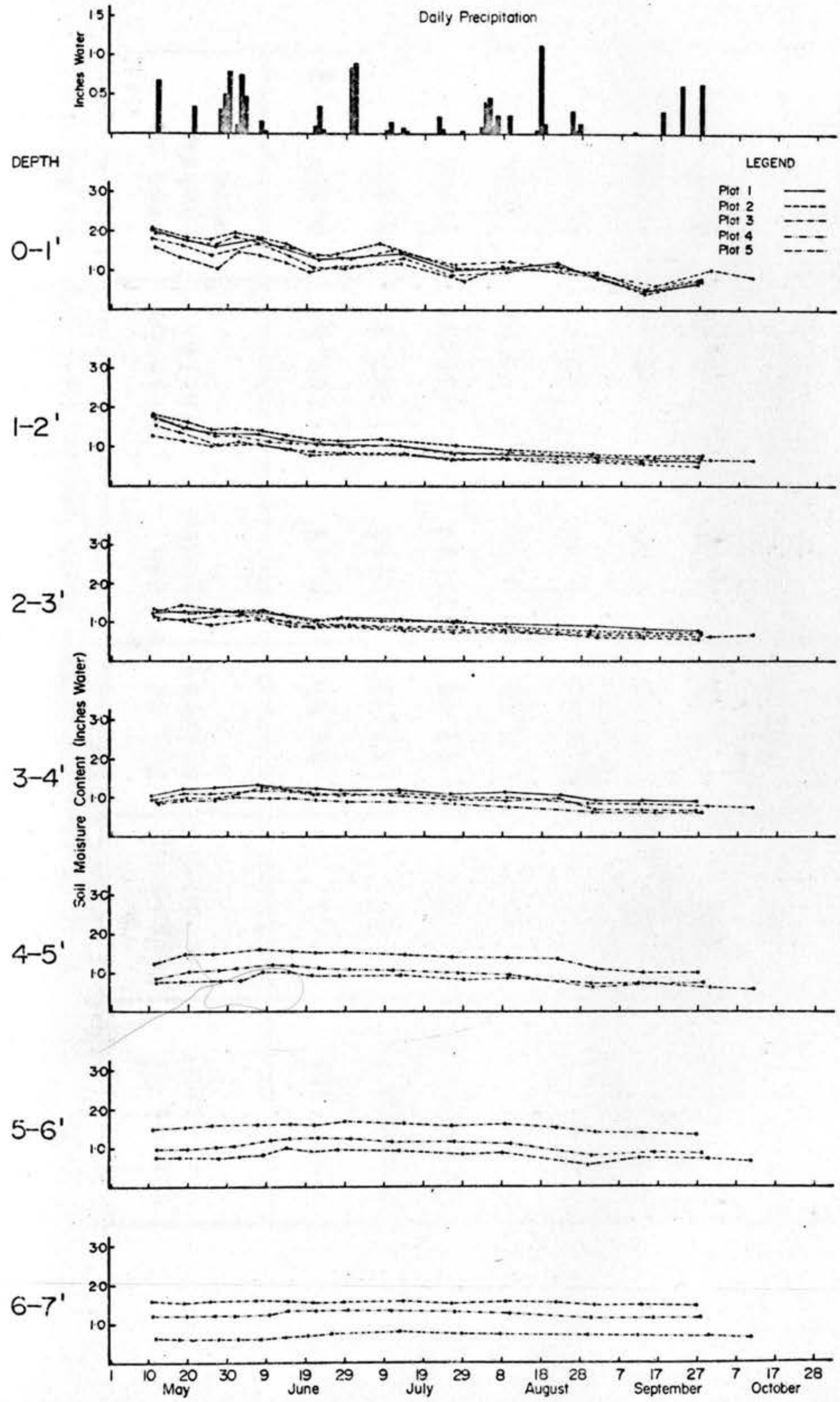


Table 49. Analysis of variance: uppermost three feet of soil, 1966 soil moisture contents (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plots (B)	4	20.60	5.15	167.64	0.005
Periods (P)[1]	15	157.72	10.52	342.32	0.005
Depths (D)	2	43.98	21.99	715.91	0.005
B x P	51	0.03	0.00	0.02	N.S.
B x D	8	4.70	0.59	19.11	0.005
P x D	30	19.89	0.66	21.59	0.005
B x P x D	102	4.26	0.04	1.36	0.025
Error	1737	53.35	0.03		
TOTAL	1949	304.52			

1. Date of measurement.

Table 50. Levels of significance associated with sources of variation in analysis of variance for uppermost three, four, seven, eight and fourteen feet of soil. 1966 soil moisture contents.

Source of variation	Three feet	Four feet.	Seven feet	Eight feet	Fourteen feet
Plot (B)	0.005	0.005	0.005	0.005	not applicable
Period (P)[1]	0.005	0.005	0.005	0.005	0.005
Depth (D)	0.005	0.005	0.005	0.005	0.005
B x P	N.S.	0.010	-	-	not applicable
B x D	0.005	0.005	0.005	0.005	not applicable
P x D	0.005	0.005	0.005	0.005	0.005
B x P x D	0.025	N.S.	-	-	not applicable

1. Date of measurement.

All Years - Comparison of Soil Moisture Contents

Readings were taken in late season 1963, early season 1964, and throughout the season in 1965 and 1966, excepting that the 1965 readings were somewhat late in beginning. A certain consistency emerges from the four years of record.

In the uppermost foot of soil, Plot 2 generally had the highest values, followed by Plots 1 and 4 which had generally similar moisture contents, followed in turn by Plots 3 and 5. Excepting during 1963, when readings were taken only in late season, when the upper soil was drier, the first foot of soil generally showed values higher than those in deeper soil depths. This was considered to be the result of its higher water holding capacity (Table 6), and the fact of its receiving more recharge than deeper soil layers.

The second foot of soil showed a similar pattern. Plot 2 values were highest, followed by Plots 1 and 4, followed in turn by Plots 3 and 5. Moisture contents, while less than the uppermost foot, were generally greater than in the soil layers immediately below, except in the case of Plot 5. Changes in soil moisture were of lower magnitude in the second foot than in the first foot.

In the third foot of soil, while a ranking similar to that noted above for the first and second feet existed, differences in moisture contents between plots tended to be relatively small (Figs. 47, 49, 51, 53). While mean moisture contents for the first foot of soil during 1965 ranged from 1.2 to 1.6 inches, in the third foot the range was from 0.9 to 1.0 inches, demonstrating both the lower moisture contents and a lower range between plots. This was in spite of the fact that Plot 2 did not extend beyond a depth of three feet.

In the fourth foot, differences between plots were similar to those in the third foot. Plot 1 had highest values, with Plots 3 and 5 occupying a central position, and Plot 4 having lowest soil moisture contents. Mean annual values showed close similarity to the third foot of soil. Plot 1 did not extend beyond four foot depth.

In the fifth foot of soil, Plot 3 always had appreciably higher values (mean 1965 value, 1.57 inches) than Plot 4 (0.94 inches) and Plot 5 (0.96 inches). As in the fourth foot, changes in soil moisture content tended to be less marked than in upper soil layers (Figs. 47, 49, 51, 53).

The sixth and seventh feet of soil showed patterns similar to the fifth foot, excepting that Plot 4 soil moisture contents were invariably considerably higher than Plot 5 values, while Plot 3 values were always the highest of the three plots. Only slight changes in soil moisture contents took place at these depths. Plot 4 did not extend beyond seven feet.

In the eighth foot, the same pattern was repeated. Plot 3 values were always considerably higher than those of Plot 5. Thus, in 1965, the mean soil moisture content measured at this depth was 1.53 inches in Plot 3 and only 0.82 inches in Plot 5. In both plots, soil moisture contents at eight feet were less than soil moisture contents at six and seven feet. Plot 3 did not extend beyond eight feet.

In Plot 5, access tubes extended to fourteen feet. Changes in soil moisture at these depths were very small. Soil moisture contents were low and ranged from 0.6 to 0.8 inches, mean measured values for all years (Figs. 47, 49, 51, 53).

The consistency shown by inspection of soil moisture trends during four years in which data were collected, extended also to the results of analysis of variance (Tables 43, 44, 45, 47, 48, 49, 50).

The results of analysis of variance showed:

(1) Differences between plots were invariably highly significant.

(2) Differences between dates of measurement periods were invariably highly significant.

(3) Differences between depths were invariably highly significant.

(4) The interaction, plot x period, was usually highly significant, but occasionally was not significant.

(5) The interaction, plot x depth, was invariably highly significant.

(6) The interaction, period x depth, was invariably highly significant.

(7) The interaction, plot x period x depth, was usually not significant but occasionally was highly significant.

The occurrence of significant interactions signifies that care must be exercised in interpretation of differences between main effects, i.e., between plots, dates of measurement and depths.

The significant interactions may be explained by the response of soil moisture to precipitation and transpiration during the period of record. Soil moisture trends in the upper soil levels, while over the long run essentially parallel, show that some depths of some plots dried more than others in a given period between measurements, or alternatively retained more incident precipitation in a given depth during certain periods between measurements (Figs. 47, 49, 51, 53). These effects were most pronounced in the upper soil layers, and were the source of the significant interactions encountered.

The significant differences in moisture contents between plots were made difficult of interpretation not only by the occurrence of significant interactions, but by the differences in soil characteristics, particularly of water storage capacity, which obtained between plots (Table 6; Appendix B).

To supplement the results of analysis of variance, the mean, maximum and minimum soil moisture contents measured in 1963, 1964, 1965 and 1966 in the soil depths used for analysis of variance (0 - 3 feet; 0 - 4 feet; 0 - 7 feet; 0 - 8 feet; 0 - 14 feet) are listed in Table 51.

While there is a general consistency in the ranking of plots one against another, departures from the general trend show up. Thus, in the mean values for depth 0 - 4 feet, Plot 3 values were generally greater than Plot 5 values. However, in 1966 the Plot 5 mean soil moisture content was slightly greater than that of Plot 3. The same was true of 1966 minimum soil moisture contents.

The ranking, furthermore, of maximum and minimum values was not always the same. In 1964, for example, the Plot 3 maximum for depth 0 - 3 feet was greater than that of Plot 5, while in minimum values the Plot 5 minimum was greater than that of Plot 3. A similar disparity in ranking was found in most cases, as can be readily determined by inspection of Table 51. The significant interactions established in analysis are believed to result from such phenomena.

Emergent from the analysis of variance is the consistency of results, regardless whether analysis was carried out for 0 - 3 feet, 0 - 4 feet, 0 - 7 feet, 0 - 8 feet or 0 - 14 feet (Tables 43 to 45, 47 to 50). This is suggestive that soil moisture measurement to a

Table 51 Mean, maximum and minimum total soil moisture contents (inches water) in all plots in four years for depths of 0-3 feet, 0-4 feet, 0-7 feet, 0-8 feet and 0-14 feet.

		1963			1964		
Plot	Depth	Mean	Maximum	Minimum	Mean	Maximum	Minimum
1	0-3'	2.44	3.04	1.73	4.02	4.70	3.29
2	0-3'	2.73	3.35	2.33	4.16	4.97	3.33
3	0-3'	2.28	2.74	2.03	3.39	4.35	2.81
4	0-3'	2.64	3.18	2.16	3.72	4.79	3.03
5	0-3'	-	-	-	3.05	4.26	2.48
1	0-4'	3.46	4.13	2.56	5.15	6.13	4.51
3	0-4'	3.15	3.74	2.68	4.46	5.57	4.01
4	0-4'	3.40	4.03	2.78	4.55	5.83	3.89
5	0-4'	-	-	-	4.08	5.42	3.56
3	0-7'	7.67	8.49	6.60	9.06	10.20	8.65
4	0-7'	6.64	7.40	5.66	7.73	8.74	7.38
5	0-7'	-	-	-	6.69	8.25	6.47
3	0-8'	9.09	9.90	8.01	10.42	11.51	10.12
5	0-8'	-	-	-	7.37	8.86	7.07
5	0-14'	-	-	-	10.90	12.75	10.51

Table 51 Mean, maximum and minimum total soil moisture contents (inches water) in all plots in four years for depths of 0-3 feet, 0-4 feet, 0-7 feet, 0-8 feet, and 0-14 feet - continued.

		1965			1966		
Plot	Depth	Mean	Maximum	Minimum	Mean	Maximum	Minimum
1	0-3'	3.68	4.31	3.19	3.36	5.03	1.91
2	0-3'	3.89	4.55	3.41	3.63	5.16	1.98
3	0-3'	3.21	3.91	2.64	2.81	4.27	1.62
4	0-3'	3.64	4.01	3.18	3.35	4.76	1.99
5	0-3'	2.97	3.63	2.59	2.89	4.36	1.74
1	0-4'	4.87	5.65	4.35	4.47	6.06	2.83
3	0-4'	4.37	5.33	3.70	3.80	5.22	2.31
4	0-4'	4.55	5.09	3.98	4.20	5.61	2.64
5	0-4'	4.09	4.94	3.68	3.87	5.21	2.56
3	0-7'	9.29	10.48	8.56	8.36	9.77	6.39
4	0-7'	8.11	9.00	7.37	7.57	8.54	5.70
5	0-7'	6.93	7.90	5.98	6.28	7.37	4.88
3	0-8'	10.82	11.97	10.11	9.85	11.00	7.79
5	0-8'	7.74	8.49	7.37	6.97	8.12	5.60
5	0-14'	12.06	13.11	10.46	11.32	12.60	9.92

depth of three or four feet only, in these soils was sufficient in itself to demonstrate differences between plots. To test this hypothesis, Duncan's Multiple Range Test (Steel and Torrie, 1960: 107-109) was applied to the plot means in the analyses of soil moisture contents in the uppermost four feet of soil.

The results of this test are shown in Table 52. These demonstrate that significant differences between plots in the analyses for the uppermost seven or eight feet of soil usually existed also in the upper most four feet of soil. However, further Duncan's Multiple Range tests applied to the uppermost seven feet plot means showed that there were significant differences between means between Plots 3 and 4 in 1964 and between Plots 3 and 5 in 1966. In addition, the eight feet analysis in 1966 (Table 50) showed a highly significant difference between Plots 3 and 5.

Thus, it must be concluded that sampling to shallow depths only did not invariably show the significant differences which appeared when measurement was extended to deeper soil layers.

Comparison of Soil Moisture Change

In this section, attention is mainly directed to individual depths or zones within the solum.

Figures 46, 48, 50, 52, already presented, show total soil moisture change over the various periods of record.

It is readily discernible that, while large differences in total soil moisture content existed between plots, differences in total soil moisture change were much smaller.

Thus, in 1966, while the soil moisture contents of Plot 2 and Plot 5 (shallowest and deepest plots) were at first measurement (May

Table 52. Results of Duncan's Multiple Range Test for plot means of soil moisture content (inches water) in 1963, 1964, 1965 and 1966 in the uppermost 4 feet of soil.[1]

YEAR	1963	1963	1963	1963	
PLOT	1	2	3	4	
YEAR	1964	1964	1964	1964	1964
PLOT	1	2	3	4	5
YEAR	1965	1965	1965	1965	1965
PLOT	1	2	3	4	5
YEAR	1966	1966	1966	1966	1966
PLOT	1	2	3	4	5

1. No significant difference between plots underlined (p = 0.05).

11-12) 5.2 inches and 12.6 inches respectively, a very large difference, the total moisture change for these two plots calculated as "first reading (May 11-12) minus last reading (Sept. 28-30)" was 3.0 inches for Plot 2 and 2.2 inches for Plot 5, an entirely negligible difference. The much greater depth of Plot 5 apparently had little effect upon total moisture change, as calculated in this manner.

Soil moisture change is fundamentally the main parameter of interest in forest hydrology studies of which soil moisture is a component. An indication of soil moisture change with time and different soil depths was given by Figures 47, 49, 51, 53.

Since detailed consideration of soil moisture change, comparable to that given to soil moisture content on the pages immediately preceding, would be repetitious, only the most important points are considered below, under the heading of soil moisture change.

The percentage disposition of total soil moisture accretion and depletion by individual depths in all years is shown in Figures 59 to 63 inclusive, while the range in soil moisture contents by year and depth is presented in Figure 58.

To make an appraisal of the statistical significance of soil moisture changes measured, analyses of variance were carried out exactly as was done for soil moisture content, the sole difference being that soil moisture change was the variable analysed.

Analysis of variance was undertaken for the uppermost 3 feet, 4 feet, 7 feet, 8 feet, and 14 feet, for 1963, 1964, 1965 and 1966. The results of analysis of variance are shown in Table 53.

These results are highly illuminating. Only the three feet analyses show significant differences between plots. The others generally show no significance. Period is always highly significant, as would be expected. Most of the interaction terms are significant.

The conclusion to be drawn from these analyses is that no significant difference exists in soil moisture change between plots.

First Year of Record - 1963

Moisture change values were obtained for the latter part of the year only during 1963. Soil moisture change with time in Plots 1, 2, 3 and 4 during 1963 is shown in Figure 54.

These values showed that soil moisture depletion took place throughout the period of record, August 7 to October 27. This depletion left soil considerably drier in late October than in early August. It extended throughout the profile in Plots 1 and 2, to six foot depth in Plot 3 and to seven foot depth in Plot 4.

Generally speaking, soil moisture depletion diminished in magnitude as depth increased. Greatest depletion amounts occurred in the uppermost foot of soil. The same was true of soil moisture accretion. As seen in Figure 54, soil moisture accretion took place frequently in the surface foot but less frequently and in lesser amounts at deeper depths.

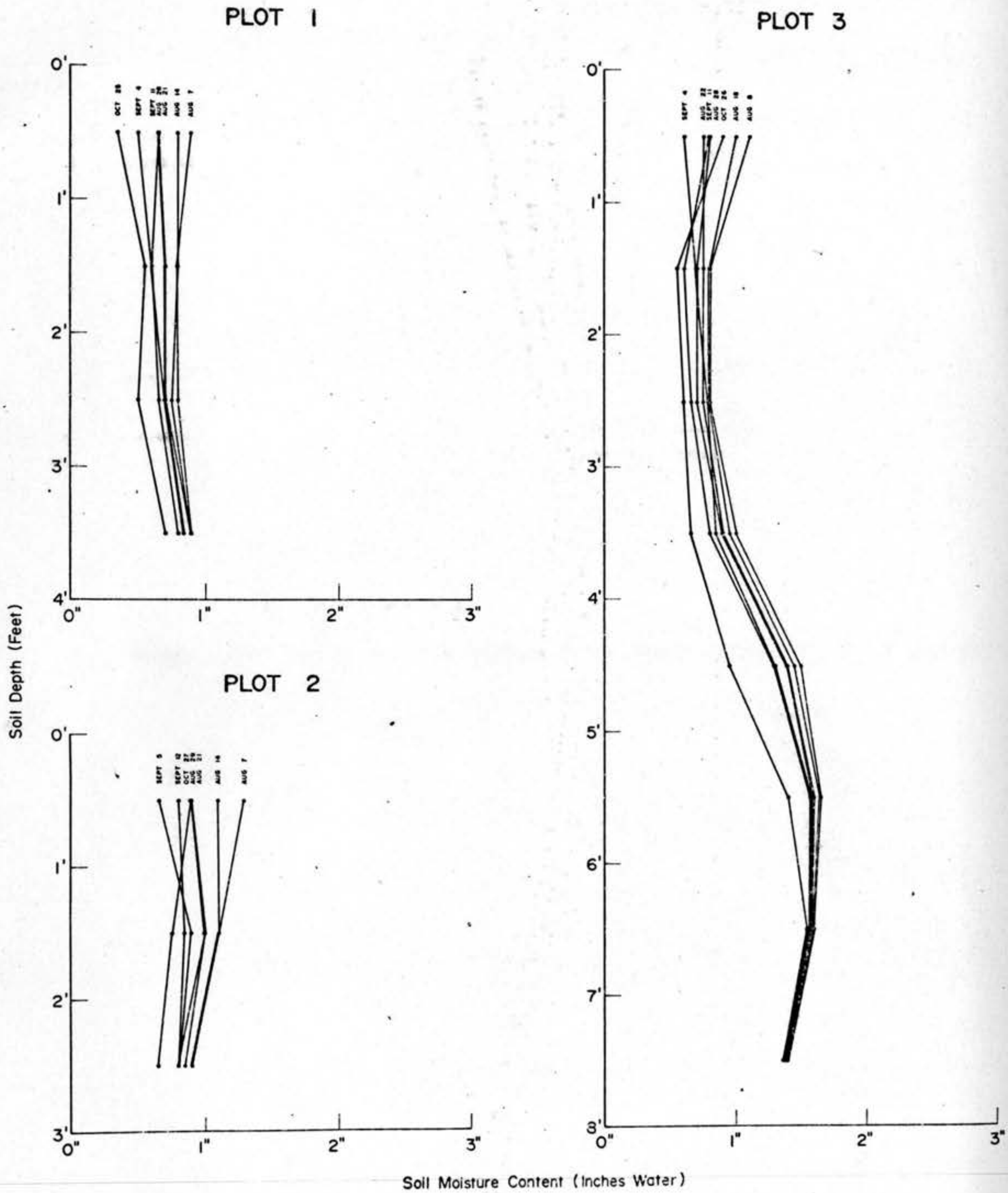
Analysis of variance tables for 1963 are given in Appendix D.

Second Year of Record - 1964

In contrast to 1963, when only late season values were obtained, during 1964 only early season readings could be taken. The period of record extended from April 8 to July 10.

Figure 54. Soil moisture change in 1963, Plots 1, 2, 3 and 4.

1963


PLOT 1
PLOT 2
PLOT 3
Soil Depth (Feet)
Soil Moisture Content (Inches Water)
0'
1'
2'
3'
4'
5'
6'
7'
8'
0"
1"
2"
3"

1963

PLOT 4

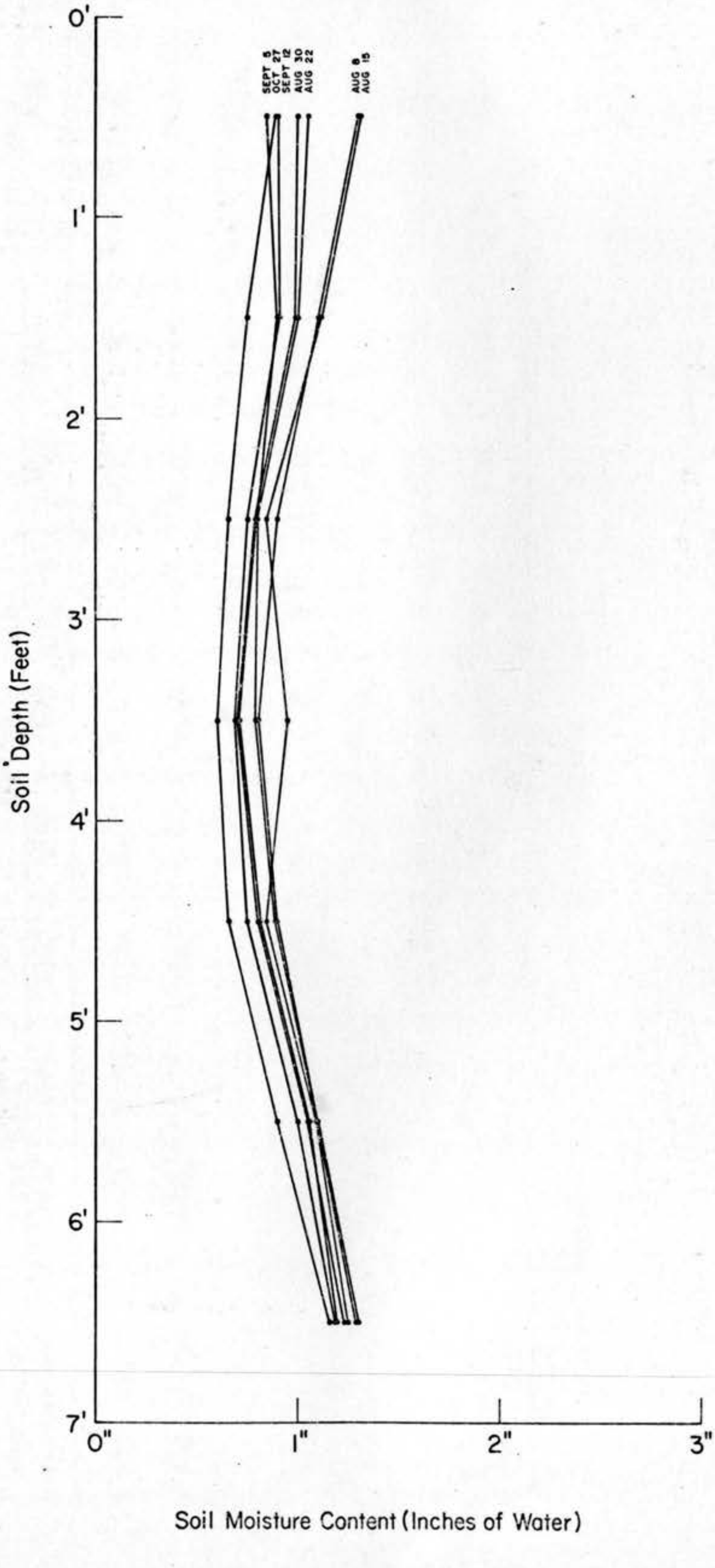

SEPT 5
OCT 27
SEPT 12
AUG 30
AUG 22
AUG 8
AUG 15
0'
1'
2'
3'
4'
5'
6'
7'
Soil Depth (Feet)
0"
1"
2"
3"
Soil Moisture Content (Inches of Water)

Table 53. Levels of significance associated with source of variation in analysis of variance dealing with uppermost 3, 4, 7, 8 and 14 feet of soil. 1963, 1964, 1965, 1966 soil moisture change (inches water).

