DISSERTATION

LOGGING EFFECTS ON SOIL MOISTURE LOSSES

Submitted by

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In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY ROBERT RUHL ZIEMER ENTITLED LOGGING EFFECTS ON SOIL MOISTURE LOSSES BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Adviser

ABSTRACT OF DISSERTATION

LOGGING EFFECTS ON SOIL MOISTURE LOSSES

The depletion of soil moisture within the surface 15 feet by an isolated mature sugar pine and an adjacent uncut forest in the California Sierra Nevada was measured by the neutron method every 2 weeks for 5 consecutive summers. Soil moisture recharge was measured periodically during the intervening winters. Groundwater fluctuations within the surface 50 feet were continuously recorded during the same period. Each fall, a wetting front progressed from the soil surface, eventually recharging the entire soil profile to "field capacity". During the recharge period, although the top portion of the soil. was at "field capacity", the trees continued to deplete moisture from the drier soil below the wetting front into early winter. Groundwater levels began to rise within days after rainfall, whereas weeks or months were required for the wetting front to progress through the unsaturated zone above the water table.

Soil moisture depletion by the isolated tree was maximum at a depth of 8 to 13 feet and extended about 15 feet away from the tree. The influence of the tree on soil moisture depletion extended to a depth of about 18 feet and to a distance of about 40 feet. An excellent linear relationship was found between the quantity of soil moisture depleted by the tree at the end of the summer and distance from the tree. The isolated tree used between 2200 and 2600

cubic feet more soil moisture than a bare portion of the plot outside of the influence of the tree.

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This research, Study PSW 1603-5, was undertaken as an integral part of the Lower Conifer Project, U. S. Forest Service, Pacific Southwest Forest and Range Experiment Station. Until 1967, the study received additional funding by the State of California, Department of Water Resources, During the 15 years since I began this study, many forestry students from the Berkeley campus of the University of California were introduced to the joys of outdoor research as seasonal employees or as work-study students collecting field or laboratory data or attempting to make sense out of the mounds of computer output. The number of men and women who worked on various aspects of this study are, unfortunately, too numerous to acknowledge individually, but their assistance is greatly appreciated.

Some individuals, however, require special recognition. Jim Agee's field work and perceptiveness was outstanding during his 2 years with the study, Hutch Wood's assistance with the laboratory soil analysis was indispensable. Bob Thomas' contribution and many years of devotion to developing the multiple computer programs required for data analysis cannot be overstated. Perhaps their involvement with this study, in some small way, induced each to follow a research career.

The resident staff at the Challenge Experimental Forest were invaluable for their daily observations, particularly Ross Cole, who carried on the field work and kept in telephone communication for the 18 months while I was attending classes at CSU.

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CHAPTER I

INTRODUCTION

Historical Perspective

Not until the middle of the seventeenth century did investigators begin to experiment with the agricultural aspects of soil moisture. An additional 200 years passed before the importance of soil moisture in forested areas was recognized as a regulator of tree growth. By the 1800's, field studies were underway to document the influence of trees on the soil moisture regime. Ebermayer (1899) was among the first to report that beech and pine forests contained considerably less soil moisture than open areas during all four seasons of the year. The difference was greatest during the late summer.

In 1892, Charmow measured soil moisture to a depth of a meter in a forest plantation in the Ukrainian steppe where the water table was deeper than 15 meters. He found soil moisture decreased as the age of the plantation increased (Wyssotzky, 1932). Wyssotzky studied soil moisture under forest stands from 1892 to 1899 and reported that the roots of the trees extracted soil moisture to a depth of about 16 meters. He further showed seasonal isopleths of soil moisture with depth and time for the 7-year duration of his study. Later, he studied the seasonal changes in soil moisture for a 2-year period, from 1928 to 1930. Wyssotzky's studies stood alone, but have been largely unrecognized, as the most elaborate and extensive soil moisture storage and depletion work in forests until the advent of neutron soil moisture meter in the mid-1950's.

The early studies required an enormous effort to obtain the gravimetric soil moisture samples at these deeper depths. In addition, since a new hole must be dug or drilled for each sample, the site is eventually rendered useless for further study because of the influence of numerous holes left by previous sampling. Wyssotzky eventually abandoned his 7-year study in 1899 because previous sample removal was adversely influencing the site and his data.

By trenching, Fricke (1904) severed the roots of surrounding trees and thereby isolated a quadrat of soil. He found two to three times more soil moisture in the trenched areas than within untrenched areas during the driest months of the year. From his experiments, Fricke concluded that decreased root competition for soil moisture was the basic cause for increased growth following thinning, rather than the previously popular concept of increased light.

Aaltonen (1926) made the next major advance in understanding the significance and spatial distribution of soil moisture in the forest. By studying detailed charts of forest stands and reproduction in Finland, Aaltonen concluded that there was a definite space arrangement between members of each species which is directly dependent upon the quality of the soil. He found that in an opening in any forest, the seedlings in the center are highest and become progressively smaller as the border trees are approached. The poorer the site, the larger the growing space necessary for each tree. This space arrangement of the above-ground portion of trees is mainly determined by their roots and the competition existing between them for water and nutrients in the soil. He then demonstrated this very clearly by means of a laboratory experiment with corn. Unfortunately, Aaltonen made no soil

moisture analysis to support his theory, nor did he verify his laboratory experiments in the field with trees.

The work of Conrad and Veihmeyer (1929) on root development and soil moisture, carried out with sorghum plants in California, led Lunt (1934) to attempt a similar study with forest trees in Connecticut. Lunt "recognized that the California type of climate, characterized by little or no rainfall during the growing season, is the ideal condition" for soil moisture studies. Nevertheless, he "felt that such a study would be of value in humid New England in spite of its frequent summer showers". Thus, having recognized the drawbacks imposed by the climate in his area, Lunt measured the distribution of soil moisture under isolated trees by digging a trench from the base of the tree out into the open. Soil moisture was determined gravimetrically from soil samples collected from the walls of the trench at several depths and distances from four trees--two pines and two oaks. The maximum depth measured was 4 feet. In one study he measured soil moisture to a distance of 41 feet from an oak. In nearly all cases, the lowest soil moisture content was found immediately beneath the crown and close to the base of the tree. Lunt recognized that three factors influenced the moisture content of the soil in his climate, namely, surface evaporation, interception by the crown, and absorption by the roots. He felt further extensive experimentation was necessary to properly evaluate the interaction of these factors. Lunt's figures also show that moisture was being depleted below a depth of 4 feet, but he did not specifically acknowledge this observation in the text.

During the 1930's the literature began to proliferate with studies related to soil moisture under forest stands. The conclusions of various

authors were often contradictory. It was becoming obvious that forest soil-water relationships, unlike their agricultural counterpart, were extremely complex and variable in both time and space. Not only was soil texture and depth, as well as climate, variable, but the response of trees, both within and between species, to these variable growing conditions differed considerably. Several authors, such as Hayes and Stoeckeler (1935) attempted to generalize about the rooting depth of trees. However, tree rooting characteristics are so interrelated with climate, soil texture, and moisture regime that such classifications are limited in usefulness. By 1955, there were well over 400 individual papers related to tree root systems alone (Karisumi and Tsutsumi, 1958). A bibliography containing more than 800 papers related to soil moisture under forests had been compiled by Ziemer by 1973. The bulk of literature seems to repeatedly demonstrate that soil moisture depletion by trees continues below the depth of measurement unless the roots are restricted by truly impervious and continuous soil layers. For example, McClurkin (1958) in Mississippi and Gaiser (1952) in Ohio found that all available soil moisture was used throughout the 40- to 42-inch measurement depth. McClurkin had earlier assumed the roots would be restricted by a heavy clay layer, but later concluded that the clay "had not seriously impeded root penetration". Lull and Axley (1958) measured soil moisture to a depth of 12 feet in the New Jersey pine barrens and concluded that depletion by the trees was probably occurring below their deepest measurement.

Hendrickson (1942) was among the first to propose that soil moisture studies could be used to determine water use by forest vegetation. A study using this approach was made by Rowe and Coleman (1951) in

woodland-chaparral and ponderosa pine in California. Annual evapotranspiration was calculated by summing soil moisture losses between storms. This approach required soil moisture measurements throughout the rooting depth of the vegetation and an adequate measurement of the spatial variation of soil moisture within the forest stand.

Very few authors have followed Lunt's early work in an effort to understand the spatial variation of soil moisture around trees. Notable exceptions have been Giulimondi (1960), Douglass (1960), and Ziemer (1964). Giulimondi (1960) measured soil moisture at increasing distances from a *Eucalyptus* shelterbelt into an adjacent cultivated field. The moisture lost 3 meters from the shelterbelt was nearly twice that lost at a distance of 5 meters, 3 times that at 9 meters, and 13 times that at 17 and 25 meters. Unfortunately, his soil moisture measurements were only made at a depth of 30 to 35 cm.

Douglass (1960) measured soil moisture at the end of the two growing seasons following thinning a 16-year-old loblolly pine plantation in South Carolina. Soil samples of the surface 4 feet were taken at 2-foot intervals along a line between trees spaced about 20 feet apart. Soil moisture was highest midway between the trees and lowest adjacent to the trees. No mention was made of soil moisture distribution with depth. In their climate, some of the differences observed by Giulimondi and Douglass may have been due to a combination of rainfall interception by the tree canopy and soil moisture depletion by the roots. As Lunt had pointed out earlier, the ideal climate to study soil moisture depletion by forests is in an area with little summer rainfall such as California.

In the subalpine zone of the Sierra Nevada in California, Ziemer (1964) measured the pattern of soil moisture storage and depletion a-long transects running from unlogged red fir forests into openings which had been cut 1, 5, 10 and 12 years earlier. Soil moisture was measured to a depth of 4 feet using the relatively new neutron meter technique. This method allowed identical locations to be repeatedly remeasured throughout the summer depletion season, a distinct advantage over the earlier gravimetric technique. Ziemer found soil moisture content progressively increased toward the center of the opening at the end of the summer, whereas in early spring, soil moisture was nearly equal throughout the plot. The trees depleted soil moisture 30 to 40 feet into the opening. As new tree seedlings occupied the opening, the differences between soil moisture in the forest and opening became smaller. Those differences would become negligible 15 years after cutting. Because of the cobbly nature of the morainal soils, Ziemer was unable to measure soil moisture depletion below the rooting depth of the trees.

Thus, through a combination of climate, soil, and study design problems, we still do not have an adequate understanding of the timing and pattern of soil moisture depletion by individual trees throughout their rooting depth.

The Soil Moisture Study

The purpose of this study was to measure the quantity, timing, and pattern of soil moisture storage and depletion throughout the rooting depth of an isolated mature sugar pine tree.

To be successful in such a study, it was necessary to identify and attempt to eliminate the problems which have been repeatedly encountered by past researchers and to select an idealized site in which to conduct this study. These problems can be grouped under 1) instrumentation, 2) climate, 3) soil, and 4) saturated groundwater flow.

1) Instrumentation. Prior to the development of the neutron soil moisture meter in the mid-1950's, nearly all soil moisture measurements were made gravimetrically, Gravimetric sampling is very time consuming, particularily when collecting deep soil samples. Since the sampling is destructive, one can not repeatedly return to the same location. Consequently, most early studies represented a few measurements taken at one point in time and at relatively shallow depths. The neutron meter was selected for use in this study because with an initial installation of the access tubes soil moisture measurements can then be made rapidly and repeatedly at the same location throughout the depth of the access tube. This is a necessary condition to in situ measurements of the timing of soil moisture depletion and recharge.

2) Climate. Lunt and others discussed the problems associated with measuring the influence of vegetation on soil moisture depletion in areas where continued summer rainfall partially recharges the soil. Following such rainfall, it is difficult, if not impossible, to separate the components of interception losses, surface runoff, variable infiltration, and redistribution of the infiltrated water from depletion of the soil moisture by the vegetation. The climate in the western U. S. and particularly in the central Sierra Nevada of California is ideally suited for soil moisture depletion studies because a rainless period extends from spring through autumn.

3) Soil. Forest soils in the west are typically shallow and rocky and are often underlain by fractured bedrock which is easily penetrated by roots. It is necessary to measure soil moisture throughout the rooting depth to understand the ability of the tree to extract soil moisture. In addition, horizontal as well as vertical uniformity of the soil is desirable to ease interpretation of the moisture depletion patterns.

4) Saturated Groundwater. If a water table or its capillary fringe is present within the rooting depth of the trees, the vegetation will have a readily available supply of soil moisture and any estimates of soil water use by the tree will be greatly complicated. In the extreme case of shallow water tables, investigators, such as Heikurainen (1964) and Urie (1966) for example, have attempted to use diurnal fluctuations of groundwater levels to estimate evapotranspiration by forests. This process requires many assumptions that are subject to error. In areas where the saturated groundwater is at an intermediate depth, the magnitude of the contribution of the water table to evapotranspiration is completely unknown and in many studies has been incorrectly ignored or assumed to be negligible. It is, thus, preferable to select well-drained sites, free from the influence of a water table and subsurface lateral saturated flow. The ideal site should also be free from surface ponding during rainfall which would result in non-uniform soil moisture recharge.

Therefore, a substantial effort was initially expended to select a forest&d study site on a deep and uniform soil with no groundwater table in a region having long rainless summers.

CHAPTER 11

THE STUDY AREA

Location

The study site is located on the Challenge Experimental Forest in Sections 33 and 34, T.19N., R.7E., M.D.M. at an elevation of 2,600 feet in the north Sierra Nevada. The Experimental Forest is located 40 miles northeast of Marysville, California at latitude 39^{o} 29' N., longitude 121^{o} 14' W. (Fig. 1).

Geomorphology

The Sierra Nevada geomorphic province developed on a tilted block, the eastern margin of which uplifted along a series of faults. The western flank or dip slope of this large fault block slopes from 120 to 180 feet per mile toward the west, and eventually passes beneath the alluvial fill of the Sacramento Valley. The parent rock of this province are metamorphosed sediments and volcanics of probable Carboniferous age, together with granitic rocks which intruded into the metamorphosed rocks in upper Jurassic time. The rocks of the Challenge area are metavolcanics of Jurassic to Triassic age.

The tilted block of the Sierra Nevada near the Challenge Experimental Forest was eroded to a tableland and then deeply incised into major drainages--Feather River to the north and Yuba River to the south.

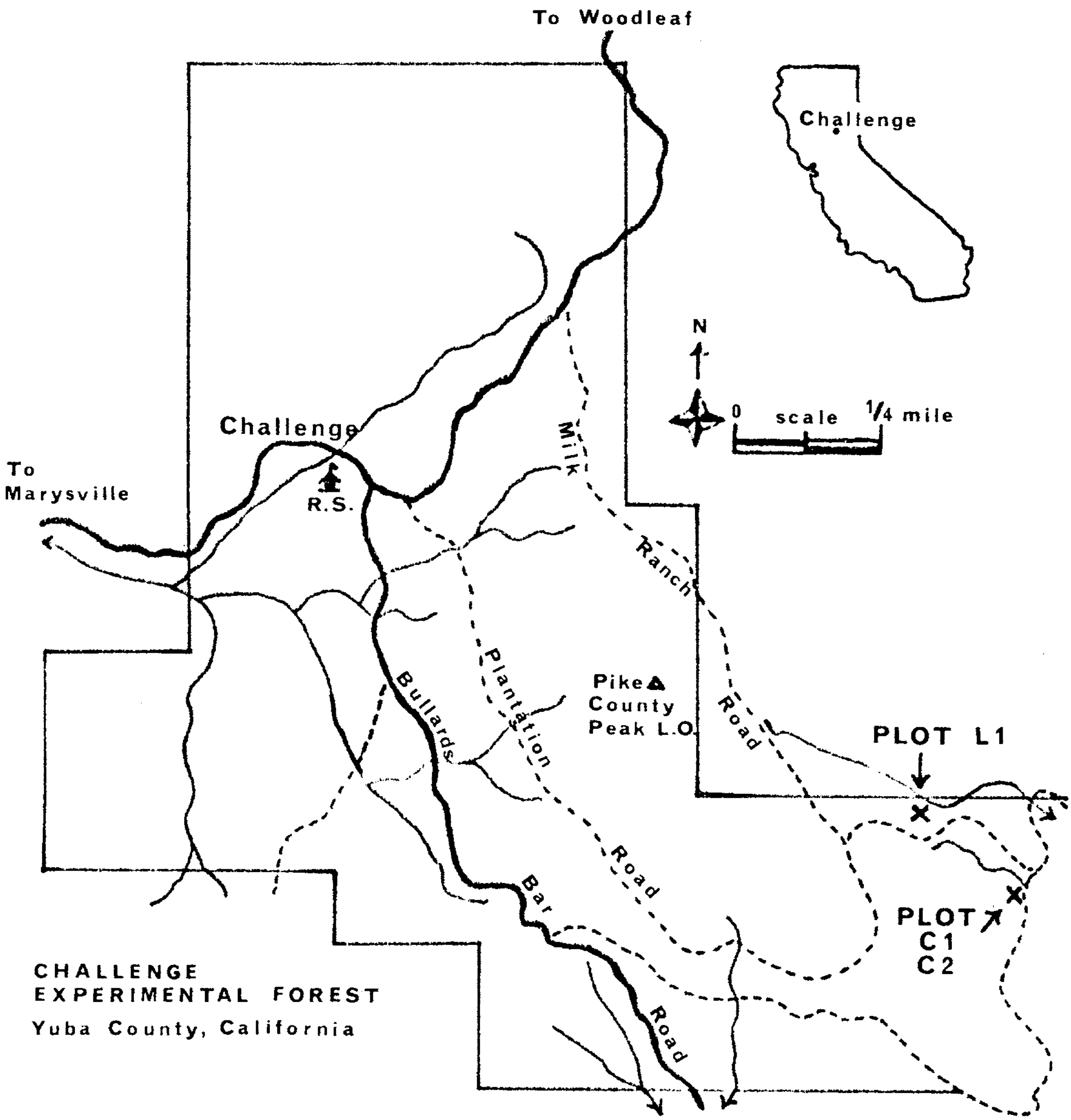


Figure 1. Location of study plots within the Challenge Experimental Forest, California.

Soils

The soil is of the Challenge series. The Challenge series consists of deep and very deep well-drained forest soils developed from metamorphosed andesite, commonly called greenstone. Greenstone is the name given to basic igneous rocks that have been hydrothermally altered. During metamorphism the original ferromagnesian minerals were largely changed into chlorite, which gives the resulting parent material rock a green color. The Challenge series has reddish brown, granular, medium acid, moderately fine textured surface soils and red, massive, medium to strongly acid, clayey subsoils. Both cobbly and non-cobbly types are recognized. The soil in many portions of the Challenge Experimental Forest is estimated to be 50 to 100 feet deep. The Challenge series covers about 50 thousand acres and is the highest timber producing site of the deep forest soils. Economically, it is a very important soil.

Climate

From 1965 through 1969, the mean annual maximum temperature at the Challenge Experimental Forest was $69^{o}F$ and the mean minimum temperature was $43^{o}F$; extremes of $104^{o}F$ and $11^{o}F$ were recorded. Monthly mean maximum temperatures ranged from $90^{o}F$ in July to $51^{o}F$ in December. Monthly mean minimum temperatures ranged from $56^{o}F$ in July to $32^{o}F$ in January (Table 1). Prior to September 1965, air temperature was measured only intermittently.

Precipitation occurs predominantly in winter with about 90 percent of the annual total falling in the 6 months from November through April. The entire soil moisture profile is usually recharged to "field

Table 1. Climatological summary - Challenge Ranger Station.

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1964-1965												
Max. (°F)	79	53	49	56	60	59	60	72	78	89	83	73
Min. (°F)	47	35	35	33	32	35	41	43	48	55	55	46
Mean (°F)	64	44	43	45	46	46	50	56	63	72	67	58
Precip. (in.)	1.89	11.49	35.35	16.75	1.88	4.30	10.09	0.40	0.51	0	0	0.63
Depart. (in.)1/	-1.96	+4.03	+23.18	+3.48	-10.10	-5.04	+4.91	-2.15	-0.07	-0.03	-0.11	+0.12
1965-1966												
Max. (°F)	79	58	52	51	52	59	72	76	81	86	91	84
Min. (°F)	46	39	29	29	30	36	43	48	51	50	56	51
Mean (°F)	63	49	41	40	41	48	58	62	66	68	74	68
Precip. (in.)	0.46	13.23	9.50	10.37	5.18	3.10	3.68	0.45	0.10	0.09	0.05	T
Depart. (in.)1/	-3.52	+6.01	-2.88	-2.38	-6.87	-6.80	-1.74	-2.32	-0.52	+0.06	-0.05	-0.61
1966-1967												
Max. (°F)	77	61	54	55	61	55	46	73	77	91	95	83
Min. (°F)	44	40	35	33	33	33	32	44	51	58	60	54
Mean (°F)	61	51	45	44	48	45	40	59	64	75	78	69
Precip. (in.)	0	19.74	11.20	24.61	1.43	13.53	12.51	1.76	3.60	0.02	0	0.25
Depart. (in.)1/	-3.86	+12.31	-1.08	+11.94	-10.38	+3.86	+7.15	-0.93	+3.00	-0.01	-0.09	-0.34
1967-1968												
Max. (°F)	74	62	51	52	57	57	68	71	87	94	82	84
Min. (°F)	47	41	31	33	40	35	43	45	56	61	54	52
Mean (°F)	58	50	40	41	48	45	55	58	71	76	67	67
Precip. (in.)	2.58	7.88	6.88	12.97	10.51	6.90	0.50	0.96	0.20	0	0.81	0.12
Depart. (in.)1/	-1.27	+0.42	-5.29	-0.30	-1.47	-2.44	-4.68	-1.59	-0.38	-0.03	+0.70	-0.44
1968-1969												
Max. (°F)	71	57	47	49	43	56	61	76	77	91	93	85
Min. (°F)	45	39	32	34	32	32	38	48	52	56	54	54
Mean (°F)	56	47	38	40	37	43	49	62	64	72	71	67
Precip. (in.)	4.87	8.05	14.18	30.93	18.41	2.07	4.71	0	0.21	0	0	0
Depart. (in.)1/	+1.02	+0.59	+2.01	+17.66	+6.43	-7.27	-0.47	-2.55	-0.37	-0.03	-0.11	-0.56
1969-1970												
Max. (°F)	68	66	54									
Min. (°F)	43	39	36									
Mean (°F)	54	49	43									
Precip. (in.)	3.10	2.37	22.67									
Depart. (in.)1/	-0.75	-5.09	+10.50									

1/ Precipitation departure from normal is based on 30 years of record (1936-1969).

capacity" by January or February. Soil moisture depletion starts in spring, usually in April or May. The summers are dry with less than 2 inches of rain falling from June through September--mainly from high intensity convectional thunderstorms. Thus, soil moisture depletion continues through the summer season without significant recharge until late October or November. Precipitation was measured at Challenge from 1939 through 1969. Average annual rainfall is 68 inches, but has ranged from 94.13 to 37.20 inches in the 30 years of record. Snow is rare-- only 3 or 4 days occur annually with measurable snow depth. A summary of monthly temperatures and precipitation for the 6 years of the study is found in Table 1. Daily precipitation for each of the 6 years is found in the Appendix, Tables 12 through 17.

Vegetation

The study site is located in the mixed conifer forest zone. The forest vegetation in the area consists of about 40 percent ponderosa pine (*Pinus ponderosa* Laws.), 20 percent Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), 8 percent sugar pine (*Pinus lambertiana* Dougl.), 6 percent incense-cedar (*Libocedrus decurrens* Torr.), 3 percent white fir (*Abies concolor* [Gord. & Glend.] Lindl.), and 23 percent hardwoods composed mainly of tanoak (*Lithocarpus densiflorus* [Hook & Arn.] Rehd.), madrone (*Arbutus menziesii* Pursh.), and California black oak (*Quercus kellogii* Newb.). The ground cover is predominantly bracken fern (*Pteridium aquilinum* [L.] Kuhn var. *pubescens* Underw.), poison-oak (*Toxicodendron diversilobum* T. & G.), Sierra gooseberry (*Ribes roezlii* Kegel.), several species of California-lilac (*Ceanothus* spp. L.), and manzanita (*Arctostaphylos* spp. Adans.), together with sprouts of tanoak and madrone.