Source of Variation	Three Feet				Four Feet				Seven Feet			
	1963	1964	1965	1966	1963	1964	1965	1966	1963	1964	1965	1966
Plot (B)	0.01	0.05	N.S.	0.05	N.S.	0.05	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Period (P) 1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Depth (D)	0.01	0.01	N.S.	0.01	N.S.	0.01	N.S.	0.01	0.05	0.01	0.01	0.01
B x P	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05	N.S.	0.01	0.01
B x D	0.01	N.S.	N.S.	N.S.	0.01	0.01	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
P x D	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
B x P x D	0.01	N.S.	0.01	0.01	0.01	N.S.	0.01	0.01	0.01	0.01	0.01	N.S.

1. Interval between two consecutive measurements.

Table 53. Cont'd. Levels of significance associated with source of variation in analysis of variance dealing with uppermost 3, 4, 7, 8 and 14 feet of soil. 1963, 1964, 1965, 1966 soil moisture change (inches water).

Source of Variation	Eight Feet				Fourteen Feet			
	1963	1964	1965	1966	1963	1964	1965	1966
Plot (B)	-	N.S.	N.S.	N.S.	-	-	-	-
Period (P) 1	0.01	0.01	0.01	0.01	-	0.01	0.01	0.01
Depth (D)	0.01	0.01	0.05	0.01	-	0.01	0.01	0.01
B x P	-	N.S.	0.05	0.01	-	-	-	-
B x D	-	N.S.	N.S.	N.S.	-	-	-	-
P x D	0.01	0.01	0.01	0.01	-	0.01	0.01	0.01
B x P x D	-	N.S.	0.01	0.01	-	-	-	-

Figure 55 clearly shows that in early April recharge of the soil mantle had not taken place, even in Plot 2, the shallowest plot, which extended only to three foot depth. Maximum values for the uppermost three to five feet of soil were attained in mid-May. In some cases, minimum values were attained at the end of April, following a depletion period in late April at middle depths. In Plot 3, maximum values at depth, effectively speaking, were attained in late May. In Plot 4, at depths of 5 to 7 feet, maximum soil moisture levels were not attained until late June, while Plot 5 maximum soil moisture levels at depths of 6 feet and more were obtained about July 10. Above six foot depth in Plot 5, considerable depletion took place from the mid-May high values.

In Plot 5 (Figure 55), the generally low range in values at depths greater than eight feet is noteworthy.

Results of analysis of variance are shown in Table 53. Analysis of variance tables for 1964 are contained in Appendix D.

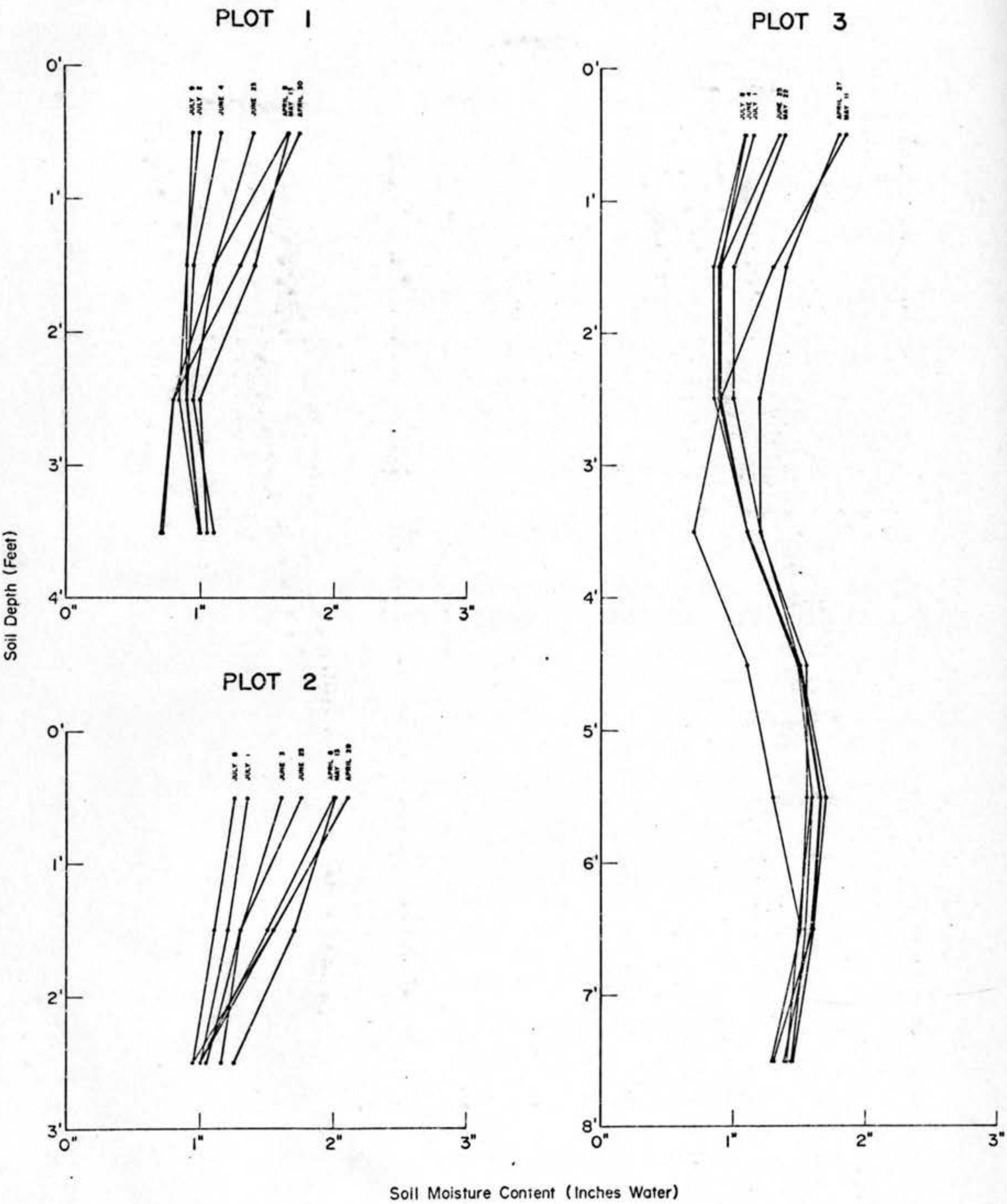
Third Year of Record - 1965

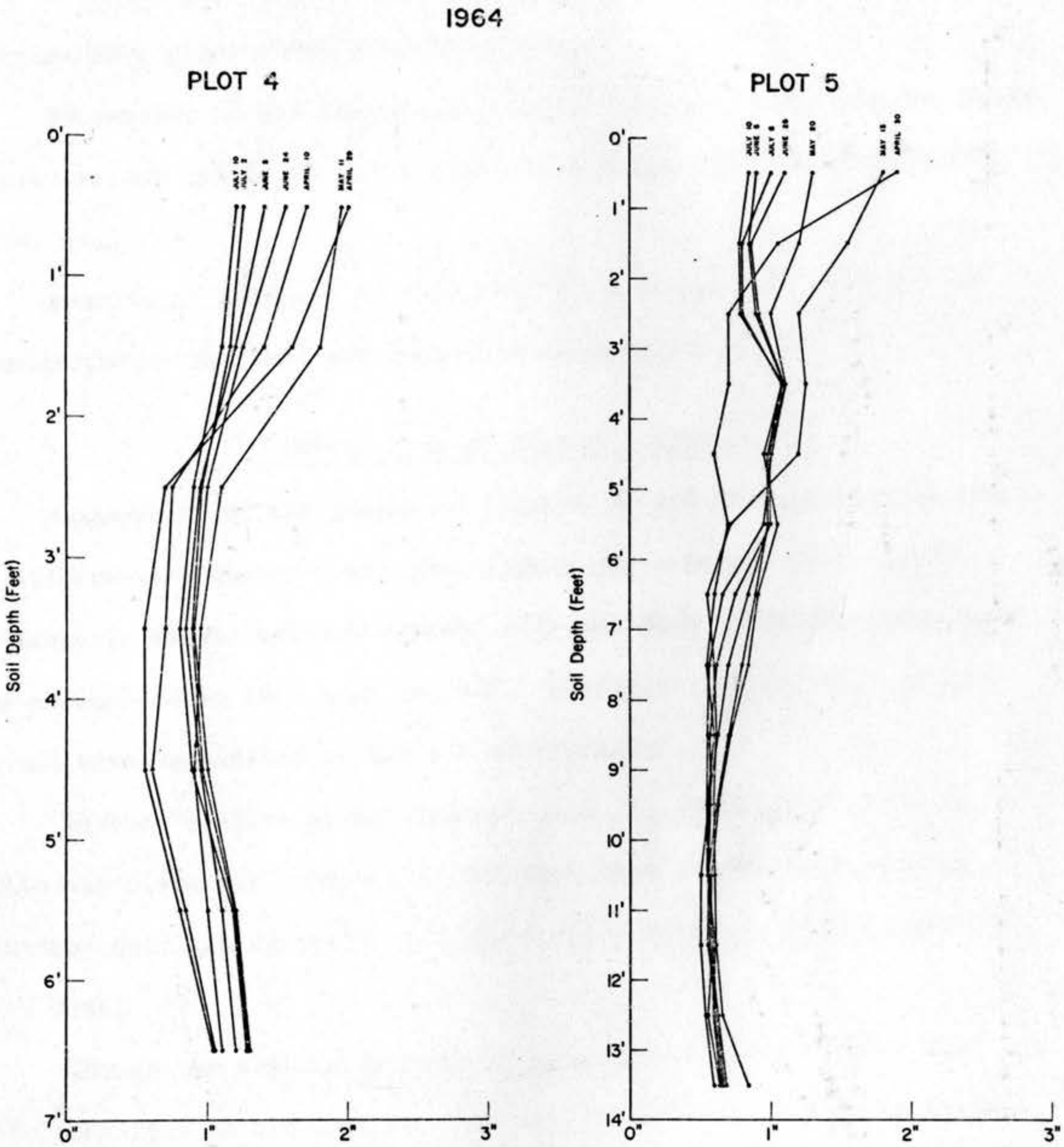
In 1965, readings began in mid-June and terminated in late October. The season, as remarked earlier, was extremely wet in comparison to the normal summer rainfall. This pattern of recurrent alternating soil moisture accretion and depletion, created the bewildering perplexity of Figure 55.

In Plots 1 and 2, maximum soil moisture levels throughout the profile were attained in early July. This was also true of Plots 3 and 4 to six foot depth and of Plot 5 to seven foot depth. The

Figure 55. Soil moisture change in 1964, Plots 1, 2, 3, 4 and 5. (Note change in vertical scale in Plot 5).

1964


PLOT 1
PLOT 2
PLOT 3
JUNE 4
APRIL 27
MAY 11
Soil Depth (Feet)
0'
1'
2'
3'
4'
5'
6'
7'
8'
0"
1"
2"
3"
Soil Moisture Content (Inches Water)


1964
PLOT 4
PLOT 5
Soil Depth (Feet)
0'
1'
2'
3'
4'
5'
6'
7'
8'
9'
10'
11'
12'
13'
14'
0"
1"
2"
3"
Soil Moisture Content (Inches of Water)

period mid-June to early July was one of marked soil moisture accretion in the uppermost six foot of mantle.

In Plot 5, at depths greater than six feet, gradual soil moisture accretion took place throughout the season.

Noteworthy in the individual plots of Figure 56 was the low range between extreme values at all depths compared to other years (Figures 54, 55, 57).

Results of analysis of variance are in Table 53. Analysis of variance tables for 1965 are contained in Appendix D.

Fourth Year of Record - 1966

Comparison of the graphs of Figures 56 and 57 dramatically shows the differences between a wet year (1965) and a normal year (1966). The range in values between extreme soil moisture levels was very much more pronounced in 1966 than in 1965. Readings in 1966 began in mid-May and were terminated at the end of September.

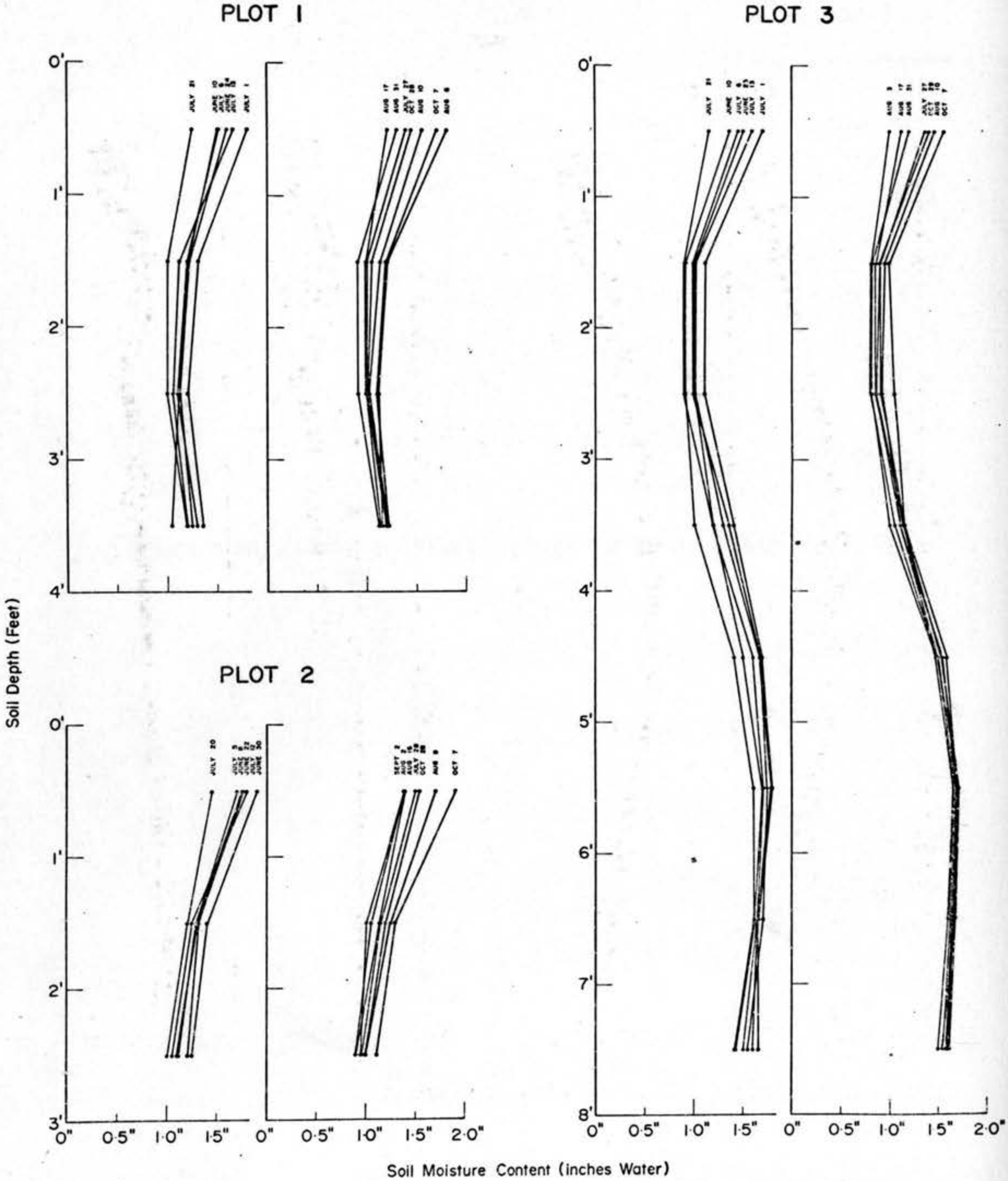
In the "shallow plots" (Plots 1 and 2), recharge of the soil mantle was virtually complete in mid-May, some slight soil moisture accretion only taking place at 3 and 4 foot depths in Plot 1 until early June.

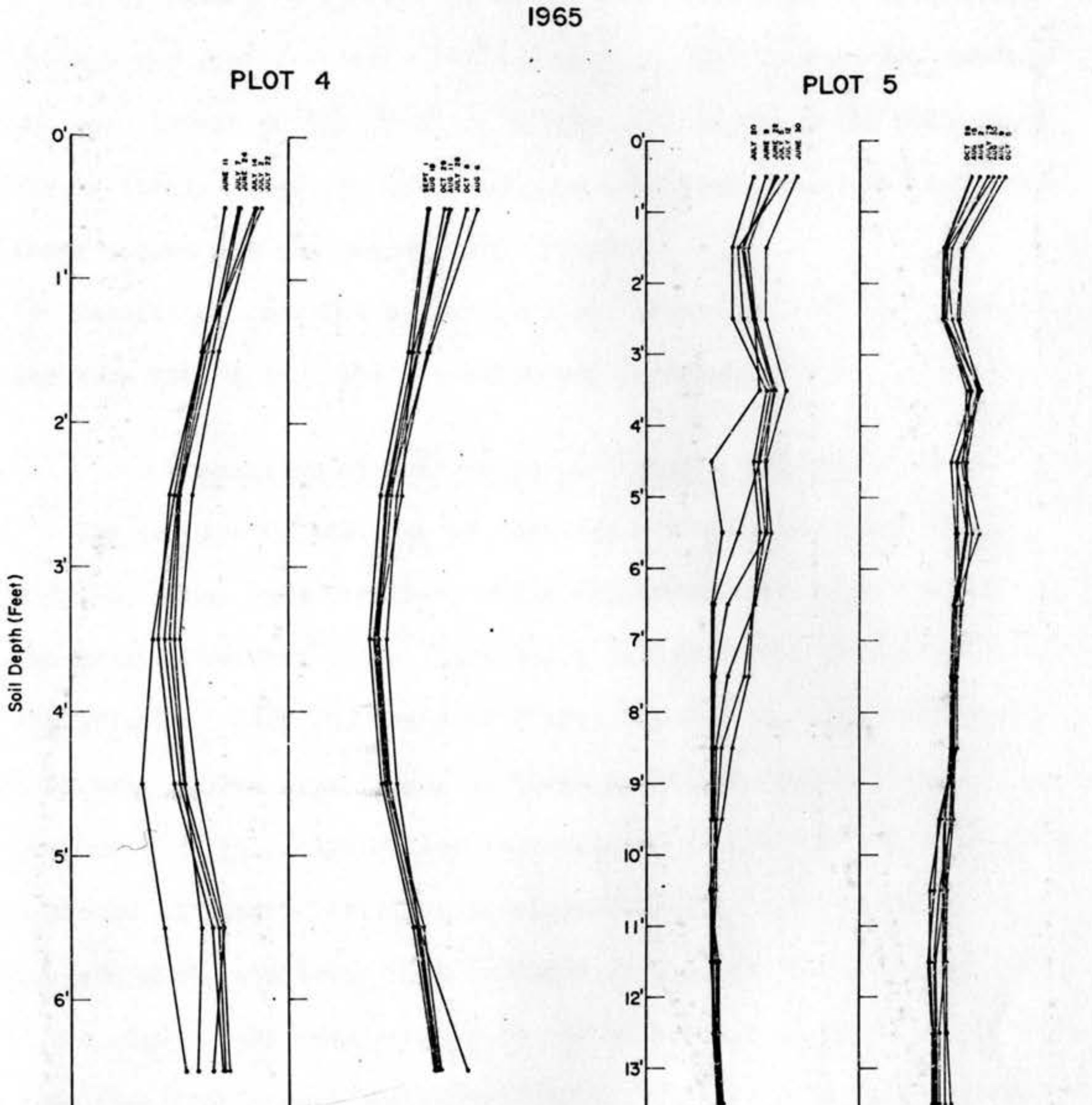
Though the shallow portion of soil mantle (0 to 3 feet) was fully recharged in mid-May, it was early to mid-June before recharge was complete at 5 foot depth in Plots 3, 4 and 5, while full recharge at 7 feet was delayed until late June (Figure 57).

In Plot 5, very little further soil moisture accretion took place at depths greater than 7 feet after early July. In any case,

Figure 56. Soil moisture change in 1965, Plots 1, 2, 3, 4 and 5.

1965


PLOT 1
PLOT 2
PLOT 3
Soil Depth (Feet)
0'
1'
2'
3'
4'
5'
6'
7'
8'
0"
0·5"
1·0"
1·5"
2·0"
Soil Moisture Content (inches Water)


1965
PLOT 4
PLOT 5
Soil Depth (Feet)
0'
1'
2'
3'
4'
5'
6'
7'
8'
9'
10'
11'
12'
13'
14'
0"
0·5"
1·0"
1·5"
2·0"
Soil Moisture Content (Inches of Water)

soil moisture accretion at these depths was comparatively slight, in marked contrast to 1965 (cf. Figure 56 and Figure 57).

After full recharge was attained, drying took place progressively through the shallow portion of the mantle. Mid to late September values were lowest on all plots to depths of 7 feet. Below this depth in Plot 5 little change in soil moisture took place, once maximum soil moisture values for the season were attained.

Results of analysis of variance are shown by Table 53. Analysis of variance tables for 1966 are contained in Appendix D.

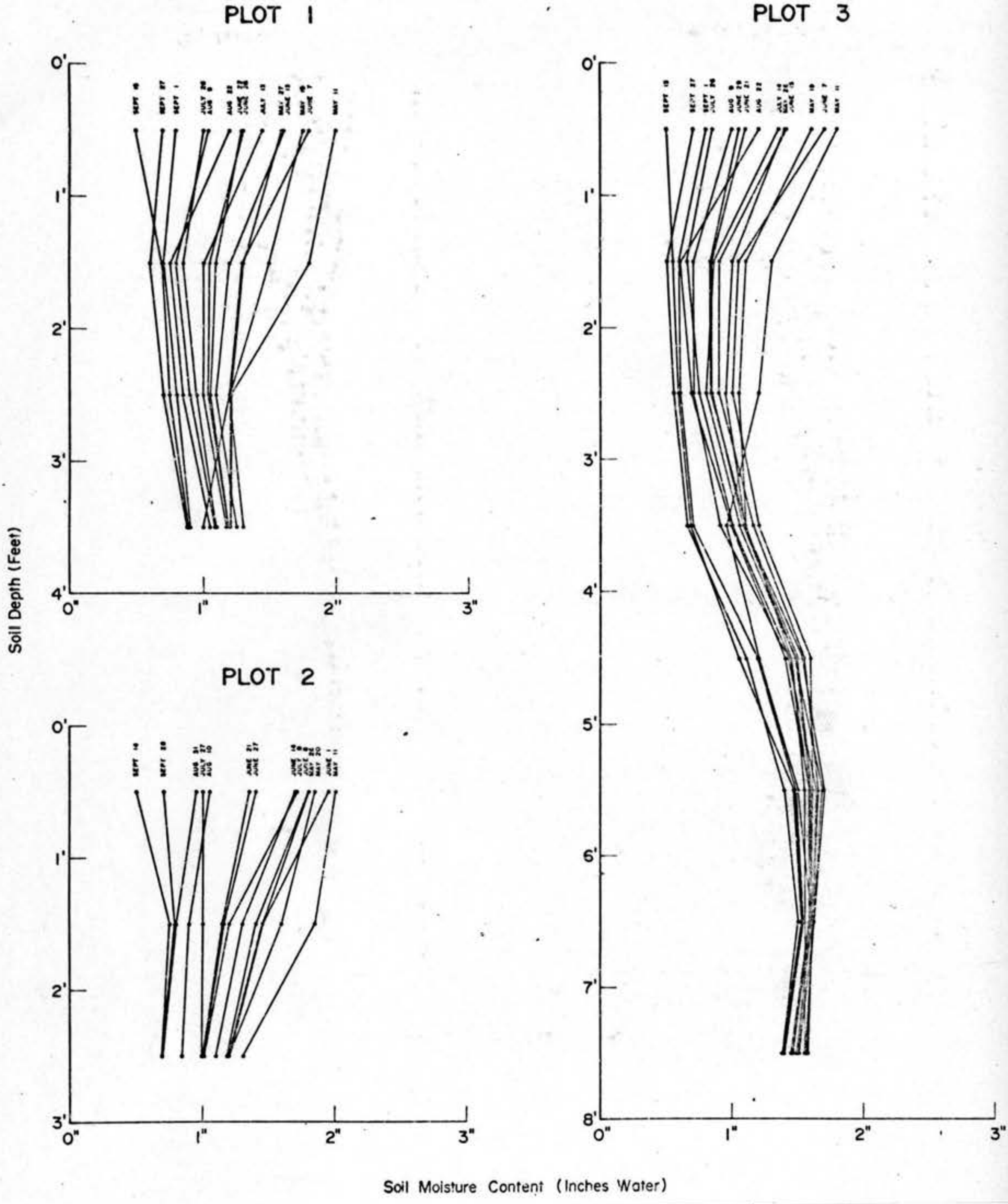
Comparison of Soil Moisture Change - All Years

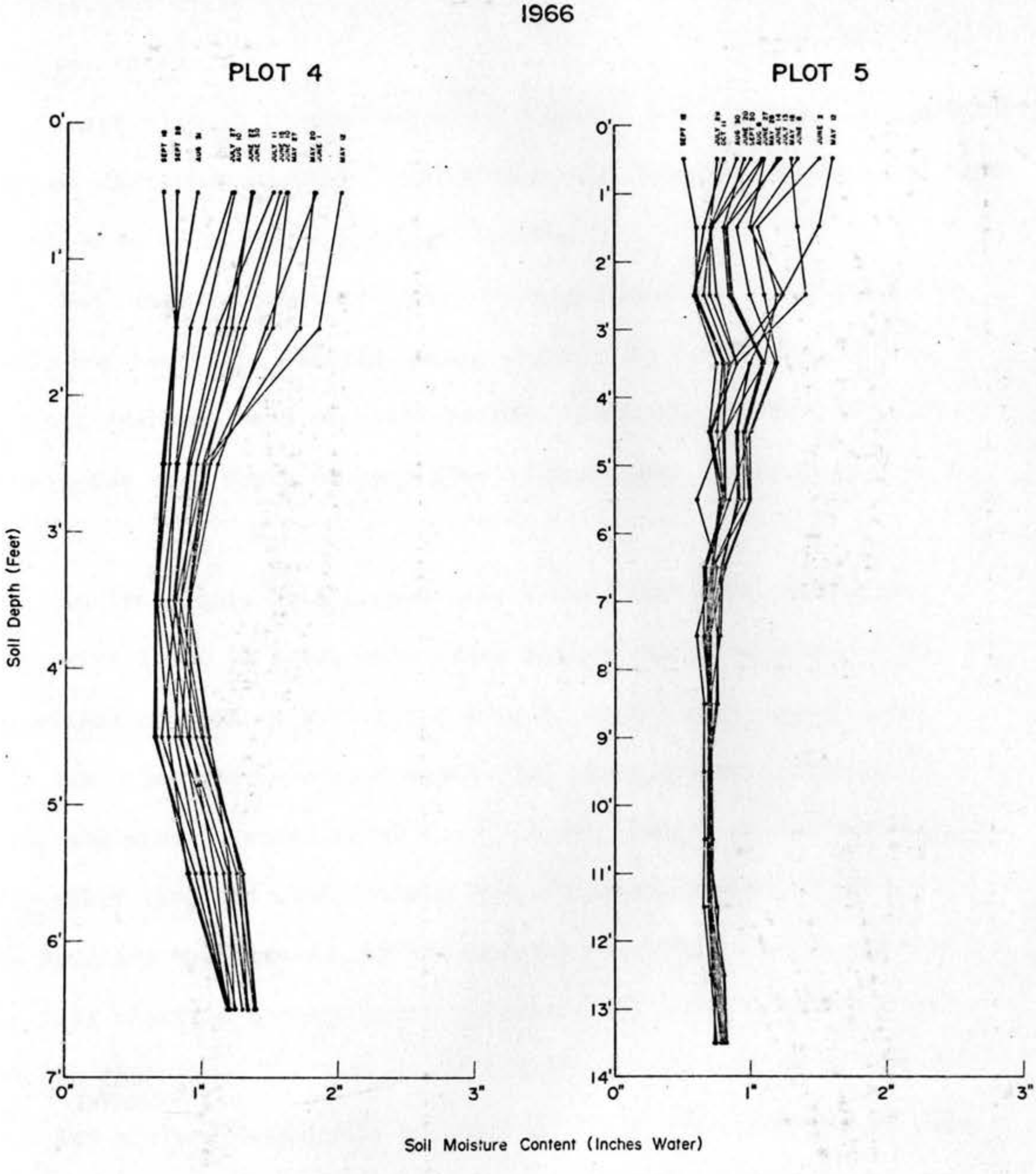
The results of analysis of variance are shown in Table 53 and Appendix D. They indicate that, while differences in soil moisture change existed between plots, they could not generally be considered as significant. Only the analysis (Table 53) for the uppermost three feet of soil showed significant differences between plots. The occurrence of highly significant interactions (Table 53) indicates that care should be used in attributing significance to differences between plots even when relatively high variance ratios are obtained (Appendix D). The significant interactions may be attributed to the same causes as were ascribed in soil moisture content analysis of variance in the preceding section of this thesis.

In order to determine which plots were significantly different one from another, Duncan's Multiple Range Test was applied to the analysis data for the uppermost three feet of soil, to determine

Figure 57. Soil moisture change in 1966, Plots 1, 2, 3, 4 and 5.

1966


PLOT 1
PLOT 2
PLOT 3
0'
1'
2'
3'
4'
5'
6'
7'
8'
0"
1"
2"
3"
Soil Depth (Feet)
Soil Moisture Content (Inches Water)


1966
PLOT 4
PLOT 5
Soil Depth (Feet)
Soil Moisture Content (Inches Water)
0"
1"
2"
3"
0'
1'
2'
3'
4'
5'
6'
7'
8'
9'
10'
11'
12'
13'
14'

whether significant differences existed between Plots 3, 4 and 5. No significant differences ($p = 0.05$) between these plots were found using this test.

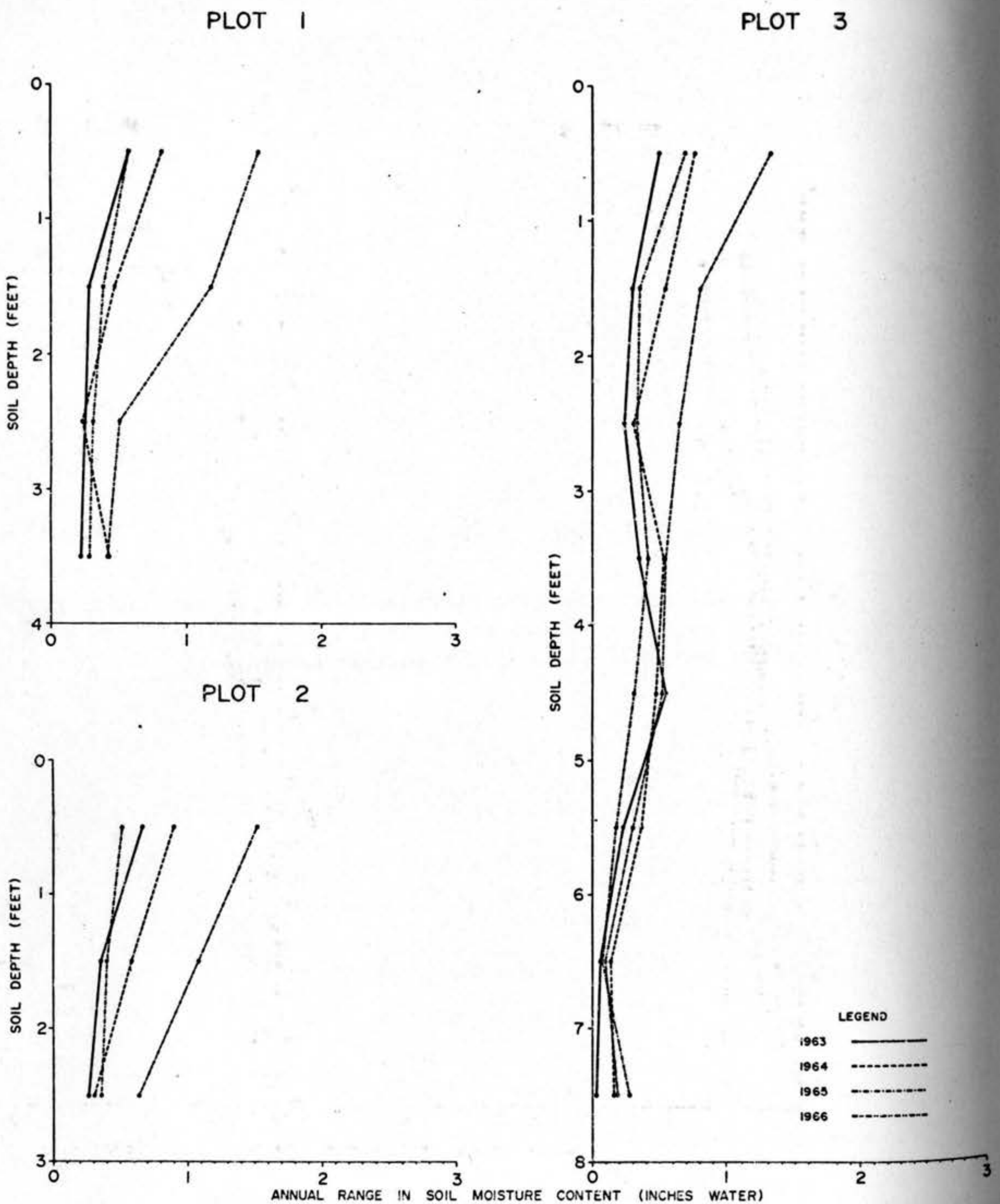
Inspection of Figures 54 to 57 provides some insight into moisture change at different depths, to supplement the impressions obtained from Figures 46 to 53 in the preceding section.

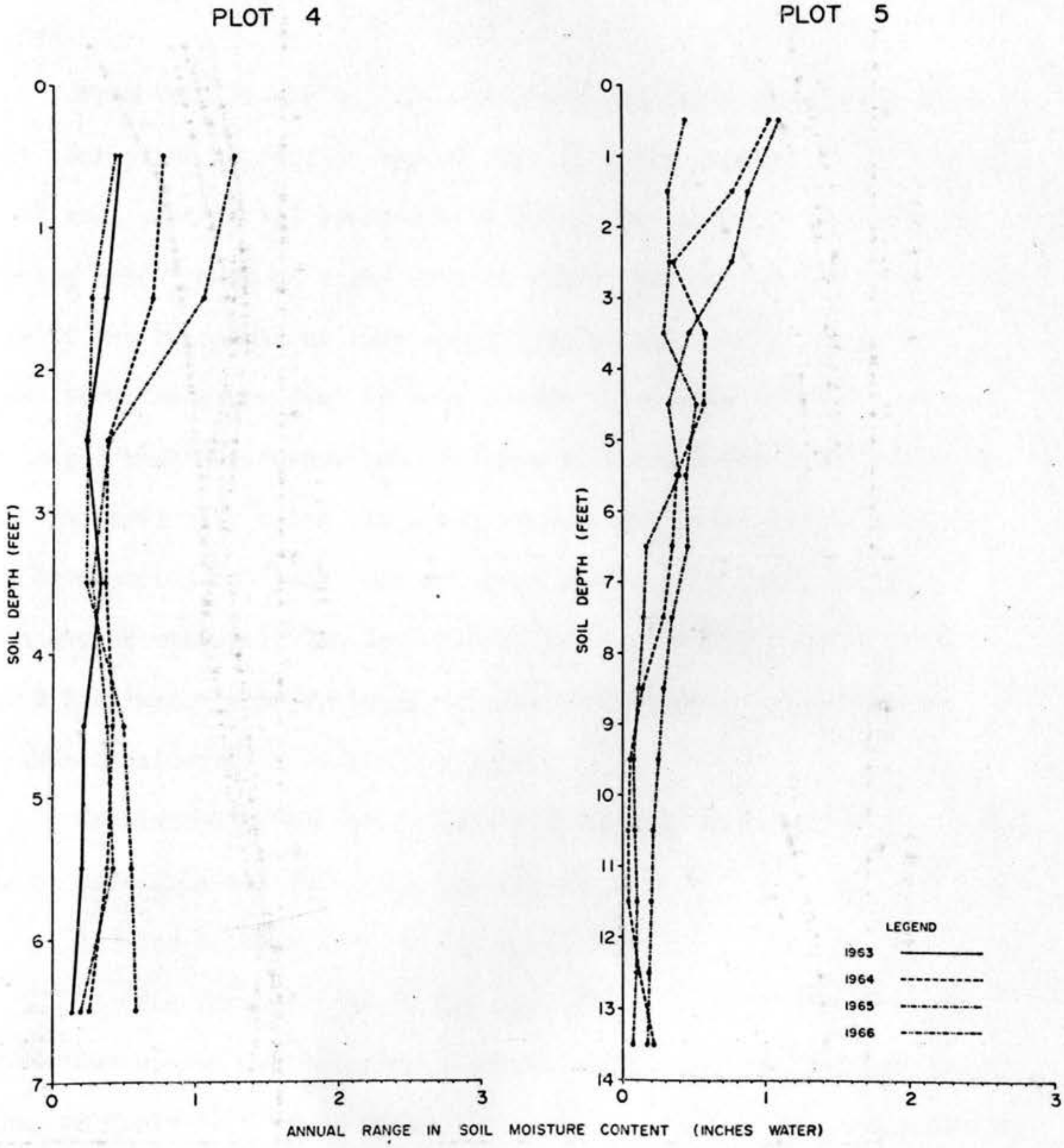
The range in moisture content was greatest in the surface foot of soil and tended to diminish progressively in succeeding depths. The range (maximum soil moisture content minus minimum soil moisture content) for each depth of each plot in each year is shown in Figure 58.

In 1963, only late season values were obtained; therefore, ranges were low. In 1964, only early season values were collected; both maxima and minima were high; ranges, accordingly, again tended to be low. In 1965, abnormal amounts of precipitation were experienced, and minima tended to be high. Again, ranges at shallow depths were rather low. In 1966, values were obtained in early season. This provided high maxima, which were not obtained in 1965, because of a late start in records being obtained. In 1966, drying was progressive throughout the season and continued into September. Therefore, low minima, comparable to those of 1963, were obtained in 1966. For the above reasons, range in soil moisture at shallow depths was greater in 1966 than in other years.

A noteworthy feature (Figure 58) is the low range associated with increasing depth. In 1963, no depth below six feet had a range of

Figure 58. Range in soil moisture contents (maximum recorded minus minimum recorded) in Plots 1, 2, 3, 4, and 5 during 1963, 1964, 1965 and 1966.


PLOT 1
PLOT 2
PLOT 3
SOIL DEPTH (FEET)
ANNUAL RANGE IN SOIL MOISTURE CONTENT (INCHES WATER)
LEGEND
1963
1964
1965
1966


PLOT 4
PLOT 5
SOIL DEPTH (FEET)
LEGEND
1963
1964
1965
1966
ANNUAL RANGE IN SOIL MOISTURE CONTENT (INCHES WATER)

0.15 inches water, with the exception of 13 to 14 feet in Plot 5. In 1965, ranges at depths below six feet were appreciably greater than in other years, due to generally higher maxima at these depths. In 1966, no depth greater than eight feet had a range greater than 0.15 inches.

From this it may be concluded that much more soil water movement took place at shallow depths than in deeper zones. Specifically, it is seen that in all years except 1965, the amount of water penetrating below seven or eight feet in Plot 5 was not substantial. From this it may be concluded that comparison of moisture budgets in the upper seven or eight feet of soil yields reasonable results. It may be judged that the comparison of Plots 3, 4 and 5 for 1963, 1964 and 1966 is physically valid, inasmuch as no significant amount of water may be expected to "leak" out of these plots, as a contribution to groundwater storage. The same assumption cannot be made for Plots 1 and 2 from which some drainage must have occurred. This point is further considered in succeeding pages.

Consideration of soil moisture change during overwinter periods can be made from the data, for two periods:

1. End-October 1963 to end-April 1964.
2. End-October 1965 to mid-May 1966.

Overwinter soil moisture change during these two periods is shown in Table 54. Large differences existed between the two years insofar as total amounts are concerned. This probably reflects higher soil moisture levels in October, 1965 than in October, 1963 (Figs. 46, 50). In spite of discrepancies between amounts, trends were the same. Over the winter months, soil moisture levels rose in the upper three

Table 54. Soil moisture change (inches water) in plots 1, 2, 3, 4, during winter 1963/64 and in Plots 1, 2, 3, 4, 5 during winter 1965/66.

Depth (feet)	Period end-October, 1963 end-April, 1964				Period: end-October 1965 mid-May, 1966				
	Plot				Plot				
	1	2	3	4	1	2	3	4	5
0-1	+1.68	+1.23	+0.93	+1.13	+0.57	+0.46	+0.41	+0.48	+0.53
1-2	+0.93	+0.78	+0.76	+0.64	+0.73	+0.64	+0.22	+0.65	+0.71
2-3	+0.35	+0.29	+0.34	+0.10	+0.15	+0.30	+0.35	+0.17	+0.46
Total: 0-3	+2.96	+2.30	+2.03	+1.87	+1.45	+1.40	+0.98	+1.30	+1.70
3-4	+0.05		+0.04	-0.05	-0.14		-0.20	-0.03	-0.21
Total: 0-4	+3.01		+2.07	+1.82	+1.31		+0.78	+1.27	+1.49
4-5			+0.14	-0.10			-0.30	-0.23	-0.28
5-6			-0.08	-0.10			-0.19	-0.22	-0.21
6-7			-0.05	-0.09			-0.07	-0.15	-0.24
Total: 0-7			+2.08	+1.53			+0.22	+0.67	+0.76
7-8			-0.10				-0.05		-0.14
Total 0-8			+1.98				+0.17		+0.62
8-9									-0.13
9-10									-0.11
10-11									-0.11
11-12									-0.07
12-13									-0.08
13-14									-0.02
Total: 0-14									+0.10

feet in both periods. At lower levels, i.e., below five feet, soil moisture levels decreased during the winter.

The accretion of soil moisture in the upper layers can be attributed to several possible sources, (a) snowmelt water, (b) spring rainfall, and (3) water vapour movement from below. The soil moisture depletion at lower depths might be attributed to (a) evapotranspiration (b) drainage (c) vapour movement upwards.

In the accretion of water in the upper layers, it is likely that snowmelt water plays a prominent part. Studies have shown (Figs. 29, 34, 35) that continual fluctuation takes place in the snowpack and that for periods it disappears altogether. Most of the snowpack water may proceed into the soil rather than evaporate, a sufficient energy source for large winter evaporation losses being debatable in spite of recurrent chinook winds. Spring rainfall does not appear to be a major pertinent factor (Table 1).

In the depletion of water from lower depths, overwinter evapotranspiration may safely be discounted. Evapotranspiration does not appear to take place to any appreciable extent below six feet in summer (Figs. 47, 49, 51, 53). It is the more unlikely that it would be occurring in winter. Drainage may take place, over the winter, but soil moisture levels at depths greater than six feet were not higher than field capacity at beginning and end of either period.

The question of water vapour movement from below to above is interesting and the hypothesis that this occurs is supported by the lack of adequate alternatives. During long portions of the winter (Figure 29), the ground surface beneath these stands was bare of snow.

Very low air temperatures are common (Table 1). A considerable temperature gradient must exist between the comparatively warm soils below and the frozen soil surface above. Along this gradient, it is reasonable to expect considerable water movement as vapour to occur.

Accordingly, it seems reasonable to suppose that some of the water occurring in May at upper soil levels, during the preceding October might have been found at greater soil depths, having migrated upwards as water vapour during the winter.

The most noteworthy feature, however, of the data is its illustration of the relatively small quantities involved in overwinter recharge. The effects of the low winter precipitation (Table 1) are effectively shown here, and the question of snowpack evaporative losses from Chinook winds suggests itself as pertinent to research.

Indeed, during winter 1965/66 recharge can scarcely be said to have taken place at all, particularly on Plots 3 and 5. This was, it will be recalled, a year in which little snow fell.

Total soil moisture accretion and depletion over each period of record in 1963, 1964, 1965 and 1966 was calculated to determine the influence of soil depth on moisture change in the various plots. These values are given in Table 55, while percentage distribution is shown in Figure 59 for depths to three feet, in Figure 60 for depths to four feet, in Figure 61 for depths to seven feet, in Figure 62 for depths to eight feet and in Figure 63 for depths to fourteen feet.

The information provided by this tabular and graphical presentation is interesting. The pre-eminence of the surface foot of soil in both accretion and depletion is immediately apparent.

Table 55. Total cumulative measured soil moisture accretion and depletion (inches water) in 1963, 1964, 1965, and 1966.

Depth	1963		1964		1965		1966	
	Plot 1		Plot 1		Plot 1		Plot 1	
(feet)	Acc.	Dep.	Acc.	Dep.	Acc.	Dep.	Acc.	Dep.
0-1	0.216	1.056	0.492	1.956	1.632	1.788	0.900	2.532
1-2	nil	0.396	0.576	1.104	0.648	0.828	nil	1.428
2-3	nil	0.360	0.492	0.564	0.480	0.612	0.048	0.672
3-4	nil	0.312	0.696	0.504	0.420	0.348	0.336	0.552
	Plot 2		Plot 2		Plot 2		Plot 2	
0-1	0.288	0.792	0.384	1.308	1.248	1.536	0.864	2.484
1-2	nil	0.432	0.360	0.816	0.66	0.840	0.048	1.356
2-3	nil	0.324	0.48	0.528	0.480	0.624	0.024	0.816
	Plot 3		Plot 3		Plot 3		Plot 3	
0-1	0.360	0.612	0.300	1.212	1.836	1.872	1.296	2.676
1-2	nil	0.360	0.096	0.66	0.600	0.636	0.060	1.044
2-3	0.072	0.336	0.300	0.384	0.588	0.696	0.048	0.804
3-4	nil	0.420	0.648	0.204	0.684	0.552	0.384	0.768
4-5	nil	0.672	0.600	0.120	0.492	0.42	0.456	0.672
5-6	nil	0.300	0.468	0.120	0.216	0.156	0.252	0.432
6-7	0.012	0.096	0.204	0.108	0.072	0.072	0.144	0.276
7-8	nil	0.036	0.276	0.132	0.216	0.156	0.252	0.408
	Plot 4		Plot 4		Plot 4		Plot 4	
0-1	0.096	0.576	0.444	1.080	1.176	1.20	0.444	1.92
1-2	nil	0.456	0.456	0.864	0.540	0.612	0.108	1.332
2-3	nil	0.288	0.480	0.348	0.492	0.588	0.108	0.504
3-4	0.204	0.432	0.492	0.372	0.444	0.432	0.156	0.348
4-5	0.048	0.312	0.492	0.144	0.720	0.456	0.480	0.444
5-6	nil	0.252	0.444	0.072	0.684	0.336	0.348	0.492
6-7	0.048	0.192	0.264	nil	0.780	0.432	0.492	0.540
	Plot 5		Plot 5		Plot 5		Plot 5	
0-1			0.216	1.68	1.236	1.368	1.740	2.70
1-2			0.240	0.756	0.624	0.828	0.132	1.224
2-3			0.444	0.408	0.408	0.702	0.144	0.948
3-4			0.612	0.144	0.468	0.528	0.432	0.612

Table 55. cont... Total cumulative measured soil moisture accretion and depletion (inches water) in 1963, 1964, 1965, and 1966.

Depth (feet)	1964 Plot 5		1965 Plot 5		1966 Plot 5	
	Acc.	Dep.	Acc.	Dep.	Acc.	Dep.
4-5	0.576	0.120	0.804	0.396	0.408	0.492
5-6	0.432	nil	0.612	0.312	0.540	0.636
6-7	0.312	0.024	0.540	0.192	0.144	0.204
7-8	0.300	0.012	0.420	0.120	0.180	0.300
8-9	0.156	0.012	0.324	0.084	0.084	0.216
9-10	0.048	0.048	0.240	0.048	0.072	0.180
10-11	0.024	0.048	0.204	0.048	0.084	0.180
11-12	0.024	0.072	0.168	0.036	0.096	0.180
12-13	0.024	0.048	0.156	0.036	0.156	0.276
13-14	0.036	0.072	0.204	0.084	0.060	0.216

Figure 59. Soil moisture accretion and depletion in each of the uppermost three feet of soil, expressed as percentage of total accretion and depletion in the uppermost three feet of soil.

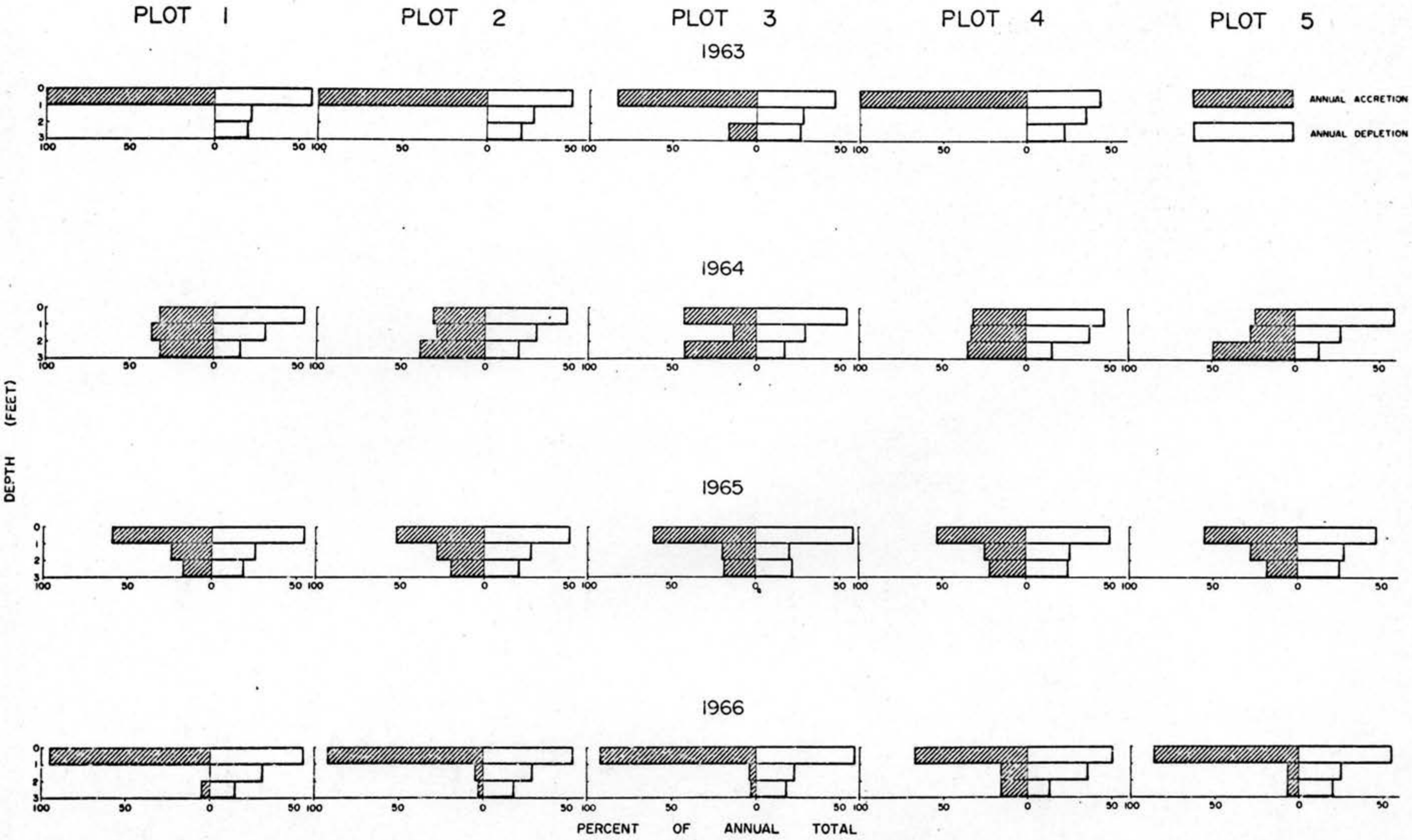

PLOT 1
PLOT 2
PLOT 3
PLOT 4
PLOT 5
1963
1964
1965
1966
ANNUAL ACCRETION
ANNUAL DEPLETION
DEPTH (FEET)
PERCENT OF ANNUAL TOTAL

Figure 60. Soil moisture accretion and depletion in each of the uppermost four feet of soil, expressed as percentage of total accretion and depletion in the uppermost four feet of soil.