The area was logged extensively from 1870-1880. The second-growth stand found on the Experimental Forest ranges from nearly pure stands of tanoak with little current commercial value to dense stands of pine and fir with stems of 40 inches dbh not uncommon. In the general study area, total stand density, expressed as basal area, averaged about 250 square feet per acre.

CHAPTER III

LOCATION AND INSTRUMENTATION OF SOIL MOISTURE SAMPLING SITES

Plot Selection

The Challenge Experimental Forest staff established about 60 permanent growth plots prior to logging in 1962. The plots had the following properties:

1) Each plot center was located such that the plot had a basal area of about 160 square feet per acre of conifers greater than 11.5 inches in diameter
2) Within a one-half acre circular plot around each plot center, all trees larger than 11.5 inches in diameter were measured and tagged.
3) In addition, within a concentric one-fourth acre circular plot, all trees between 3.5 inches and 11.5 inches in diameter were measured and tagged.

An after-logging mortality survey was made of all growth plots in 1962.

In 1963, 21 of these growth plots were selected for a studv of soil moisture storage and depletion. A 50- by 50-foot grid of 100 blocks was located at the center of each plot and 3 of the blocks were selected at random. Within each block a neutron access tube was installed to a depth of 20 feet if soil conditions allowed. In late summer 1964, a water table observation well was drilled in each plot to a depth of 50 feet using a truck-mounted auger, A 2-inch diameter plastic casing with 1 mm perforations in the bottom 2 1/2 feet was installed in each auger hole. On the basis of 2 years' observations of

soil moisture depletion and one winter of observing the water table well, 3 of the 21 plots were selected for this study--one logged plot (Ll) and two adjacent unlogged control plots (Cl and C2). Growth and mortality measurements were made annually in each of these three plots for the duration of the study. The criteria for plot selection were:

1) No water table present to a depth of 50 feet at any time during the year.

2) Uniform pattern of soil. moisture recharge with no indication of lateral or subsurface flow.

3) Well-drained site with no surface ponding or water runoff concentration.

4) No unexplained anomalies in soil moisture data during depletion or recharge.

5) Uniform soil with all access tubes at least 15 feet in depth.

These criteria were established to reduce the variability between the control and study plots and to make comparison of depletion data between plots and between access tubes within a plot possible.

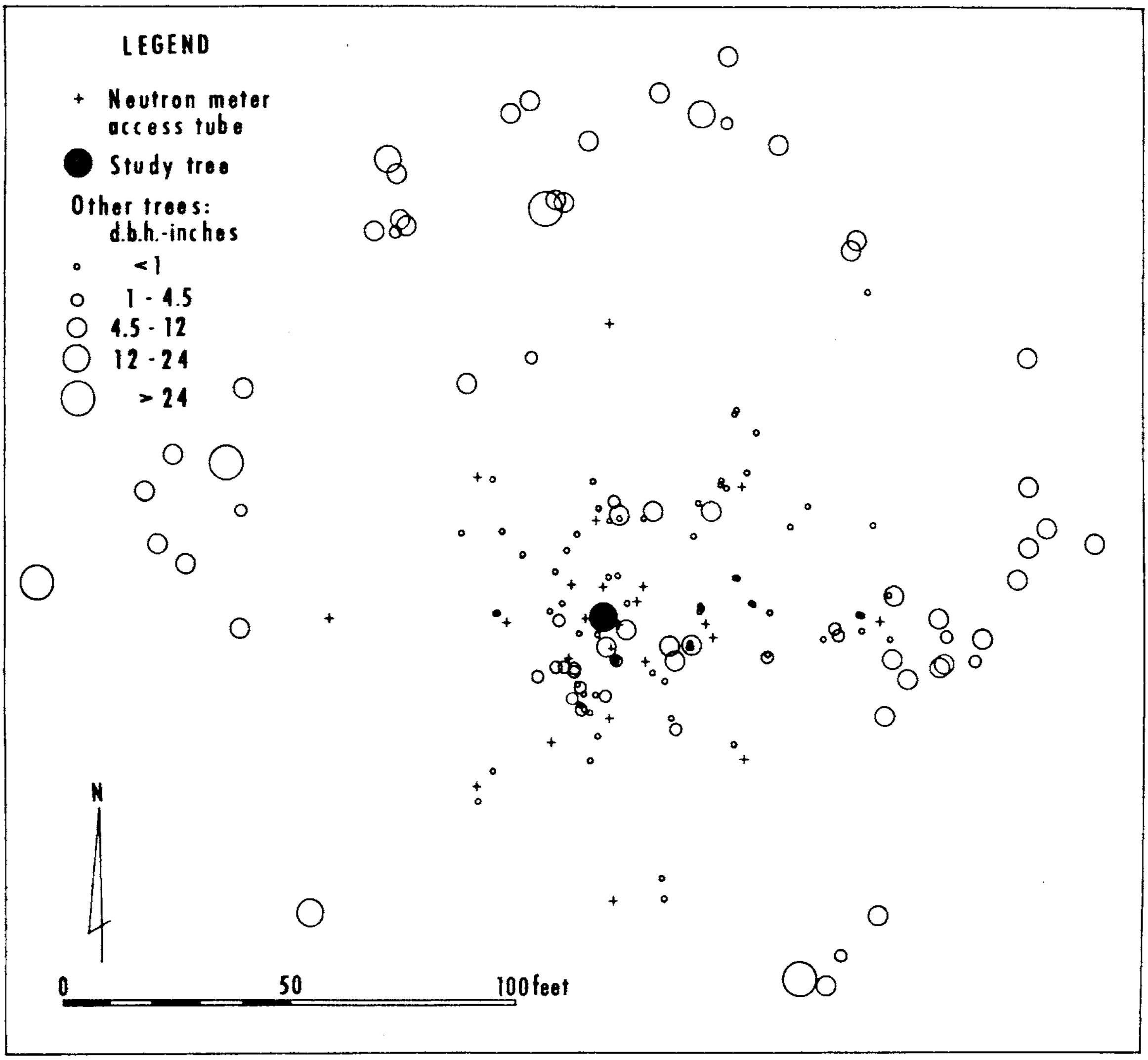
Plot Description and Instrumentation

All hardwoods in the logged plot (Ll) were poisoned with 2,4,5-T in the fall of 1961. During summer 1962, 2 years prior to the beginning of this study, 88 percent of the original basal area of the logged plot (Ll) was cut. There were only 12 trees larger than 4 inches dbh left uncut on the one-half acre permanent growth plot established in 1962--l ponderosa pine (28.5-inch diameter), 2 sugar pines (28.7-inch and 27.7~inch), 1 incense-cedar (9.4-inch), 4 tanoaks ($\leq$ 9.1 inches), and 4 madrones ($\leq$ 6.0 inches) (Table 2, Fig. 2).

Table 2. Distribution of basal area by species and size class in the study plots.

Plot no.	Diameter	Species						Total
		S.P.	P.P.	W.F.	D.F.	I.C.	HWD	
	-inches-	Basal area (sq. ft./acre)						
C1								
	3-12	6.2	-	2.5	23.2	2.4	24.0	58.3
	12-24	6.5	-	-	24.1	4.8	20.4	55.8
	>24	72.5	21.9	-	63.7	-	-	158.1
TOTAL		85.2	21.9	2.5	110.0	7.2	44.4	272.2
C2								
	3-12	-	-	0.4	0.7	6.5	20.0	27.6
	12-24	54.7	-	-	4.3	5.1	1.7	65.8
	>24	154.7	13.1	-	-	-	-	167.8
TOTAL		209.4	13.1	0.4	5.0	11.6	21.7	261.2
L1 (Before logging)								
	3-12	-	-	0.3	4.1	2.5	37.9	44.8
	12-24	37.8	4.5	-	20.7	2.4	4.3	67.7
	>24	48.7	66.5	-	-	-	-	115.2
TOTAL		86.5	71.0	0.3	24.8	4.9	42.2	229.7
L1 (After logging)								
	3-12	-	-	-	-	1.9	8.3	10.2
	12-24	-	-	-	-	-	-	-
	>24	8.9	8.4	-	-	-	-	17.3
TOTAL		8.9	8.4	-	-	1.9	8.3	27.5

Figure 2. Spacial distribution of trees and neutron access tubes in plot L1.



The control plots (Cl and C2) have not been treated for about 90 years (Table 2, Fig. 3). The one-half acre plot Cl contains 11 trees larger than 20 inches dbh--5 Douglas-fir, 5 ponderosa pine, and 1 sugar pine--and 87 trees larger than 4 inches dbh. Plot C2 contains 24 trees larger than 20 inches dbh--22 ponderosa pine, 1 sugar pine, and 1 California black oak--and 70 trees larger than 4 inches dbh.

In general, the composition of the vegetation in the logged plot prior to cutting was quite similar to that in the control plots. This similarity was an additional criterion for selection of these plots for study.

During summer 1965, 20 additional soil moisture access tubes were installed in the logged plot Ll to depths varying from 16 to 21 feet in specific quadrants at six distances from the 27.7-inch diameter sugar pine (Fig. 4). The placement of access tubes at 2, 5, 10, 20, 40, and 60 feet from the study tree assured a greater density of sampling points where the influence of the tree was expected to be greatest.

The location, size, and species of each tree was measured within a 120-foot radius of the study tree (Fig. 2, 4). All trees within 60 feet of the study tree were less than 12 inches dbh, with the great majority less than 4.5 inches dbh. There were several large trees 80 to 90 feet from the study tree, and a group of smaller trees about 10 feet southeast of the study tree. Scattered throughout the plot area were clumps of tanoak and madrone sprouts growing from stumps left from the 1962 logging.

In December 1966 all trees and other vegetation within 120 feet of the study tree were cut, isolating the sugar pine. Sprouts and

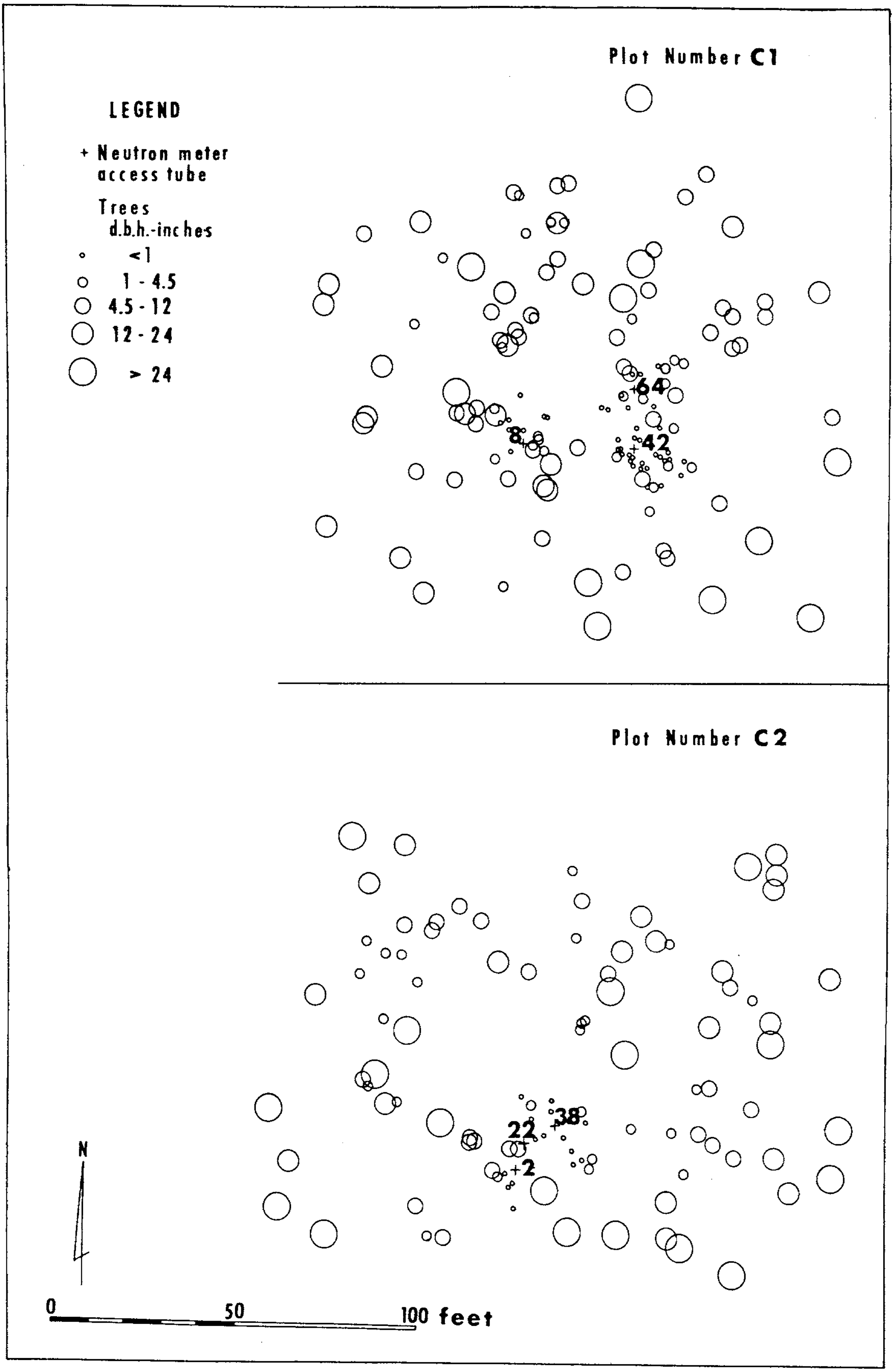
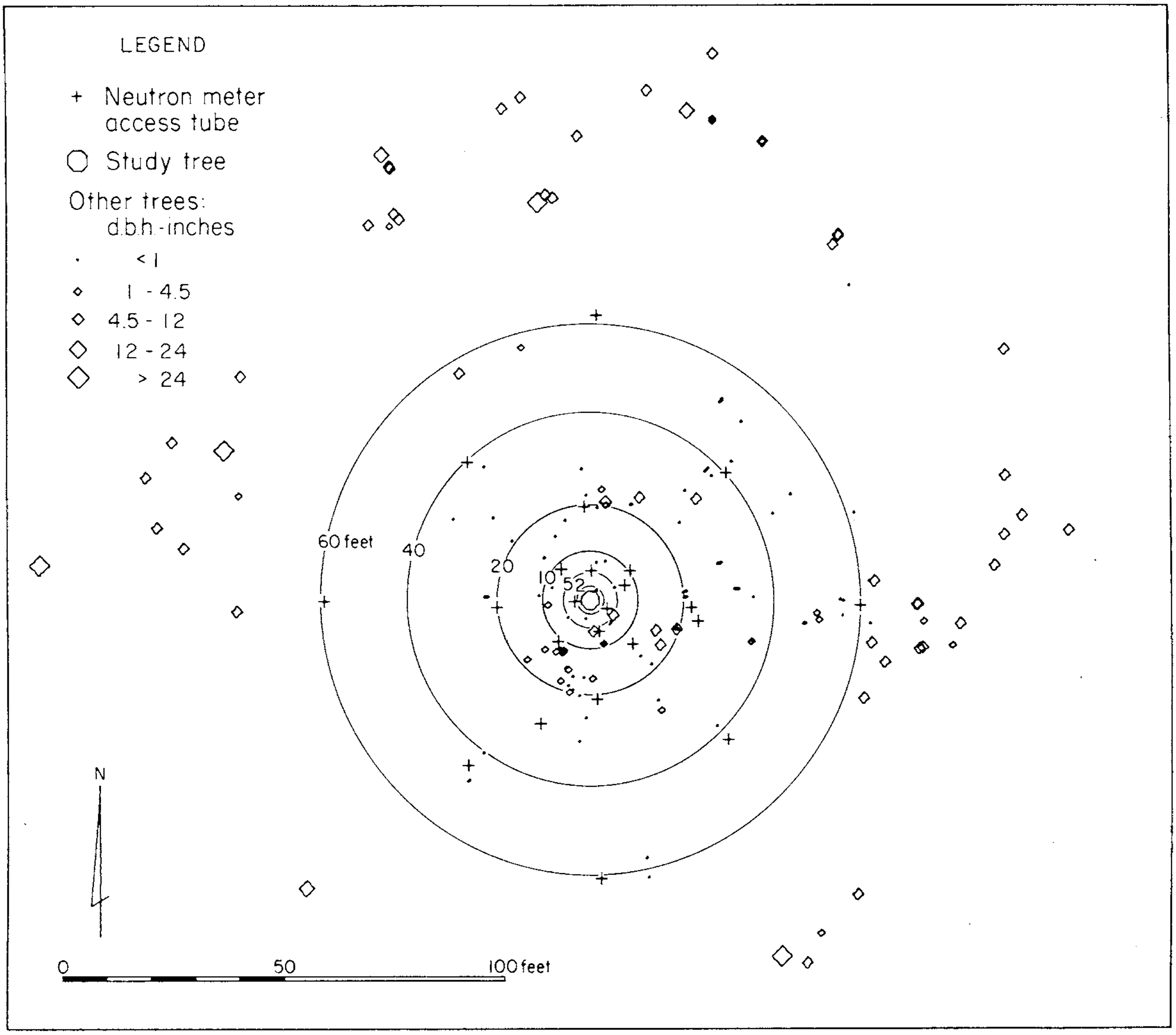


Figure 3. Spacial distribution of trees and neutron access tubes in the uncut control plots.

Figure 4. Concentric distance classes and location of neutron access tubes around the study tree plot L1.



herbaceous vegetation were removed at least monthly as they appeared until the conclusion of the study. On March 10, 1969, the study tree was cut. It measured 31.6 inches dbh and 128 feet tall. At a height of 95 feet the tree was 13 inches dib, at which point the tree forked into two stems, each having a size of 10 inches dib. A tree ring count 1 foot above ground level indicated the tree to be 85 years old.

The plot was kept in a bare condition for the remainder of 1969 by cutting sprouts and herbaceous vegetation at least monthly.

Tree Growth

The basal area growth of the study tree at stump height was measured by marking the position of each growth ring on paper tape from the center growth ring along radii spaced every 30° of arc (12 radii). The annual growth in square inches was computed for the 21-year period, 1949-1969, by:

$$\text{Annual Growth} = \frac{\sum_{i=1}^{12} (\pi r_i^2 - \pi R_i^2)}{12}$$

Where: r_i is the radius of the tree in the year of interest along the i^{th} arc,

R_i is the radius of the tree in the preceding year along the i^{th} arc.

The results are found in Figure 5. The growth for the period prior to logging, 1949-1962, averaged 11.8 square inches per year. A least-squares fit of the data showed:

Annual Growth = -0.98 + 0.18 x (age of tree)

After the heavy harvest thinning in 1962, the study tree responded with a substantial increase in growth rate, which continued through the removal of the residual vegetation in 1967 and until the study tree was cut in 1969. The data after 1962 showed:

Annual Growth = -256.82 + 3.42 x (age of tree)

The added annual increment prior to 1962 was 0.18 square inches per year and after the 1962 logging was 3.42 square inches per year.

In a nearby uncut stand, the growth of an 81-year-old ponderosa pine with a diameter of 26.1 inches dbh averaged 7.0 square inches per year for the period 1949-1962, (Fig. 5), and:

Annual Growth = 4.72 + 0.03 x (age of tree)

The slope of the curve of annual growth for the sugar pine study tree for the period 1949-1962 and for the ponderosa pine for the period 1949-1962 and 1963-1969 was not significantly different from zero at the 95 percent level of confidence. The slope of the growth regression for the sugar pine for the post-logging period, 1963-1969, was significantly different from the slope of the regression for the pre-logging period, 1949-1962, at the 99 percent level of confidence.

Thus, the sugar pine study tree could be characterized as being in a period of moderately rapid growth and competing with its neighbors prior to the harvest cut in 1962. A period of release followed the heavy harvest cut in 1962. A second period of release may have occurred following December 1966 when the residual vegetation surrounding the

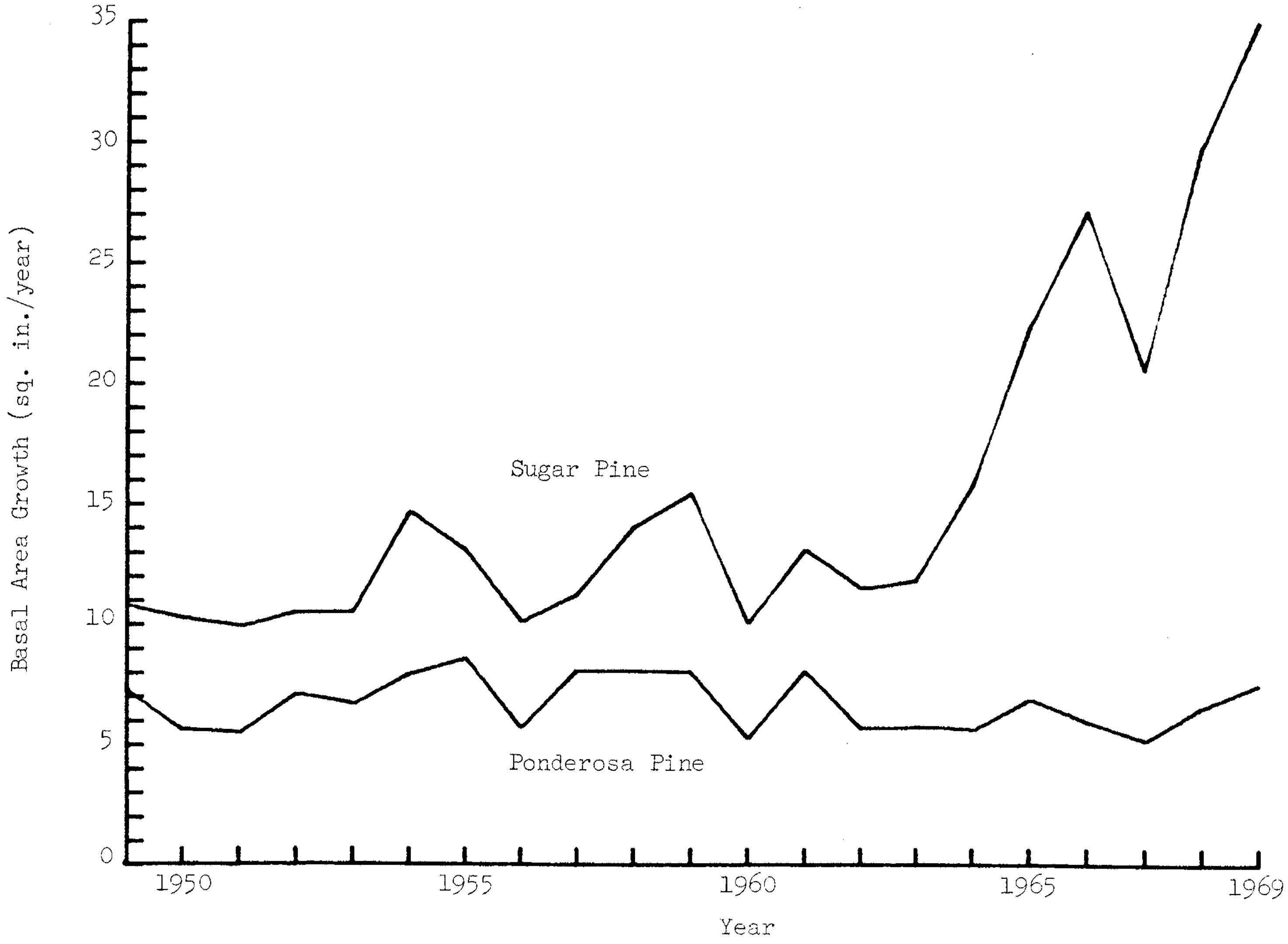


Figure 5. Annual growth of the sugar pine study tree and of a ponderosa pine from a nearby uncut stand.

tree was cut. Thus, when the competition for light and moisture was eliminated, the tree responded with accelerated growth for the remainder of the study. The root system may have been actively expanding into regions previously occupied by the roots of adjacent competing vegetation as reported by Ziemer (1964) for red fir. However, the design of this study did not permit observations of root growth or root expansion,

Soil Analysis

Description. The Challenge soil series is the most extensive timber producing soil. in the area. One of the California Cooperative Soil-Vegetation Survey classification plots for the Challenge series is located in the same general area as the three study plots. Seven soil horizons have been identified and described by the Soil-Vegetation Survey as typical. of the Challenge soil (Table 3):

O1 to O2	3 inches to 9, fresh and partially decomposed litter of oak and shrub leaves and conifer needles. 1 to 4 inches thick.
All	0 to 2 1/2 inches, brown (7.5YR 4/4) light clay loam, dark reddish brown (5YR 3/3) moist; strong fine and medium granular structure; soft when dry, very friable moist, nonsticky and nonplastic wet; common very fine and fine roots; many very fine and fine pores; common fine and medium shot; slightly acid; clear smooth boundary. 2 to 5 inches thick.