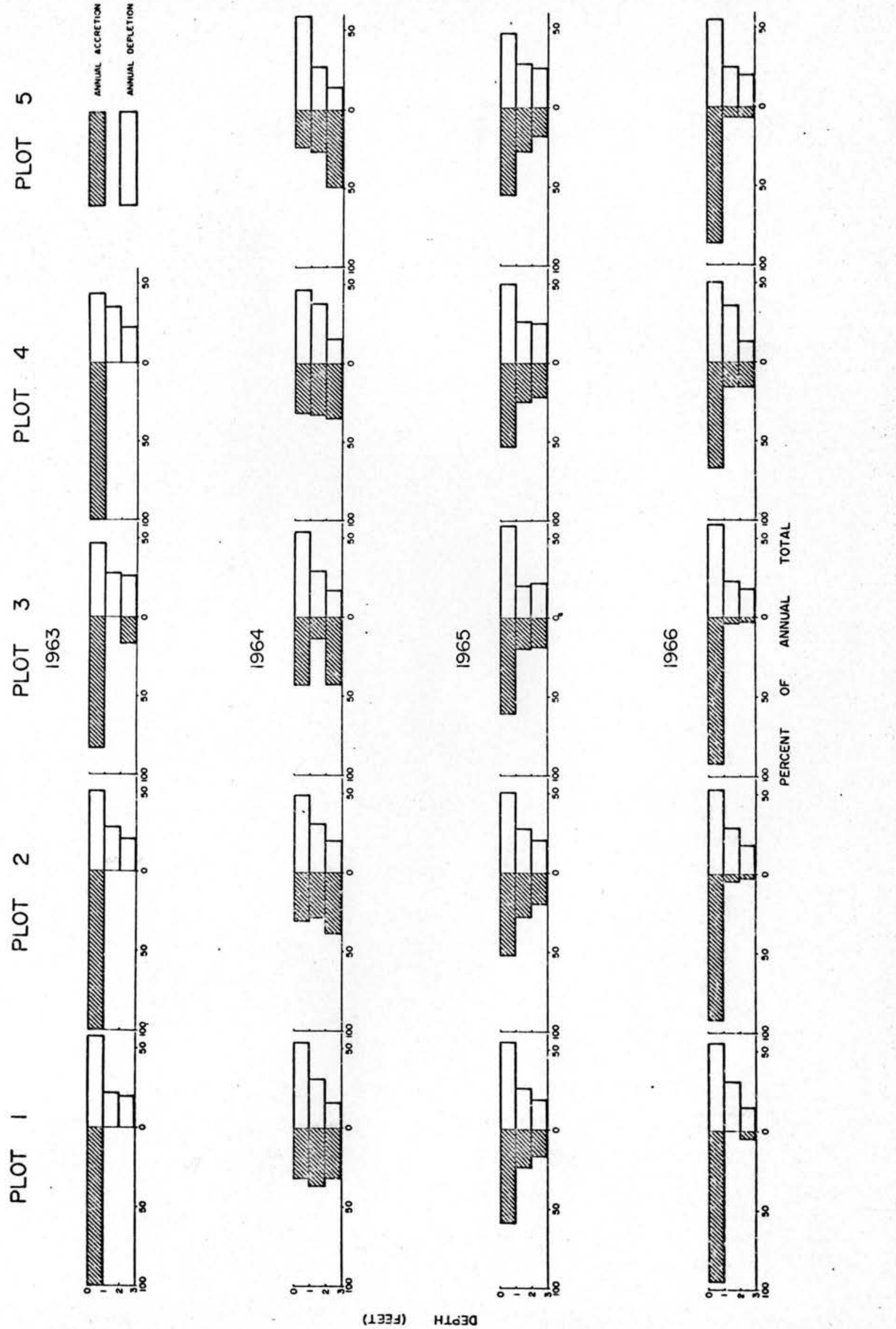

PLOT 1
PLOT 2
PLOT 3
PLOT 4
PLOT 5
ANNUAL ACCRETION
ANNUAL DEPLETION
1963
1964
1965
1966
DEPTH (FEET)
PERCENT OF ANNUAL TOTAL

Figure 60. Soil moisture accretion and depletion in each of the uppermost four feet of soil, expressed as percentage of total accretion and depletion in the uppermost four feet of soil.

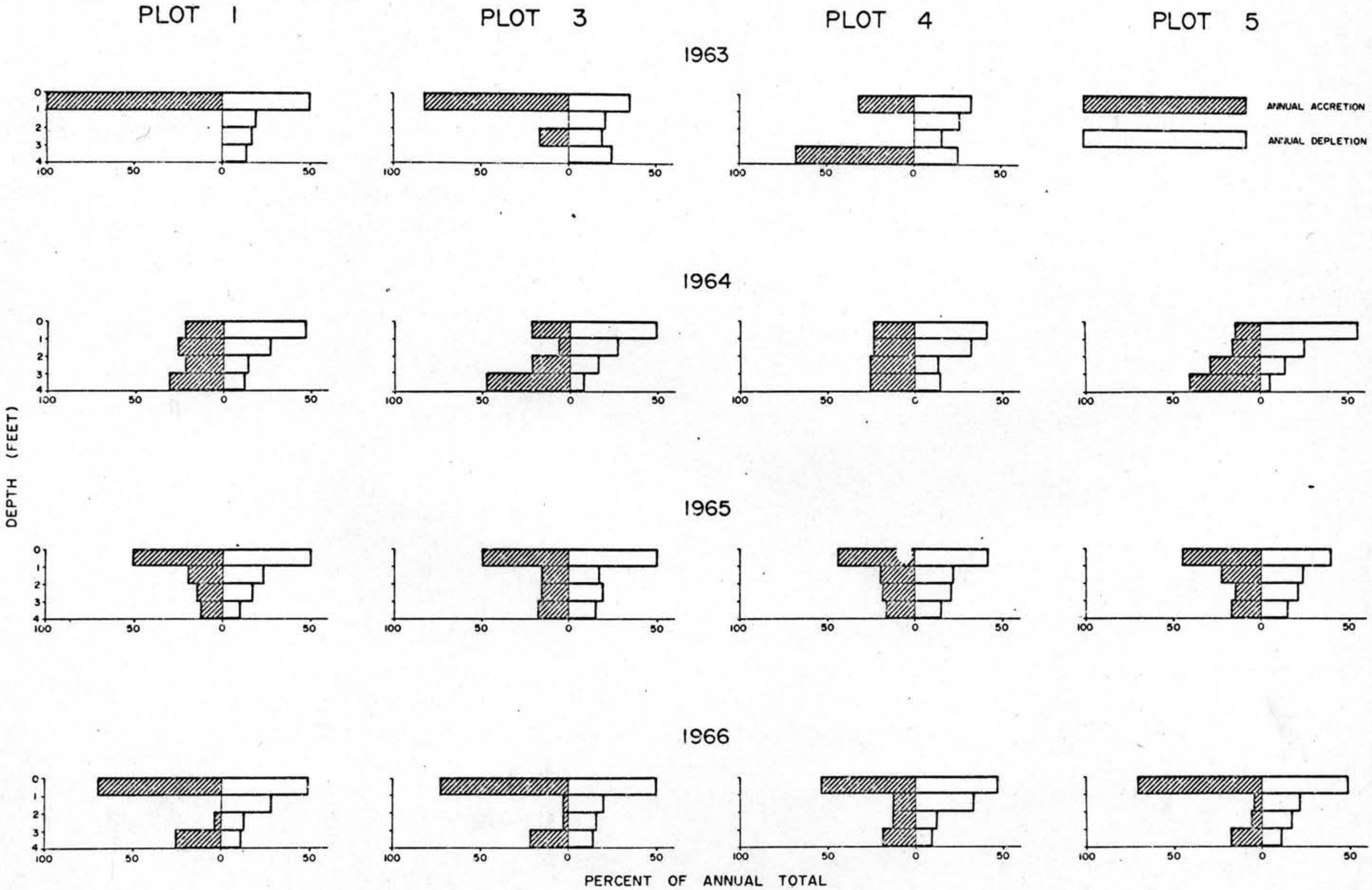

PLOT 1
PLOT 3
PLOT 4
PLOT 5
1963
1964
1965
1966
ANNUAL ACCRETION
ANNUAL DEPLETION
DEPTH (FEET)
0
1
2
3
4
100
50
0
50
PERCENT OF ANNUAL TOTAL

Figure 61. Soil moisture accretion and depletion in each of the uppermost seven feet of soil, expressed as percentage of total accretion and depletion in the uppermost seven feet of soil.

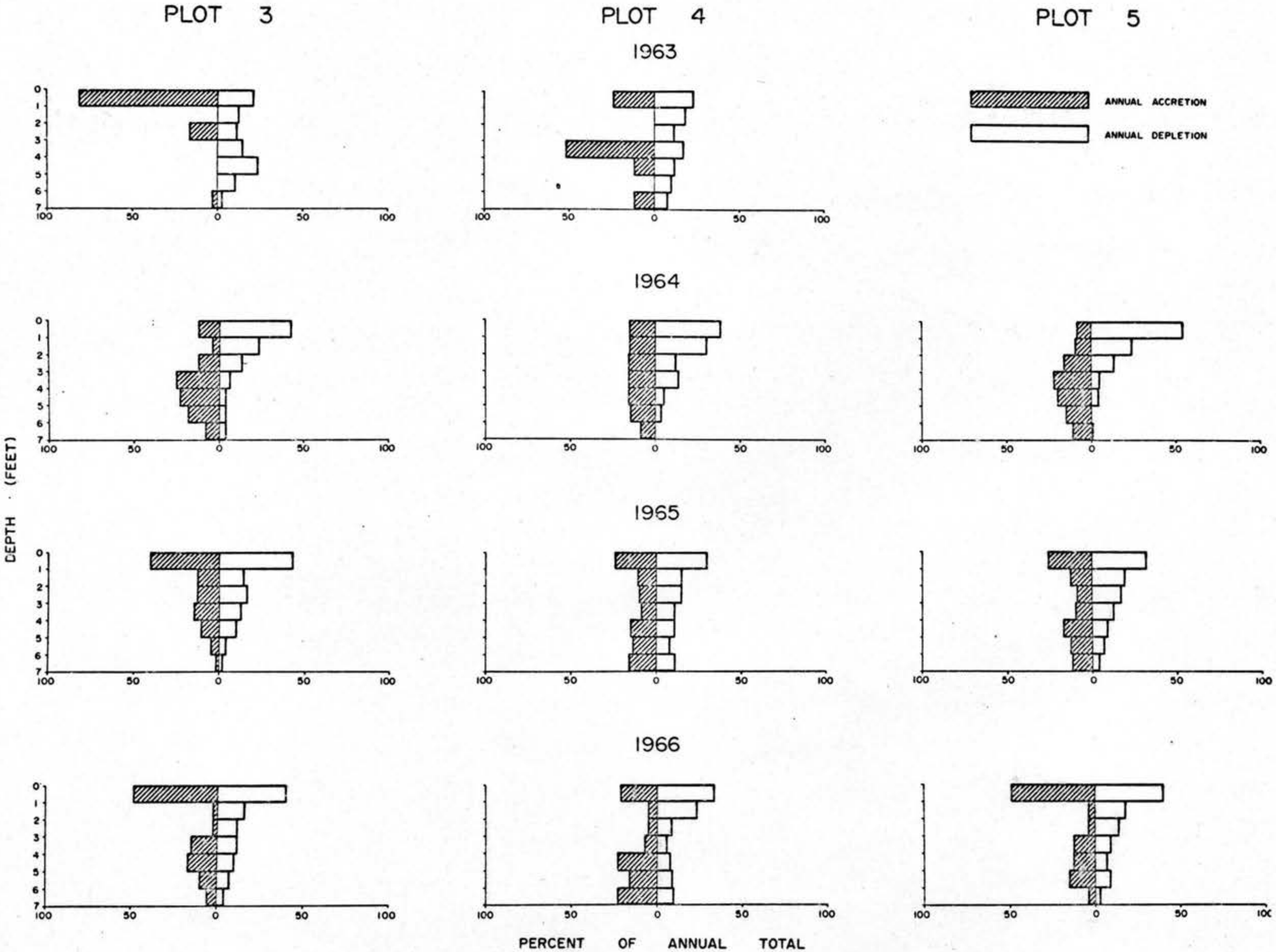

PLOT 3
PLOT 4
PLOT 5
1963
1964
1965
1966
ANNUAL ACCRETION
ANNUAL DEPLETION
DEPTH (FEET)
0 1 2 3 4 5 6 7
100 50 0 50 100
PERCENT OF ANNUAL TOTAL

Figure 62. Soil moisture accretion and depletion in the uppermost eight feet of soil expressed as percentage of total accretion and depletion in the uppermost eight feet of soil.

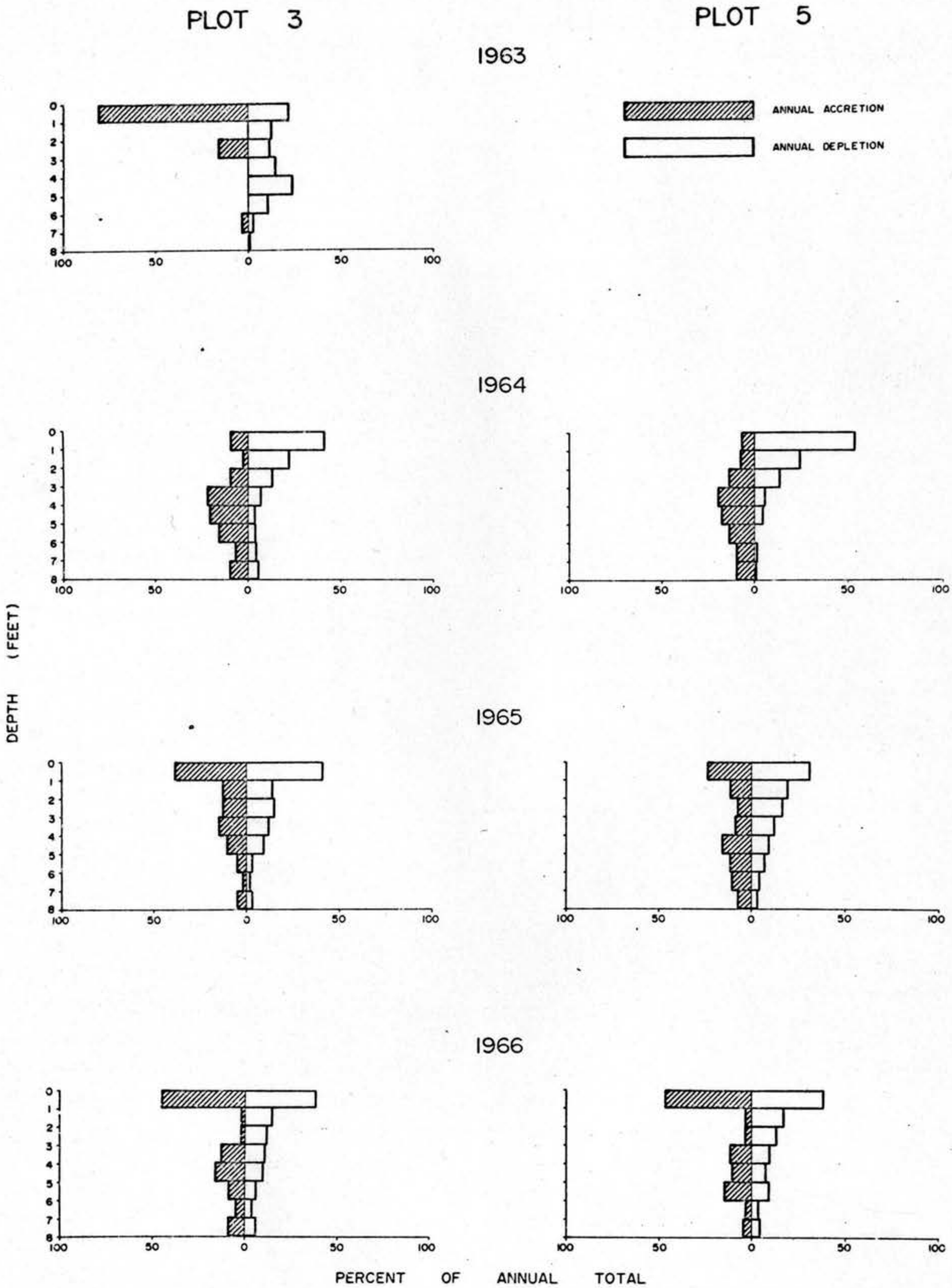
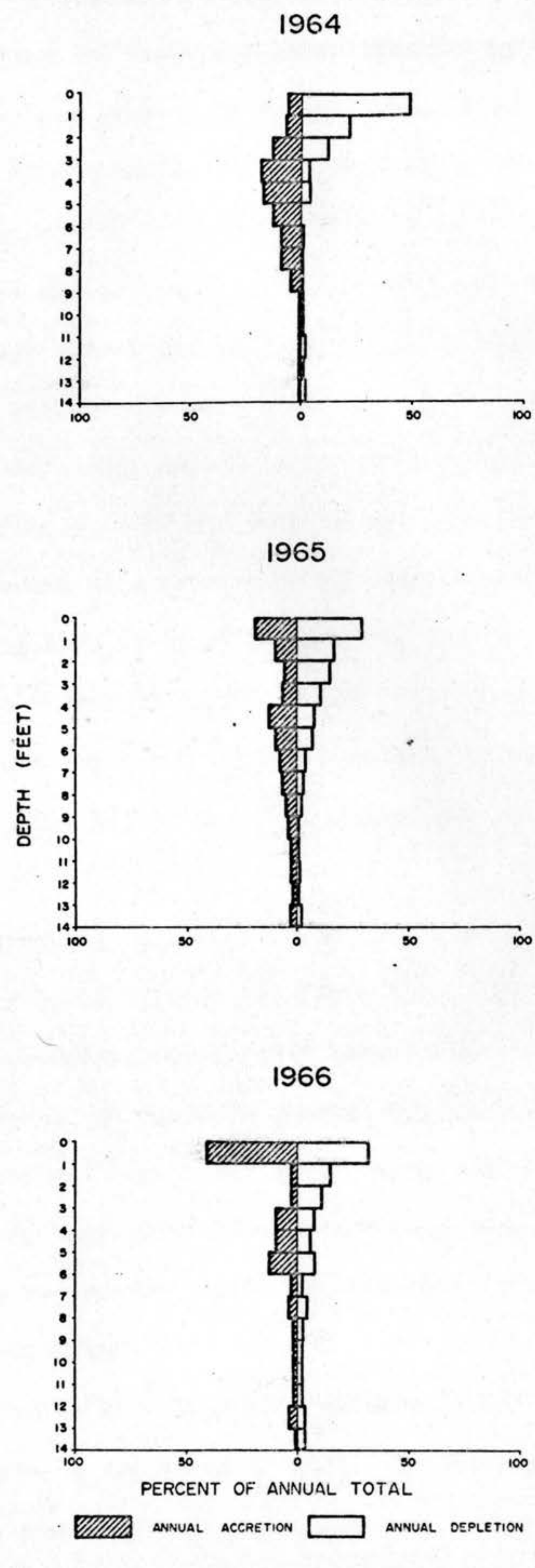

PLOT 3
PLOT 5
1963
1964
1965
1966
ANNUAL ACCRETION
ANNUAL DEPLETION
DEPTH (FEET)
PERCENT OF ANNUAL TOTAL
0
1
2
3
4
5
6
7
8
100
50
0
50
100

Figure 63. Soil moisture accretion and depletion in each of the uppermost fourteen feet of soil, expressed as percentage of total accretion and depletion in the uppermost fourteen feet of soil.

PLOT 5


1964
1965
1966
DEPTH (FEET)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
100
50
0
50
100
PERCENT OF ANNUAL TOTAL
ANNUAL ACCRETION
ANNUAL DEPLETION

Soil moisture depletion in the first foot (0 - 1 feet) expressed as a percentage of total depletion from the uppermost three feet varied, in the four periods of record, from 54 to 58 percent in Plot 1, from 49 to 53 percent in Plot 2, from 47 to 59 percent in Plot 3, from 44 to 51 percent in Plot 4, and from 47 to 59 percent in Plot 5. Accretion values did not show a similar constancy (Figure 59).

The percentage values for the upper foot of soil naturally diminished as more soil depths were introduced into the computation, and the apparent consistency between plots and years tended to disappear. Thus, in Plot 3, soil moisture depletion measured in the first foot of soil, expressed as a percentage of total depletion in seven feet of soil, varied from 22 to 43 percent, in Plot 4 from 23 to 37 percent and in Plot 5 from 23 to 54 percent. It should be noted, however, that the values for Plots 3 and 4 became considerably smaller in range (Table 55, Figure 61) if the late season data of 1963 were ignored.

Generally speaking, moisture depletion from depths below seven feet was relatively small (Figure 63, Table 55). The same tended to be true of moisture accretion, though 1965 values were of greater magnitude than other years. It would in general appear that measurement of soil moisture to and not beyond depths of seven feet in these soils would result in only negligible loss of accuracy in water balance studies. Sampling to greater depths in this soil and this climate does not appear to be justified.

Previous studies have suggested (Horton, 1956) that lodgepole pine roots penetrate to depths of 12 feet. In these plots roots were found to depths of over eight feet (Appendix B). Nevertheless, there was no evidence that evapotranspiration removed water from depths greater than seven feet, even though water was available at these greater depths.

Comparison of Evapotranspiration

For each of the years of study, the data obtained were critically examined to determine the feasibility of comparing evapotranspiration losses among the five plots.

In order to make an estimate of evapotranspiration losses from soil moisture budget techniques, the following assumptions are necessary: (1) Evapotranspiration = change in soil moisture content plus precipitation: in equation form:

$$ET = P - \Delta SM,$$

where ET = evapotranspiration for period (inches)

P = precipitation for period (inches)

Δ SM = change in moisture content of whole profile (inches)

This also assumes that surface runoff is negligible. In the study area, for the periods of record, this assumption is valid. (2) Losses of soil water by downward percolation and lateral movement off the study area are negligible.

This assumption is not valid for considerable periods of record. It has already been shown (Figs. 54, 55, 56, 57) that downward percolation is a marked feature of all five study plots, and that in the case of Plots 1 and 2, it undoubtedly must result in the movement of large quantities of water laterally outside the study area, during certain periods of the year, particularly in the early season.

(3) The groundwater table is assumed to be below the zone of measurement, therefore making no appreciable contribution of water to the zone of measurement. This assumption appears to be valid, in the light of the moisture contents measured throughout the experiment. No measured moisture content at depth indicated a saturated condition.

The non-tenability of assumption (2) above means that comparison of evapotranspiration can only be made for restricted periods of the year, viz. those periods when downward percolation of water has ceased.

By applying this criterion conservatively, in relation to the march of soil moisture at depth (Figs. 54 to 57), the periods of record for which comparison of evapotranspiration is valid were:

1. 1963 - whole period (August 7 - October 25)
2. 1964 - no period
3. 1965 - July 1 - October 29 (Plots 3 and 5 only)
4. 1966 - June 27 to October 11.

Determination of the applicable periods was made by reference to soil moisture march at depth, as shown by Figure 54 for 1963, Figure 56 for 1965 and Figure 57 for 1966.

Analysis of variance was carried out using calculated evapotranspiration amounts for the various periods of measurement in 1963, 1965 and 1966. Total evapotranspiration amounts are presented in Table 56.

It is interesting to note that Plot 3, having the lowest stand density (108 $feet^2$ per acre basal area versus 190 $feet^2$ basal area

Table 56. Evapotranspiration estimates for individual plots for pertinent periods of 1963, 1965 and 1966.

Plot	Year					
	1963		1965		1966	
	Period	ET (inches)	Period	ET (inches)	Period	ET (inches)
1	Aug.7-Oct.25	5.08	N/A	N/A	June 28-Sept.27	8.11
2	Aug.7-Oct.27	4.53	N/A	N/A	June 27-Sept 28	7.83
3	Aug. 8-Oct.26	5.40	July 1-Oct.29	14.02	June 29-Sept.27	8.92
4	Aug.8-Oct.27	5.21	N/A	N/A	June 30-Sept.28	8.41
5	N/A	N/A	June 30-Oct.28	12.47	June 27-Oct.11	8.68

in unthinned Plot 5) consistently showed highest evapotranspiration losses of all plots, though differences were not significant.

Larger water storage capacity of the soil in Plot 3 (Table 6) may have contributed to this result.

The results of analysis of variance were consistent for the three years. Differences among plots were not significant ("F" = 0.53, 1.28, 0.05), while differences among periods were highly significant ("F" = 56.89, 35.44, 5.71). This result is exactly that found by Lull and Axley (1958) in their comparison of evapotranspiration rates.

Periods were of unequal length. Analysis of variance using calculated daily evapotranspiration rates resulted in the same conclusion, though "F" values for differences between periods were appreciably reduced (F = 9.94, 5.34, 2.98), remaining significant, however.