Table 3. Typical profile characteristics of the Challenge Soil Series [1/]

Soil property	Soil depth in inches				
	0-4	4-12	12-19	19-45	45-65
Horizon symbol	A11	A12	B1	B21T	B22T
Color (Munsel)	5 yr	2.5 yr	2.5 yr	2.5 yr	2.5 yr
Consistence					
Dry	soft	soft	soft	slightly hard	hard
Moist	friable	friable	friable	firm	firm
Structure					
Grade	strong	strong	moderate	weak	weak
Size	medium	fine-medium	fine	medium	medium-coarse
Form	granular	crumb	granular	subangular blocky	subangular blocky
pH	5.5	5.5	5.5	5.5	5.4
Bulk density [2/]	1.1	1.2	1.3	1.5	1.6
Texture	gravelly SiCL	SiCL	gravelly SiC	C	C
Particle-size analysis					
Gravel [3/]	26	19	22	10	8
< 2 mm [4/]					
Sand	16	13	9	8	8
Silt	49	47	47	35	37
Clay	35	40	44	57	55
Moisture retention [5/]					
Air dry	6.3	5.2	3.3	3.5	3.2
1/3-Atm	42.5	39.1	32.8	28.5	29.7
15-Atm	22.2	20.7	18.8	20.3	20.9
Available moisture	20.2	18.4	14.0	7.9	8.8

1/ From Soil-Vegetation Plot Record, Plot 13, Map 13, Quadrangle 50 A-2, Soil Sample 68-58-130x, Sept. 17, 1968.

2/ Density of air dry clod (g/cc).

3/ Percent by weight based on weight of field sample.

Al2 — 2 1/2 to 12 inches, reddish brown (5YR 4/4) clay loam, dark reddish brown (5YR 3/4) moist; moderate very fine to medium granular structure; soft when dry, very friable moist, nonsticky and nonplastic wet; many fine to coarse roots; common very fine to medium pores; common fine shot; medium acid; clear smooth boundary. 6 to 14 inches thick.

B1t — 12 to 22 inches, yellow red (5YR 5/5) heavy clay loam, dark reddish brown (2.5YR 3/5) moist; weak medium subangular structure; slightly hard dry, friable moist, slightly sticky and plastic wet; common fine to coarse roots; common fine to medium pores; few thin clay films; medium acid; clear wavy boundary. 4 to 15 inches thick.

B22t — 32 to 50 inches, red (2.5YR 4/7) heavy clay, dark red (2.5YR 3/7) moist; few gravels and cobbles; massive structure breaking to angular blocky; very hard dry, very firm moist, very sticky and very plastic wet; very few medium roots; few very fine and fine pores; many moderately thick clay films; medium acid; clear irregular boundary. 10 to 25 inches thick.

B3t & C — 50 inches plus, red (2.5YR 5/6) and yellowish red (5YK 5/6) very cobbly clay; light yellowish

brown (10YR 6/4) to yellow (10YR 7/6) weathered greenstone cobbles; massive structure; very few roots; medium acid; many inches thick to unweathered greenstone.

The surface horizons range in color from brown or dark brown to reddish brown and the subsoil horizons are red or yellowish red. Surface textures are heavy loams to clay loams with fine to medium size shot and a few small gravels. Subsoil textures are light clays or clays with a few gravels and cobbles which increase in size and amount with depth. The soil reaction becomes more acid with depth, ranging from slightly to medium acid in the surface horizons and medium to strongly acid in the subsoil layers. Base saturation is low. Rock outcrops are very rare. Table 4 describes the physical and chemical characteristics of the Soil-Vegetation Survey's classification plot nearest the study area. Variability between classification plots is evident by comparing Tables 3 and 4

Texture. Soil samples were takennear the center of each of the soil moisture study plots while drilling the water table observation well. About 500 grams of disturbed soil was extracted from the drill hole at 2.5-foot intervals to a depth of 45 feet. The samples were placed in plastic bags and stored open in the laboratory to air dry for about 6 weeks. The fraction greater than 2 mm (gravel) was separated by sieving. The remaining fractions were determined by the hydrometer procedure described by Day (1965). The soil was dispersed by shaking the sample in sealed l-liter hydrometer cylinders for 18 hours with a reciprocating shaker. Hydrometer readings were taken at 35 sec., 45 sec., 6 hr., and 24 hr. The hydrometer readings were then

Table 4. Physical and chemical analyses of the Challenge Soil Series collected by the California Cooperative Soil-Vegetation Survey at the series classification plot.

Horizon symbol	Depth		Gravel[1]	Particle size distribution[2]									Texture	pH[4]	Bulk[5] density
				Sand					Total sand	Silt	Clay[3]				
	From	To		VCS	CS	MS	FS	VFS			Coarse	Fine			
	---Inches---			---Percent---											
A11	0.0	2.5	10.9	3.8	2.8	1.7	4.5	6.7	19.4	52.4	28.2	20.3	SiCL	6.4	1.1
A12	2.5	12.0	7.5	4.9	4.1	2.4	5.7	9.8	26.8	39.7	33.5	25.6	CL	5.8	1.2
B1t	12.0	22.0	4.2	3.4	3.0	1.9	4.0	8.1	20.4	39.7	39.9	33.4	CL	5.8	1.2
B21t	22.0	32.0	3.1	2.5	2.2	1.6	4.3	8.1	18.7	37.4	43.9	36.3	Clay	5.9	1.6
B22t	32.0	50.0	2.6	1.7	1.7	1.1	2.9	4.0	11.5	34.7	53.8	48.0	Clay	5.9	1.7

Horizon symbol	Moisture retention data				Extractable cations					CEC[8]	Base sat.	Organic		C/N ratio
	Air dry	1/3 Atm	15 Atms	Available moisture	P	Ca	Mg	Na	K			C	N	
	---Percent by weight-----				Ppm[6]	Me/100 grams soil[7]					------Percent------			
A11	4.2	39.6	19.2	20.4	5.3	15.0	2.2	0.0	1.2	33.3	55.2	6.62	0.295	22.
A12	3.2	30.3	15.7	14.6	0.6	4.0	1.0	0.0	0.9	21.2	28.5	2.63	0.120	22.
B1t	3.0	24.9	15.6	9.3	4.3	3.7	0.8	0.0	0.5	14.9	34.2	0.83	0.043	19.
B21t	2.7	24.2	16.2	8.0	1.5	4.4	0.8	0.0	0.5	14.4	40.4	0.74	0.039	19.
B22t	2.6	27.8	20.1	7.7	<.1	4.6	0.9	0.0	0.4	14.9	40.2	0.45	0.038	12.

[1] Based upon weight of field sample
[2] By weight of soil less than 2mm
[3] Hydrometer clay - less than 2 and 1 micron
[4] Glass electrode (sat. soil paste)
[5] Density of air dry clod (in g/cc)
[6] Sodium bicarbonate extractable pH 8.5
[7] In ammonium acetate pH 7.0
[8] Barium saturated pH 8.1

converted to textural classes (Fig. 6, 7, 8; Table 5). It may be noted the amount of gravel found in the plot samples (Table 5) is much less than reported at the Soil-Vegetation Survey classification plot (Table 4) or the typical profile characteristics of the Challenge soil series (Table 3) for comparable depths. The remaining fractions are similar. Comparison is difficult, however, due to the different sampling methods and depths. The soil. in the study plots is quite typical of the Challenge soil series (Colwell, personal communication).

Water Retention. Soil moisture retention was determined using a pressure membrane apparatus (Richards, 1949). Duplicate soil samples of approximately 25 grams each were taken from each sampling depth within a plot. The samples were placed in plastic retainer rings, saturated for 24 hours and placed in a ceramic plate extractor at l/3 atmosphere (4.9 lb. in^{-2}) or 15 atmospheres (220.5 lb. in^{-2}) for 48 hours. The moisture content of the samples was then determined by oven drying for 24 hours (Fig. 9, 10, 11; Table 5). In this manner 197 paired samples were run with excellent precision. At 1/3 atmosphere, the standard deviation of the paired samples was 1.2 percent moisture by weight and at 15 atmospheres was 1.5 percent by weight. The mean deviation between paired samples was 0.2 and 0.3 percent moisture by weight respectively.

Soil Moisture Measurement

The neutron scattering method of soil moisture determination was selected for use in this study. The neutron method is particularly suited to a study of soil moisture depletion in that access tubes are permanently installed and the same point may be measured as frequently

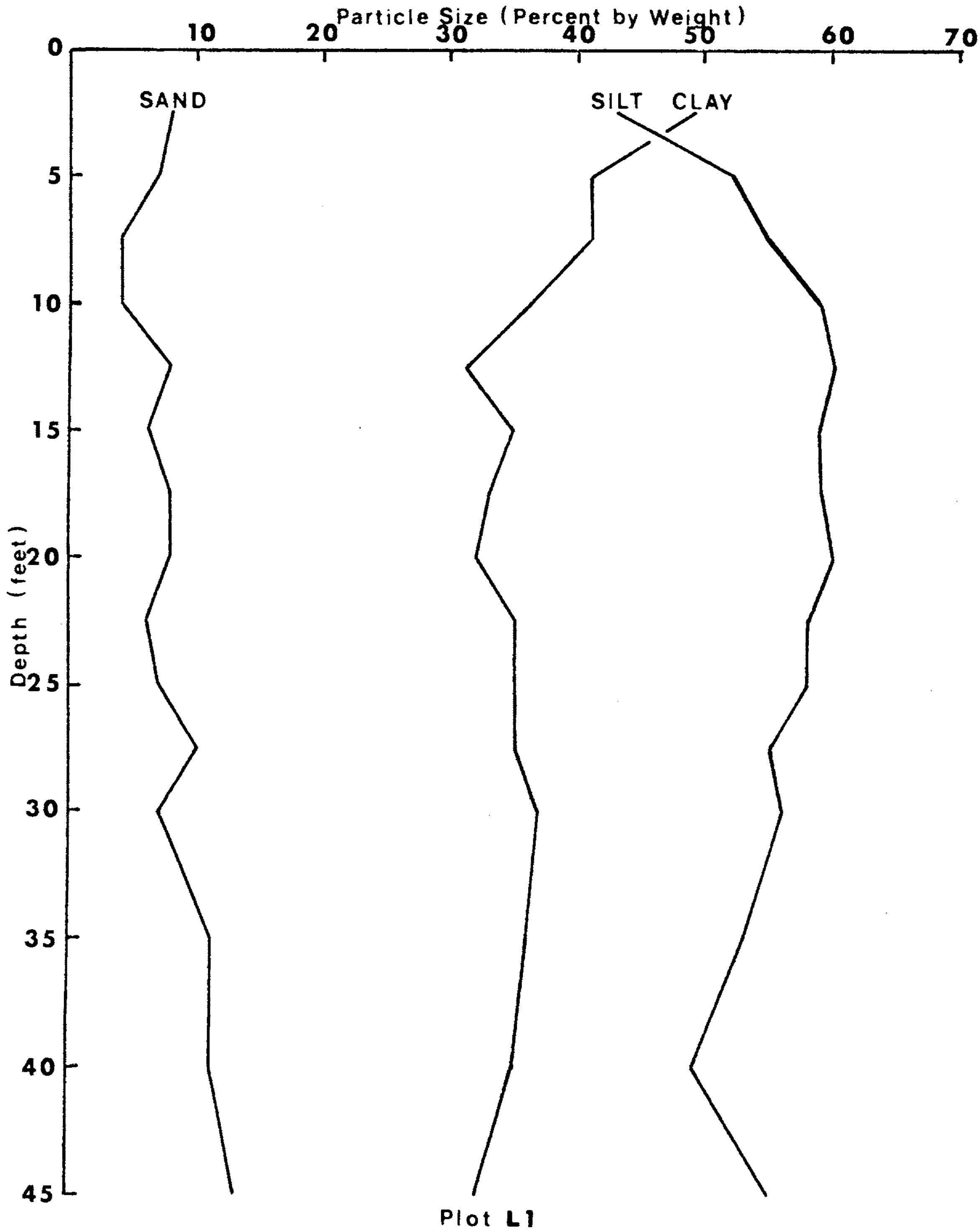


Figure 6. Distribution of sand, silt, and clay in the study tree plot L1.

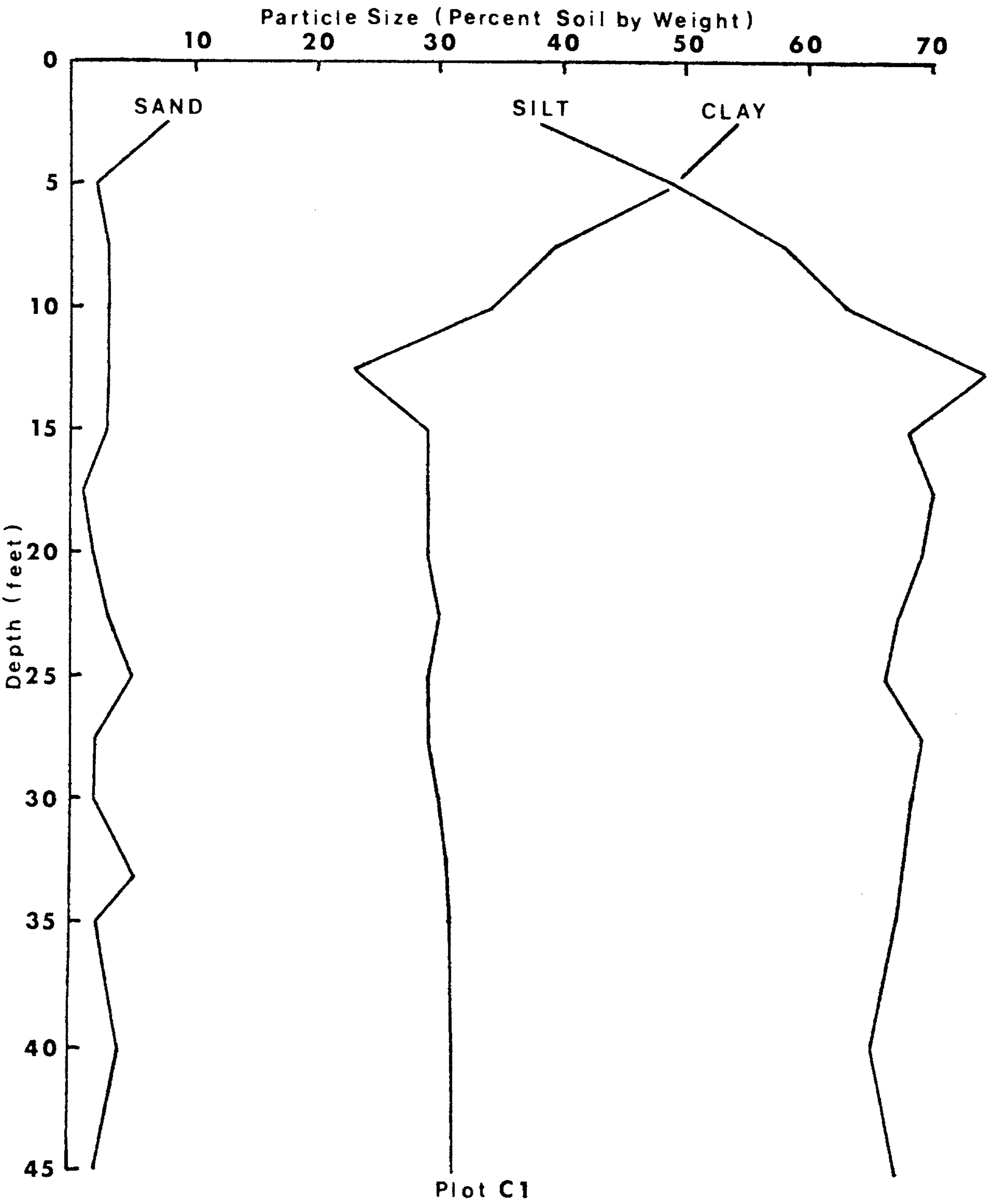


Figure 7. Distribution of sand, silt, and clay in the uncut control plot C1.

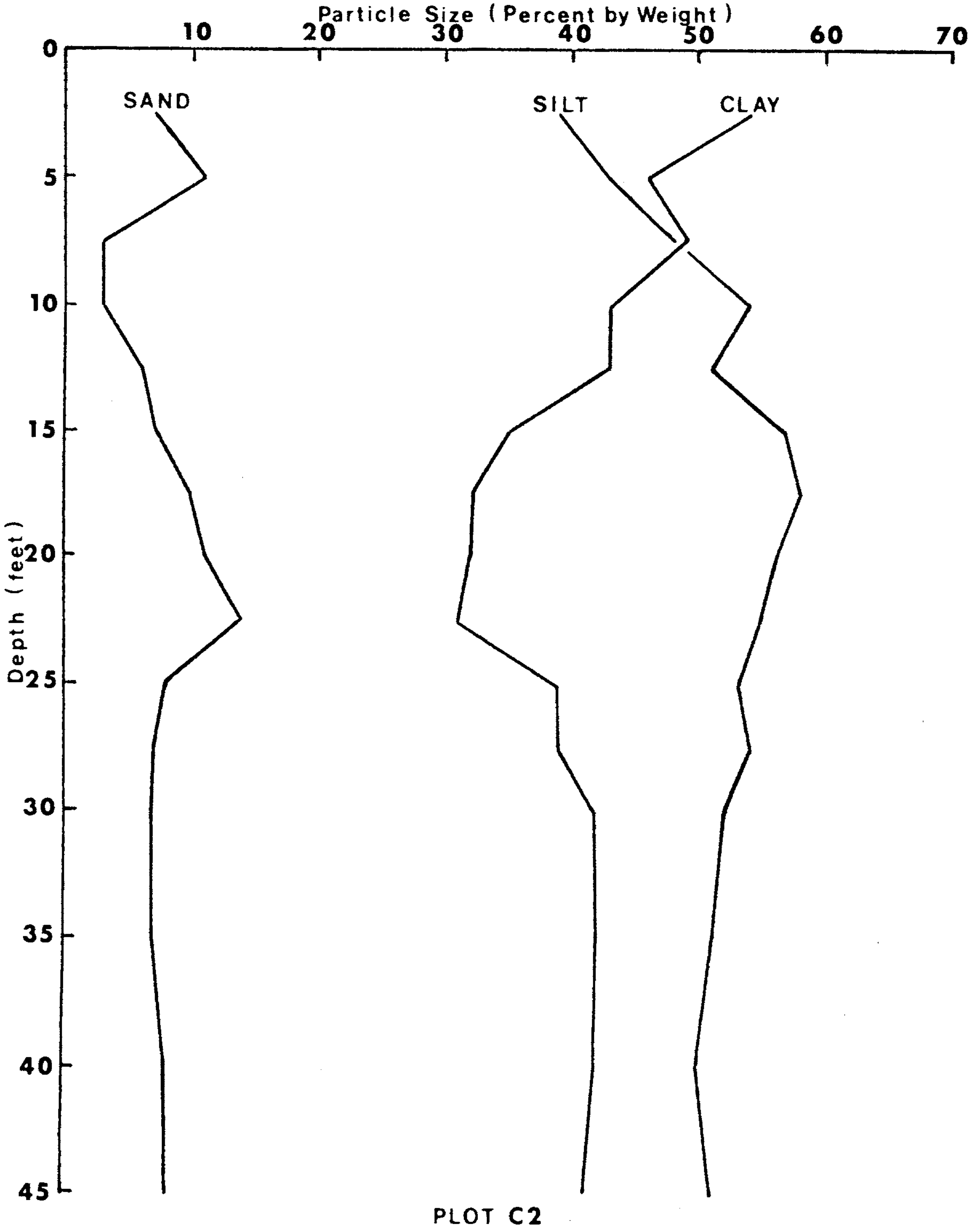


Figure 8. Distribution of sand, silt, and clay in the uncut control plot C2.

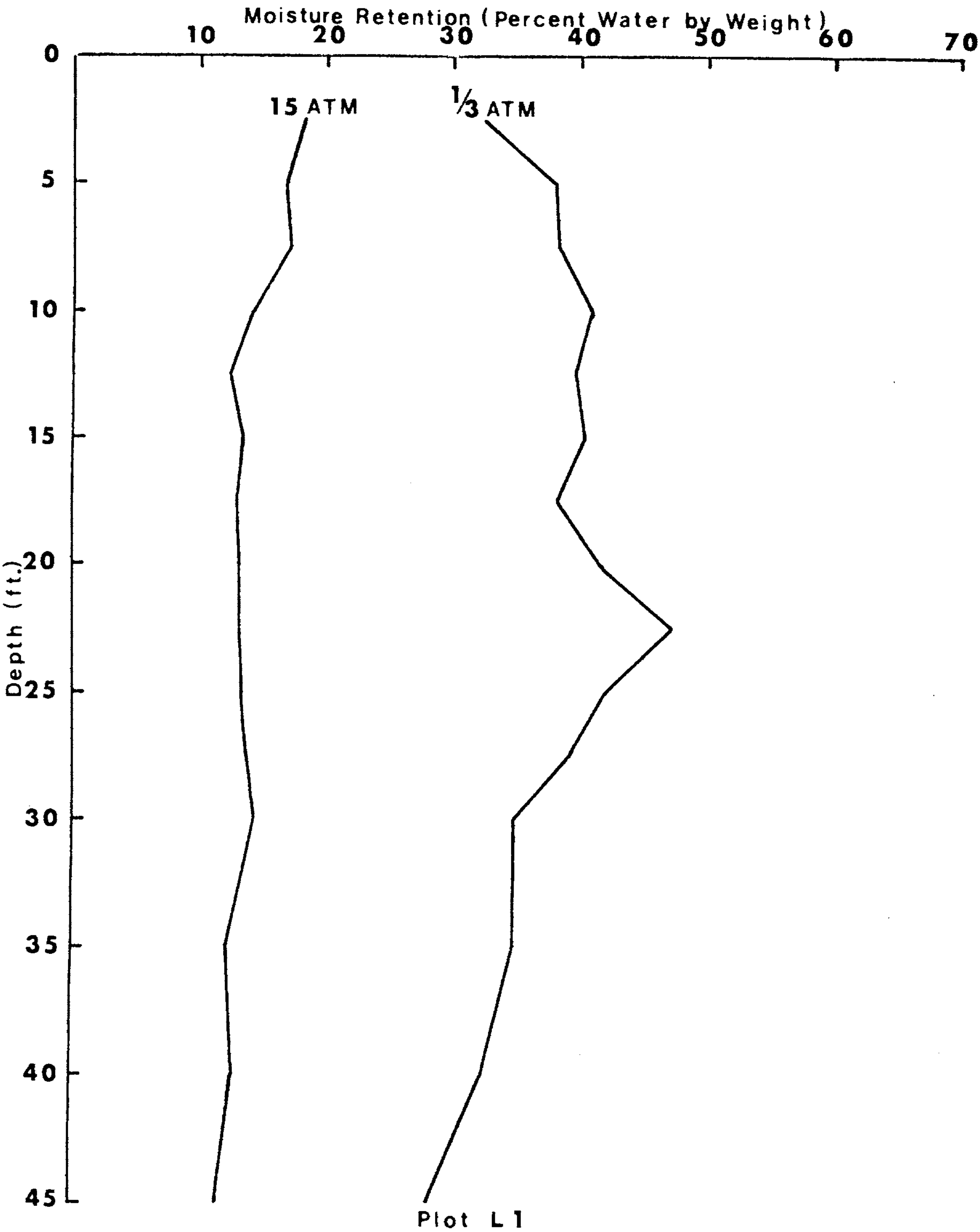


Figure 9. Soil moisture retention in the study tree plot L1.