Certainly from these results, it is valid to conclude that at the time of this study, no hydrologic effect of thinning in the form of evapotranspiration reduction persisted.

Also, the results conclusively demonstrate that variation in stand density, in this case, had no effect upon evapotranspiration. Inasmuch as the range, both in basal area and stem numbers (Table 5), was large, this result was not in agreement with prevalent opinion as expressed in the literature (see Douglass, 1967).

Persistent large discontinuities in canopy existed in Plots 2 and 3 (Figs. 15 to 18). It is suggested that these were not indicative of discontinuities in the root network. Alternatively, the shrub growth of Alnus crispa in Plot 2, and of Populus tremuloides in Plot 3, may have utilized water which would not have been taken up by the lodgepole pine forest.

The march of evapotranspiration in 1963, 1965 and 1966 is shown in Figures 64, 65 and 66.

Lull and Axley (1958) pointed out that a wide variation in evapotranspiration rate estimates was to be expected, when small periods were used for estimation purposes. An identical finding was made here, as shown by the values of Table 57.

The average daily evapotranspiration rate in 1966 was 0.09 approximately, for the period of late June to late September. This estimate lies within the boundaries of previously published evapotranspiration estimates, and is of the same order as the estimate of 0.12 inches per day, suggested by Munn and Storr (1967) from their micrometeorological measurements in Marmot Creek Basin's spruce-fir forest, during August, 1965.

From Table 57 it is seen that the August, 1965 mean evapotranspiration rate in Plots 3 and 5 was 0.14 inches per day, very close to Munn and Storr's (1967) "best" estimate in the same general area.

Precision in Soil Moisture Sampling

The planning of soil moisture studies using neutron probe techniques necessitates that a decision be made concerning the number of access tubes which will be installed. In the present study, 10 access tubes were used in Plots 1 to 4 inclusive and six access tubes in Plot 5. In Plots 1 to 4 the selection of 10 as the number of tubes

Figure 64. Cumulative evapotranspiration in 1963, on Plots 1, 2, 3, and 4.

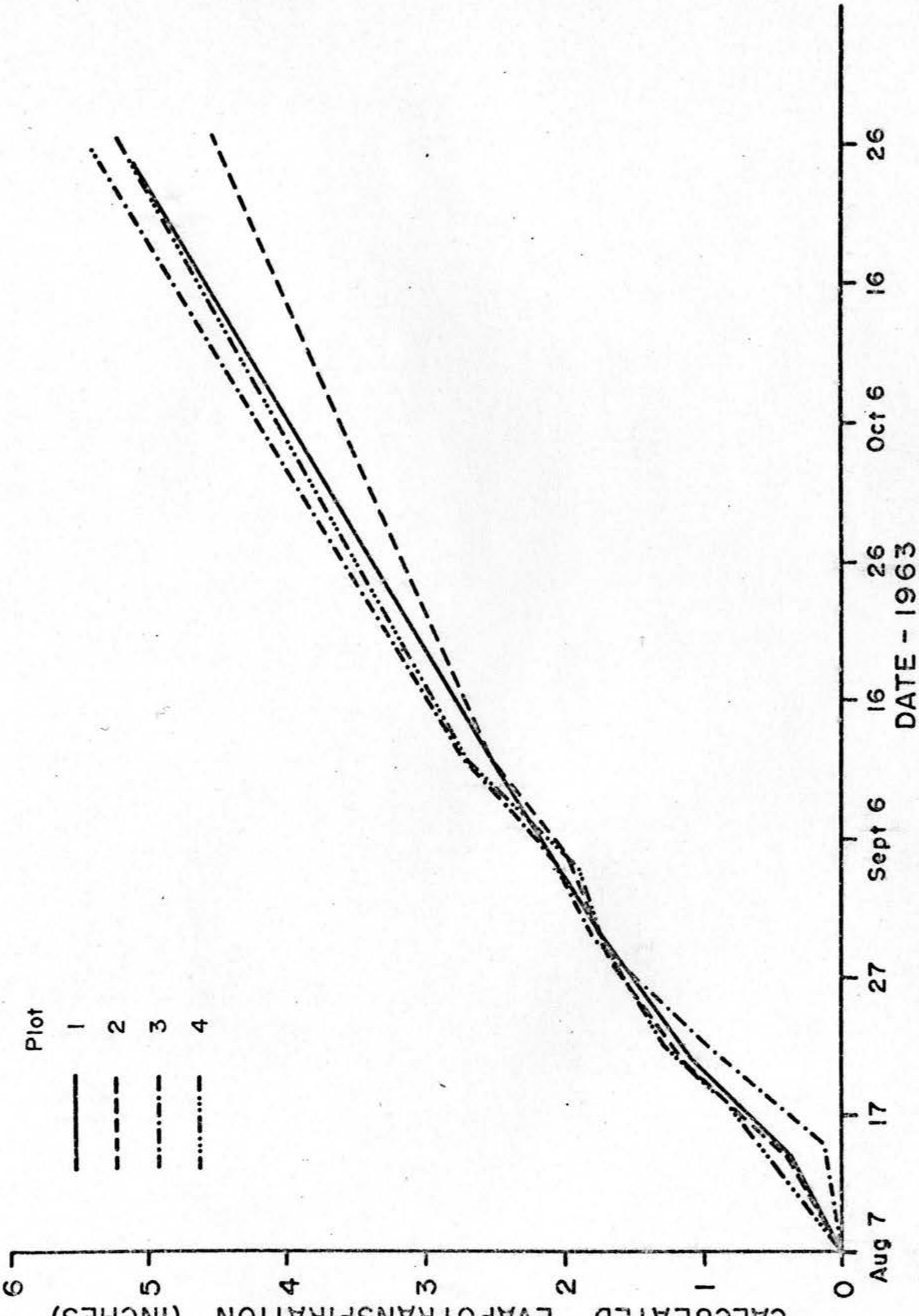

CALCULATED EVAPOTRANSPIRATION (INCHES)
0
1
2
3
4
5
6
DATE - 1963
Aug 7
17
27
Sept 6
16
26
Oct 6
16
26
Plot
1
2
3
4

Figure 65. Cumulative evapotranspiration in 1965 in Plots 3 and 5.

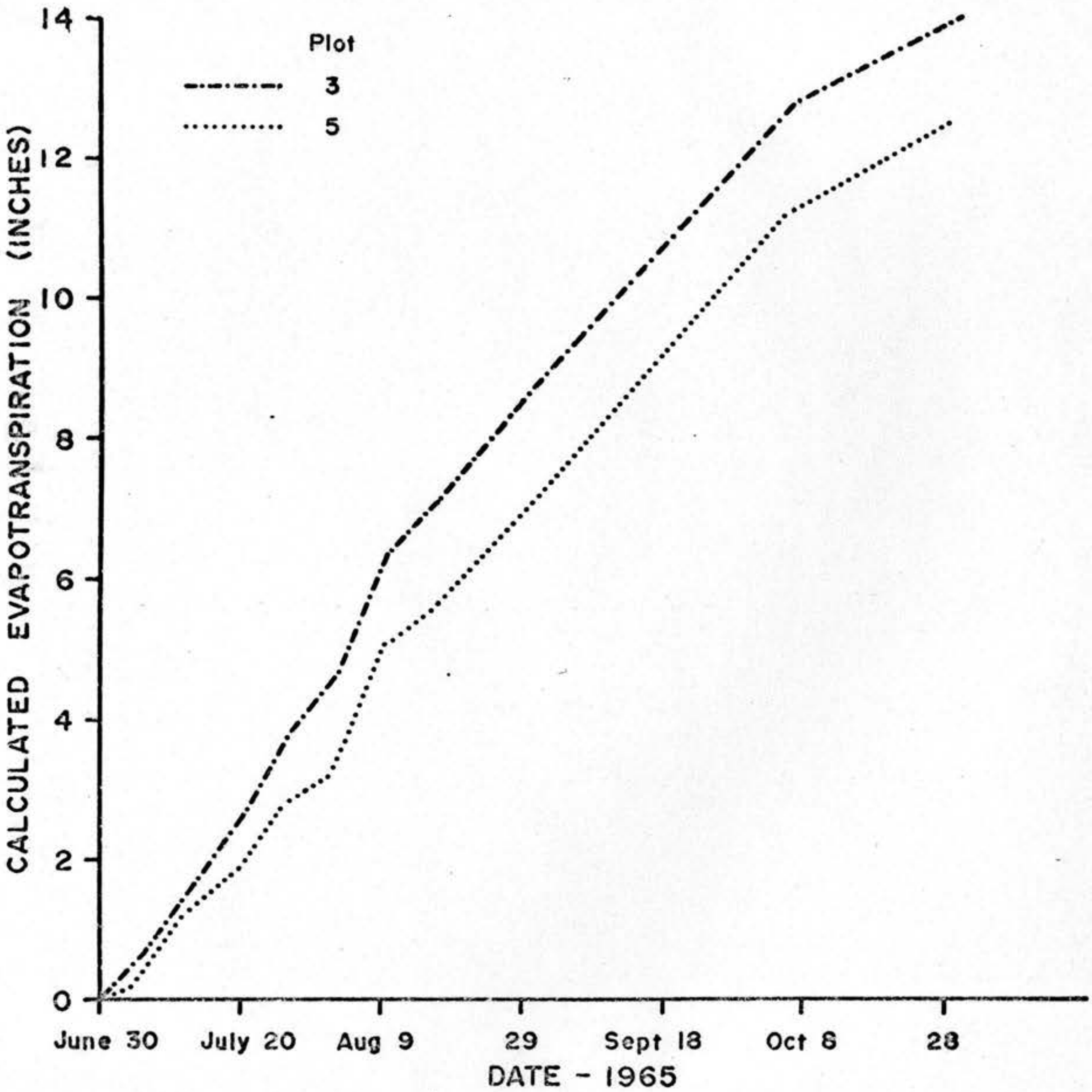

Plot
3
5
CALCULATED EVAPOTRANSPIRATION (INCHES)
14
12
10
8
6
4
2
0
June 30
July 20
Aug 9
29
Sept 18
Oct 8
28
DATE - 1965

Figure 66. Cumulative evapotranspiration in 1966 in Plots 1, 2, 3, 4, and 5.

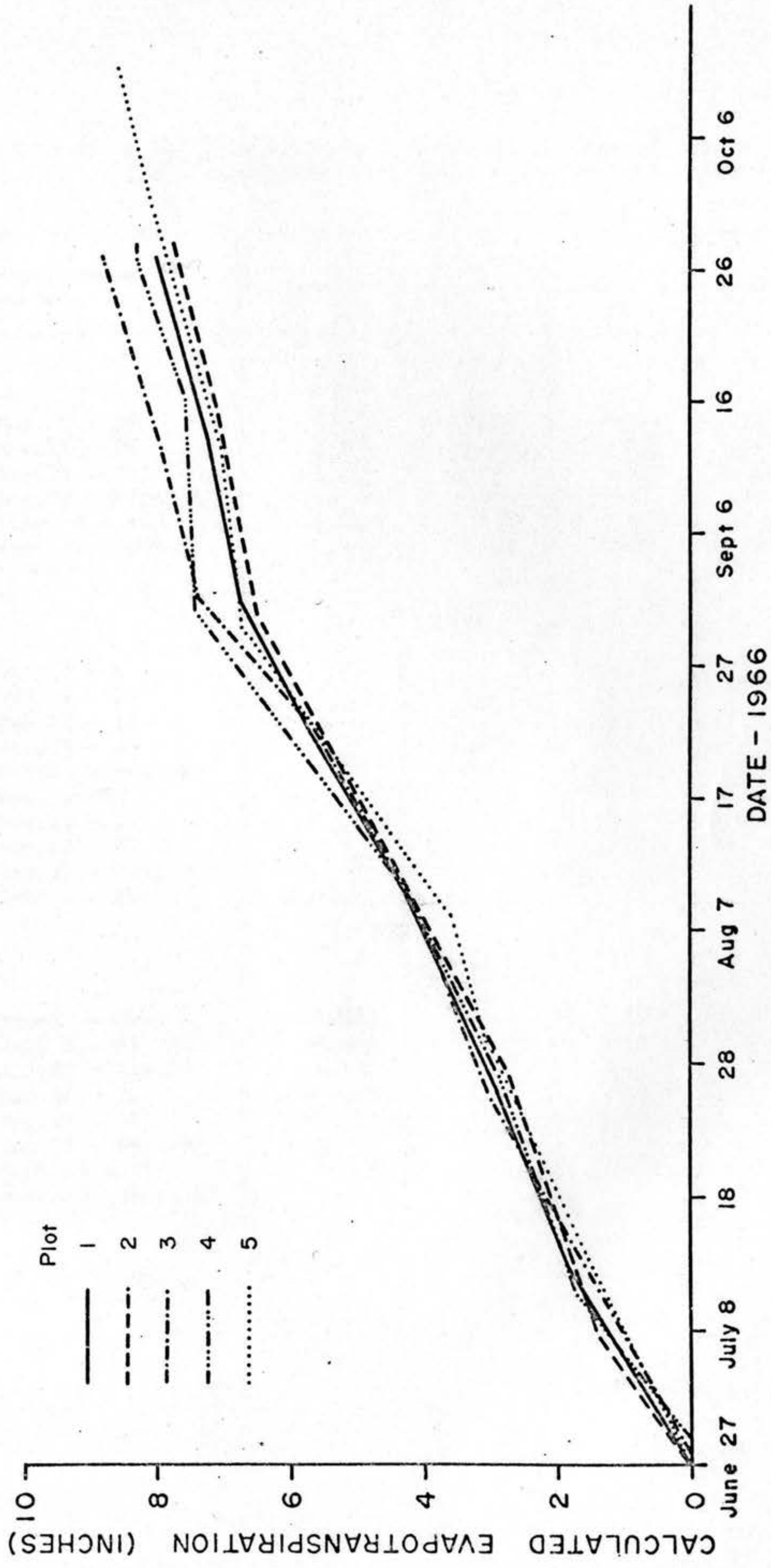

CALCULATED EVAPOTRANSPIRATION (INCHES)
0
2
4
6
8
10
June 27
July 8
18
28
Aug 7
17
27
Sept 6
16
26
Oct 6
DATE - 1966
Plot
1
2
3
4
5

Table 57 Daily Evapotranspiration rates (inches water) - estimates for pertinent measurement periods in 1963, 1965 & 1966.

Approximate period	Plot 1	2	3	4	5
		1963			
Aug. 7 - 14	0.055	0.600	0.085	0.021	
Aug.14 - 21	0.102	0.102	0.106	0.118	
Aug.21 - 28	0.075	0.043	0.081	0.104	
Aug.28 - Sept. 4	0.046	0.050	0.033	0.048	
Sept. 4 - 11	0.078	0.076	0.106	0.092	
Sept.11 - Oct.25.	0.059	0.045	0.059	0.055	
		1965			
July 1 - 6			0.120		0.048
July 6 - 13			0.140		0.142
July13 - 21			0.138		0.084
July21 - 27			0.186		0.149
July27 - Aug. 6			0.119		0.060
Aug. 6 -10			0.245		0.258
Aug.10 - 17			0.108		0.081
Aug.17 - 31			0.121		0.108
Aug.31 - Oct. 7			0.108		0.114
Oct. 7 - 29			0.056		0.056
		1966			
June27 - July 8	0.123	0.130	0.115	0.157	0.096
July 8 - 27	0.083	0.070	0.113	0.074	0.094
July27 - Aug.10	0.092	0.106	0.081	0.102	0.065
Aug.10 - 22	0.120	0.112	0.110	0.152	0.142
Aug.22 - 31	0.150	0.039	0.181	0.010	0.025
Aug.31 - Sept.14	0.042		0.046		
Sept.14 - 28	0.057	0.050	0.065	0.064	0.057
Sept.28 - Oct. 11					0.040

to be installed was based upon a desire to make a study of precision of estimate in soil moisture sampling. In Plot 5, which was sampled to a depth of 14 feet, six access tubes were installed because of man-power considerations.

Hewlett, Douglass and Clutter (1964) carried out a study of soil moisture variance. They concluded that instrument and timing errors were insignificant, and that locational variance made the most important contribution. They took measurements in a large number of locations in forest soils of North and South Carolina. Measurements were taken at a depth of 24 inches only, over a period of approximately 14 days. Moisture contents averaged 40 percent by volume, ranging from 25 to 50 percent. They concluded that an expected standard error of estimate of one percent by volume could be obtained for moisture contents by 38 measurements, but to obtain the same precision for moisture change required only two or three measurements.

Earlier, Douglass (1962) had studied soil moisture variance at one location in South Carolina, and had pointed out this difference in sampling requirement between soil moisture content and soil moisture change. He also suggested that the amount of clay in the soil had a strong influence on required sample numbers. For a standard error of estimate of one percent by volume (0.12 inches per foot of soil depth) in moisture change, three samples were required at a clay content of 20 percent whereas about six were needed at a clay content of 40 percent. Ten samples gave a standard error of estimate in moisture content of 0.2 inches at 20 percent clay content, and of 0.3 inches at 40 percent clay content.

The present studies differed from those reviewed above in that:

(1) Drier soil conditions were studied than those in the Carolina region.

(2) Lower clay contents were studied.

(3) The study data were obtained in an operative research program and were not especially collected for variance estimation in soil moisture sampling.

(4) A wider range in time of sampling was available, to allow appraisal to be made of seasonal effects.

(5) The study combined data from greater depths with a large number of samples over a large time period.

Procedure

Only 1966 data were used in the initial analysis. Measurements in 1966 extended from early May to late September. Plot 5, having only six access tubes, was excluded from the analysis. Soil moisture was measured on 14 occasions in each plot.

From these data, variances and standard deviations of soil moisture and soil moisture change were calculated for each measurement date, or measurement period, at each depth on each plot.

These variances were used to calculate sample number required for a precision level of 0.12 inches (1 percent by volume) per foot of soil depth. To calculate sample number required the formula used was:

$$n = \frac{t^2 s^2}{E^2}$$

n = required sample number

t = Student's "t" value

E = desire precision level

s^2= calculated variance

This is the standard sample number formula for infinite, normally - distributed populations.

Soil Moisture Content

The results of analysis dealing with soil moisture content are shown in Table 58 for Plot 1, Table 59 for Plot 2, Table 60 for Plot 3, and Table 61 for Plot 4.

In Plot 1, the required sample number varied from 4 to 19 in the first foot, from 4 to 13 in the second foot, from 12 to 23 in the third foot, and from 12 to 17 in the fourth foot.

In Plot 2, the first foot required 4 to 13 samples, the second foot 11 to 22 samples, and the third foot 6 to 23 samples.

In Plot 3, the first foot required 4 to 33 samples, the second foot 4 to 38 samples, the third foot 5 to 28 samples, the fourth foot 6 to 29 samples, the fifth foot 5 to 25 samples, the sixth foot 3 to 7 samples, the seventh foot 3 to 4 samples, and the eighth foot 7 to 12 samples.

In Plot 4, the first foot required 4 to 25 samples, the second foot 11 to 39 samples, the third foot 5 to 17 samples, the fourth foot 1 to 44 samples, the fifth foot 4 to 17 samples, the sixth foot 7 to 11 samples, the seventh foot 4 to 12 samples.

There is, of course, a direct relationship between standard deviation and sample number required. For S = 0.020, n = 1; for S = 0.150, n = 9; for S = 0.225, n = 17; for S = 0.365, n = 39.

TABLE 58. Required sample numbers for E=0.12 inches water, and standard deviation, obtained for different soil depths and measurement dates: 1966 soil moisture contents (inches water): plot 1.

DEPTH (FEET)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	DATE OF MEASUREMENT														
	May 11	May 19	May 27		June 7	June 13	June 22	June 28	July 13	July 26	Aug.9	Aug.22	Sept.1	Sept.13	Sept.27
0-1 S. D.	0.083	0.075	0.075		0.080	0.138	0.087	0.154	0.111	0.151	0.182	0.249	0.208	0.146	0.158
No. of samples	4	4	4		4	8	4	9	6	9	12	19	14	8	9
1-2 S. D.	0.159	0.187	0.197		0.188	0.180	0.163	0.153	0.139	0.132	0.109	0.091	0.103	0.092	0.078
No. of samples	9	12	13		12	11	10	9	8	7	6	5	5	5	4
2-3 S. D..	0.240	0.235	0.245		0.251	0.250	0.249	0.268	0.241	0.226	0.228	0.217	0.278	0.188	0.206
No. of samples	18	17	19		20	19	19	22	18	16	17	15	23	12	14
3-4 S. D.	0.191	0.228	0.212		0.202	0.214	0.203	0.227	0.204	0.186	0.197	0.189	0.196	0.209	0.215
No. of samples	12	17	15		14	15	14	16	14	12	13	12	12	14	15

TABLE 59. Required sample numbers for E=0.12 inches water and standard deviation, obtained for different soil depths and measurement dates: 1966 soil moisture contents (inches water): plot 2.

DEPTH (FEET)	1	2	3	4	5	6	7	8	9	10	11	13	14	15
	DATE OF MEASUREMENT													
	May 11	May 20	May 26	June 1	June 8	June 14	June 21	June 27	July 8	July 27	Aug. 10	Aug. 31	Sept. 14	Sept. 28
0-1 S. D.	0.134	0.120	0.150	0.064	0.084	0.115	0.158	0.156	0.097	0.165	0.139	0.193	0.140	0.140
No. of samples	9	6	9	3	4	6	9	9	5	10	8	13	8	8
1-2 S. D.	0.206	0.262	0.267	0.252	0.212	0.203	0.192	0.176	0.193	0.197	0.202	0.206	0.199	0.223
No. of samples	14	21	22	20	15	14	13	11	13	13	14	14	13	16
2-3 S. D.	0.130	0.118	0.117	0.146	0.143	0.140	0.137	0.127	0.137	0.278	0.129	0.109	0.123	0.125
No. of samples	7	6	6	10	8	8	8	7	8	23	7	6	7	7

TABLE 60. Required sample numbers for E=0.12 inches water and standard deviation, obtained for different soil depths and measurement dates: 1966 soil moisture contents (inches water): plot 3.

DEPTH (FEET)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	DATE OF MEASUREMENT														
	May 11	May 19	May 26		June 7	June 15	June 21	June 29	July 14	July 26	Aug. 9	Aug. 22	Sept. 1	Sept. 13	Sept. 28
0-1 S. D.	0.169	0.174	0.211		0.218	0.198	0.193	0.223	0.333	0.198	0.177	0.292	0.216	0.092	0.075
No. of samples	10	11	15		15	13	13	16	33	13	11	26	15	5	4
1-2 S. D.	0.359	0.287	0.245		0.190	0.200	0.196	0.213	0.198	0.078	0.213	0.202	0.162	0.136	0.104
No. of samples	38	25	19		12	13	13	15	13	4	15	14	10	8	5
2-3 S. D.	0.308	0.156	0.128		0.124	0.110	0.107	0.107	0.124	0.101	0.103	0.149	0.123	0.128	0.114
No. of samples	28	9	7		7	5	6	6	7	5	5	9	7	7	6
3-4 S. D.	0.230	0.187	0.164		0.204	0.187	0.207	0.194	0.198	0.174	0.187	0.315	0.119	0.125	0.127
No. of samples	17	12	10		14	12	14	13	13	11	12	29	6	7	7
4-5 S. D.	0.265	0.202	0.136		0.144	0.091	0.090	0.109	0.128	0.114	0.172	0.219	0.258	0.290	0.291
No. of samples	22	14	8		8	5	5	6	7	6	11	16	20	25	25
5-6 S. D.	0.114	0.127	0.119		0.149	0.076	0.060	0.067	0.066	0.062	0.072	0.071	0.094	0.110	0.114
No. of samples	6	7	6		9	4	3	4	4	3	4	4	5	6	6
6-7 S. D.	0.080	0.061	0.084		0.061	0.058	0.050	0.055	0.060	0.053	0.056	0.074	0.066	0.078	0.071
No. of samples	4	3	4		3	3	4	4	3	4	4	4	4	4	4
7-8 S. D.	0.117	0.190	0.148		0.160	0.155	0.150	0.133	0.130	0.126	0.149	0.161	0.120	0.130	0.123
No. of samples	6	12	9		10	9	9	7	7	7	9	10	6	7	7

TABLE 61. Required sample numbers for E=0.12 inches water and standard deviation, obtained for different soil depths and measurement dates: 1966 soil moisture contents (inches water): plot 4.

DEPTH (FEET)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	DATE OF MEASUREMENT														
	May 12	May 20	May 27	June 1	June 10	June 15	June 22	June 30	July 11	July 27	Aug. 10		Aug. 31	Sept. 16	Sept. 30
0-1 S. D.	0.100	0.127	0.129	0.109	0.123	0.086	0.227	0.176	0.163	0.260	0.232		0.168	0.274	0.289
No. of samples	5	7	7	6	7	4	17	11	10	21	17		10	23	25
1-2 S. D.	0.282	0.364	0.345	0.322	0.279	0.306	0.311	0.327	0.299	0.261	0.359		0.163	0.178	0.321
No. of samples	24	39	35	31	24	28	29	31	27	21	38		10	11	30
2-3 S. D.	0.086	0.063	0.095	0.135	0.157	0.159	0.185	0.171	0.162	0.162	0.155		0.234	0.211	0.234
No. of samples	9	3	5	8	9	9	12	11	10	10	9		17	15	17
3-4 S. D.	0.390	0.085	0.077	0.088	0.021	0.031	0.039	0.048	0.055	0.063	0.055		0.141	0.121	0.171
No. of samples	44	4	5	5	1	2	2	3	4	3	4		8	7	10
4-5 S. D.	0.108	0.149	0.142	0.154	0.144	0.147	0.151	0.159	0.167	0.148	0.145		0.088	0.080	0.234
No. of samples	6	9	8	9	8	8	9	9	10	9	8		5	4	17
5-6 S. D.	0.144	0.143	0.153	0.141	0.168	0.159	0.166	0.131	0.139	0.143	0.145		0.148	0.141	0.179
No. of samples	8	8	9	8	10	9	10	7	8	8	8		9	8	11
6-7 S. D.	0.134	0.140	0.122	0.115	0.133	0.186	0.152	0.145	0.138	0.140	0.157		0.114	0.103	0.098
No. of samples	7	8	7	6	7	12	9	8	8	8	9		4	5	5

Tables 58 to 61 show that with 10 access tubes per plot the desired precision level of 0.12 inches water per 12 inches soil depth was attained much more frequently at deeper depths than at shallow depth. At depths of one and two feet it was attained relatively seldom.

Variation therefore was appreciably less at depth than in the upper soil layers. In Plot 2, there was less variation in the third foot than at shallower depths. In Plot 3, there was much less variation beginning in the sixth foot than at shallower depths. In Plot 4, there was much less variation beginning in the fourth foot than at shallower depths.

However, there was little evidence of progressive decrease in soil moisture variance with increasing depth, such as suggested by Striffler (1961) and Bethlamy (1963). Highest standard deviations were encountered in the third foot in Plot 1, in the second foot in Plots 2 and 4, and in the first, second and fourth foot of Plot 3.

The required sample numbers calculated lay within the range to be expected from the work of Douglass (1962) and Hewlett, Douglass and Clutter (1964). The maximum values obtained were often at shallow depths, close to the n = 40 conclusion arrived at in the latter work. Soils (Appendix B; Table 6) did not have large clay fractions. Therefore, one would expect lower sample numbers to be in general required than were determined from the Carolina region, according to the postulates of Douglass (1962). This would seem to be borne out by the results, and it is interesting to note the higher standard deviations in the eighth foot of Plot 3 (Table 60) in comparison to the depth zones immediately above. This depth (Appendix B) had appreciably higher soil moisture constant values, and presumably a larger clay fraction, than these other depths.

Tables 58 to 61 suggest that variation was greater in either early season (early May) and in late season (late September) than it was in the intervening period, though no consistent pattern emerged for all plots.

To check upon any such pattern, the data for 1963, 1964 and 1965 were subjected to analysis. The 1963 analyses were inconclusive. Plot 1 showed higher variation at end season, but other plots did not to any extent.

The 1964 analysis, which dealt with early season data only, demonstrated a marked diminution of variation from early season to mid-summer.

In 1965, relatively little variation in moisture levels was found, due to the wetness of the summer. No trend could be distinguished from the 1965 analysis.

It would appear that soil moisture variation definitely tended to be greater in early season, while in late season this was not established, and may or may not occur.

Soil Moisture Change

The results of analysis dealing with soil moisture change are presented in Table 62 for Plot 1, Table 63 for Plot 2, Table 64 for Plot 3, and Table 65 for Plot 4.

The required numbers of samples for moisture change, as would be expected from previous work, were considerably smaller than the comparable values for soil moisture content.

In Plot 1, the required sample number for the first foot was 1 to 21, in the second foot 1 to 8, in the third foot 1 to 8, and in the fourth foot 1 to 6.

In Plot 2, required sample number in the first foot was 2 to 5, in the second foot 1 to 9, and in the third foot 1 to 5.

In Plot 3, required sample number in the first foot was 3 to 30, in the second foot 1 to 14, in the third foot 1 to 5, in the fourth foot 2 to 21, in the fifth foot 1 to 27, in the sixth foot 1 to 5, in the seventh foot 1 to 4, and in the eighth foot 1 to 13.

In Plot 4, required sample number in the first foot was 3 to 17, in the second foot 1 to 42, in the third foot 1 to 5, in the fourth foot 1 to 44, in the fifth foot 1 to 10, in the sixth foot 1 to 5, and in the seventh foot 1 to 4.

The results show that the actual sample number of 10 tubes yielded results within the desired precision level in 92 percent of Plot 1 measurements, in 95 percent of Plot 2 measurements, in 87 percent of Plot 3 measurements, and in 93 percent of Plot 4 measurements. Plot 3 contained a number of clay lenses in its soil profile (Appendix B). This may account for the disparity between this plot and the other three.

It is noteworthy that there was considerable variation between periods, with a number of extreme values showing up. Previous work had indicated that three samples might be expected to yield the

TABLE 62. Required sample numbers for E=0.12 inches water, and standard deviations obtained, for different soil depths and measurement dates: 1966 soil moisture change (inches water): plot 1.

DEPTH (FEET)	1	2	3	5	6	7	8	9	10	11	12	13	14
	DATE OF MEASUREMENT												
	May 11-19	May 19-27	May 27-June 7	June 7-15	June 15-22	June 22-28	June 28 July 13	July 13-26	July 26 Aug. 9	August 9-22	Aug. 22 Sept. 1	Sept. 1-13	Sept. 13-27
0-1 S. D.	0.047	0.022	0.070	0.131	0.157	0.106	0.073	0.105	0.079	0.219	0.262	0.115	0.084
No. of samples	3	1	4	7	9	6	4	5	4	16	21	6	4
1-2 S. D.	0.059	0.050	0.030	0.023	0.025	0.014	0.041	0.139	0.124	0.045	0.034	0.034	0.038
No. of samples	3	4	1	1	1	3	3	8	7	3	2	2	2
2-3 S. D.	0.098	0.019	0.019	0.027	0.029	0.132	0.135	0.109	0.090	0.024	0.115	0.029	0.039
No. of samples	5	1	1	1	1	7	8	6	5	1	6	1	2
3-4 S. D.	0.080	0.024	0.035	0.038	0.023	0.079	0.077	0.028	0.112	0.105	0.117	0.039	0.032
No. of samples	4	1	2	2	1	4	4	1	6	6	6	2	2

TABLE 63. Required sample numbers for E=0.12 inches water, and standard deviations, obtained for different soil depths and measurement dates: 1966 soil moisture change (inches water): plot 2.

DEPTH (FEET)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	DATE OF MEASUREMENT													
	May 11-20	May 20-26	May 26 June 1	June 1-8	June 8-14	June 14-21	June 21-27	June 27	July 8-27	July 27 Aug. 10	Aug. 10-31		Aug.31 Sept.14	Sept. 14-28
0-1 S. D.	0.039	0.045	0.091	0.034	0.040	0.080	0.050	0.074	0.101	0.063	0.083		0.093	0.045
No. of samples	2	3	5	2	3	4	4	4	5	3	4		5	3
1-2 S. D.	0.123	0.062	0.051	0.057	0.024	0.028	0.042	0.047	0.047	0.023	0.055		0.148	0.147
No. of samples	7	3	4	3	1	1	3	3	3	1	4		9	8
2-3 S. D.	0.062	0.098	0.060	0.030	0.012	0.019	0.030	0.030	0.025	0.027	0.033		0.022	0.027
No. of samples	3	5	3	1	2	1	1	1	1	1	2		1	1

TABLE 64. Required sample numbers for E=0.12 inches, and standard deviations, obtained for different soil depths and measurement dates: 1966 soil moisture change (inches water): plot 3.

DEPTH (FEET)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	DATE OF MEASUREMENT													
	May 11-19	May 19-26	May 26 June 7		June 7-15	June 15-21	June 21-29	June 29 July 14	July 14-26	July 26 Aug. 9	August 9-22	Aug. 22 Sept. 1	Sept. 1-13	Sept. 13-27
0-1 S.D.	0.154	0.183	0.135		0.116	0.078	0.090	0.321	0.308	0.153	0.174	0.206	0.156	0.058
No. of samples	9	12	8		6	4	5	30	28	9	11	14	9	3
1-2 S. D.	0.085	0.062	0.081		0.034	0.025	0.022	0.034	0.196	0.204	0.096	0.057	0.038	0.040
No. of samples	4	3	4		2	1	1	2	13	14	5	3	2	2
2-3 S. D.	0.230	0.068	0.033		0.034	0.013	0.016	0.032	0.040	0.016	0.092	0.097	0.018	0.023
No. of samples	17	4	2		2	2	3	2	3	4	5	5	4	1
3-4 S. D.	0.129	0.091	0.098		0.039	0.080	0.111	0.065	0.062	0.032	0.229	0.264	0.048	0.057
No. of samples	7	5	5		2	4	6	3	3	2	17	21	3	3
4-5 S. D.	0.302	0.125	0.071		0.069	0.023	0.039	0.024	0.042	0.091	0.117	0.118	0.218	0.247
No. of samples	27	7	4		4	1	2	1	3	5	6	6	16	19
5-6 S. D.	0.099	0.046	0.128		0.138	0.034	0.025	0.024	0.020	0.031	0.067	0.068	0.032	0.040
No. of samples	5	3	7		8	2	1	1	1	2	4	4	2	3
6-7 S. D.	0.085	0.065	0.031		0.024	0.025	0.022	0.042	0.038	0.018	0.039	0.061	0.018	0.028
No. of samples	4	3	2		1	1	1	3	2	4	2	3	4	1
7-8 S. D.	0.072	0.055	0.018		0.022	0.018	0.026	0.016	0.030	0.067	0.080	0.105	0.040	0.028
No. of samples	4	4	4		1	4	1	1	1	4	4	5	2	1

TABLE 65. Required sample numbers for E=0.12 inches water, and standard deviations, obtained for different soil depths and measurement dates: 1966 soil moisture change (inches water): plot 4.

DEPTH (FEET)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
						DATE OF MEASUREMENT								
	May 12-20	May 20-27	May 27 June 1	June 1-10	June 10-15	June 15-22	June 22-30	June 30 July 11	July 11-27	July 27 Aug. 10	Aug. 10-31		Aug.31 Sept.16	Sept. 16-28
0-1 S. D.	0.053	0.040	0.058	0.137	0.139	0.142	0.061	0.096	0.181	0.142	0.133		0.234	0.214
No. of samples	4	2	3	8	8	8	3	5	11	8	7		17	15
1-2 S. D.	0.087	0.062	0.040	0.043	0.028	0.033	0.028	0.079	0.306	0.378	0.261		0.042	0.275
No. of samples	5	3	3	3	1	2	1	4	28	42	21		3	23
2-3 S. D.	0.096	0.043	0.055	0.040	0.011	0.023	0.019	0.019	0.011	0.010	0.101		0.026	0.030
No. of samples	5	3	4	2	2	1	1	1	2	2	5		1	1
3-4 S. D.	0.387	0.015	0.073	0.069	0.023	0.013	0.027	0.015	0.013	0.012	0.089		0.029	0.057
No. of samples	44	3	4	4	1	2	1	3	2	2	5		1	3
4-5 S. D.	0.075	0.057	0.044	0.048	0.034	0.022	0.021	0.053	0.043	0.026	0.061		0.009	0.165
No. of samples	4	3	3	3	2	1	1	4	3	1	3		1	10
5-6 S. D.	0.033	0.042	0.036	0.086	0.040	0.024	0.037	0.024	0.007	0.022	0.091		0.022	0.052
No. of samples	2	3	2	4	3	1	2	1	1	1	5		1	4
6-7 S. D.	0.005	0.019	0.009	0.031	0.062	0.048	0.017	0.026	0.034	0.029	0.020		0.071	0.071
No. of samples	1	1	1	2	3	3	4	1	2	1	1		4	4

desired level of precision. These results show that three samples would not be adequate in these soils, but that eight samples would provide the desired result in the large majority of measurements (about 90 percent).

Variance in soil moisture change was greatest in the surface foot in all plots, though not markedly so in Plot 2. To this extent, the findings of Striffler (1961) and Bethlamy (1963) may be regarded as confirmed.

Again, there appeared to be a tendency for extreme variance to show up at the beginning and end of the season. The 1963, 1964 and 1965 data were processed to determine whether any pattern might appear.

From the analysis for these other years, a definite trend appeared for soil moisture change variance to be higher in early season. The 1964 data very clearly indicated this trend on all four plots. In the late season data, the trend for soil moisture change variance to be greater in late season was less definite, but it was nevertheless discernible in the upper soil layers. The 1963 data showed this trend, as did the 1965 results also, though not so clearly.

Presumably, these high variances were due to wetting of the profile by spring and fall rains (Table 1), with spring rain and snow-melt water having an influence to greater depth than did fall precipitation.

In the tables extreme values showed up (e.g. Table 64, fifth foot, periods 13 and 14). It seemed unlikely that these values could be due to anything other than human error. However, similar unexpected extreme variances appeared in the results for the other years (1963, 1964, 1965). Different operators collected the data in each year. The extreme variances may have been due to some factor other than human error, and if they were due to this cause, then it would appear to be largely unavoidable in routine soil moisture sampling.

Number of Access Tubes Required

Preceding pages have dealt solely with required sample numbers at individual depths. Often, however, the researcher is interested in determining the sample numbers required to obtain a given precision level for the whole instrumented solum. This is particularly true of water balance studies in experimental and representative watersheds.

To obtain this information, soil moisture content and soil moisture change variances for the whole profile were calculated and required sample numbers derived from these. Results are shown in Table 66. These results are based upon readings in each 12 inches depth increment; in other words the total number of measurements required is the required number of access tubes multiplied by the depth (feet) of the instrumented solum.

Again, a great deal of variation in time appeared in the analysis. Required access tube number for soil moisture content determination was 9 to 27 in Plot 1, 12 to 23 in Plot 2, 14 to 40 in Plot 3, and 7 to 49 in Plot 4.

For soil moisture change, number of access tubes required was 1 to 9 in Plot 1, 1 to 11 in Plot 2, 1 to 7 in Plot 3, and 1 to 15 in Plot 4.

TABLE 66. Required number of access tubes for E=0.12 inches water for whole instrumented solum, based on readings at each 12 inches depth, 1966 data, soil moisture content and soil moisture change.

	Period of measurement														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
					SOIL MOISTURE CONTENT										
Plot 1	14	15	17	--	16	21	15	27	17	14	15	11	9	9	11
Plot 2	12	15	23	20	15	15	17	12	12	20	15	--	17	17	17
Plot 3	40	24	31	--	28	22	20	22	30	14	29	40	26	19	17
Plot 4	7	13	12	10	5	11	21	21	17	18	25	--	19	25	49
					SOIL MOISTURE CHANGE										
Plot 1	2	1	1	--	2	2	3	2	2	3	9	9	5	2	
Plot 2	2	2	1	1	1	1	1	1	11	11	1	-	1	3	
Plot 3	6	5	1	--	1	1	1	5	7	5	5	5	3	3	
Plot 4	15	1	2	2	2	3	1	1	3	5	13	-	13	8	

King (1967), utilizing the results of Hewlett, Douglass and Clutter (1967) recommended that three access tubes be installed in unit source areas of instrumented watersheds. These results indicate that this number would be insufficient on many occasions to obtain a precision of one percent soil moisture by volume. However, there are many circumstances in which this precision would not be needed.

The results of these analyses may be summarized, as follows:

(1) Large variances in soil moisture content existed in the soils under study, so that, at depths of one and two feet, ten samples per foot of soil depth relatively seldom yielded precisions equal to one percent soil moisture by volume, at least in the upper solum. In deeper soil layers variance was less.

(2) There was little evidence of progressive decrease of soil moisture content variance with increasing depth. Maximum variance was often encountered in the second and third feet of the solum. Variance in soil moisture change was greatest in the surface foot of soil.

(3) There was appreciable range in variance from one sampling date to another. Variances were less, generally speaking, than has been found in finer textured soils in the more humid region of the Carolinas.

(4) Results suggested that variance was higher at beginning and end of the season, though all plots did not show a consistent pattern. Results from years other than 1966 confirmed this trend, at least for early season data. Variances definitely were greater in early season.

(5) Appreciable range in variance of soil moisture change was encountered according to season of year. Results from other years

confirmed this trend. Variance was consistently higher in early season. Greater variance in soil moisture change was also discernible in late season, but only in the upper soil layers.

(6) The previous finding from the Carolinas that three samples might be expected to yield estimates of soil moisture change with a precision of one percent soil moisture by volume was not confirmed by this study. Eight samples yielded this level of precision for 90 percent of the measurement events.

(7) Total variances for the whole profile were calculated and numbers of access tubes required for E = 0.12 inches water derived from them. A wide range in total variance according to date of measurement was again obtained.

(8) To estimate total soil moisture change with a precision level of 0.12 inches water required from 1 to 15 access tubes. Eight access tubes would have yielded this result in 90 percent of the measurement periods, and three access tubes in about 70 percent of the measurement periods.

Chapter V

SUMMARY AND CONCLUSIONS

The study was carried out in the Kananaskis Forest Experiment Station in western central Alberta. Its primary objectives were to determine whether any hydrologic effect of thinning lodgepole pine stands persisted 20 years after thinning had been undertaken, and whether stand density, as expressed by basal area or number of stems per acre, had an influence upon the hydrology of lodgepole pine forests. Secondary objectives dealt with sample numbers required in soil moisture sampling, precipitation redistribution at the ground surface beneath lodgepole pine stands, and the utility of trough gauges in throughfall estimation.

Three parameters were chosen for study. These were (1) snow accumulation (2) canopy interception of rainfall (3) soil moisture and, inferentially, evapotranspiration.

Snow Accumulation

Snowpack was ephemeral in the study locations. During long periods the ground was free of snow beneath lodgepole pine stands. In some winters there was snow on the ground for only relatively short periods of the year. Snow disappearance was believed to result from recurrent Chinook winds. The disposition of the snowpack water equivalent (i.e., melt versus evaporation) is not known. Large evaporative losses are usually considered to be unlikely, on the basis of the absence of a sufficiently large energy source.

Though data, over four winters (1963-1966) of study, were inevitably sparse, some evidence emerged that there was greater accumulation of snow in stands with lower basal areas or numbers of stems per acre, more than 20 years after thinning was carried out.

Canopy Interception of Rainfall

Three stands were studied, one thinned, the other two unthinned. Two summers of rainfall record were obtained (1963 and 1964).

No evidence emerged that, more than 20 years after thinning, any residual effect of thinning on canopy interception of rainfall remained. In fact, interception in the thinned plot was slightly higher than in its unthinned counterpart. The two unthinned stands had virtually identical basal areas, though widely divergent numbers of stems per acre. Throughfall in these two stands was significantly different. Neither basal area nor number of stems per acre was helpful in explaining differences between stands.

A number of other approaches was attempted to explain these differences. Of these, canopy density showed the most promise though, with only three plots, it could not be statistically tested. Of the following variables (1) crown length (2) crown projectional area (3) crown circumference, none were of any value in explaining "between-stand" differences. Crown volume and crown surface area, it was found, could not be estimated from DBH distribution data, though high correlations were obtained with DBH.

The throughfall equation for the stand (Plot 3) having the highest interception was virtually identical with that derived by

Niederhof and Wilm (1943) for their unthinned stand, which had structural and mensurational characteristics very different from Plot 3.

It can be concluded that, contrary to opinion in the literature (Rogerson, 1967; Kittredge, 1948), basal area was of no value in explaining "between-stand" throughfall differences. Canopy density seemed to be a better estimator. This would tend to confirm the conclusions of Rothacher (1963) and Skau (1964). A hydrologically pertinent measure of vegetative differences needs to be developed.

Initial storage values (0.30 to 0.40 inches) of rainfall stored on tree crowns were higher than previously published for lodgepole pine.

Stemflow was negligible, as found by Wilm and Niederhof (1941) and Wilm and Dunford (1948). Stemflow only occurred in storms greater than 0.29 inches gross precipitation. Stemflow was conclusively shown not to be proportional to tree size (DBH), a result conforming to the findings of Rowe and Hendrix (1951). Stemflow was tested against (1) crown length (2) crown width (3) crown surface area (4) crown volume, and (5) crown projectional area, of instrumented trees. None of these variables showed any significant correlation with stemflow volume. Stemflow was significantly correlated with storm size.

In comparison of throughfall variation within stands, standard deviations and coefficients of variation were calculated. It was found that, based on comparison of standard deviations, variation in throughfall increased as storm size became greater. There was no evidence that any plot demonstrated any higher or lower variability in throughfall than any other plot.

In studying throughfall catch in relation to gauge position within the stand, it was confirmed that, regardless of gauge position, throughfall percentage increased as storm size increased. No evidence was found of either increased or decreased throughfall in the annular zone within one foot radius of the tree stem. Throughfall percentage was appreciably greater at the crown edge than in other gauge positions beneath tree crowns. Throughfall beneath gaps in the canopy never reached 100 percent of gross precipitation. In storms of 0.50 inches or less, more throughfall was experienced beneath canopy gaps than in any other gauge position, whereas in storms greater than 0.50 inches, throughfall appeared greater beneath crown perimeters than beneath canopy gaps.

The relationship between throughfall and distance from tree stems was examined. A relationship was found to exist, but it was not strongly expressed. When all data, including those collected beneath canopy gaps, were included, high levels of significance ($p = 0.005$) were obtained, but coefficients of determination were seldom higher than 25 percent and generally were considerably less.

When data collected beneath canopy gaps were excluded, the relationship tended to be weakened rather than improved.

Models were tested which attempted to take into account variation in tree size and accordingly crown width. None of these models gave consistently improved relationships.

The combination of low "r" values and wide data "scatter" was thought to be the expression of a relatively open crown habit in lodgepole pine. Organized distribution of precipitation in lodgepole pine forests was not pronounced, other than in the occurrence of a zone of greater throughfall at the crown edge. Variation in throughfall was large and appeared to be approximately 85 percent randomly distributed. This is at variance with the findings of Leyton and Carlisle (1959) in a U.K. Norway spruce stand.

Stemflow in lodgepole pine stands made no major contribution to soil moisture variation.

In comparison of trough gauges and standard gauges for throughfall estimation purposes, trough gauges were found to function poorly in large storms. This was attributed to the catch collection system utilized and not to gauge performance. Even when the few storms with gross precipitation greater than 0.75 inches were excluded, mean trough gauge catch was not found to be identical with mean standard gauge catch.

Trough gauges tended to undercatch. This was believed, through elimination, to be a function of the aerodynamic efficiency of the trough gauges used, though two types, one of which might be expected to be aerodynamically more efficient than the other, were utilized. In all plots, and both years, the relationship between mean throughfall catch by trough and standard gauges was very precise, for storms < 0.75 inches. No significant differences existed in the expression of this relationship for different plots and years.

Trough gauges, in permanent, random locations offer considerable manpower savings for interception studies. If calibrated against standard gauges, they are believed to be worthwhile research tools. They cannot, however, be shown to yield results identical to standard gauges, but rather a slight underestimate of throughfall, and consequently an overestimate of canopy interception.

The addition of a gauge slope parameter into the trough gauge catch expression, as suggested by Reigner (1964), sometimes resulted in improvement of the standard error of estimate, in the relationship with standard gauge catch.

SOIL MOISTURE

Five plots were studied. Three of these had been thinned in 1939-40. A wide range in basal area (108 $feet^2$ to 190 $feet^2$) was a characteristic of these plots. Readings were tkane in 1963 to 1966 inclusive.

Wide discrepancies were found between values obtained for 1/3 bar and 15 bar soil moisture tensions, using pressure apparatus, and highest and lowest values obtained in field measurement by calibrated neutron probe. The probe calibration was shown not to be a significant factor in the occurrence of these discrepancies. The divergence was greatest in the uppermost layers of the solum. It is suggested that the probe calibration, carried out using C horizon material, may not have been accurate for A and B horizon material. The ranges in laboratory-determined available water storage and the difference between highest and lowest neutron probe readings were closely similar in all plots. Comparisons between plots could be made with confidence. It is suggested that research should look into the question of separate probe calibration for A and B soil horizons.

In the comparison of soil moisture contents between plots, dates of measurement and individual soil depths, results from all four years were very similar. Plots, dates of measurement and depths were invariably highly significantly different in analysis of variance. However, first order interactions were also invariably highly significantly different. These interactions were attributed to differences in soil moisture recharge and withdrawal patterns in the various plots, particularly in the upper soil layers. These significant interactions necessitated care in the interpretation of treatment effects.

It was shown that sampling to depths of seven or eight feet brought to light differences between plots which were not apparent when data for the uppermost three or four feet alone were analysed.

In analysis of variance utilizing data on soil moisture change, the results obtained were completely different. Significant differences between plots appeared only when analysis was confined to the uppermost three feet of soil. Again, highly significant first order interactions were encountered. It was concluded that thinning carried out more than 20 years previously had retained no persistent effect upon soil moisture change. It was further concluded that, within the range of basal areas and numbers of stems per acre, stand density had no significant effect upon soil moisture change. Therefore, these parameters were concluded to be poor descriptors of stand variation for hydrologic purposes. This is in opposition to convention, the literature consistently referring to basal area, in particular, to describe differences in stand density (see Douglass, 1967).

Soil moisture change was largest in uppermost soil depths. At depths greater than six, or at most eight feet, virtually no change in soil moisture took place in some years. Water was available for evapotranspiration at these depths but there was no evidence of it being utilized. From this it is suggested that the effective rooting depth of lodgepole pine may extend to six or eight feet only. Previous studies (Horton, 1957) had suggested rooting to 12 feet depth.

Conversely, soil moisture sampling to a depth of eight feet gave completely adequate results, and measurement below this depth was not economically justifiable.

Plots with deep soils contributed virtually no water to groundwater during at least three of the four periods studied. Shallower plots did contribute water to groundwater storage.

Considerable movement of water vapour upwards through the soil profile during the winter months was suggested by the data collected. This movement was believed to be thermally induced.

The surface layers of soil were seen to play the main role in measured soil moisture accretion and depletion, particularly the surface foot. This is the same finding as obtained by Lull and Axley (1958).

Evapotranspiration was compared between plots for periods of 1963, 1965 and 1966. Comparison was made only for periods when downward drainage of soil water had become insignificant. These were rather conservatively estimated, to ensure a valid comparison. The

1964 data were not used since they were all early season data, and drainage had not ceased before readings had to be discontinued.