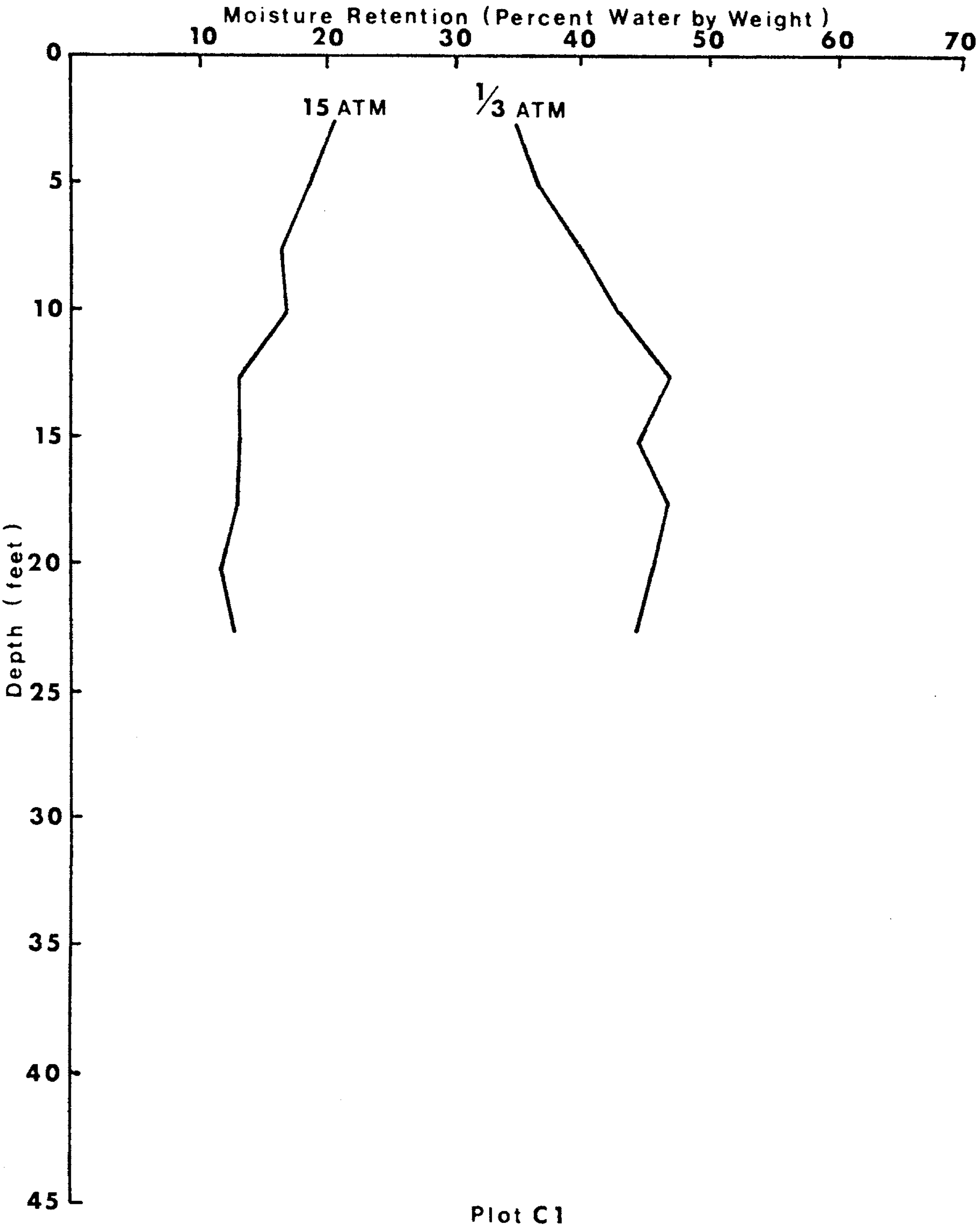


Figure 10. Soil moisture retention in the uncut control plot C1.

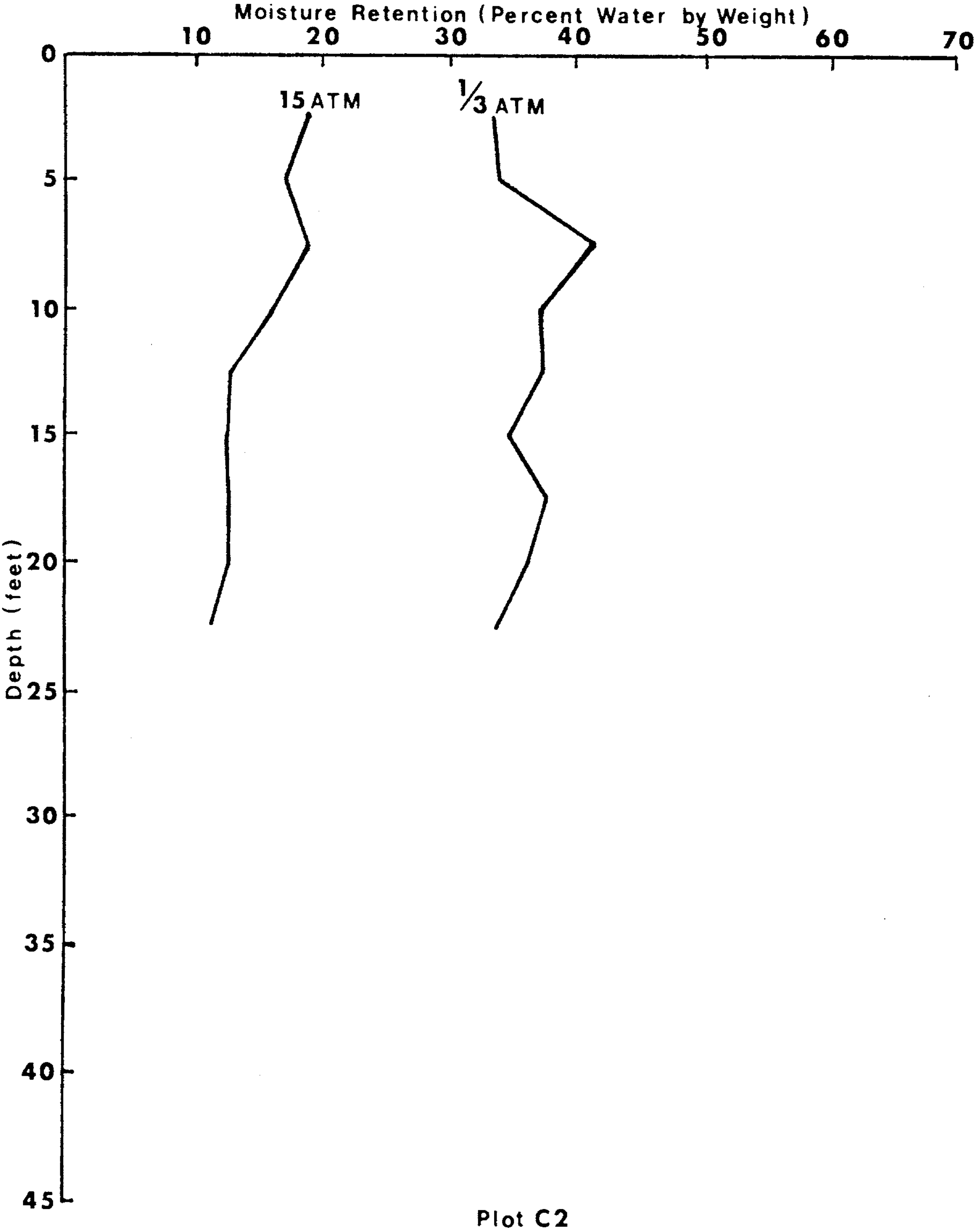


Figure 11. Soil moisture retention in the uncut control plot C2.

Table 5. Physical characteristics of the soil in the study plots.

Plot no.	Depth	Texture	Gravel 1/	Particle-size 2/			Moisture retention		
				Sand	Silt	Clay	1/3-Atm	15-Atm	Available moisture 3/
	-----Feet-----		-----Percent by weight-----						
L1	2.5	SiC	2	8	43	49	32.3	18.2	14.1
	5.0	SiC		7	52	41	38.0	16.9	21.1
	7.5	SiC		4	55	41	38.1	17.1	21.0
	10.0	SiCL		4	59	36	40.8	14.3	26.5
	12.5	SiCL		8	60	31	39.6	12.3	27.3
	15.0	SiCL		6	59	35	40.3	13.3	27.0
	17.5	SiCL		8	59	33	38.0	13.0	25.0
	20.0	SiCL		8	60	32	41.5	13.1	28.4
	22.5	SiCL	1	6	58	35	47.1	13.2	33.9
	25.0	SiCL		7	58	35	41.8	13.3	28.5
	27.5	SiCL		10	55	35	39.0	13.6	25.4
	30.0	SiCL		7	56	37	34.9	14.3	20.6
	35.0	SiCL		11	53	36	34.8	12.1	22.7
	40.0	SiCL		11	54	35	32.3	12.8	19.5
	45.0	SiCL		13	55	32	27.9	11.4	16.5
C1	2.5	C	4	8	38	54	35.0	20.6	14.4
	5.0	SiC		2	49	49	36.6	18.9	17.7
	7.5	SiCL		3	58	39	40.1	16.4	23.7
	10.0	SiCL		3	63	34	42.9	14.8	28.1
	12.5	SiL		3	74	23	46.8	13.3	33.5
	15.0	SiCL	1	3	68	29	44.3	13.2	31.1
	17.5	SiCL		1	70	29	46.8	13.0	33.8
	20.0	SiCL		2	69	29	45.6	11.9	33.7
	22.5	SiCL		3	67	30	44.4	12.8	31.6
	25.0	SiCL	1	5	66	29			
	27.0	SiCL	4	2	69	29			
	30.0	SiCL		2	68	30			
	35.0	SiCL		2	67	31			
	40.0	SiCL		4	65	31			
	45.0	SiCL		2	67	31			
C2	2.5	C	1	7	39	54	33.5	18.8	14.7
	5.0	SiC	7	11	43	46	33.9	17.0	16.9
	7.5	SiC		3	48	49	41.0	18.7	22.3
	10.0	SiC		3	54	43	37.2	16.1	21.1
	12.5	SiC		6	51	43	42.1	12.8	29.3
	15.0	SiCL		7	57	35	34.8	12.5	22.3
	17.5	SiCL		10	58	32	37.6	12.8	24.8
	20.0	SiCL		11	56	32	36.1	12.6	23.5
	22.5	SiCL	2	14	55	31	33.9	11.4	22.5
	25.0	SiCL		8	53	39			
	27.5	SiCL		7	54	39			
	30.0	SiC		7	52	42			
	35.0	SiC		7	51	42			
	40.0	SiC		8	50	42			
	45.0	SiC		8	51	41			

1/ Percent by weight based on weight of field sample.

2/ Percent by weight based on weight of soil less than 2 mm.

3/ Available moisture = 1/3-Atm moisture - 15-Atm moisture.

as needed. The instrument may be recalibrated as often as desired and checked periodically for instrument error.

Access Tube Installation. Aluminum access tubes[1] were installed at each measurement site to a depth of about 20 feet to allow lowering the neutron probe into the soil. The tubes were placed in holes augered about one-fourth inch oversize with a Minuteman power auger. The access tubes were sealed at the bottom with a #9 rubber stopper. In the clayey soils at Challenge this procedure proved to be effective in obtaining a tight fit between the soil and the access tube. Between measurements the tubes were covered with cans to prevent accumulation of rain water inside the tube.

Calibration. Since the development of the neutron soil moisture meter in the 1950's, the principle of the use of the method had been thoroughly discussed by a number of authors (Stone, et al, 1955; McGuinness, et al, 1961; Van Bavel, et al, 1963). The questionable adequacy of the factory calibration of the instrument for accurate field soil moisture determination led Professor D. Nielsen of the University of California at Davis in cooperation with the California Department of Water Resources to develop an independent calibration procedure. Dr. Nielsen made neutron observations in cylindrical tanks, 4 feet high by 4 feet in diameter, filled with soil of known moisture content. Nielsen collected data at 10 different soil moisture contents ranging from 0.9 to 27.8 percent by volume. One additional point was determined at 43 percent moisture in a tank filled with pea

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[1] The access tubes used in this study were purchased in 21-foot lengths of aluminum alloy 6061-T6, 1.625-inch O.D. x 1.555-inch I.D.

gravel and saturated with water. Nielsen then made counts with the same probe in a small. drum containing solutions of boric acid (a neutron absorber) of various concentrations. Additional probes were then calibrated by making neutron counts in the U. C. boric acid drum. Soil moisture data collected in field moisture depletion plots indicated the Davis boric acid calibration to be quite satisfactory within the working range of 8 to 25 percent soil moisture. This conclusion was based upon comparisons of indicated soil moisture change, as determined with the probe, to careful measurements of the volume of irrigation water applied to small field plots. The pea gravel calibration point was later questioned by MacGillivray (personal communication) and found to yield values too low. The calibration was then revised, departing from the original boric acid curve at a moisture content of 36 percent and extrapolating a straight line through a field calibration point at 49 percent. This line passed very close to the measured count rate for water.

The procedure for calibrating-the neutron probe used In this study was to simultaneously measure a large number of soil moisture sites at Challenge with a probe calibrated by the Nielsen-MacGillivray method and one probe which had not been calibrated. In October and November 1964, 1,028 paired measurements were made. In June 1965, 730 additional paired measurements were made to obtain values at the wet end of the curve. A ratio is made of the field count at the sampling depth to the mean standard count in a paraffin shield. A linear regression was initially run with the computed soil moisture for the calibrated probe and the count ratio for the uncalibrated probe to obtain an interim calibration. The soil moisture for each of the 1,758

paired points was composed of soil moisture measurements taken at 1 foot increments in 88 holes having a depth of about 20 feet. If more than five measurements per hole were found to have differences greater than 2 percent, it was assumed that the vertical positioning of the two probes were not equal, thus, all measurements from that hole were removed from the calibration. In this manner, 3 holes of the 88 holes surveyed were removed and the edited data consisted of 1,696 points. The greatest field moisture content observed was about 63 percent by volume. It is theoretically reasonable to expect the calibration curve to pass through a point near 100 percent moisture content. Thus, 23 additional points were taken in a 55-gallon barrel of water. The calibrated probe contained a 226-radium-beryllium neutron source and the uncalibrated probe contained a 241-americium-beryllium neutron source. Significant differences in soil moisture determination have been found to be due to the type of source used (Goldberg, et al, 1967; Ziemer, et al, 1967). These differences are due primarily to the neutron energy characteristics of the different sources. Errors are predominantly evident when measuring soil moisture in regions of discontinuity or abrupt soil water change such as near the soil surface, water table or pockets of wet or dry soil. Coincidence loss of neutrons became significant at the higher count rates which were obtained with the uncalibrated probe. Consequently, the relationship was not linear and a third degree equation was necessary to satisfactorily fit the data ($r^2 = 0.992$).

Field Measurement. The tubes were surveyed with a modified P-19 Nuclear-Chicago Soil Moisture Probe and Model 2800-A Scaler. The P-19 Probe was obtained without source. An aluminum source-holder was

milled locally to hold a 0.1 Curie 241-americium-beryllium neutron source having a neutron flux of 2.33 x 10^5 n/sec. This meter produced a count rate of about 53,500 counts per minute in a water standard.

One minute thermal neutron counts were made at the 9- and 18-inch depth and at successive 1 foot intervals to the depth of the access tube. The shallowest measurement could not be made at a depth less than 9 inches because measurements made closer to the surface are biased by the loss of neutrons to the atmosphere and the indicated moisture content would be less than the actual (Ziemer, et al, 1967).

The sites were measured at 2- to 3-week intervals beginning in the spring following the last heavy rains, generally in May, and continued until the first heavy rains of the fall. Several measurements were made during the winter period to evaluate the progress of soil moisture recharge.

The count data was plotted in the field and compared to previous surveys. Any questionable readings were repeated by repositioning the probe and taking another count. At times an entire hole would be resurveyed if the data appeared questionable.

CHAPTER IV

SOIL WATER REGIME

During the 5-year course of the study, a tremendous quantity of soil moisture data was collected. Each of the 23 access tubes in the isolated tree plot and 6 tubes in the uncut control plots were measured 51 times. This translates into about 30,000 individual soil moisture measurements which required some form of presentation in order to visualize and understand spatial and time related processes. The raw field data were first screened for obvious errors and then reduced to tabular computer output of soil moisture content based upon the neutron probe calibration. Graphic profiles of soil moisture in the logged plot on each measurement date from August 16, 1965 through February 25, 1970 were constructed (Fig. 12-27). The profiles shown on the left represent isopleths of the total moisture held in a 15-foot soil depth on the particular date in the logged plot. Each contour line is expressed in feet of soil water in 15 feet of soil. The contour interval is 0.2 feet of water. The profiles shown on the right represent the average soil moisture in the logged plot related to depth and distance from the study tree. The values are the average soil moisture by volume, expressed as feet of water per foot of soil, for the particular depth and distance from the tree on a given date. For example, two values were averaged for each depth and date of measurement 2 and 5 feet from the study tree and four measurements were averaged for each depth and date for the 10-, 20-, 40-, and 60-foot distances. Twenty-three points provided the data base for the contours

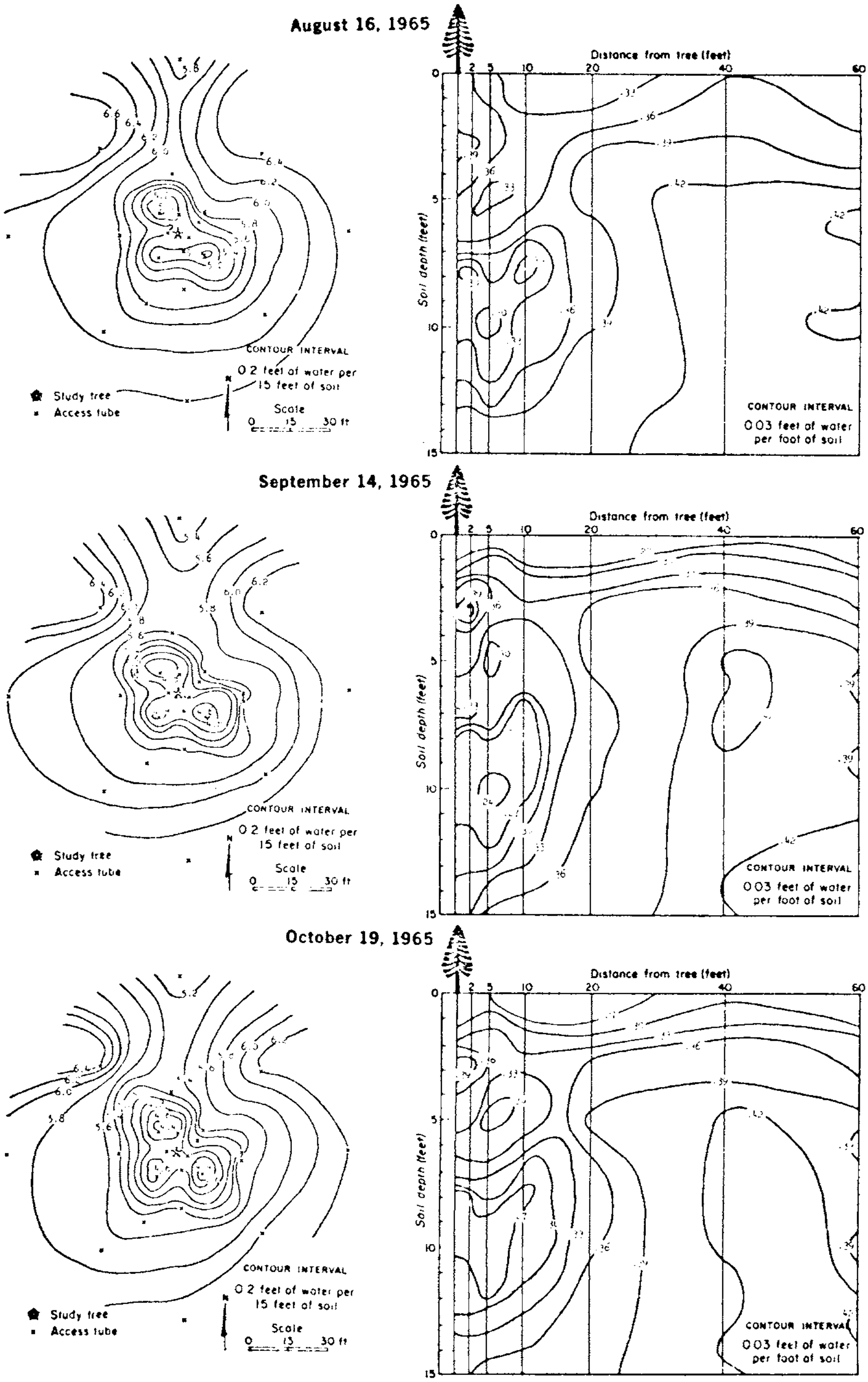

Figure 12. Isopleths of soil moisture in the partially cut study plot I.1 on a) August 16, b) September 14, and c) October 19, 1965.