No significant differences in calculated evapotranspiration were found. Highly significant differences between periods of measurement were encountered. It was concluded that 23 years after thinning took place no evapotranspiration difference remained. The effect of thinning therefore was not persistent, and any hydrologic benefits of thinning in the sense of evapotranspiration savings, were relatively short-lived. The stand which had been most heavily thinned demonstrated the greatest evapotranspiration loss. However, a greater water storage capacity on this plot might help explain this result.

Two heavily thinned plots showed large persistent discontinuities in canopy. Yet no evapotranspiration differences were found. This suggests that canopy discontinuities did not necessarily indicate discontinuities in rooting, or alternatively that undergrowth shrub species utilized water which was not transpired by the lodgepole pine forest.

The mean daily evapotranspiration rate in late June to early October, 1966 was 0.09 inches water, which agreed approximately with evapotranspiration values previously published. A study carried out in the same general area (Munn and Storr, 1967) in August, 1965, estimated an evapotranspiration rate of 0.12 inches per day. The current study provided an estimate of 0.14 inches per day for the same period.

Stand density differences, as expressed in basal area or number of stems per acre, were large. The absence of differences in evapotranspiration amounts casts doubt upon the prevalent opinion of the literature which states that differences in stand density of more than 20 percent signify differences in evapotranspiration. The literature does not generally make a proper distinction between "difference in stand density" and "reduction in stand density."

Using the data collected in soil moisture sampling, standard deviations of moisture content and soil moisture change were obtained. Large variances in soil moisture content existed. There was little evidence of progressive decrease in soil moisture content variance with increasing depth (cf. Bethlamy, 1963). There was appreciable range in variance between sampling dates. Soil moisture content variance was higher in early season. The data suggested that this might be true of late season also.

From variances, the number of samples required to estimate soil moisture with a precision of 0.12 inches water per foot of soil depth was calculated. Maximum values were close to the 40 samples recommended by Hewlett et al. (1964).

The same calculations were carried out for soil moisture change. Again, ranges in variance between measurement periods were large. Variance was definitely greater in early season, and also in late season, but in the latter case only in the upper soil layers. The number of samples required to measure soil moisture change, with a precision of 0.12 inches water per foot of soil depth, was greater than the three samples suggested by Hewlett et al. (1964). Eight samples yield this precision in 90 percent of the measurement events.

Total variances for the whole profile were calculated, and sample numbers estimated from these data. Based upon measurements in each 12 inch depth increment of the solum, 1 to 15 access tubes were required to measure total soil moisture change with a precision of 0.12 inches water for the whole profile. Three access tubes would have yielded this precision in 70 percent of the measurement periods, and eight access tubes in 90 percent of the measurement periods.

General Conclusions

The primary conclusions emerging from this study are that measurable hydrologic benefit from thinning, does not persist for one-fifth of the expected rotation length, and therefore is economically questionable. This applies to even very heavy thinnings, such as that applied to soil moisture Plot 3 in this study. These conclusions must be qualified by the recognition that little knowledge is available of overwinter evaporative losses, which might vary with stand condition.

Stand density was found to have no effect on evapotranspiration rate, at least within the rather wide range of conditions encountered.

Measures of stand density are inadequate for hydrologic studies. Basal area and number of stems per acre are meaningful to the timber manager, but not to the hydrologist. A new measure is needed, and until it is available, such timber-oriented measures should be utilized with extreme care. The available literature needs to be interpreted with a similar caution when it deals in these parameters.

Nor should this be surprising, for forest mensurationists have been aware of the discrepancy between crown closure, which surely must be a hydrologically pre-eminent factor, and conventional stand density measures. Husch (1963) states:

> The percentage of the land area covered by the crown canopy of a stand has also been used as a measure of stand

> density.....The weakness of crown closure as a descriptive characteristic is that the percentage of an area covered by tree crowns is not closely correlated with number of trees or tree sizes in the stand. Crowns of individual trees in a stand will expand to occupy openings in the canopy, so that a sparsely stocked stand may show the same relative crown closure as a dense stand.

In the case of the canopy interception studies reported, this statement is highly apropos. There, hydrologic differences existed where stand basal area differences did not. However, that the situation is more complex than this is shown by the soil moisture study where valid stand differences, conventionally expressed, existed but hydrologic differences did not.

Future Studies

No longer being associated, other than by goodwill and common, shared research enthusiasms, with the agency responsible for these studies, a certain delicacy intrudes in recommending further work.

It is evident, however, that in the hydrologic management of Alberta lodgepole pine forests, more useful results may be expected from research into cover reduction by blocks and patches, rather than from further work with thinning procedures.

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APPENDIX CONTENTS

APPENDIX A

SOME RESULTS OF CANOPY INTERCEPTION OF RAINFALL STUDIES IN PLOTS 4 AND 5 IN MARMOT CREEK BASIN

TABLE A. Stand characteristics in canopy interception Plots 4 and 5 in Marmot Creek Basin. (All values per acre where appropriate).

Characteristic	Units	PLOT 4	PLOT 5
Basal area (lP)	$feet^2$	14.7	124.4
Basal area (eS)	"	146.1	62.9
Basal area (aF)	"	28.1	33.2
Total basal area	"	189.0	220.5
No. of stems (lP)	No.	22	218
No. of stems (eS)	"	631	301
No. of stems (aF)	"	366	226
Total No. of stems	"	1019.	745
Mean DBH	inches	5.9	7.4
Height range (eS)	feet	9 - 81	8 - 78
Height range (aF)	"	9 - 52	6 - 43
Height range (lP)	"	---	39 - 70
Age range	years	65 -230	70 -260

lP = lodgepole pine
eS = Engelmann spruce
aF = alpine fir

Table B Basic statistics of 1963 precipitation used for analysis, showing number of storms, total gross precipitation, mean, maximum, minimum precipitation per storm, standard deviation and coefficient of variation percent.

	Plot number	
	4	5
No. of storms	23	24
Total gross precipitation	9.65	11.64
Mean precipitation	0.42	0.49
Maximum precipitation	2.84	2.84
Minimum precipitation	0.01	0.01
Standard deviation	0.63	0.70
Coefficient of variation %	1.51	1.43

Table C Basic statistics of 1964 precipitation used for analysis, showing number of storms, total gross precipitation, mean, maximum, minimum precipitation per storm, standard deviation and coefficient of variation percent.

	Plot number	
	4	5
No. of storms	18	18
Total gross precipitation	3.91	3.91
Mean precipitation	0 22	0.22
Maximum precipitation	0.72	0.72
Minimum precipitation	0.01	0.01
Standard deviation	0.24	0.24
Coefficient of variation %	111	111

Table D. Basic statistics of 1963 + 1964 precipitation used for analysis, showing number of storms, total gross precipitation, mean, maximum, minimum precipitation per storm, standard deviation, and coefficient of variation percent.

	Plot number	
	4	5
No. of storms	41	42
Total gross precipitation	13.56	15.53
Mean precipitation	0.33	0.35
Maximum precipitation	2.84	2.84
Minimum precipitation	0.01	0.01
Standard deviation	0.50	0.51
Coéfficient of variation %	153	147

Table E Frequency distribution of storm size in 1963 and 1964 in Plots 4 and 5.

Plot	4		5	
Year	1963	1964	1963	1964
Storm Size (In.)	n %	n %	n %	n %
0.00-0.10	7 30	9 50	7 29	9 50
0.11-0.20	4 17	2 11	4 17	2 11
0,21-0.30	5 22	3 17	5 21	3 17
0.31-0.40	2 9	1 6	2 8	1 6
0.41-0.50	-	-	-	-
0.51-0.60	-	-	-	-
0.61-0.70	1 4	1 6	1 4	1 6
0.71-0.80	1 4	2 11	1 4	2 11
0.81-0.90	-	-	-	-
0.91-1.00	1 4	-	1 4	-
1.01-1.25	-	-	-	-
1.26-1.50	1 4	-	1 4	-
1.51-1.75	-	-	-	-
1.76-2.00	-	-	1 4	-
2.01-2.25	-	-	-	-
2.26-2.50	1 4	-	1 4	-
Total	23	18	24	18
Total %	100	100	100	100

Table F. Simple linear regression equations of throughfall (Y) on gross precipitation (X) in plots 4 and 5 for 1963 and 1964 with basic statistics and computed initial storage.

Plot	Year	No. storms	Regression constant	Regression coefficient	SE_E	r^b	$r^2\%$
4	1963	23	-0.0084	0.7942	0.135	0.967	93.5
	1964	18	-0.0004	0.5824	0.020	0.991	98.1
5	1963	24	-0.0771	0.9390	0.074	0.994	98.8
	1964	18	-0.0132	0.6950	0.035	0.981	96.2

Table G. Simple linear regression equations of throughfall (Y) on gross precipitation (X) in Plots 4 and 5 for 1963/4 combined.

Plot	No. storms	Regression constant	Regression coefficient	SE_E	r^b	r^2%
4	41	-0.0208	0.7811	0.107	0.966	93.3
5	42	-0.0646	0.9178	0.069	0.991	98.2

Table H Variation in throughfall (1963 and 1964 combined) in Plots 4 and 5 for seven storm size classes

Storm class (inches gross precipitation)	No. of observations	Mean throughfall (inches)	Standard deviation (inches)	Coefficient of variation (percent)	Range (inches)
			Plot 4		
0.01-0.05	55	0.0275	0.0234	85.34	0.00-0.08
0.06-0.10	75	0.0405	0.0251	61.90	0.00-0.10
0.11-0.25	95	0.0958	0.0649	67.72	0.00-0.27
0.26-0.50	40	0.2070	0.1016	49.09	0.01-0.39
0.51-0.75	25	0.4776	0.2355	49.31	0.03-1.12
0.76-1.00	5	0.6440	0.2628	40.81	0.40-1.06
1.01 +	5	1.6940	0.5292	31.24	1.10-2.48
			Plot 5		
0.01-0.05	55	0.0229	0.0203	88.77	0.00-0.07
0.06-0.10	74	0.0416	0.0303	72.90	0.00-0.11
0.11-0.25	94	0.0841	0.0539	64.11	0.00-0.22
0.26-0.50	40.	0.1800	0.0846	46.99	0.00-0.35
0.51-0.75	25	0.5248	0.2097	39.96	0.13-0.98
0.75-1.00	5	0.6420	0.1099	17.11	0.47-0.73
1.01 +	5	1.3200	0.3202	24.25	0.75-1.49

APPENDIX B

SOILS PROFILE DESCRIPTIONS AND ASSOCIATED SOILS DATA

APPENDIX B

SOILS PROFILE DESCRIPTIONS ANS ASSOCIATED SOILS DATA

SOIL MOISTURE PLOT 1

Soil Profile Description:

Well-drained, weakly developed podzol. Parent material fluvial-deposited sand. Parent material variable both vertically and horizontally - 1 stratified: weakly developed cross-bedding noted in C-horizon. Thin discontinuous layers of silt and gravel noted as well as very fine clay bonds within the profile. The layers are horizontal but discontinuous. Permeability generally high to moderate throughout profile. Major root concentration within the A and B horizons. Fine roots noted within entire depth of sampling (75"). Roots tend to be concentrated within zones of finest-textured horizons. Texture finer than in Plots 2, 4, or 5.

2-0 L.F.H. layers. Quite variable throughout plot. Ranges from heavy concentration of spruce and pine needles to well-decomposed organic matter. Mor-type humus layer.

0-2 A. Fine sandy loam to loamy sand. Single-grained to weakly granular structure; low incorporation of organic matter; 10 YR 7/3 (dry).

2-4" A_2 loamy fine sand. Horizon weakly developed; weakly developed granular structure; pH 6.8; Eff. - nil. 10 YR 7/3 (dry).

4-6" A_3. Weakly developed platy structure; fine to medium sandy loam to loamy sand. Boundary gradual wavy; pH 6.8; Eff. - nil. 10 YR 7/3 (dry).

6-7" B. Fine sandy loam to loamy sand; pale reddish color (transitional from A to B_2 horizon). Friable - granular structure; pH 7.6; Eff. - high.

7-9" B_{21}. Reddish-brown to orange color (FE - oxidation product) - Hematite stain in sand grains. (Fine sand to medium sand.) Boundary wavy, distinct; friable - fine sandy loam. Granular structure - weakly developed. pH 7.6; Eff. - high. 10 YR 6/2 (dry).

9-16" B_{22}. Fine sandy loam; weakly developed platy structure; very friable when dry; dark brown color; does not show reddish-orange color of B_{21} horizon; lower boundary grades into C horizon pH 7.6; Eff. - high. 10 YR 6/2 (dry).

16-75" C. Fine to medium sandy loam; weakly granular; weakly developed cross bedding noticeable. Stratification of fine to medium sand, silt and coarse gravel; pH 8.2+; Eff. - very high. Color with increase in depth; 10 YR 5/2; 10 YR 7/1 (dry). Gravel layer encountered at 75" below ground surface.

SOIL MOISTURE PLOT 2

Soil Profile Description:

Soil profile generally coarser-textured than Plots 1, 3, 4 and 5. Parent material consists of fluvially-deposited medium sand with fine layers of gravel and till (clay to loam) interbedded in the sand.

Profile weakly developed podzol, developed under well-drained conditions. Generally more shallow profile than other profiles. Major root concentration in B_2 horizon, although fine roots extend through entire depth of the profile.

3-0" L.F.H. layers, well decomposed. No incorporation of organic matter with mineral soil. Depth of organic layer variable throughout plot. Varies from well decomposed to poorly decomposed spruce and pine needles, and ground vegetation. Mor-type humus layer.

0-1" A_2. Sandy loam; ashy-gray color; horizon developed immediately beneath organic layer; pH 6.2; Eff. - nil; 10 YR 7/3 (dry).

1-3" A_3. Sandy loam; weakly-devéloped granular structure; pH 6.2; Eff. - nil.

3-4" B_1. Fine sandy loam: reddish-orange hematite stain on sand grains. Granular structure; pH 7.6; Eff. - med; 10 YR 6/2 (dry).

4-7" B_2. Dark brown color; medium to fine sandy loam; granular structure; friable; pH 7.6; Eff. - med.; 10 YR 6/2 (dry).

7-58" C. Alternating layers of sand, clay and gravel. 3" thick gravel layer at 40-inch. (Gravel cse.) Cross-bedding and stratification apparent in profile. Coarse gravel layer encountered at 58". Gravel 1 to 2½" diameter, water polished. Weakly developed granular structure; loamy fine sand texture; pH 8.0+; Eff. - high to very high; 10 YR 7/1 (dry).

SOIL MOISTURE PLOT 3

Soil Profile Description:

Weakly developed podzol; well-drained profile. Good permeability throughout profile. Major root concentration within twenty-four inches from the ground surface. Parent material fluvially deposited sand with interbedded gravel bands.

1-0" L.F.H. layers - moderately well decomposed. Thickness of organic layer variable. Little incorporation of organic matter into A_1 horizon. Mor-type humus layer.

0-1" A_1. Fine sandy loam - weakly developed granular structure to single grain; little incorporation of organic matter with mineral soil. Poorly-developed horizon.

1-2" A_2. Medium to fine sandy loam; very weakly developed ashy-gray layer; boundaries wavy and gradual. Weak granular structure; 10 YR 4/3 (dry); pH 6.5.

2-3" A_3. Loamy fine to medium sandy loam; boundary with underlying horizon wavy and gradual weakly-developed granular structure; 10 YR 4/3; Eff. - slight; pH 6.5.

3-5" B_1. Medium to fine sandy loam; very weakly developed platy structure - may be associated with cross-bedding. Boundary wavy, generally distinct. 10 YR 4/3 (dry); pH 7.2; Eff. - slight.

5-9" B_2. Medium to fine sandy loam; reddish-orange hematite stain on sand particles. Limited organic matter accumulation associated with top of B_2 horizon. Fine dark band. Friable; 10 YR 5/2 (dry); pH 7.4; Eff. - high.

9-102" C. Medium to fine sandy loam. Light grayish color; weakly granular; weak aggregation of particles noted. Texture appears to be fairly uniform throughout C horizon. Friable; 10 YR 6/2 (dry); pH 8.2+; Eff. - very high.

at 102" Layer of coarse gravel encountered in profile. Gravel well-rounded, average approximately to 1½ inches in diameter. Thickness of gravel layer 2-3 inches.

SOIL MOISTURE PLOT 4

Soil Profile Description:

Profile developed under well-drained conditions. Weakly developed podzol profile developed in fluvial deposit of fine to medium sand. Some cross-bedding notable within profile. Possibly some textural stratification; however, did not appear in the profile examination. Roots concentrated within top 24" of profile - profile similar to Plots 3 and 5. Fine roots extend to 96".

1-0" L.F.H. layers - moderately to moderately decomposed muck-like texture. Mor-type humus.

0-2" A_1. Medium to fine sandy loam; only limited development of horizon; weak granular structure.

2-3" A_2. Fine to medium sandy loam; horizon and podzol - ashy grey color weakly developed. Very weakly granular to single-grained; 10 YR 6/4; pH 6.4; Eff. - nil.

3-6" AB. Fine to medium sandy loam; granular structure; color light reddish-brown; boundary with B_2, wavy, sharp.

6-12" B_2. Fine to medium sandy loam; reddish-organge color (hematite stain). Friable; boundary with B_3, sharp, wavy. Weakly developed granular structure; 7.5 YR 4/4 (dry); pH 7.0; Eff. - nil.

12-15" B_3. Fine sandy loam; light brown to grey color; granular structure - weakly developed; pH 7.6; Eff. - high; 10 YR 6/2 (dry).

15-96" C. Fine to medium sandy loam; some stratification; light grayish color; pH 7.8; Eff. - very high; 10 YR 6/1 (dry).

SOIL MOISTURE PLOT 5

Soil Profile Description:

Soil profile well-drained - both topographic position and internal drainage. Weak podzolic development. Iron stain on sand grains and accumulation in B_2 soil colors generally bright throughout profile. Iron oxidized to bright orange-red color (hematite).

Roots concentrated within the upper four feet of the soil profile. Few roots extend to 96" (depth of excavation). Root density greatest in A_1 and B_2 horizons. Permeability high throughout profile. Parent material - well sorted glacial-fluvial sand deposit. Parent material variable both vertically and horizontal.

2-0" L.F.H. layers; moderately well decomposed. Fibrous Mor-type humus layer.

0-2" A_1. Fine to medium sandy loam, moderate to poor incorporation of organic matter with mineral soil; structure single grained to weakly granular aggregates. Boundary of AB wavy, distinct. 10 YR 6/4 (dry); pH 6.2; Eff. - nil.

2-4" AB. Fine to medium sandy loam; weak granular structure. Boundaries wavy, distinct; friable.

4-8" B_2. Fine to medium sandy loam; weakly granular structure; oxidized iron stain on sand grains - bright hematite stain. Boundaries wavy and distinct; friable; 10 YR 5/4; pH 6.8; Eff. - nil.

8-14" B_3. Loamy fine to medium sand; single-grained structure, lower boundary wavy, generally gradual transition with C horizon.

14-96" C. Medium to fine sandy loam; weakly granular structure. Texture appears uniform throughout 14-96" depth. No visible clay or gravel layers within profile. Sand deposit shows some weakly developed cross bedding. Fine roots found throughout entire profile depth. 10 YR 6/1; pH 8.0 to 8.2+; Eff. - very high.

Table A. Comparison of soil moisture constants, obtained by pressure apparatus, and highest and lowest values obtained by field measurement, using calibrated neutron probe: Plot 1, 1966 measurements.

Depth (feet)	Field[1] capacity (inches)	Highest[2] measurement (inches)	Difference (2) - (3) (inches)	Wilting[1] point (inches)	Lowest[2] measurement (inches)	Difference (5) - (6) (inches)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0-1	2.30	2.01	+0.29	0.97	0.48	+0.49
1-2	2.15	1.79	+0.36	1.06	0.62	+0.44
2-3	1.66	1.23	+0.23	0.71	0.72	-0.01
3-4	1.55	1.32	+0.23	0.89	0.89	0.00

1. Obtained by pressure apparatus; % moisture by weight X bulk density X depth (inches)

2. Measurement by neutron probe; conversion of count ratio, to % moisture by volume X depth.

Table B. Comparison of soil moisture constants, obtained by pressure apparatus, and highest and lowest values obtained by field measurement, using calibrated neutron probe: Plot 2, 1966 measurements.

Depth (feet)	Field[1] capacity (inches)	Highest[2] measurement (inches)	Difference (2) - (3) (inches)	Wilting 1 point (inches)	Lowest 2 measurement (inches)	Difference (5) - (6) (inches)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0-1	2.53	2.02	+0.51	1.30	0.50	+0.80
1-2	2.15	1.84	+0.31	0.96	0.72	+0.24
2-3	1.15	1.31	-0.16	0.37	0.68	-0.31

1. Obtained by pressure apparatus; % moisture by weight X bulk density X depth (inches)

2. Measurement by neutron probe; conversion of count ratio to % moisture by volume X depth.

Table C. Comparison of soil moisture constants, obtained by pressure apparatus, and highest and lowest values obtained by field measurement, using calibrated neutron probe: Plot 3, 1966 measurements.

Depth (feet)	Field[1] capacity (inches)	Highest[2] measurement (inches)	Difference (2) - (3) (inches)	Wilting[1] point (inches)	Lowest[2] measurement (inches)	Difference (5) - (6) (inches)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0-1	2.73	1.80	+0.93	1.43	0.48	+0.95
1-2	1.14	1.29	-0.15	0.63	0.49	+0.14
2-3	1.14	1.19	-0.05	0.63	0.55	+0.08
3-4	1.11	1.20	-0.09	0.66	0.66	0.00
4-5	2.39	1.60	N/A	1.14	1.07	+0.07
5-6	2.78	1.70	N/A	1.03	1.40	N/A
6-7	2.14	1.62	N/A	0.94	1.53	N/A
7-8	3.30	1.56	N/A	1.93	1.38	N/A

1. Obtained by pressure apparatus; % moisture by weight X bulk density X depth (inches).

2. Measurement by neutron probe; conversion of count ratio, to % moisture by volume X depth.

Table D. Comparison of soil moisture constants, obtained by pressure apparatus, and highest and lowest values obtained by field measurement, using calibrated neutron probe: Plot 4, 1966 measurements.

Depth (feet)	Field[1] capacity (inches)	Highest[2] measurement (inches)	Difference (2) - (3) (inches)	Wilting 1 point (inches)	Lowest 2 measurement (inches)	Difference (5) - (6) (inches)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0-1	2.42	1.97	+0.45	1.25	0.71	+0.54
1-2	1.50	1.84	-0.34	0.78	0.78	0.00
2-3	1.29	1.12	+0.17	0.99	0.71	+0.28
3-4	1.42	0.93	N/A	0.99	0.64	+0.35
4-5	2.07	1.04	N/A	1.54	0.64	+0.90
5-6	2.29	1.31	N/A	1.16	0.88	+0.28
6-7	2.12	1.38	N/A	1.20	1.19	+0.01

1. Obtained by pressure apparatus; % moisture by weight X bulk density X depth (inches).

2. Measurement by neutron probe; conversion of count ratio, to % moisture by volume X depth.

Table E. Comparison of soil moisture constants, obtained by pressure apparatus, and highest and lowest values obtained by field measurement, using calibrated neutron probe: Plot 5, 1966 measurements.

Depth (feet)	Field[1] capacity (inches)	Highest[2] measurement (inches)	Difference (2) - (3) (inches)	Wilting[1] point (inches)	Lowest[2] measurement (inches)	Difference (5) - (6) (inches)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0-1	2.20	1.59	+0.61	1.20	0.71	+0.49
1-2	1.43	1.39	+0.04	0.74	0.67	+0.07
2-3	1.16	1.25	-0.09	0.61	0.65	-0.04
3-4	1.37	1.49	-0.12	0.78	0.65	+0.13
4-5	1.91	1.36	+0.55	1.07	0.65	+0.42
5-6	1.64	1.19	+0.45	0.85	0.66	+0.19
6-7	1.12	1.10	+0.02	0.51	0.62	-0.11
7-8	0.93	1.08	-0.15	0.43	0.68	-0.25
8-9	1.12	1.17	-0.05	0.48	0.69	-0.21
9-10	1.13	0.97	N/A	0.47	0.67	N/A
10-11	1.27	1.08	N/A	0.59	0.72	N/A

1. Obtained by pressure apparatus; % moisture by weight X bulk density X depth (inches).

2. Measurement by neutron probe; conversion of count ratio, to % moisture by volume X depth.

APPENDIX C

RESULTS FROM ADDITIONAL MODELS EXPRESSING THROUGHFALL PERCENT AS A FUNCTION OF DISTANCE FROM STEM(S) AND STEM SIZE CHARACTERISTICS

Table A. Regression equations showing the relationship between percent throughfall (Y) and (X) mean ratio (L_1/BA_1) of distance to nearest tree (L_1): basal area of nearest tree (BA_1) for three storm classes in Plots 1, 2 and 3, with all 1963 and 1964 data combined.

Storm class inches	No. of observ- ations	Regression equation	SE_E	r	r^2
		PLOT 1			
0.06-0.10	63	Y=33.07+0.08X	23.03	0.033	0.001
0.11-0.25	150	Y=55.65+0.39X	22.62	0.135	0.018
0.26-0.50	60	Y=66.92+0.20X	34.58	0.061	0.003
		PLOT 2			
0.06-0.10	83	Y=39.95+0.29X	21.76	0.350	0.122
0.11-0.25	149	Y=56.99+0.30X	22.51	0.340	0.115
0.26-0.50	65	Y=73.98+0.04X	25.35	0.042	0.001
		PLOT 3			
0.06-0.10	65	Y=48.63-0.04X	31.08	0.067	0.004
0.11-0.25	135	Y=49.12+0.14X	23.75	0.282	0.079
0.26-0.50	49	Y=59.18+0.17X	20.42	0.338	0.114

Table B. Regression equations showing the relationship between percent throughfall (Y) and (X) mean ratio (L_3/BA_3) of distance to nearest three trees (L_3): basal area of nearest three trees (BA_3) for three storm classes in Plots 1, 2 and 3, with all 1963 and 1964 data combined.