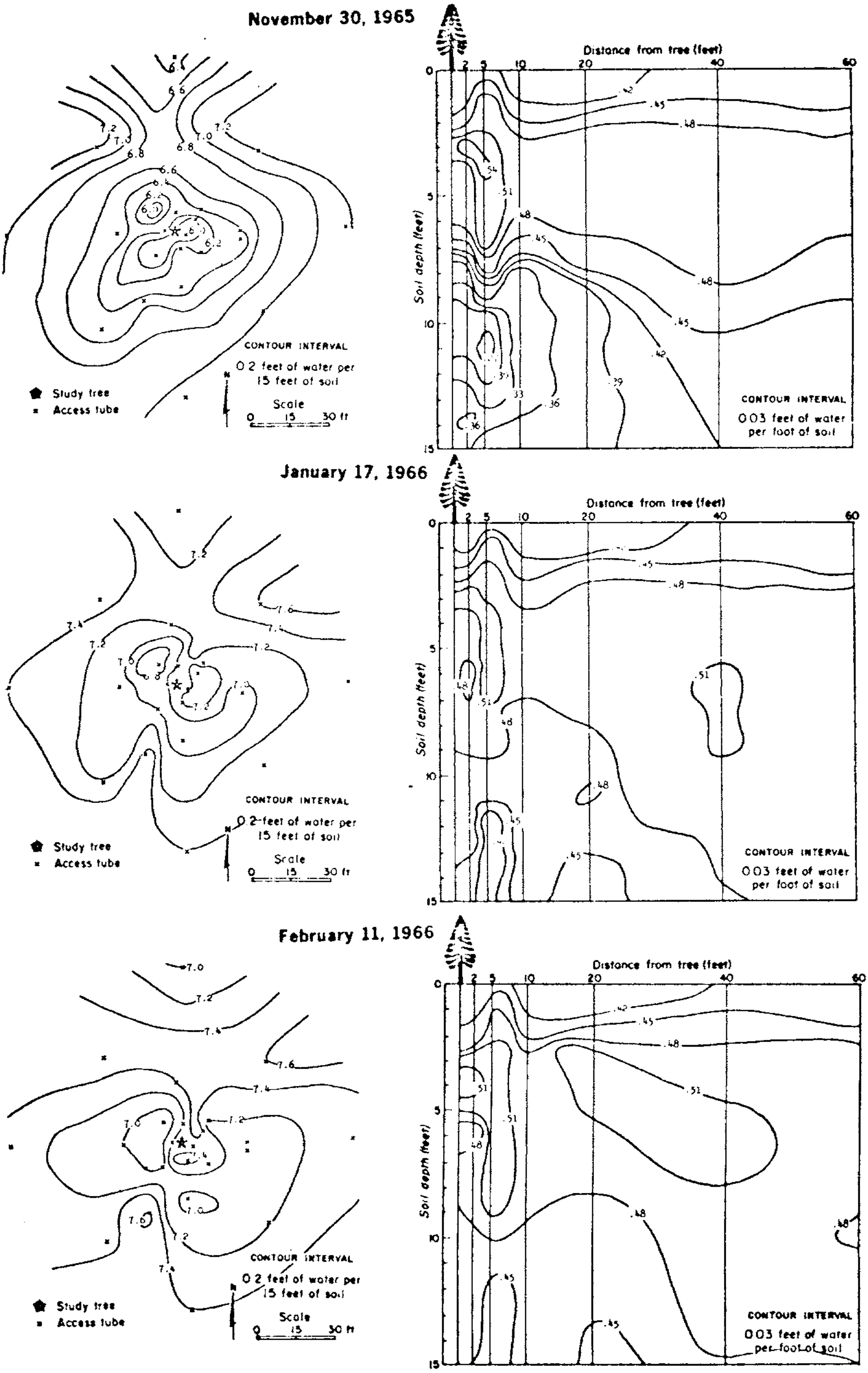

Figure 13. Isopleths of soil moisture in the partially cut study plot L1 on a) November 30, 1965, b) January 17, and c) February 11, 1966.

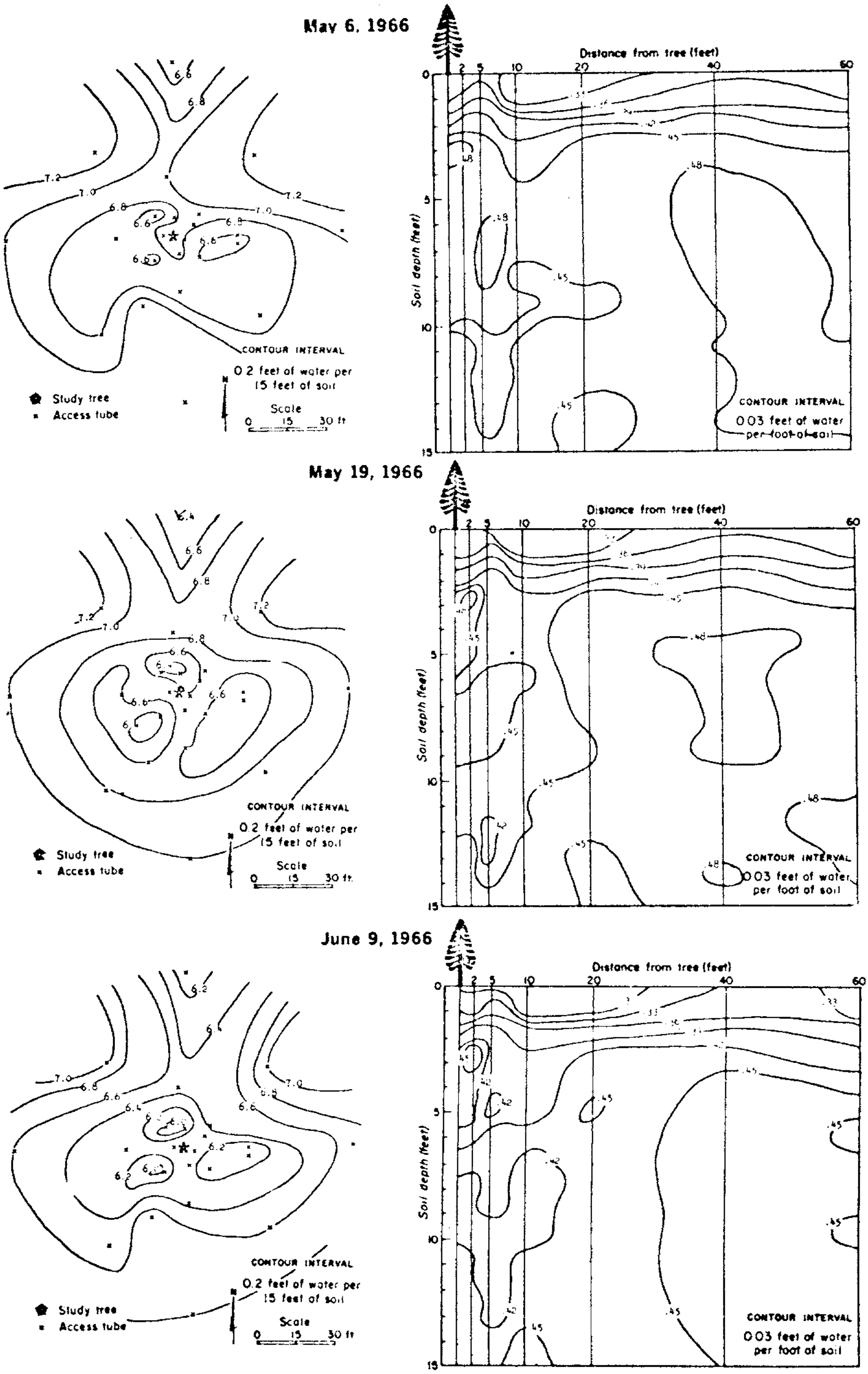

Figure 14. Isopleths of soil moisture in the partially cut study plot I.1 on a) May 6, b) May 19, and c) June 9, 1966.

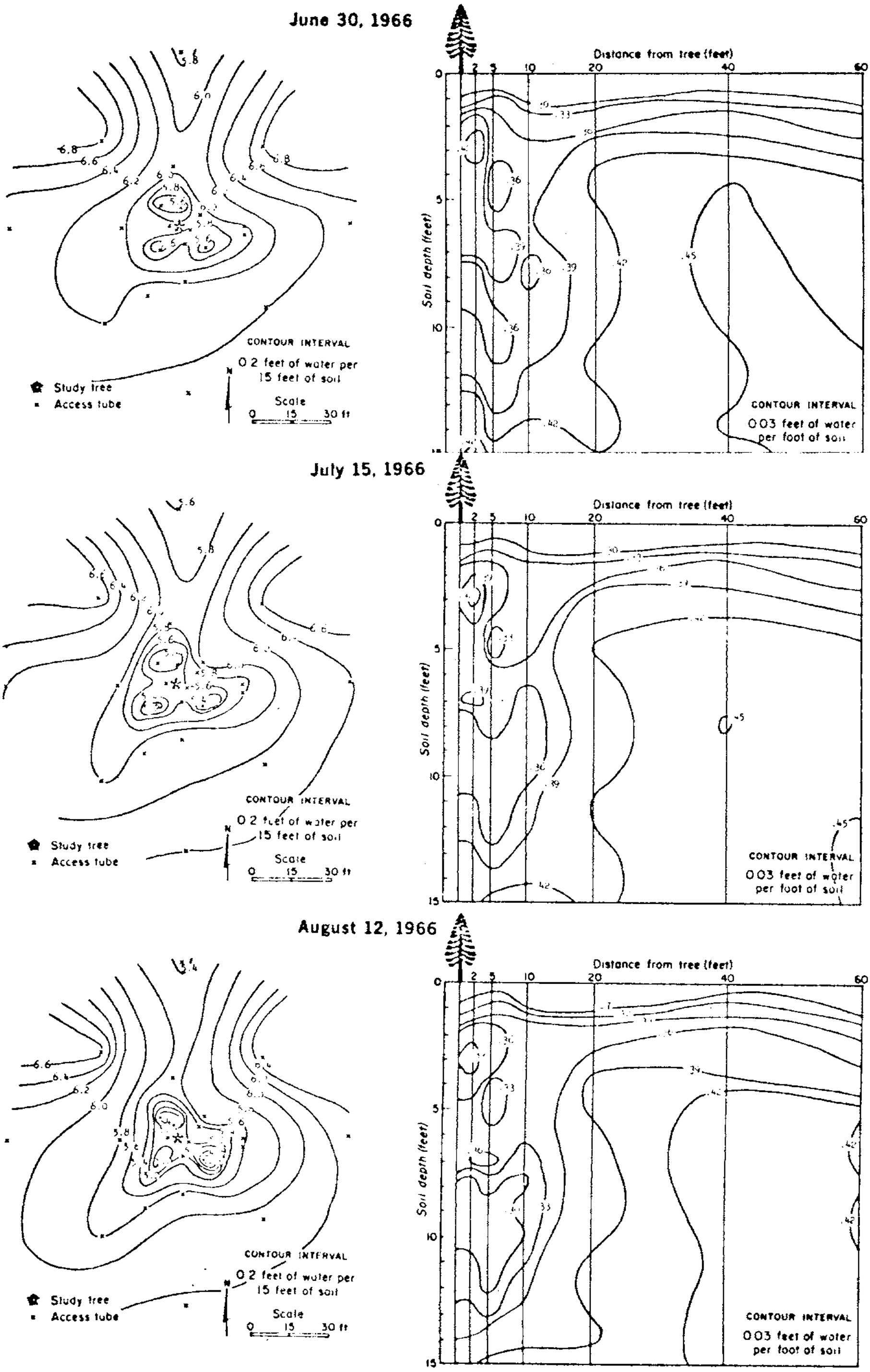

Figure 15. Isopleths of soil moisture in the partially cut study plot L1 on a) June 30, b) July 15, and c) August 12, 1966.

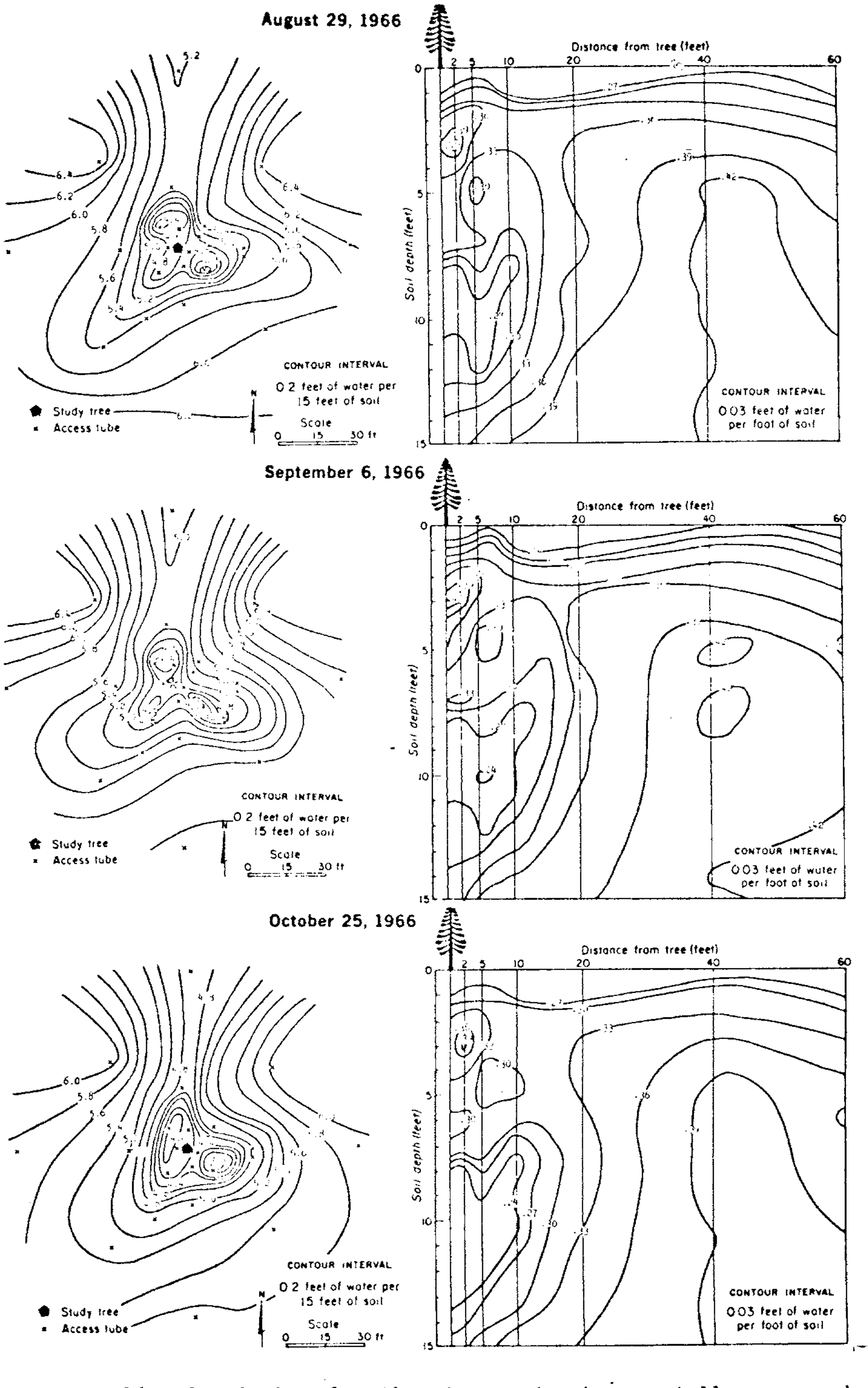

Figure 16. Isopleths of soil moisture in the partially cut study plot L1 on a) August 29, b) September 6, and c) October 25, 1966.

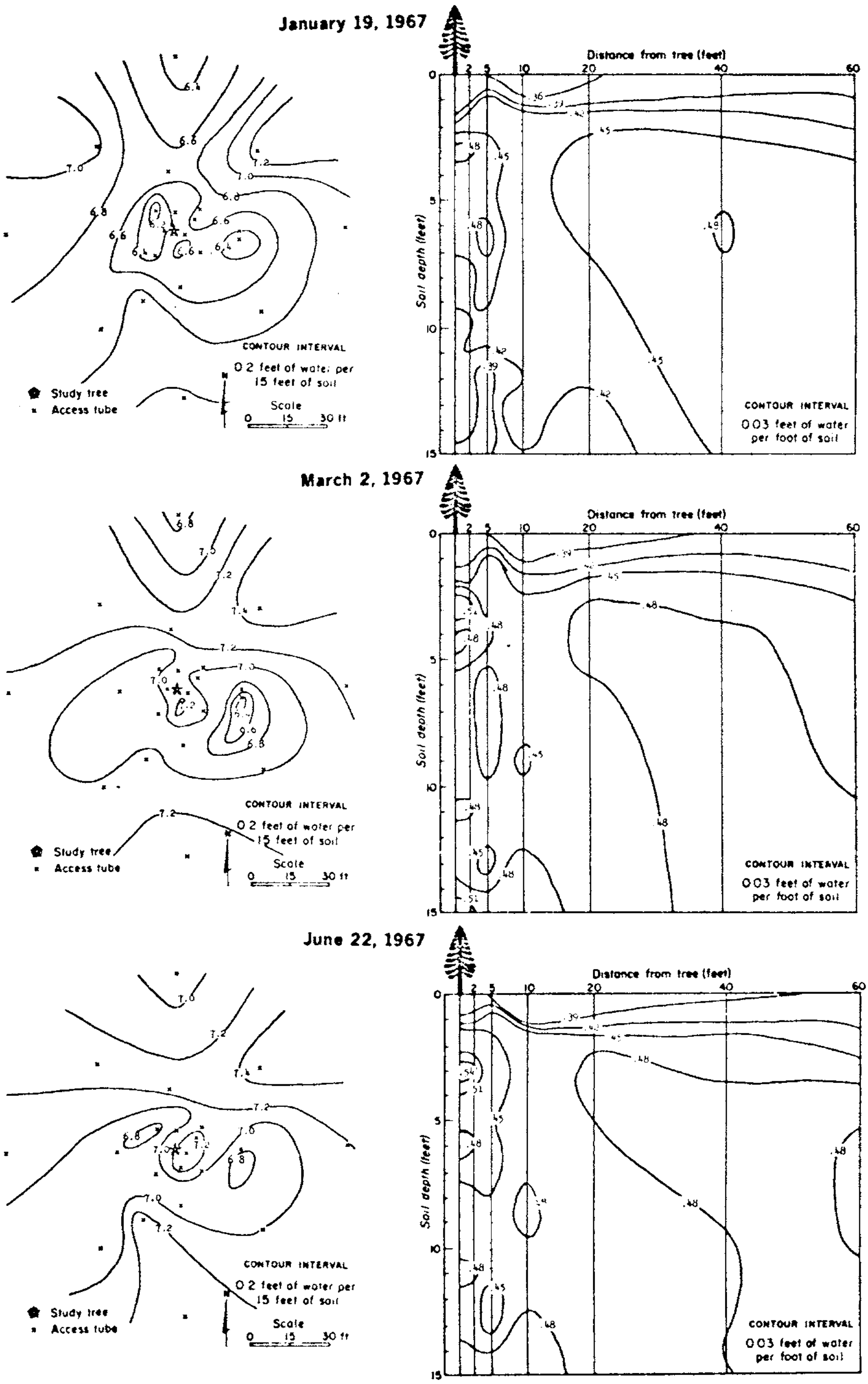

Figure 17. Isopleths of soil moisture in the isolated tree study plot L1 on a) January 19, b) March 2, and c) June 22, 1967.

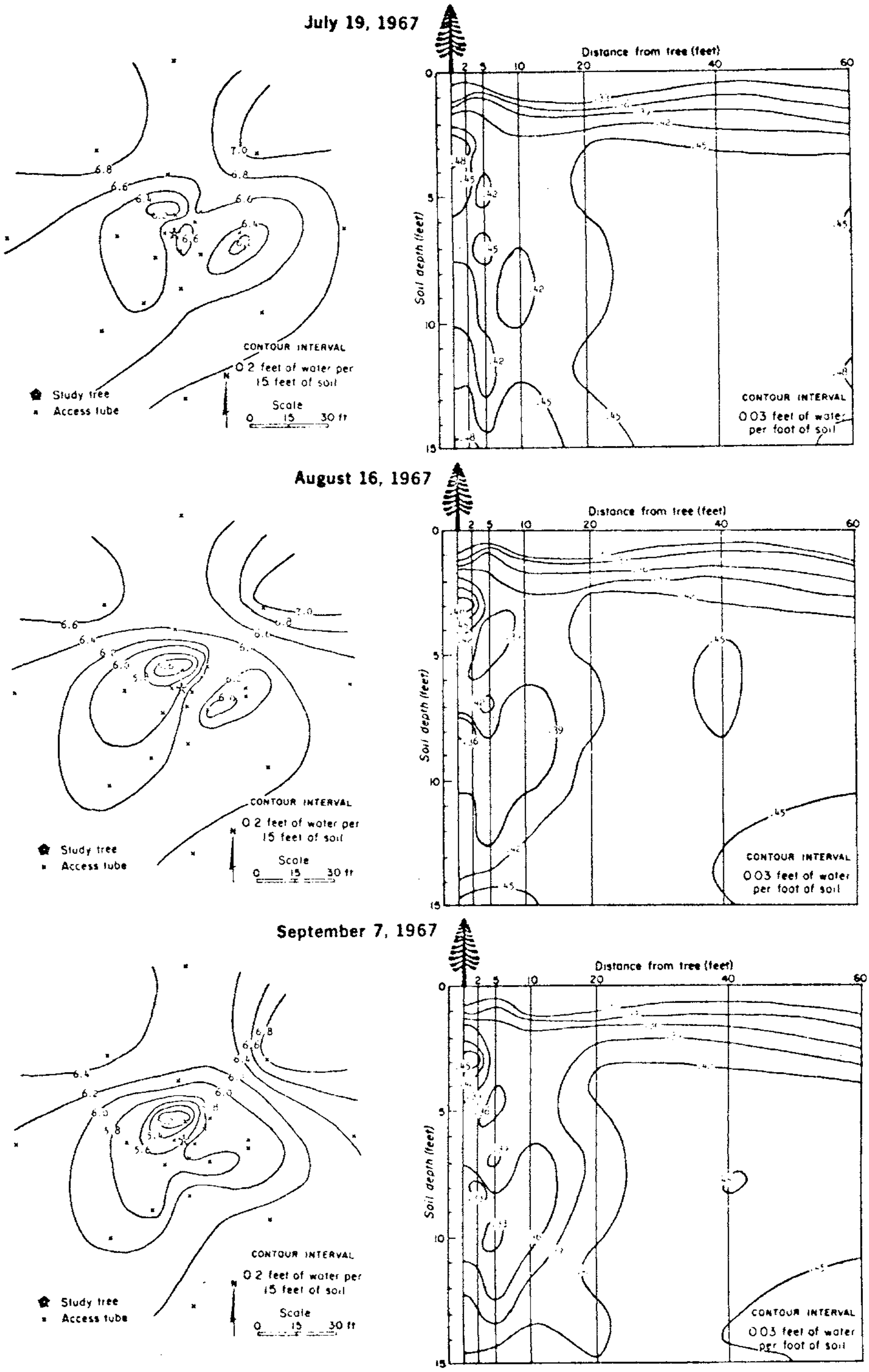

Figure 18. Isopleths of soil moisture in the isolated tree study plot L1 on a) July 19, b) August 16, and c) September 7, 1967.

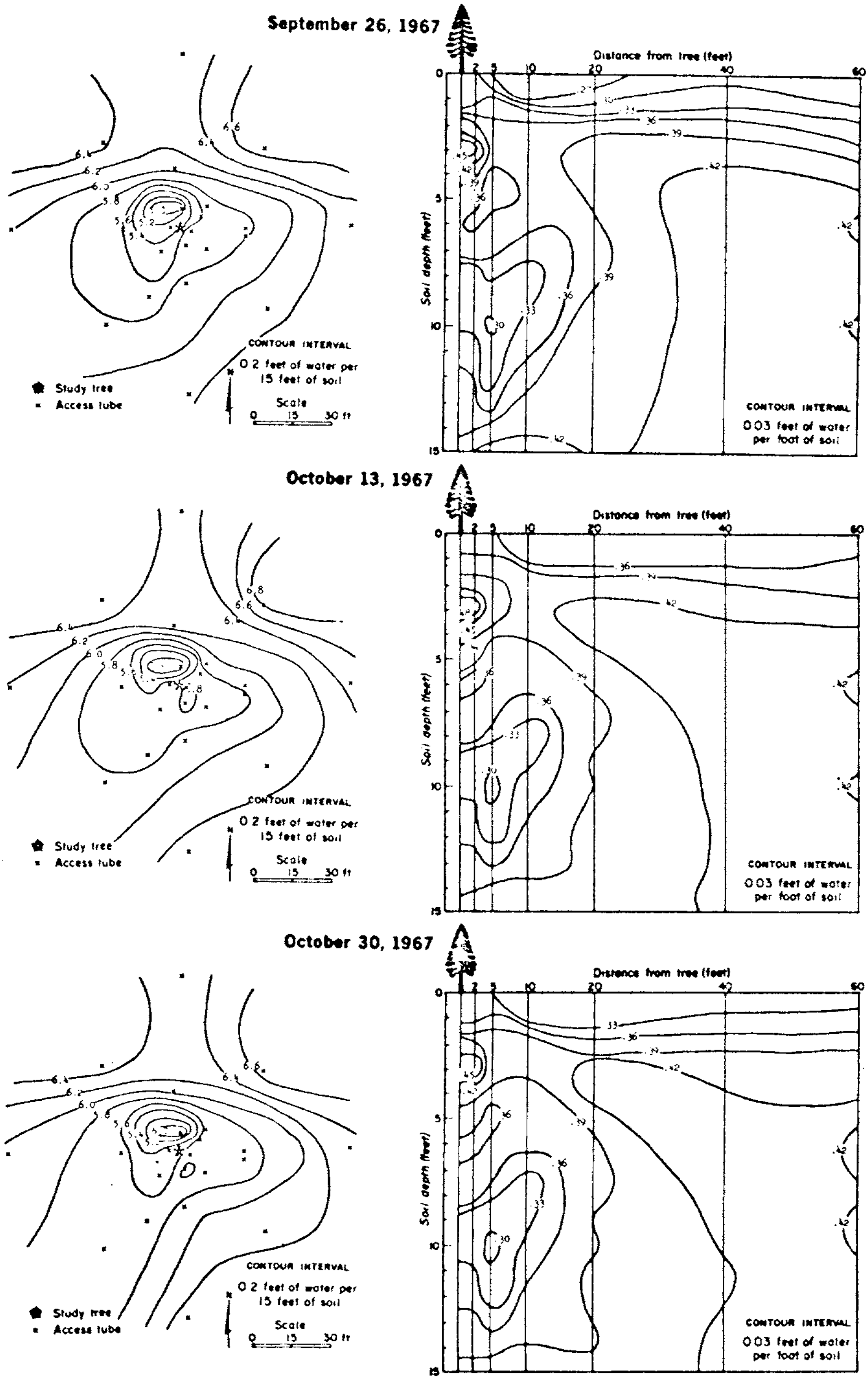

Figure 19. Isopleths of soil moisture in the isolated tree study plot L1 on a) September 26, b) October 13, and c) October 30, 1967.

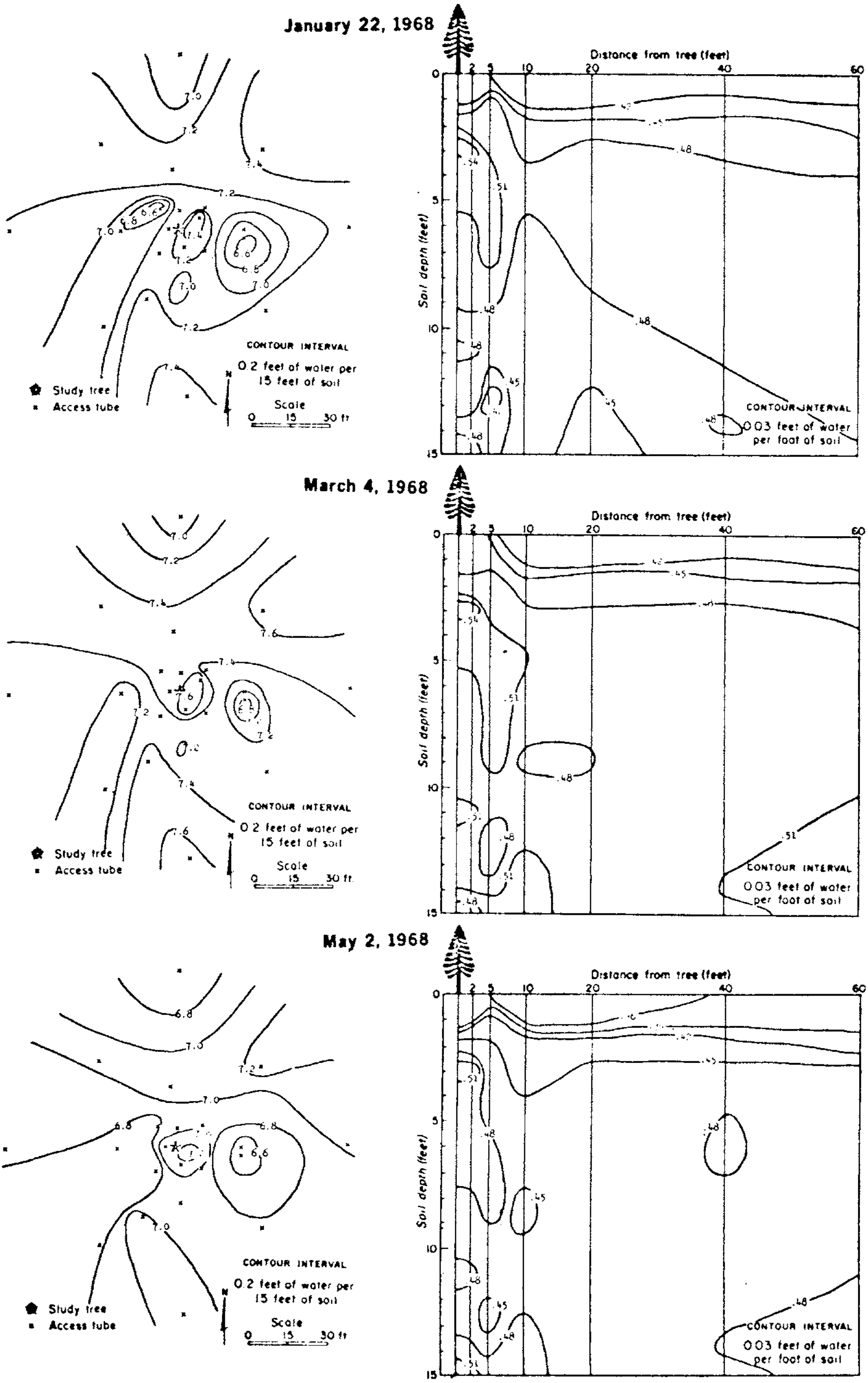

Figure 20. Isopleths of soil moisture in the isolated tree study plot L1 on a) January 22, b) March 4, and c) May 2, 1968.

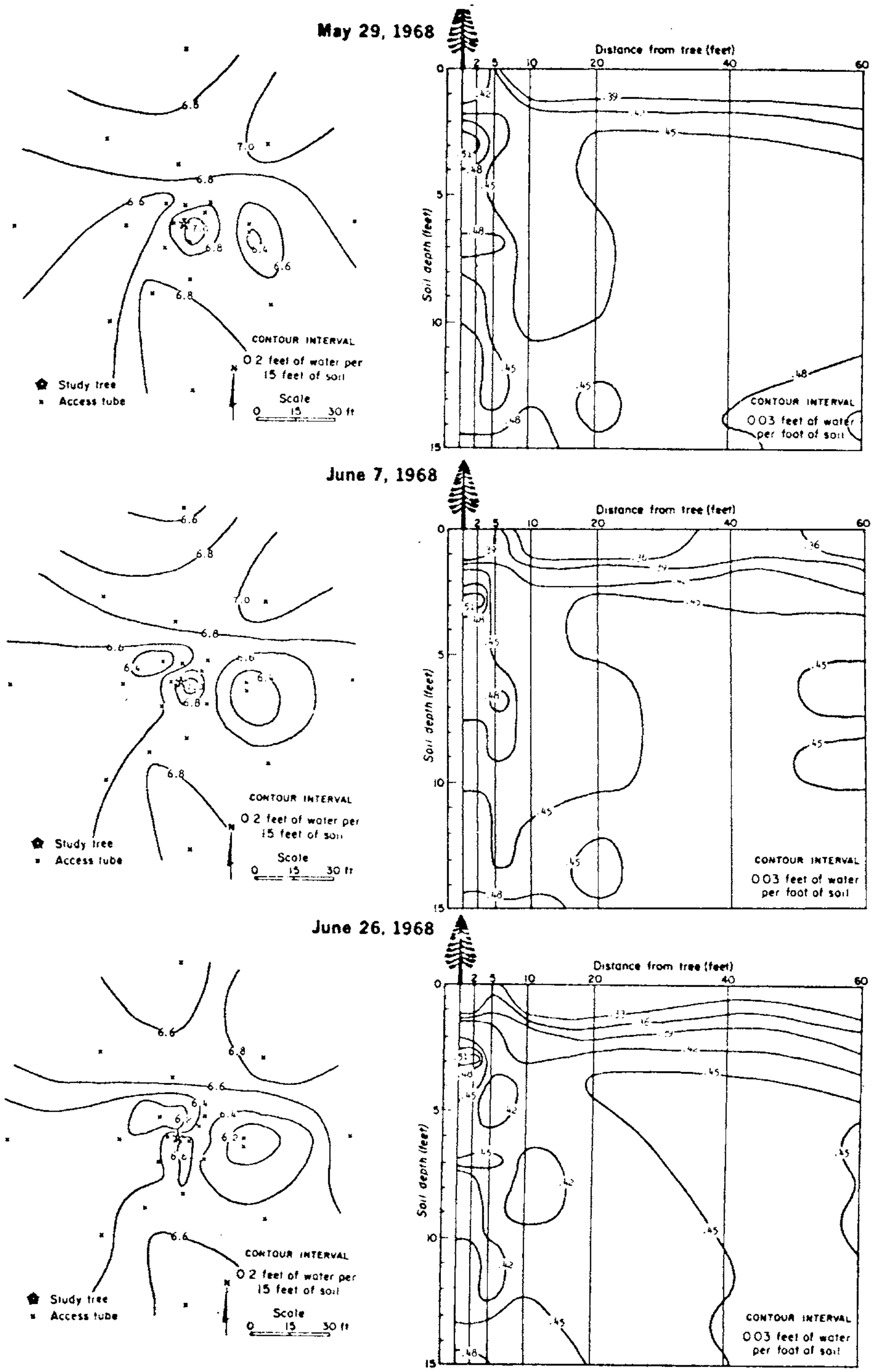

Figure 21. Isopleths of soil moisture in the isolated tree study plot L1 on a) May 29, b) June 7, and c) June 26, 1968.

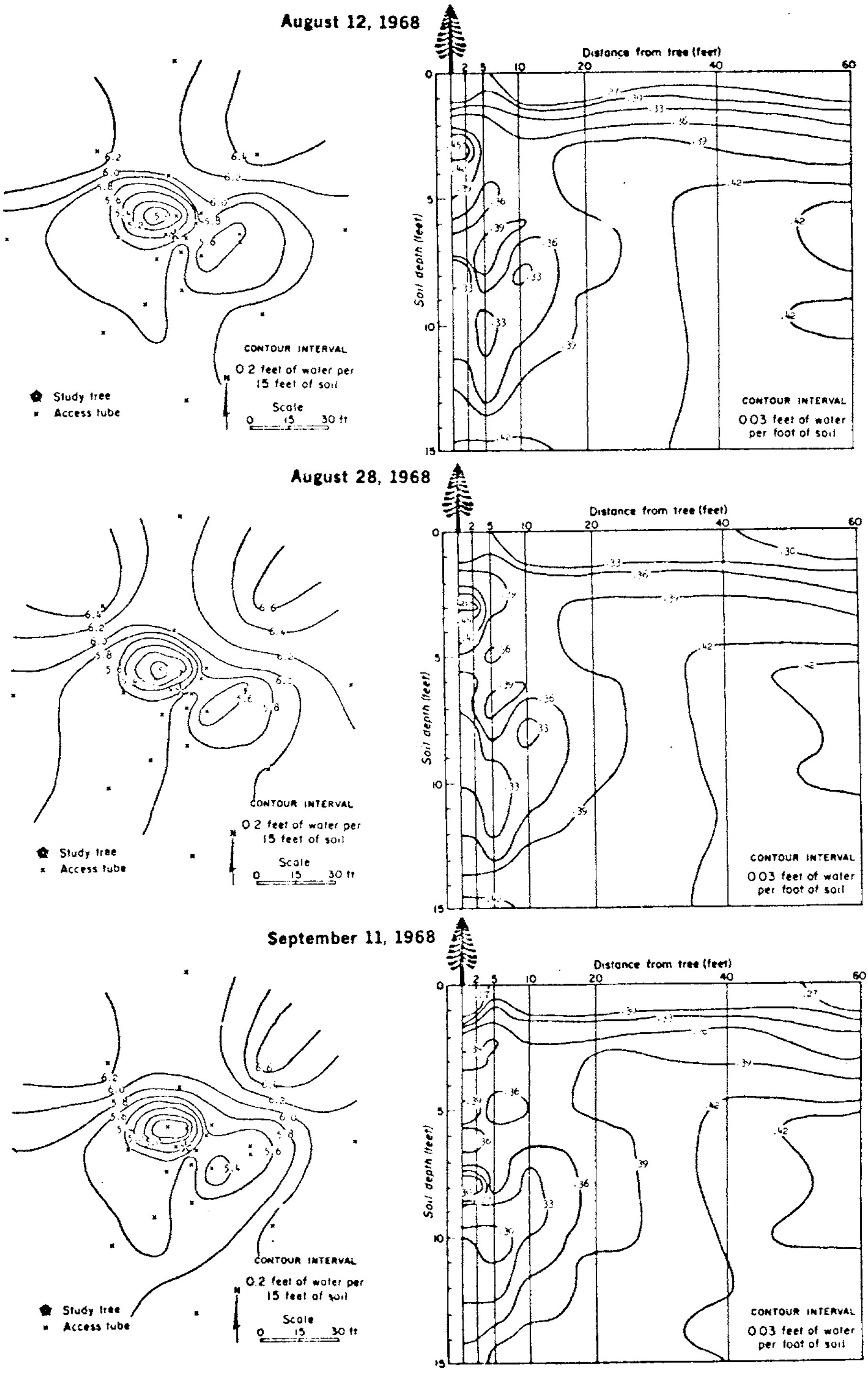

Figure 22. Isopleths of soil moisture in the isolated tree study plot L1 on a) August 12, b) August 28, and c) September 11, 1968.

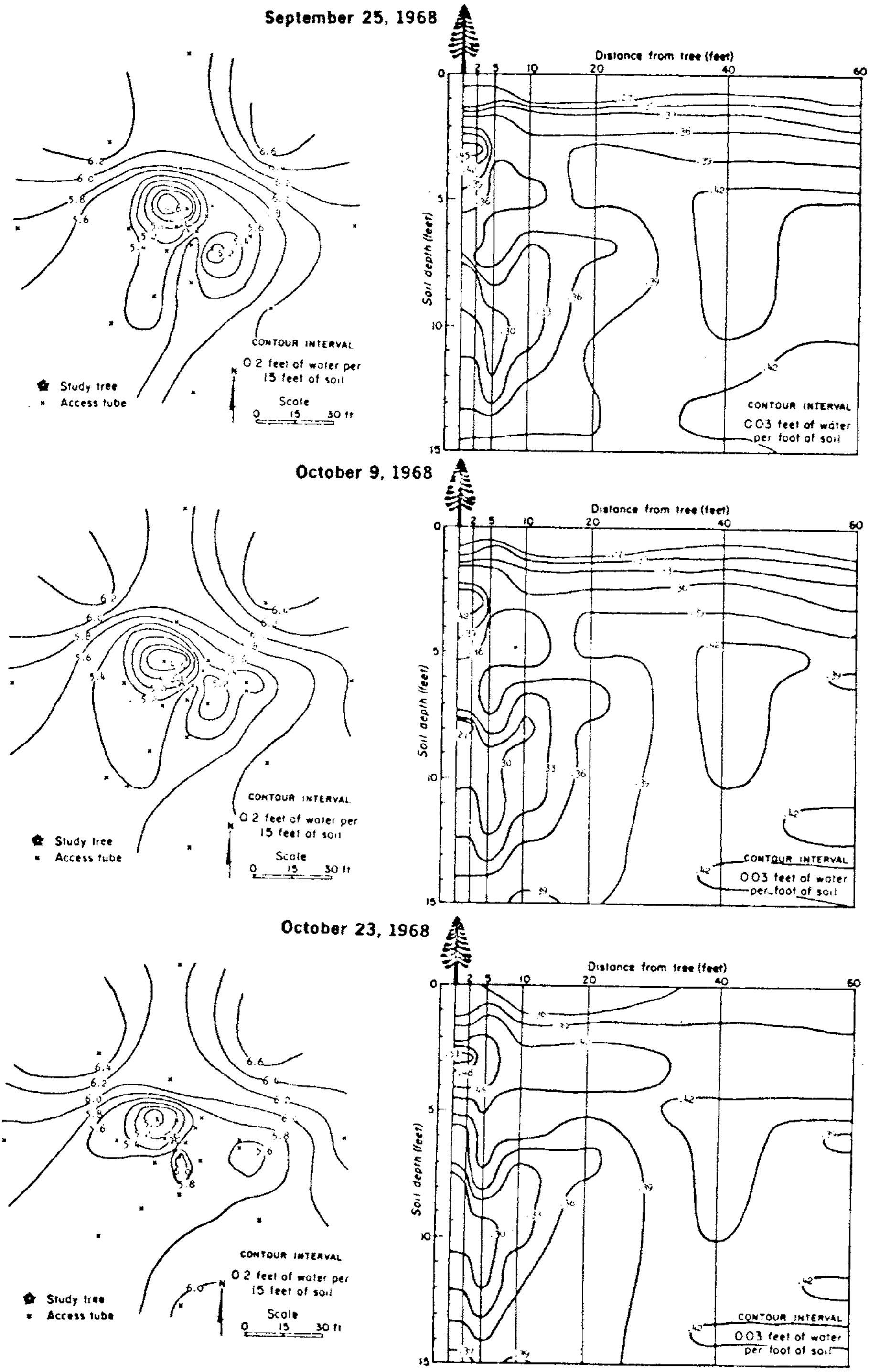

Figure 23. Isopleths of soil moisture in the isolated tree study plot L1 on a) September 25, b) October 9, and c) October 23, 1968.

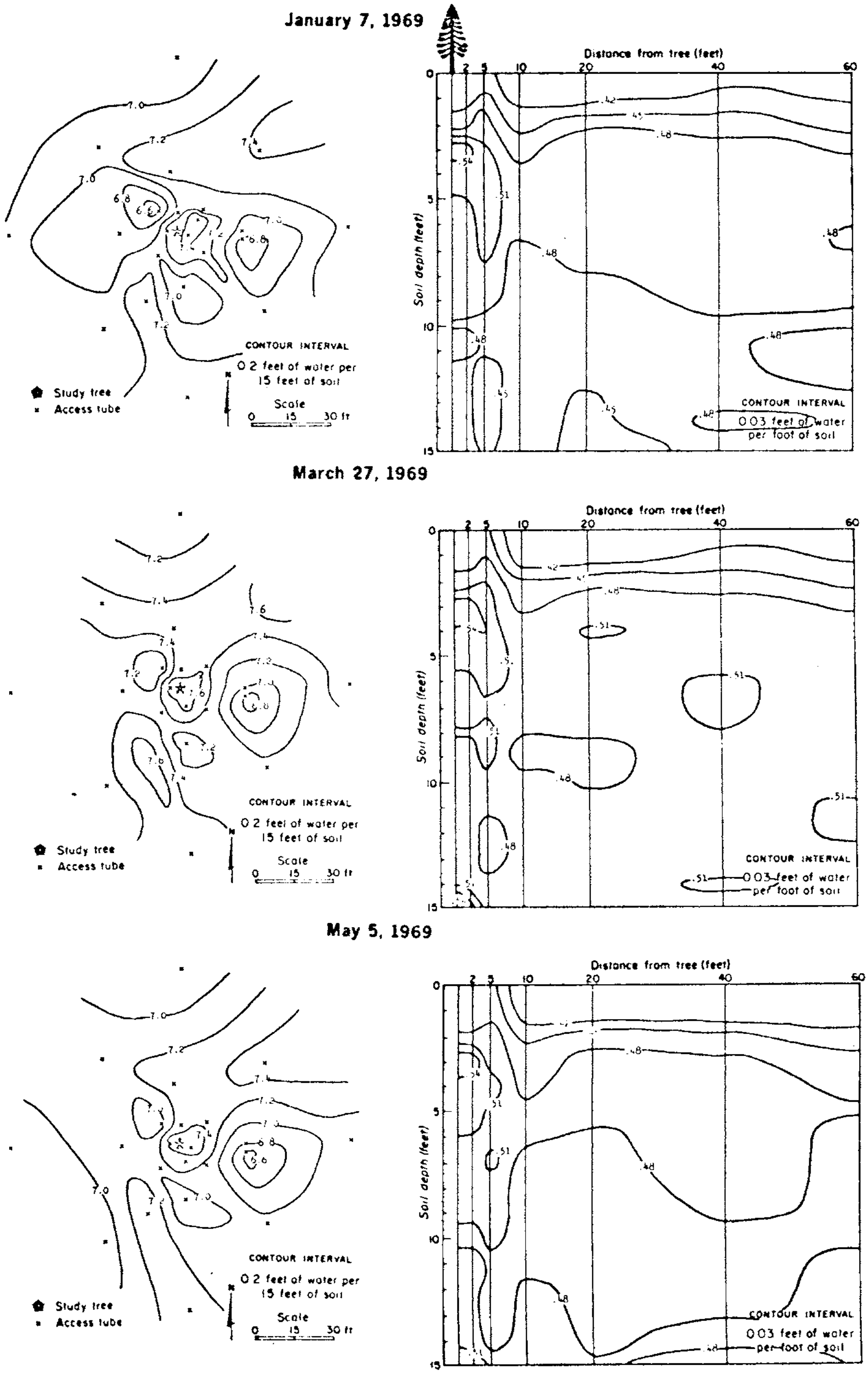

Figure 24. Isopleths of soil moisture in the isolated tree study plot L1 on a) January 7, 1969 and in the bare study plot L1 on b) March 27, and c) May 5, 1969.

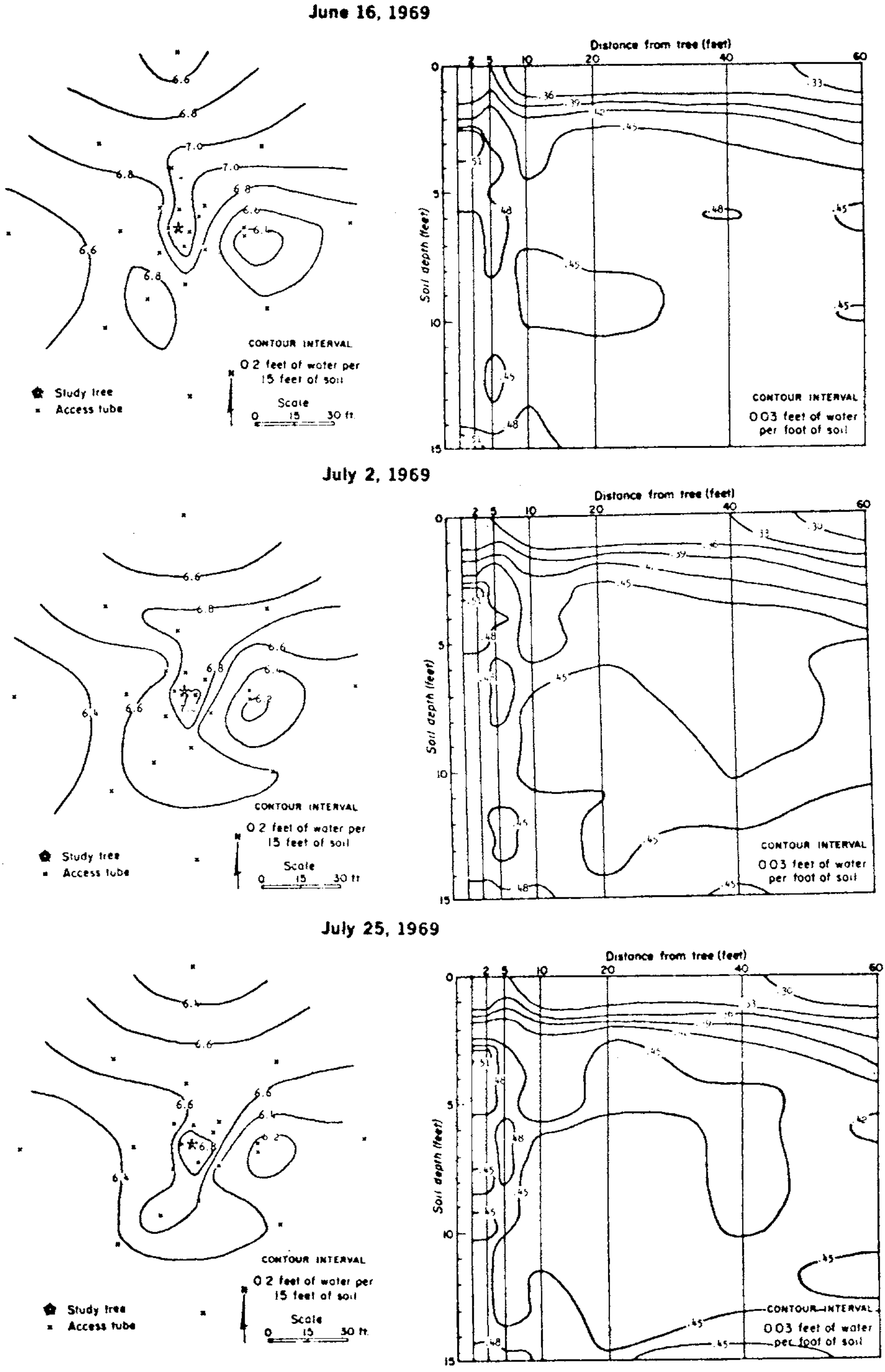

Figure 25. Isopleths of soil moisture in the bare study plot L1 on a) June 16, b) July 2, and c) July 25, 1969.