Storm class inches	No. of observ- ations	Regression equation	SE_E	r	r^2
		PLOT 1			
0.06-0.10	63	Y=23.17+0.44X	22.54	0.207	0.043
0.11-0.25	150	Y=50.70+0.42X	22.52	0.164	0.026
0.26-0.50	60	Y=60.30+0.38X	34.46	0.102	0.010
		PLOT 2			
0.06-0.10	83	Y=27.45+0.49X	20.52	0.469	0.220
0.11-0.25	149	Y=45.39+0.46X	21.38	0.450	0.202
0.26-0.50	65	Y=74.69+0.01X	25.37	0.011	0.0001
		PLOT 3			
0.06-0.10	65	Y=56.82-0.14X	30.76	0.157	0.024
0.11-0.25	135	Y=46.05+0.15X	24.31	0.188	0.035
0.26-0.50	49	Y=61.93+0.07X	21.53	0.126	0.015

Table C. Regression equations showing the relationship between percent throughfall (Y) and (L_3) mean distance to three nearest trees (X), for three storm classes in Plots 1, 2 and 3, with all 1963 and 1964 data combined.

Storm class inches	No. of observ-ations	Regression equation	SE_E	r	r^2
		PLOT 1			
0.06-0.10	63	Y=-20.84+10.68X	20.68	0.441	0.194
0.11-0.25	150	Y=23.53+7.08X	21.62	0.320	0.102
0.26-0.50	60	Y=57.65+2.22X	34.56	0.069	0.004
		PLOT 2			
0.06-0.10	83	Y=13.66+9.73X	19.78	0.524	0.275
0.11-0.25	149	Y=39.59+7.22X	22.36	0.357	0.127
0.26-0.50	65	Y=57.78+4.81X	24.78	0.214	0.045
		PLOT 3			
0.06-0.10	65	Y=5.27+17.26X	29.04	0.361	0.130
0.11-0.25	135	Y=28.17+11.58X	22.93	0.376	0.142
0.26-0.50	49	Y=38.70+11.16X	19.52	0.437	0.191

Table D. Regression equations showing the relationship between percent throughfall (Y) and (X) mean ratio (L_3/D_3) of distance to nearest three trees (L_3): DBH of nearest three trees (D_3) for three storm classes in Plots 1, 2 and 3, with all 1963 and 1964 data combined.

Storm class inches	No. of observ- ations	Regression equation	SE_E	r	r^2
		PLOT 1			
0.06-0.10	63	Y=1.85+39.45X	21.65	0.343	0.117
0.11-0.25	150	Y=28.93+39.40X	21.83	0.292	0.085
0.26-0.50	60	Y=56.98+15.18X	34.52	0.083	0.007
		PLOT 2			
0.06-0.10	83	Y=11.64+41.21X	19.02	0.574	0.329
0.11-0.25	149	Y=32.78+36.21X	20.84	0.492	0.242
0.26-0.50	65	Y=66.99+9.08X	25.21	0.113	0.012
		PLOT 3			
0.06-0.10	65	Y=40.74+6.30X	31.10	0.056	0.003
0.11-0.25	135	Y=33.02+25.80X	23.49	0.315	0.099
0.26-0.50	49	Y=45.99+21.95X	20.51	0.327	0.106

Table E. Regression equations showing the relationship between percent throughfall (Y) and (X) ratio (L_1/BA_1) of distance to nearest tree (L_1): basal area of nearest tree (BA_1) for three storm classes in Plots 1, 2 and 3, with 1963 and 1964 data combined, position 3 omitted.

Storm class inches	No. of observ-ations	Regression equation	SE_E	r	r^2
		PLOT 1			
0.06-0.10	38	Y=36.73-0.89X	19.86	0.336	0.113
0.11-0.25	95	Y=50.23+0.59X	23.71	0.180	0.032
0.26-0.50	34	Y=71.00-0.55X	33.64	0.128	0.016
		PLOT 2			
0.06-0.10	58	Y=40.61+0.23X	22.27	0.242	0.058
0.11-0.25	94	Y=57.85+0.21X	23.50	0.190	0.036
0.26-0.50	44	Y=65.62+0.41X	27.13	0.287	0.082
		PLOT 3			
0.06-0.10	59	Y=49.21-0.06X	31.03	0.113	0.012
0.11-0.25	119	Y=48.17+0.14X	23.51	0.258	0.066
0.26-0.50	41	Y=62.25+0.07X	20.93	0.124	0.015

Table F. Regression equations showing the relationship between percent throughfall (Y) and (X) mean ratio (L_3/BA_3) of mean distance to nearest three trees (L_3): Mean basal area of nearest three trees (BA_3) for three storm classes in Plots 1, 2 and 3, with 1963 and 1964 data combined, position 3 omitted.

Storm class inches	No. of observ- ations	Regression equation	SE_E	r	r^2
		PLOT 1			
0.06-0.10	38	Y=20.91+0.18X	21.05	0.068	0.004
0.11-0.25	95	Y=39.12+0.74X	23.27	0.261	0.068
0.26-0.50	34	Y=47.01+0.66X	33.50	0.156	0.024
		PLOT 2			
0.06-0.10	58	Y=29.81+0.40X	21.39	0.362	0.131
0.11-0.25	94	Y=45.35+0.42X	22.13	0.381	0.145
0.26-0.50	44	Y=64.73+0.30X	27.95	0.159	0.025
		PLOT 3			
0.06-0.10	59	Y=62.86-0.24X	30.18	0.256	0.065
0.11-0.25	119	Y=46.33+0.12X	24.02	0,160	0.025
0.26-0.50	41	Y=62.51+0.04X	21.04	0.067	0.004

Table G. Regression equations showing the relationship between percent throughfall (Y) and (L_3) mean distance to three nearest trees (X) for three storm classes in Plots 1, 2 and 3, with 1963 and 1964 data combined, position 3 omitted.

Storm class inches	No. of observ-ations	Regression equation	SE_E	r	r^2
		PLOT 1			
0.06-0.10	38	Y=-13.02+7.63X	20.18	0.291	0.084
0.11-0.25	95	Y=26.00+6.31X	23.36	0.246	0.060
0.26-0.50	34	Y=53.16+2.00X	33.88	0.046	0.002
		PLOT 2			
0.06-0.10	58	Y=-2.01+15.32X	19.70	0.512	0.263
0.11-0.25	94	Y=34.85+8.32X	22.62	0.327	0.107
0.26-0.50	44	Y=29.97+14.75X	25.91	0.403	0.162
		PLOT 3			
0.06-0.10	59	Y=7.42+16.31X	29.81	0.298	0.088
0.11-0.25	119	Y=28.94+11.13X	22.93	0.335	0.112
0.26-0.50	41	Y=43.50+8.96X	19.88	0.332	0.110

Table H. Regression equations showing the relationship between percent throughfall (Y) and (X) mean ratio (L_3/D_3) of mean distance to nearest three trees (L_3): Mean DBH of nearest three trees (D_3) for three storm classes in Plots 1, 2 and 3, with 1963 and 1964 data combined, Position 3 omitted.

Storm class inches	No. of observ-ations	Regression equation	SE_E	r	r^2
		PLOT 1			
0.06-0.10	38	Y=4.00 +28.15X	20.67	0.200	0.040
0.11-0.25	95	Y=23.24+42.93X	22.86	0.316	0.100
0.26-0.50	34	Y=43.71+24.25X	33.67	0.119	0.014
		PLOT 2			
0.06-0.10	58	Y=10.25+44.07X	20.01	0.490	0.240
0.11-0.25	94	Y=31.10+37.99X	21.50	0.439	0.192
0.26-0.50	44	Y=44.08+41.16X	26.89	0.313	0.098
		PLOT 3			
0.06-0.10	59	Y=56.34-12.01X	31.10	0.091	0.008
0.11-0.25	119	Y=34.95+22.56X	23.41	0.273	0.074
0.26-0.50	41	Y=50.00+16.34X	20.49	0.236	0.055

APPENDIX D

ANALYSIS OF VARIANCE TABLES FOR ANALYSES OF SOIL MOISTURE CONTENT AND SOIL MOISTURE CHANGE

Table A. Analysis of variance--uppermost three feet of soil, 1963.

SOIL MOISTURE CONTENT (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	3	2.87	0.96	31.80	0.005
Period (P)	6	10.45	1.74	57.88	0.005
Depth (D)	2	1.82	0.91	30.27	0.005
B x P	18	0.60	0.03	1.11	N. S.
B x D	6	2.56	0.43	14.18	0.005
P x D	12	3.20	0.27	8.87	0.005
B x P x D	36	0.99	0.03	0.92	N. S.
Error	756	22.75	0.03		
Total	839	45.25			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	3	0.09	0.03	3.93	0.005
Period (P)	5	1.05	0.21	26.22	0.005
Depth (D)	2	0.10	0.05	6.29	0.005
B x P	15	0.61	0.04	5.04	0.005
B x D	6	0.12	0.02	2.48	0.005
P x D	10	3.37	0.34	42.01	0.005
B x P x D	30	1.21	0.04	5.02	0.005
Error	648	5.20	0.01		
Total	719	11.75			

Table B. Analysis of variance--uppermost three feet of soil, 1964.

SOIL MOISTURE CONTENT (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	4	14.81	3.70	94.941	0.005
Period (P)	7	33.58	4.80	123.008	0.005
Depth (D)	2	51.74	25.87	663.282	0.005
B x P	23	*	*	*	
B x D	8	3.81	0.48	12.221	0.005
P x D	14	18.81	1.34	34.459	0.005
B x P x D	46	*	*	*	
Error	897	37.94	0.04		
Total	932	157.30			

* Best estimate is zero.

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	4	0.31	0.08	2.63	0.005
Period (P)	6	25.02	4.17	142.51	0.005
Depth (D)	2	2.42	1.21	41.30	0.005
B x P	19	3.60	0.19	6.47	0.005
B x D	8	0.15	0.02	0.66	N. S.
P x D	12	6.07	0.51	17.29	0.005
B x P x D	38	1.17	0.03	1.06	N. S.
Error	660	19.31	0.03		
Total	749	58.06			

Table C. Analysis of variance--uppermost three feet of soil, 1965.

SOIL MOISTURE CONTENT (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	4	19.46	4.87	165.01	0.005
Period (P)	12	17.30	1.44	48.89	0.005
Depth (D)	2	87.12	43.56	1477.20	0.005
B x P	48	4.44	0.09	3.14	0.005
B x D	8	4.47	0.56	18.97	0.005
P x D	24	2.88	0.12	4.07	0.005
B x P x D	96	3.05	0.03	1.08	N. S.
Error	1590	46.89	0.03		
Total	1784	185.61			

SOIL MOISTURE CONTENT (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	4	0.05	0.01	1.25	N. S.
Period (P)	11	23.80	2.16	224.59	0.005
Depth (D)	2	0.00	0.00	0.01	N. S.
B x P	44	7.91	0.18	18.65	0.005
B x D	8	0.01	0.00	0.18	N. S.
P x D	22	7.06	0.32	33.30	0.005
B x P x D	88	5.89	0.07	6.95	0.005
Error	1449	13.96	0.01		
Total	1628	58.68			

Table D. Analysis of variance--uppermost three feet of soil, 1966.

SOIL MOISTURE CONTENT (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	4	20.60	5.15	167.64	0.005
Period (P)	15	157.72	10.52	342.32	0.005
Depth (D)	2	43.98	21.99	715.91	0.005
B x P	51	0.03	0.00	0.02	N. S.
B x D	8	4.70	0.59	19.11	0.005
P x D	30	19.89	0.66	21.59	0.005
B x P x D	102	4.26	0.04	1.36	0.005
Error	1737	53.35	0.03		
Total	1949	304.52			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	4	0.11	0.03	2.51	0.005
Period (P)	14	17.09	1.22	112.85	0.005
Depth (D)	2	0.72	0.36	33.40	0.005
B x P	47	2.95	0.06	5.81	0.005
B x D	8	0.13	0.02	1.55	N. S.
P x D	28	17.00	0.61	56.13	0.005
B x P x D	94	3.20	0.03	3.14	0.005
Error	1614	17.46	0.01		
Total	1811	58.67			

Table E. Analysis of variance--uppermost four feet of soil, 1963.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	2	0.66	0.33	15.86	0.005
Period (P)	6	6.21	1.04	49.76	0.005
Depth (D)	3	1.61	0.54	25.79	0.005
B x P	12	0.28	0.02	1.13	N. S.
B x D	6	3.36	0.56	26.88	0.005
P x D	18	1.74	0.09	4.65	0.005
B x P x D	36	0.75	0.02	1.00	N. S.
Error	756	15.73	0.02		
Total	839	30.34			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	3	0.05	0.02	1.87	N. S.
Period (P)	5	0.93	0.19	19.97	0.005
Depth (D)	3	0.06	0.02	2.04	N. S.
B x P	13	0.55	0.04	4.51	0.005
B x D	9	0.23	0.03	2.68	0.005
P x D	15	3.62	0.24	25.88	0.005
B x P x D	39	1.31	0.03	3.61	0.005
Error	792	7.39	0.01		
Total	879	14.14			

Table F. Analysis of variance--uppermost four feet of soil, 1964.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of Significance
Plot (B)	3	5.59	1.86	73.354	0.005
Period (P)	7	12.63	1.80	71.059	0.005
Depth (D)	3	30.48	10.16	400.000	0.005
B x P	17	0.64	0.04	1.480	N. S.
B x D	9	5.30	0.59	23.186	0.005
P x D	21	21.12	1.01	39.594	0.005
B x P x D	51	*	*	*	
Error	923	23.459	0.0254		
Total	983	99.221			

* Best estimate is zero.

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	4	0.29	0.07	2.59	0.005
Period (P)	6	23.16	3.86	140.36	0.005
Depth (D)	3	3.49	1.16	42.35	0.005
B x P	14	3.78	0.27	9.81	0.005
B x D	12	1.85	0.15	5.62	0.005
P x D	18	9.83	0.55	19.86	0.005
B x P x D	42	0.41	0.01	0.36	N. S.
Error	720	19.80	0.03		
Total	819	62.61			

Table G. Analysis of variance--uppermost four feet of soil, 1965.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	3	8.34	2.78	89.00	0.005
Period (P)	12	14.51	1.21	38.70	0.005
Depth (D)	3	65.30	21.77	696.71	0.005
B x P	36	3.08	0.09	2.74	0.005
B x D	9	13.95	1.55	49.60	0.005
P x D	36	3.32	0.09	2.95	0.005
B x P x D	108	3.63	0.03	1.08	N. S.
Error	1652	51.61	0.03		
Total	1859	163.73			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	3	0.04	0.01	1.92	N. S.
Period (P)	11	18.75	1.70	221.96	0.005
Depth (D)	3	0.05	0.02	2.36	N. S.
B x P	33	5.38	0.16	21.23	0.005
B x D	9	0.01	0.00	0.15	N. S.
P x D	33	7.16	0.22	28.27	0.005
B x P x D	99	6.78	0.07	8.92	0.005
Error	1500	11.52	0.01		
Total	1691	49.70			

Table H. Analysis of variance--uppermost four feet of soil, 1966.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	3	9.76	3.25	100.73	0.005
Period (P)	15	105.83	7.06	218.52	0.005
Depth (D)	3	34.97	11.66	361.08	0.005
B x P	38	1.99	0.05	1.62	0.005
B x D	9	9.73	1.08	33.50	0.005
P x D	45	30.11	0.67	20.72	0.005
B x P x D	114	4.09	0.04	1.11	N. S.
Error	1812	58.50	0.03		
Total	2039	254.98			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	3	0.06	0.02	1.92	N. S.
Period (P)	14	11.68	0.83	77.87	0.005
Depth (D)	3	1.49	0.50	46.32	0.005
B x P	35	2.26	0.06	6.04	0.005
B x D	9	0.16	0.02	1.64	N. S.
P x D	42	16.29	0.39	36.21	0.005
B x P x D	105	3.08	0.03	2.74	0.005
Error	1684	18.04	0.01		
Total	1895	53.06			

Table I. Analysis of variance--uppermost seven feet of soil, 1963.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	1	3.53	3.53	128.12	0.005
Period (P)	6	4.92	0.82	29.76	0.005
Depth (D)	6	57.97	9.66	350.59	0.005
B x P	6	0.08	0.01	0.48	N. S.
B x D	6	15.68	2.61	94.85	0.005
P x D	36	2.62	0.07	2.64	0.005
B x P x D	36	0.65	0.02	0.65	N. S.
Error	637	17.55	0.03		
Total	734	103.00			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	1	0.00	0.00	0.28	N. S.
Period (P)	5	0.51	0.10	9.60	0.005
Depth (D)	6	0.18	0.03	2.80	0.005
B x P	5	0.12	0.02	2.26	0.005
B x D	6	0.10	0.02	1.55	N. S.
P x D	30	2.47	0.08	7.83	0.005
B x P x D	30	0.64	0.02	2.02	0.005
Error	546	5.75	0.01		
Total	629	9.76			

Table J. Analysis of variance--uppermost seven feet of soil, 1964.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	2	20.62	10.31	377.729	0.005
Period (P)	7	7.90	1.13	41.348	0.005
Depth (D)	6	22.90	3.82	139.795	0.005
B x P	11	*	*	*	
B x D	12	28.09	2.34	85.747	0.005
P x D	42	28.15	0.67	24.548	0.005
B x P x D	66	*	*	*	
Error	931	25.457	0.0273		
Total	1000	133.12			

* Best estimate is zero.

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	2	0.06	0.03	2.55	N. S.
Period (P)	6	8.28	1.38	122.14	0.005
Depth (D)	6	3.25	0.54	48.02	0.005
B x P	9	0.17	0.02	1.71	N. S.
B x D	12	0.17	0.01	1.23	N. S.
P x D	36	9.93	0.28	24.42	0.005
B x P x D	54	1.25	0.02	2.05	0.005
Error	700	7.91	0.01		
Total	825	31.01			

Table K. Analysis of variance--uppermost seven feet of soil, 1965.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	2	39.12	19.56	702.76	0.005
Period (P)	12	9.72	0.81	29.11	0.005
Depth (D)	6	60.68	10.11	363.42	0.005
B x P	24	1.48	0.06	2.22	0.005
B x D	12	55.72	4.64	166.86	0.005
P x D	72	7.11	0.10	3.55	0.005
B x P x D	144	4.64	0.03	1.16	N. S.
Error	1617	45.00	0.03		
Total	1889	223.47			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	2	0.01	0.00	0.30	N. S.
Period (P)	11	11.45	1.04	122.01	0.005
Depth (D)	6	0.17	0.03	3.35	0.005
B x P	22	1.47	0.07	7.82	0.005
B x D	12	0.10	0.01	1.02	N. S.
P x D	66	7.79	0.12	13.83	0.005
B x P x D	132	6.20	0.05	5.50	0.005
Error	1449	12.36	0.01		
Total	1700	39.54			

Table L. Analysis of variance--uppermost seven feet of soil, 1966.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	2	33.95	16.98	676.295	0.005
Period (P)	15	43.96	2.93	116.757	0.005
Depth (D)	6	48.32	8.05	320.817	0.005
B x P	25	*	*	*	
B x D	12	73.58	6.13	244.279	0.005
P x D	90	46.30	0.51	20.496	0.005
B x P x D	150	*	*	*	
Error	1967	49.517	0.0251		
Total	2092	294.62			

* Best estimate is zero.

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	2	0.03	0.02	1.37	N. S.
Period (P)	14	6.42	0.46	40.01	0.005
Depth (D)	6	1.57	0.26	22.80	0.005
B x P	23	2.03	0.09	7.68	0.005
B x D	12	0.10	0.01	0.71	N. S.
P x D	84	14.44	0.17	14.99	0.005
B x P x D	138	3.97	0.03	2.51	0.005
Error	1666	19.10	0.01		
Total	1945	47.66			

Table M. Analysis of variance--uppermost eight feet of soil, 1963.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	0				
Period (P)	6	2.83	0.47	20.07	0.005
Depth (D)	7	73.28	10.47	445.50	0.005
B x P	0				
B x D	0				
P x D	42	2.99	0.07	3.03	0.005
B x P x D	0				
Error	504	11.84	0.02		
Total	559	90.94			

SOIL MOISTURE CHANGE

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of Significance
Plot (B)	0				
Period (P)	5	0.40	0.08	9.01	0.005
Depth (D)	7	0.32	0.05	5.16	0.005
B x P	0				
B x D	0				
P x D	35	2.47	0.07	7.99	0.005
B x P x D	0				
Error	432	3.82	0.01		
Total	479	7.01			

Table N. Analysis of variance--uppermost eight feet of soil, 1964.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	1	28.41	28.41	1060.22	0.005
Period (P)	6	5.75	0.96	35.769	0.005
Depth (D)	7	18.81	2.69	100.272	0.005
B x P	6	*	*	*	
B x D	7	17.27	2.47	92.067	0.005
P x D	42	19.07	0.45	16.942	0.005
B x P x D	42	2.96	0.07	2.633	0.005
Error	750	20.17	0.0268		
Total	855	112.45			

* Best estimate is zero.

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	1	0.01	0.01	0.88	N.S.
Period (P)	5	5.17	1.03	64.05	0.005
Depth (D)	7	2.92	0.42	25.87	0.005
B x P	5	0.06	0.01	0.78	N.S.
B x D	7	0.11	0.02	1.03	N.S.
P x D	35	7.90	0.23	14.00	0.005
B x P x D	35	0.65	0.02	1.16	N.S.
Error	608	9.81	0.02		
Total	703	26.66			

Table O. Analysis of variance--uppermost eight feet of soil, 1965.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	1	57.25	57.25	2216.50	0.005
Period (P)	12	6.52	0.54	21.03	0.005
Depth (D)	7	58.10	8.30	321.33	0.005
B x P	12	1.06	0.09	3.42	0.005
B x D	7	39.66	5.67	219.38	0.005
P x D	84	9.41	0.11	4.34	0.005
B x P x D	84	2.47	0.03	1.14	N. S.
Error	1432	36.99	0.03		
Total	1639	211.46			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	1	0.00	0.00	0.15	N. S.
Period (P)	11	8.33	0.76	98.36	0.005
Depth (D)	7	0.13	0.02	2.33	0.005
B x P	11	0.24	0.02	2.81	0.005
B x D	7	0.10	0.01	1.87	N. S.
P x D	77	10.27	0.13	17.32	0.005
B x P x D	77	2.34	0.03	3.94	0.005
Error	1272	9.79	0.01		
Total	1463	31.19			

Table P. Analysis of variance--uppermost eight feet of soil, 1966.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	1	56.66	56.66	3001.01	0.005
Period (P)	15	35.57	2.37	125.59	0.005
Depth (D)	7	48.18	6.88	364.56	0.005
B x P	12	*	*	*	
B x D	7	66.35	9.48	502.03	0.005
P x D	105	40.76	0.39	20.56	0.005
B x P x D	84	*	*		
Error	1704	32.065	0.0188		
Total	1839	279.59			

* Best estimate is zero.

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	1	0.03	0.03	2.94	N. S.
Period (P)	14	6.19	0.44	45.58	0.005
Depth (D)	7	1.18	0.17	17.44	0.005
B x P	11	0.82	0.07	7.70	0.005
B x D	7	0.04	0.01	0.58	N. S.
P x D	98	13.91	0.14	14.64	0.005
B x P x D	77	2.58	0.03	3.46	0.005
Error	1496	14.51	0.01		
Total	1711	39.26			

Table Q. Analysis of variance--uppermost fourteen feet of soil, 1964.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	0				
Period (P)	6	0.80	0.13	7.04	0.005
Depth (D)	13	21.65	1.67	87.55	0.005
B x P	0				
B x D	0				
P x D	38	10.39	0.13	7.01	0.005
B x P x D	0				
Error	434	8.26	0.02		
Total	531	41.11			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	0				
Period (P)	5	0.71	0.14	51.27	0.005
Depth (D)	13	1.06	0.08	29.40	0.005
B x P	0				
B x D	0				
P x D	65	2.86	0.04	15.81	0.005
B x P x D	0				
Error	308	0.86	0.00		
Total	391	5.49			

Table R. Analysis of variance--uppermost fourteen feet of soil, 1965.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	0				
Period (P)	12	2.14	0.18	9.80	0.005
Depth (D)	13	26.04	2.00	109.88	0.005
B x P	0				
B x D	0				
P x D	156	9.48	0.06	3.33	0.005
B x P x D	0				
Error	896	16.33	0.02		
Total	1077	53.99			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	0				
Period (P)	11	1.45	0.13	27.93	0.005
Depth (D)	13	0.21	0.02	3.43	0.005
B x P	0				
B x D	0				
P x D	143	6.30	0.04	9.35	0.005
B x P x D	0				
Error	840	3.96	0.00		
Total	1007	11.92			

Table S. Analysis of variance--uppermost fourteen feet of soil, 1966.

SOIL MOISTURE CONTENTS (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	0				
Period (P)	14	5.09	0.36	19.51	0.005
Depth (D)	13	17.92	1.38	73.92	0.005
B x P	0				
B x D	0				
P x D	182	18.02	0.10	5.31	0.005
B x P x D	0				
Error	1050	19.58	0.02		
Total	1259	60.62			

SOIL MOISTURE CHANGE (inches water)

Source of variation	Degrees of freedom	Sum of squares	Mean square	Variance ratio	Level of significance
Plot (B)	0				
Period (P)	13	2.15	0.17	44.43	0.005
Depth (D)	13	0.51	0.04	10.60	0.005
B x P	0				
B x D	0				
P x D	169	8.22	0.05	13.07	0.005
B x P x D	0				
Error	980	3.65	0.00		
Total	1175	14.54			