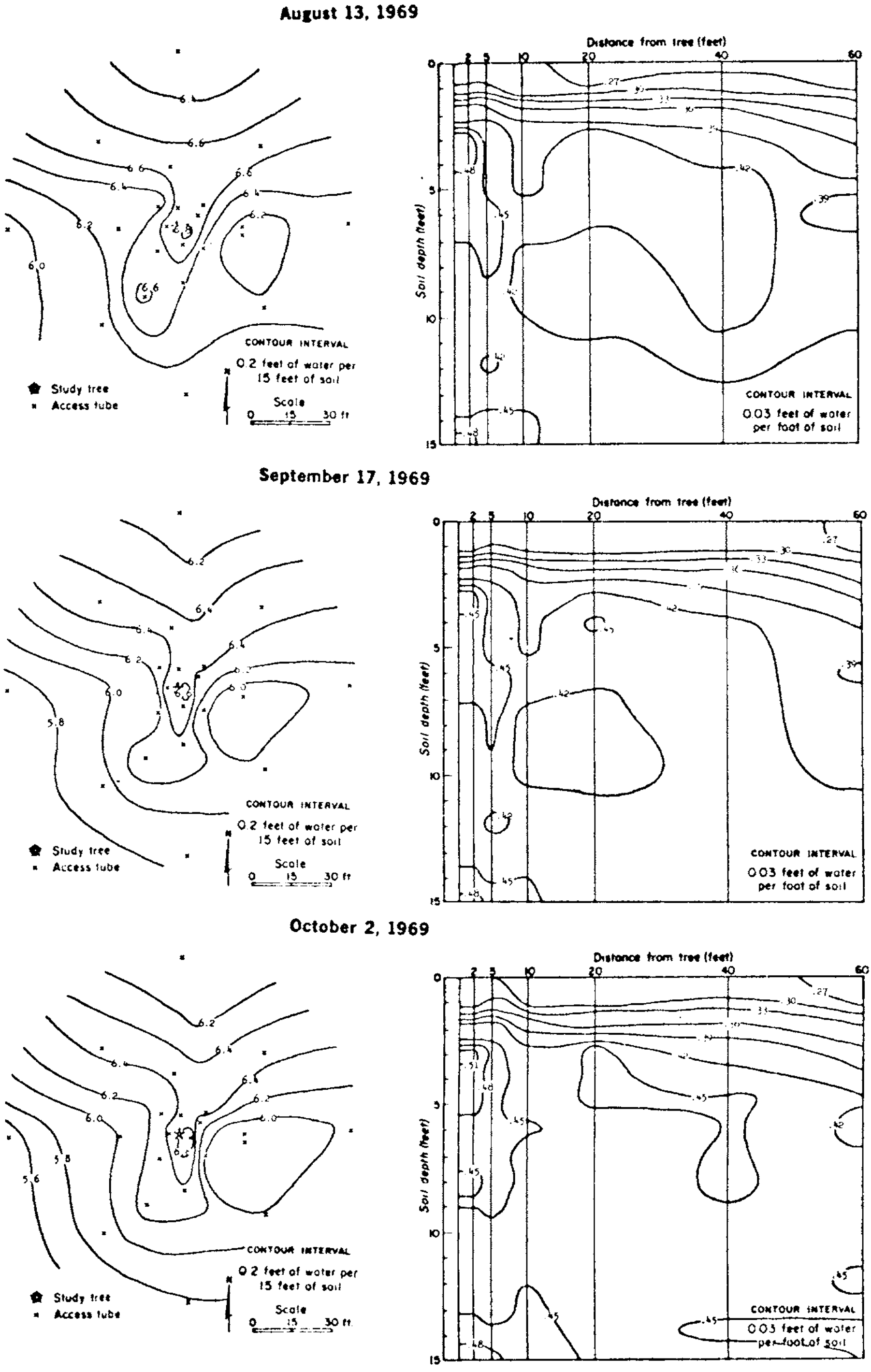

Figure 26. Isopleths of soil moisture in the bare study plot L1 on a) August 13, b) September 17, and c) October 2, 1969.

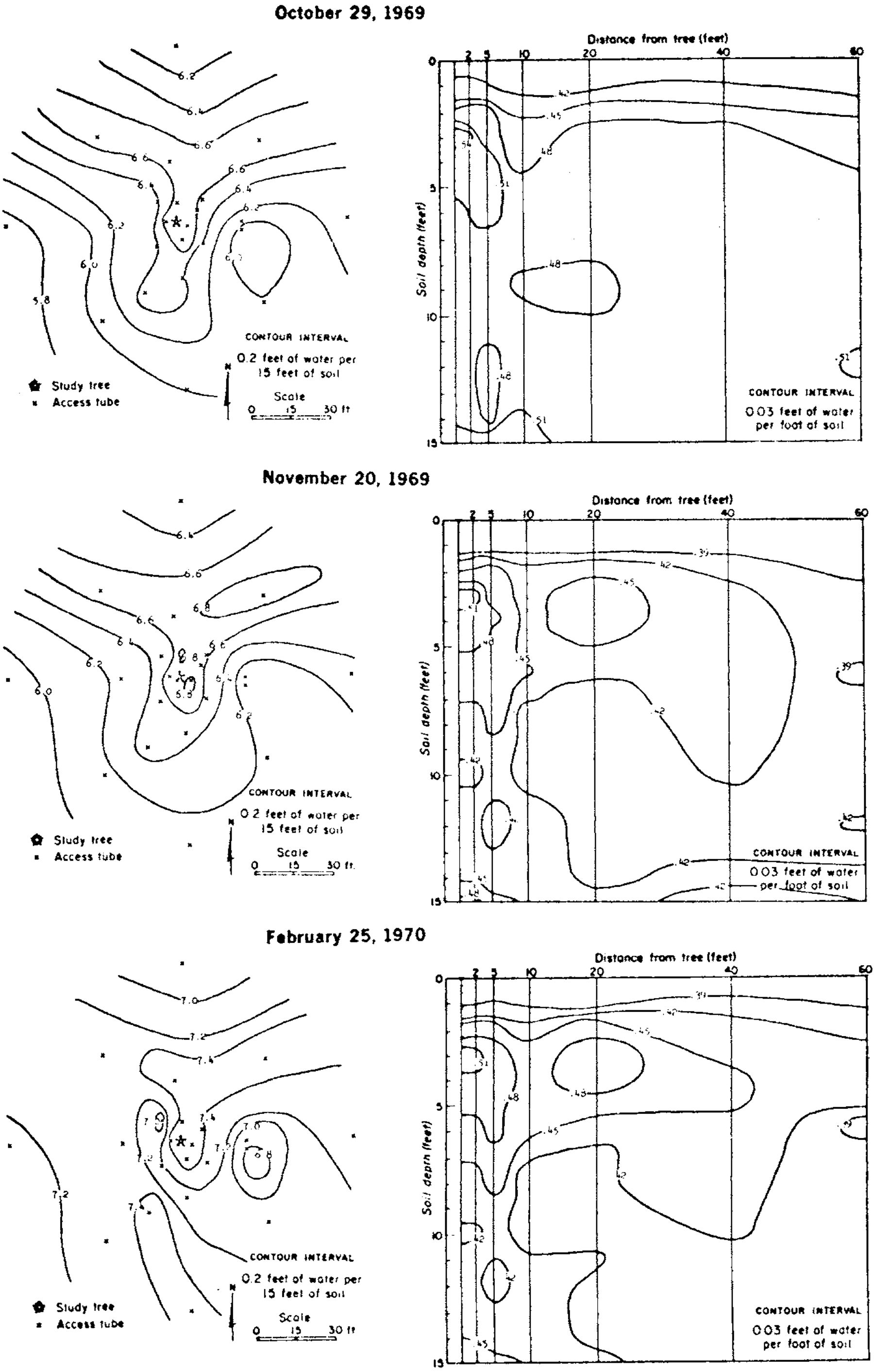

Figure 27. Isopleths of soil moisture in the bare study plot L1 on a) October 29, b) November 20, 1969, and c) February 25, 1970.

in the left profile and 90 points were used to produce the profile on the right. After the data grid was established the contours were drawn by eye using the standard rules of interpolation for constructing topographic and isohyetal maps.

Soil Moisture at Recharge

Soil moisture in the isolated tree study plot (L1) from late winter to early spring, the time when the soil was totally recharged, was quite similar from year to year. Though it was not the intent of the study to measure the maximum soil moisture held in the profile or to determine the time of recharge during any year, we did measure soil moisture within 5 days to a week after a number of major winter storms throughout the duration of the study.

In 1966, the first winter of measurement in plot Ll, soil moisture reached 45 to 51 percent moisture by volume at all depths, with the exception of the surface foot. Total soil moisture recharge was attained by the February 11 measurement, following more than 34 inches of rainfall. The distribution of soil moisture with depth and distance from the study tree was quite uniform (Fig. 13c). The only discrepancies were a zone of slightly higher moisture about 2 feet away from the tree at a depth of 4 feet and a zone of slightly lower moisture below a depth of about 12 feet. In horizontal profile, soil moisture storage around the study tree varied from 7.0 to 7.6 feet of water in 15 feet of soil. The 7.0-foot isomoisture lines were about 10 feet northwest and south of the tree and also 60 feet due north of the tree. The 7.6-foot profile was found 40 feet in the northwest

direction and a very small zone in the southwest direction about 20 feet from the study tree.

During the winter of 1967, the surrounding vegetation was cut isolating the study tree. On March 2, a uniform soil moisture content was observed throughout the study plot (Fig. 17b). Nearly 57 inches of rain had fallen prior to the March measurement. The recharge had progressed deeper than in February 1966. At the 15-foot depth, the soil. moisture was 48 percent by volume, whereas in 1966 it had reached 45 percent. January 1967 had been an unusually wet month. Precipitation was about 24 inches--nearly 12 inches above normal. In contrast, February 1967 had been an unusually dry and warm month. Precipitation was less than 1.5 inches--over 10 inches below normal. Transpiration by the coniferous vegetation was certainly a probability during this month. By March, the soil had drained substantially more than for the comparable period in 1966. There were very few zones of 51 percent soil moisture and the majority of the area contained 48 percent soil moisture. The surface had dried to 39 percent soil moisture and the 45 percent isomoisture line was found 3 to 4 feet in depth as in 1966. The total amount of water held in storage in 1967 was lower than in 1966--reflecting drainage and probably evapotranspiration. The driest zone in the plot was about 20 feet due east of the study tree--an area which contained 6.4 feet of water in 15 feet of soil. The wettest zone contained 7.4 feet of soil water. The pattern of soil moisture in winter 1967 was similar to that for 1966, except there was about 0.2-foot less water per 15 feet of soil in 1967 than in 1966.

The remainder of spring 1967 was quite wet. An additional 31 inches of rain fell between March and July--more than 13 inches above

normal for this period. Soil moisture held in the study plot at the end of June 1967 exceeded that measured in early May 1966, including that in the surface foot of soil.

The soil moisture in storage on March 4, 1968 (Fig. 20b) was again quite uniform and was very similar to the winter soil moisture storage in previous years. Seasonal rainfall to the March 1968 measurement was about 41 inches. There was a zone of 54 percent soil moisture at the 3-foot depth. The majority of the area was 48 percent moisture. A larger zone of 51 percent moisture was found below 13 feet than was observed in 1967. The surface 2 feet of soil were less than 45 percent soil moisture, but the soil moisture in the plot was fully recharged.

On March 27, 1969, after the study tree had been cut, soil moisture in the plot appeared quite similar to previous winters (Fig. 24b). About 80 inches of rain had fallen by the end of March. Fall and early winter rainfall was substantially above normal, but March rainfall was only about 2 inches--about 7 inches below normal. The majority of the study plot contained 48 percent soil moisture. Above 2 feet, the soil moisture was less than 45 percent, as was observed in earlier years. There was still a zone of high moisture at a depth of 3 to 4 feet. There were several zones of 51 percent moisture throughout the plot. Uniform soil moisture content is evident throughout the plot as can be seen in both the horizontal as well as vertical profiles. During this wet year, some zones reached 7.6 feet of water in the southwest, the northeast, and immediately surrounding the study tree, but a nearly identical pattern can be seen in the March 4, 1968 profile. As in prior years, the zone of low soil moisture was found

about 20 feet from the study tree in an easterly direction. By this late in the spring there had been an opportunity for substantial evapotranspiration. However, light rains fell periodically throughout March replenishing evaporated surface soil moisture.

In summary, soil moisture in the logged study plot was very uniformly recharged in terms of both depth and distance from the study tree. This uniformity was found each winter during the study. The "field capacity" of the logged plot was about 48 percent by volume with a zone of higher soil moisture about 3 to 4 feet beneath the tree and extending to a distance of 2 feet from the tree. Areas of lower soil. moisture were found within the surface 2 feet which could be attributable to texture, organic content of the soil, and surface evaporation between storms. The procedure of waiting 5 rainless days following storms before making a soil moisture measurement provided a substantial opportunity for surface evaporation as well as allowing internal drainage of the soil profile to proceed.

Depletion Trends

Each summer depletion season began with a fully recharged and uniform soil moisture profile with depth and distance from the study tree. Soil moisture depletion by evapotranspiration generally began in the spring after the last significant rain. Depletion of soil moisture continued through the summer without further recharge and was a function of atmospheric evapotranspirational demand and the amount of vegetation available to transpire soil water.

1. Partially cut condition. In 1962, 88 percent of the stand basal area in plot L1 was removed by logging. Consequently, in 1965

and 1966, study plot L1 was in a partially cut condition. Based on the degree of soil moisture depletion in the uncut control plots C1 and C2, 1965 had one of the lowest evapotranspirational uses and 1966 had one of the highest. The average amount of soil moisture left in a 15-foot deep soil profile in the uncut control plots was 6.15 feet of water at the end of the 1965 depletion season and only 4.56 feet of water in 1966.

Beginning with a uniform soil moisture profile in early spring 1966, by May 6, the surface moisture had been depleted to between 33 and 39 percent while the remainder of the soil remained between 45 and 48 percent moisture by volume (Fig. 14a). By May 19, soil moisture within 20 feet of the tree had been depleted to a nearly constant 45 percent (Fig. 14b). By early June, soil moisture within 20 feet of the tree had become about 42 percent and beyond 30 feet from the tree it was approximately 45 percent (Fig. 14c). The surface layers had dried to near 30 percent. The initial development of the three distinct lobes of lower soil moisture can begin to be observed in the May 6 profiles with 6.6 feet of water at the driest points. By early June these lobes had reached 6.0 feet of water in 15 feet of soil. This general pattern continued at progressively lower soil moisture contents through the summer.

By mid-July, beyond 30 feet from the tree, the soil moisture remained between 42 and 45 percent (Fig. 15b). A zone of low soil moisture at 36 percent developed from 2 to 15 feet from the tree at a depth of 8 to 12 feet. This region of low soil moisture began to appear in early June, but became more distinct by July. By the end of August, very distinct patterns of increasing soil moisture with

increasing distance from the tree had developed (Fig. 16a). The uniform zone of high soil moisture remained beyond 30 feet from the tree, as did the zone of low soil moisture 8 to 12 feet under the tree to a distance of 10 feet. There was a region of high soil moisture about 2 feet from the tree and 3 to 4 feet in depth that was observed throughout the spring and summer. The surface foot of soil had dried to about 27 percent soil moisture by mid-August where it remained for the rest of the summer.

By October 25, the end of the 1966 depletion period, the pattern of soil moisture throughout the plot was similar to earlier in the season, except soil moisture differences with depth and distance from the study tree had become much more graphic (Fig. 16c). The soil remained at a quite uniform 39 percent moisture content beyond a distance of about 40 feet from the tree below a depth of 4 feet. The soil moisture content 60 feet from the tree was less than that 40 feet from the tree due to the influence of surrounding vegetation which was not removed until the next phase of the study in 1967. The zone of lowest soil moisture in the plot was at a depth of 8 to 13 feet extending to a distance of 10 to 15 feet from the tree. In this zone, soil moisture had been depleted to about 24 percent by volume. The zone of high soil moisture at a distance of 2 feet from the tree and at a depth of 3 feet remained throughout the summer.

The pattern of soil moisture found in the partially logged plot on October 19, 1965 (Fig. 12c), was quite similar to the pattern on September 6, 1966 (Fig. 16b), one month earlier. There were three lobes of low soil moisture around the study tree at the end of the 1965 depletion season--a southeastern lobe with 4.4 feet of soil moisture in

15 feet of soil, a northwestern lobe also with 4.4 feet of moisture, and a southwestern lobe with 4.6 feet of moisture. With an additional 1 1/2 months of depletion in 1966, soil moisture by October 25 had been depleted to 3.8 feet of water per 15 feet of soil in the southeastern lobe and 4.0 feet of water in the western lobes (Fig. 16c). At the extreme northern edge of the plot, 60 feet from the study tree, there was a zone of low soil moisture. In 1965, the soil moisture in this region was depleted to 5.2 feet of water (Fig. 12c), and in 1966 reached 4.8 feet of water (Fig. 16c). The depletion of soil moisture in this area was not affected by the study tree, but was due to a large tree immediately outside the plot (Fig. 4). Zones of high soil moisture were found 40 to 60 feet from the tree in the northwestern and northeastern portions of the plot where soil moisture was 6.2 to 6.4 feet of water per 15 feet of soil at the end of the 1965 summer. At the end of the 1966 summer, these areas each contained 6.0 feet of water.

2. Isolated tree condition. The study tree was isolated by removing all of the peripheral vegetation within a 120-foot radius in December 1966. The depletion patterns in 1967 and 1968 were similar to those for the period prior to isolating the tree, but with some notable exceptions. As the depletion season progressed, the region from 20 to 40 feet from the tree no longer contained more soil moisture than the 40- to 60-foot region. The residual vegetation outside the plot had been removed and the isolines of soil moisture with depth were nearly horizontal beyond 20 feet from the tree. For example, in mid-July 1967, the main zone of soil moisture difference was found within a distance of 20 feet from the tree (Fig. 18a). Beyond 20 feet

from the tree below a depth of 4 feet, the soil moisture content was a uniform 45 percent by volume. At a depth of less than 4 feet, the influence of surface evaporation and transpiration by annual grasses and herbs was evident. Within these surface layers, the depletion of soil moisture was very similar from 20 to 60 feet from the tree. Closer to the tree, the depletion pattern was similar, in general, to the period before cutting, but differed in detail. The zone of low soil moisture remained 8 to 12 feet in depth and to a distance of 10 feet from the tree. The zone of high moisture at the 3-foot depth to a distance of 2 feet from the tree was still apparent. No longer were three primary lobes of depletion developing in the horizontal pattern. There were now only one or two main areas of depletion. The primary area of depletion was north and west of the study tree. Another small area of depletion developed southeast of the study tree. The major zone of low soil moisture in the extreme north portion of the plot 60 feet from the tree had been diminished.

The lowest soil moisture in the surface 2 feet was reached in late September (Fig. 19a). An early October rainfall of 2.8 inches partially wetted the surface 4 feet of soil by the October 13 re-measurement (Fig. 19b).

By October 30 (Fig. 19c), the end of the 1967 depletion season, the pattern of soil moisture below a depth of 2 feet had essentially returned to that observed on September 26. The influence of the isolated study tree extended 40 feet from the tree at a depth of 11 feet and 20 feet from the study tree at a depth of 5 feet. The greatest zone of soil moisture depletion occurred at a depth of 10 feet, where the soil moisture had been depleted to 30 percent by volume. Soil

moisture became progressively greater upward, outward, and downward from this point. The zone of highest soil moisture in the plot was directly under the study tree at a depth of 3 feet. The influence of surface evaporation seemed to extend to a depth of 2 feet. The primary zone of soil moisture depletion in the horizontal profile was 5 to 10 feet north and northwest of the tree. Soil moisture increased with distance from this region,

The uncut control plots, C1 and C2, were drier in 1968 than in 1967--4.8 feet of soil water remained in the 15-foot soil profile at the end of summer 1968, whereas 5.1 feet of water remained at the end of 1967. The minimum soil moisture attained in the isolated tree study plot in early October 1968 (Fig. 23b), was similar to that found in late September and late October 1967. However, in 1968 the lowest soil moisture attained northwest of the study tree was 4.6 feet of water in 15 feet of soil and in 1967 was 5.0 feet of moisture. The minimum soil moisture content was 27 percent in 1968 and 30 percent in 1967. The minimum soil moisture content found 40 feet from the study tree was about 42 percent by volume in both 1967 and 1968.

3. Bare condition. The study tree was cut in March 1969, leaving a bare plot which was maintained throughout the summer by cutting tanoak sprouts and herbaceous vegetation every 2 weeks as it appeared. The pattern of soil moisture in the study plot through this depletion season was dramatically different than that observed in either the 1965 and 1966 partially cut period or in the 1967 and 1968 isolated tree period. At the beginning of the depletion period in late March 1969 (Fig. 24b), the soil in the plot was very similar in moisture content with depth as was observed in previous years.

As the depletion season progressed, the zone of the lower soil moisture in the eastern portion of the plot remained distinct until early July when that area contained 6.2 feet of soil moisture (Fig. 25b), At that time the soil moisture content in this zone stabilized while soil moisture in the surrounding area continued to be depleted to about the same moisture content. The zone of high soil moisture at a depth of 3 feet and a distance of 2 feet from the stump of the study tree also remained as the season progressed.

By early October (Fig. 26c), the end of the depletion season for 1969, soil moisture in the plot had a dramatically different pattern than in comparable periods prior to cutting the study tree. Although the zone of high soil moisture 3 feet under the stump remained as it had prior to cutting the tree, the zone of low soil moisture 8 to 13 feet under the tree had completely disappeared. No longer were there major differences between the soil moisture within 20 feet of the study tree stump and that 20 to 60 feet from the stump. Below about 3 feet in depth, the soil moisture content remained quite uniform at about 45 percent by volume, which is similar to that in the region 40 to 60 feet from the tree during the period before the study tree was cut. Soil moisture closest to the study tree stump was higher than at any other location in the plot. This was opposite to that which had been observed when the tree was alive. The increased moisture is probably due to the contribution of the zone of high soil moisture immediately under the tree which had been observed throughout the study. Soil moisture in the surface foot of soil appeared to progressively increase toward the stump of the study tree. This was perhaps due to the presence of a greater volume of herbaceous vegetation such as

bracken fern and poison-oak farther from the tree. Shade and needle fall from the study tree probably retarded the growth of this ground-cover vegetation. In the first year after removing the study tree, the herbaceous vegetation had not yet invaded the plot within about 20 feet of the stump. Attempts to keep the surface in a bare condition after the study tree was isolated in 1967 were not entirely successful because herbaceous plants such as bracken fern and poison-oak are difficult to control by periodically cutting the tops. The density of low lying herbaceous vegetation was observed to generally increase beyond a distance of about 20 feet from the study tree prior to removal each fortnight during 1967, 1968, and 1969.

Total Summer Soil Moisture Depletion

The average soil moisture contained in each of three 5-foot depth classes at the end of the five summer seasons was obtained by planimetering the area within the right-hand portions of Figures 12c, 16c, 19c, 23b, and 26c bounded by the depth and distance from the study tree (Table 6). The soil moisture content in each of the six distance classes are plotted for the 2 years prior to isolating the study tree, the 2 years following isolating the study tree, and the 1 year after cutting the study tree and when the plot was in a bare condition (Fig. 28). The soil moisture content of the uncut control plot is included for comparison,

Surface 5 feet. Soil moisture contained in the surface 5 feet of soil at the end of depletion season was primarily the result of surface evaporation and evapotranspiration by shallow rooted grasses and herbs (Fig. 28a). The soil moisture content appears to be poorly related to

Table 6. Average soil moisture by 5-foot depth classes at the end of each summer depletion season in study plot L1.

Date	Depth (feet)	Distance from study tree (feet)					
		0-2	2-5	5-10	10-20	20-40	40-60
		Soil moisture (feet of water per foot of soil)					
10-19-65	0-5	.350	.335	.314	.318	.361	.363
	5-10	.294	.295	.307	.332	.392	.402
	10-15	.306	.296	.300	.346	.394	.406
10-25-66	0-5	.322	.319	.296	.295	.326	.334
	5-10	.274	.278	.272	.296	.362	.387
	10-15	.244	.250	.271	.320	.369	.395
10-30-67	0-5	.401	.390	.376	.375	.385	.382
	5-10	.354	.349	.340	.361	.410	.424
	10-15	.359	.350	.352	.379	.406	.424
10-9-68	0-5	.364	.355	.334	.335	.351	.345
	5-10	.313	.326	.332	.345	.395	.411
	10-15	.335	.325	.335	.365	.397	.414
10-2-69	0-5	.410	.401	.377	.368	.371	.350
	5-10	.447	.451	.437	.417	.424	.414
	10-15	.441	.441	.442	.433	.426	.426

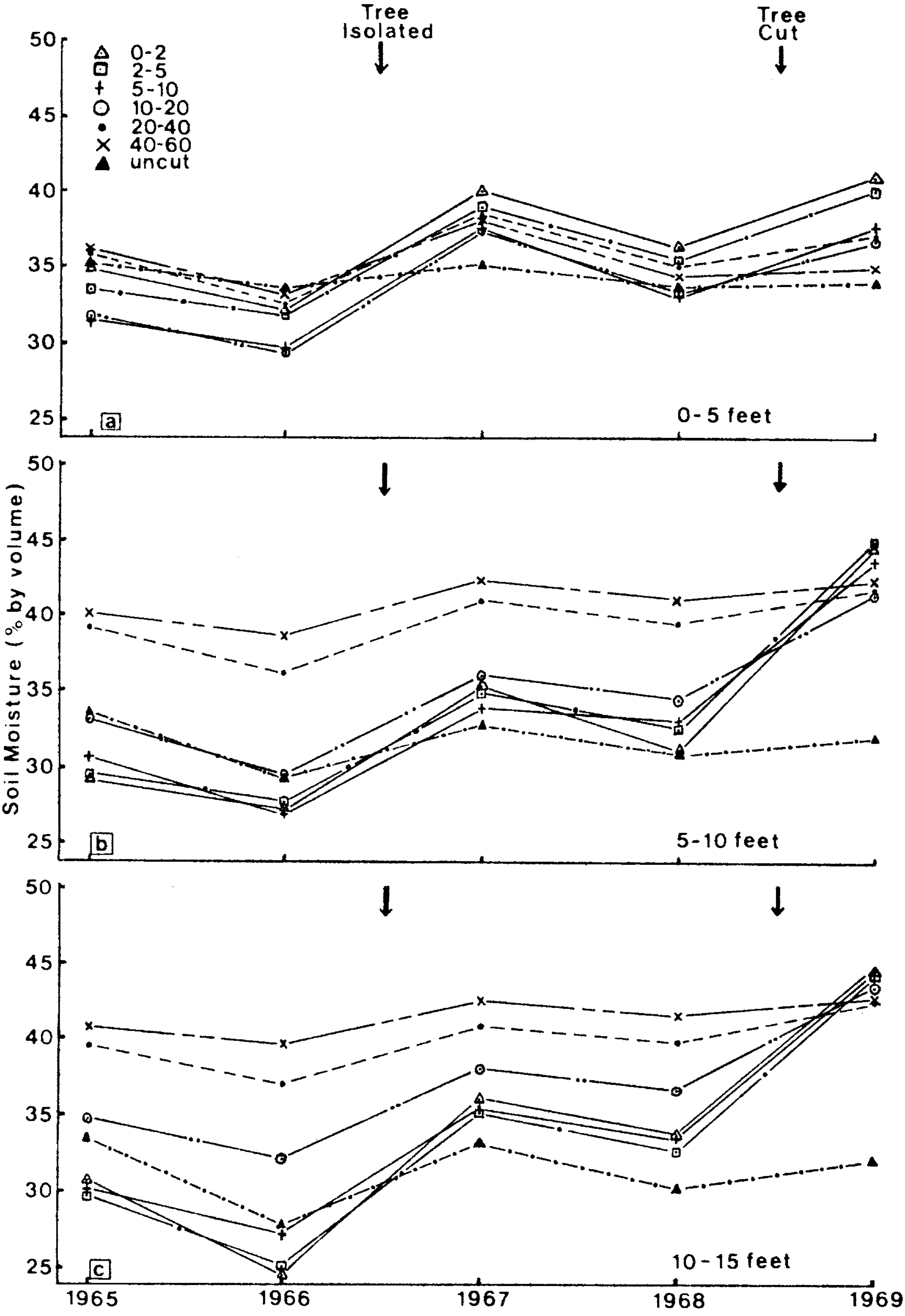

Figure 28. Average soil moisture content at the end of each summer depletion season between the depths of a) 0-5 feet, b) 5-10 feet, and c) 10-15 feet for different distances from the study tree and for the uncut plots.

distance from the study tree, but was affected by tree removal. Prior to isolating the study tree in spring 1967, the area 40 to 60 feet from the study tree had more soil moisture at the end of the growing season than the regions closer to the study tree. The region 20 to 40 feet from the tree contained slightly less soil moisture, but was similar to that 40 to 60 feet from the tree. An intermediate soil moisture content was found in the region closest to the study tree. The lowest soil moisture content was found in the two regions which ranged from 5 to 20 feet from the study tree. During these first 2 years of the study, the uncut control plot experienced the highest and lowest soil moisture content observed for this depth class at the end of the 1965 and 1966 summer periods, respectively.

During the next 2 years, 1967 and 1968, after the study tree was isolated, the soil moisture content in the uncut control plot was nearly identical to the previous 2 years. Soil moisture was higher in the 0- to 2-foot and the 2- to 5-foot distance classes than in the regions beyond 20 feet from the study tree. The area within 5 to 20 feet from the study tree continued to have the lowest soil moisture.

In 1969, following removal. of the study tree, the region 40 to 60 feet from the stump of the study tree contained less soil moisture than any other zone in the plot. It is of interest to note that the four regions within 20 feet of the study tree stump produced nearly parallel lines when the soil moisture content at the end of the depletion season for each of the 5 years are connected. This is an indication that the process of evaporating soil moisture within this area was similar when the plot was partially cut, when the study tree was isolated, and when the study tree was cut. If different mechanisms

of evaporation were present, we would expect the slope of the soil moisture curves to change from year to year relative to adjacent areas. For example, during high potential evapotranspiration years, such as 1965 and 1967, we would expect a larger difference between each strata than in low evapotranspiration years, such as 1966 and 1968. This is found for the regions beyond 20 feet from the tree, but not for the regions closer than 20 feet from the tree. Between 1966 and 1967, when the plot was relogged to isolate the study tree, the curves crossed. During the isolated tree phase, in 1967 and 1968, the 20- to 40-foot and 40- to 60-foot distance class moisture curves were parallel as in the partial-cut phase in 1965 and 1966. This relationship diverged slightly when the study tree was cut in 1969.

The soil moisture stored in the uncut control plots at the end of the depletion season can be used as a form of climatic control on the effect of the vegetation treatments in the logged study plot. Average soil moisture in the uncut control plots was within 1 percent of that found 40 to 60 feet from the study tree for all years except 1967, the year immediately following the isolation of the study tree. During this year soil moisture in the uncut control plots was about 3 percent lower than that 40 to 60 feet from the study tree. It is of interest to note that lines connecting the end-of-season soil moisture are parallel for the regions 0 to 2, 2 to 5, 5 to 10, and 10 to 20 feet from the study tree from the beginning to the end of the study. The line for the region 20 to 40 feet from the study tree is intermediate between the variation found between the 0- to 20-foot region and the 40- to 60-foot region. The 20- to 40-foot zone is the transition between that area which is affected by the study tree and that area

which is outside the influence of the tree. There was less variation in soil moisture contained in the uncut control plot than in the study tree plot. The roots of trees and herbaceous vegetation probably fully occupied the surface 5 feet of soil in the uncut control plot. For this reason, the soil moisture in the control plot was depleted to essentially the same moisture content during years of both low and high potential evapotranspiration.

In summary, soil moisture loss from the surface 5 feet of soil seems to be due to surface evaporation and evapotranspiration by small herbaceous vegetation. The vegetation treatments in the study plot had a minor affect on soil moisture storage in the surface layers at the end of the summer depletion period.

5 to 10 feet. Soil moisture at a depth of 5 to 10 feet was much more variable and much more dependent upon distance from the study tree than was the soil moisture within the surface 5 feet (Fig. 28b). Apparently surface evaporation and transpiration by herbaceous vegetation and grasses had less influence on soil moisture depletion at this depth than tree roots. The soil moisture content 40 to 60 feet from the study tree was higher than at any other distance for each year with the exception of 1969, the year after the study tree was cut. In 1965 and 1966, before the study tree was isolated, there was a progressive decrease in soil moisture content as distance from the tree increased. Within 10 feet of the study tree, the soil moisture content was quite similar. After the study tree was isolated in 1967, there was an increase in soil moisture relative to that in the uncut control plot at all distances from the study tree. Beyond 5 feet from the study tree,

the soil contained the same ratio of moisture relative to the uncut control plot for both 1967 and 1968. That is, the slopes of the lines connecting the end-of-season soil moisture for 1967 and 1968 for each distance region beyond 5 feet from the study tree were essentially the same as the slope for the uncut control plot. A similar relationship can be observed for the 2 years prior to isolating the study tree, except the quantity of soil moisture in the plot was less, relative to the uncut control plot. Within 5 feet of the study tree, the slope of these lines was not parallel to that in the uncut control plot.

In 1969, the year after the study tree was cut, a major change occurred in the relationship between the soil moisture contained in the various regions. The highest soil moisture content was found within 5 feet of the stump of the study tree, followed by the region 5 to 10 feet from the stump. The average soil moisture for the three regions beyond 10 feet from the stump was within 1 percent of each other. All of the distance regions showed a substantial increase in soil moisture in 1969 relative to the period before cutting the study tree with the exception of the region 40 to 60 feet from the stump.

Lines connecting the end-of-season soil moisture in the uncut control plot were essentially parallel to lines connecting similar data for the 40- to 60-foot distance region for all years within this 5- to 10-foot depth class. However, the uncut control plot contained about 10 percent less soil moisture by volume than the region 40 to 60 feet from the study tree for all years. Lines connecting end-of-season soil moisture for the region 20 to 40 feet from the study tree were also parallel to those for the 40- to 60-foot distance and for the uncut control plot except after the study tree was removed in 1969. The uncut

control plot contained 2 to 3 percent more soil moisture than the region within 20 feet of the study tree for the 2 years before the tree was isolated early in 1967. Then in 1967 and 1968, the uncut control plot contained 1 to 2 percent less water than the region within 20 feet of the study tree. In 1969, after the study tree was removed, there was 10 to 13 percent less soil water in the uncut control than in this area of the study plot.

10 to 15 feet. During years of high evaporative demand, such as in 1966 and 1968, the uncut control plot utilized more soil water at 10 to 15 feet in depth than at a depth of 5 to 10 feet (Fig. 28c). During periods of lower demand, such as in 1965, 1967, and 1969, soil moisture depletion was nearly identical from the 5- to lo-foot depth and from the 10- to 15-foot depth in the uncut control plot.

In the study tree plot, the soil moisture in the area from 20 to 60 feet from the tree at a depth of 10 to 15 feet was nearly identical to that at a depth of 5 to 10 feet for all years of the study. However, prior to isolating the study tree in 1967, soil moisture in the uncut control plot at the end of the 1965 and 1966 depletion seasons contained about 3 percent more soil moisture than the area within 2 feet of the study tree. After isolating the study tree, the uncut control plot contained about 3 percent less soil moisture than the area within 2 feet of the study tree. The parallel soil moisture curves are a good indication that the use of soil moisture by the isolated tree was similar to that by the uncut forest.

Before isolating the study tree, the uncut control plot contained about 1 percent more soil moisture than the area within 20 feet of the tree. After isolating the study tree, the vegetative surface area

available for evapotranspiration was reduced in the study plot and the uncut control plot contained about 3 percent less soil moisture than the area within 20 feet of the isolated tree. In 1969, after the study tree was cut and the plot was bare, the uncut control plot contained about 12 percent less soil moisture than the area within 20 feet of the stump of the study tree. This is a definitive statement on the relative use of soil moisture by the isolated tree compared to an uncut forest.

<u>Total 15-foot profile</u>. The total amount of soil moisture contained in the 15-foot deep soil profile at the end of the summer depletion periods for each of the six concentric distances from the study tree is found in Table 7. These values were obtained by superimposing the concentric distances shown in Figure 4 on the appropriate soil moisture isopleth represented in the left portion of Figures 12 through 27 for the desired date. The average soil moisture within each concentric region was calculated by measuring the area within each isopleth. The pattern generally follows that discussed earlier for the three 5-foot depth classes.

Let us assume the soil moisture at the end of the summer depletion season in the area 40 to 60 feet from the study tree is unaffected by the study tree. This is a reasonable assumption based on the lack of response by this region after the study tree was cut in 1969. If we subtract the soil moisture in the regions closer to the tree from the soil moisture 40 to 60 feet from the tree, we obtain a form of climatic adjustment to the soil moisture depletion within the plot which is independent of vegetation treatments (Table 8). This calculation can be generalized by the equation:

Table 7. Average soil moisture within the surface 15 feet of soil at the end of each summer depletion period in study tree plot L1 for each of the six concentric distances from the study tree from 1965 through 1969.

Date of survey	Distance from study tree (feet)					
	0-2	2-5	5-10	10-20	20-40	40-60
	feet of water					
10-19-65	4.72	4.73	4.72	4.98	5.59	5.93
10-25-66	4.16	4.17	4.20	4.69	5.35	5.65
10-30-67	5.60	5.56	5.48	5.61	5.98	6.20
10-9-68	5.07	5.12	5.06	5.24	5.64	5.92
10-2-69	6.57	6.49	6.34	6.22	6.15	6.05

Table 8. Average soil moisture within the surface 15 feet of soil at the end of each summer depletion period in study tree plot L1 for each of the six concentric distances from the study tree relative to soil moisture 40 to 60 feet from the study tree from 1965 through 1969 (from Table 7).

Date of survey	Distance from study tree (feet)					
	0-2	2-5	5-10	10-20	20-40	40-60
	feet of water					
10-19-65	1.21	1.20	1.21	.95	.34	0
10-25-66	1.49	1.48	1.45	.96	.30	0
10-30-67	.60	.64	.72	.59	.22	0
10-9-68	.85	.80	.86	.68	.28	0
10-2-69	-.52	-.44	-.29	-.17	-.10	0

$$y_i = x_{40\ \text{to}\ 60_i} - x_{d_i},$$

where y_i is the adjusted soil moisture in year i, $x_{40\ \text{to}\ 60_i}$ is measured soil moisture 40 to 60 feet from the study tree in year i, and x_{d_i} is the measured soil moisture within the d^{th} distance region in the year i.

As we discussed earlier, there is a general pattern of decreasing soil moisture content at the tree is approached. However, each of the three regions within 10 feet of the study tree contained about equal soil moisture at the end of each summer except 1969. Relative to the area 40 to 60 feet from the tree, there was about twice the moisture use within 10 feet of the study tree in 1965 and 1966 than in 1967 and 1968, after the tree was isolated (Table 8). For example, in 1965 there was about 1.2 feet less soil moisture within 10 feet of the study tree than in the region 40 to 60 feet from the tree. In 1966, the difference between these regions was about 1.5 feet of water. In comparison, the same relationship yielded a difference of about 0.65 and 0.85 feet of water for 1967 and 1968, respectively. In 1969, the pattern reversed and soil. moisture content increased as the tree stump was approached relative to the area 40 to 60 feet from the stump.

In 1969, the plot was kept essentially bare of vegetation. As discussed earlier, it is probably not unreasonable to assume that the increase in soil moisture toward the tree stump in this bare plot at the end of the 1969 depletion season was principally due to a combination of several factors including:

1) Variability in soil texture and moisture holding characteristics within the plot.

2) An artifact of the neutron method of soil moisture measurement. The neutron method measures the concentration of principally hydrogen atoms within the influence of the neutron swarm. Hydrogen atoms contained in soil water, root moisture, and organic matter such as root tissue are equally and indiscriminately measured as "soil moisture". It is reasonable to assume the concentration of organic matter, primarily in the form of roots, increases near the tree. Large structural roots are particularly concentrated near the base of trees and contain substantial amounts of hydrogen in the form of wood and water.

3) There may have been more persistent herbaceous vegetation beyond the influence of the tree which was difficult to control and keep removed. These herbs may have extracted a greater amount of soil moisture as the distance from the tree increased. This is probably a minor factor, however, and the relative influence would remain constant from year to year.

In any case, the exact cause of the "moisture" difference before and after cutting the study tree is not greatly important, because a similar influence would have been present prior to cutting the study tree. Certainly, vegetation conditions throughout the plot were essentially identical in 1967, 1968, and 1969, with the exception that study tree was absent in 1969. In 1965 and 1966, several trees near the study tree were removed, but the region from 40 to 60 feet from the study tree was relatively unaffected. Thus, we could further adjust the relative soil moisture from Table 8 to reflect equal soil moisture throughout the study plot in 1969 (Table 9, Fig. 29). That is, the average soil moisture in each distance region found in Table 7 was

Table 9. Average soil moisture within the surface 15 feet of soil at the end of each summer depletion period in study tree plot L1 for each of the six concentric distances from the study tree relative to soil moisture in the plot after the tree cut in 1969 (from Table 8).

Date of Survey	Distance from study tree (feet)					
	0-2	2-5	5-10	10-20	20-40	40-60
	feet of water					
10-19-65	1.73	1.64	1.50	1.12	.44	0
10-25-66	2.01	1.92	1.74	1.13	.40	0
10-30-67	1.12	1.08	1.01	.76	.32	0
10-9-68	1.37	1.24	1.15	.85	.38	0
10-2-69	0	0	0	0	0	0

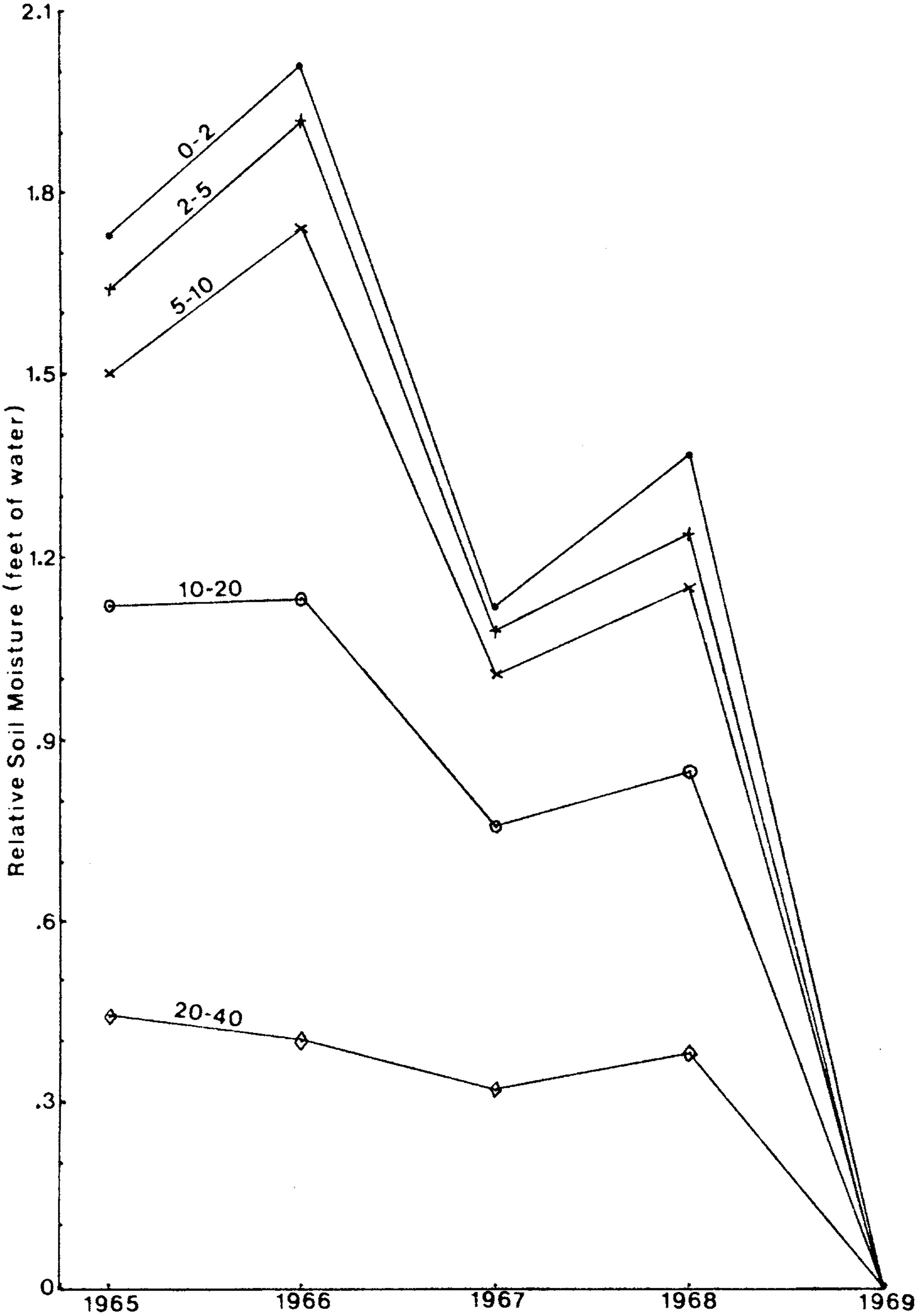

Figure 29. Relative soil moisture in the study tree plot at the end of each summer depletion period for each of 5 concentric distances from the study tree from Table 9.

first climatically adjusted to equalize the differences in the soil moisture content within the region 40 to 60 feet from the study tree at the end of each summer depletion season (Table 8). Then the values found in Table 8 were further adjusted to equalize the soil moisture differences between each distance from the stump of the study tree at the end of the 1969 depletion season (Table 9). This calculation can be generalized by the equation:

$$s_i = (x_{40\ to\ 60_{69}} - x_{d_{69}}) - (x_{40\ to\ 60_i} - x_{d_i}),$$

$$= (x_{40\ to\ 60_{69}} - x_{d_{69}}) - y_i,$$

where s_i is the adjusted soil moisture in the year i, $x_{40\ to\ 60_{69}}$ is the measured soil moisture 40 to 60 feet from the study tree in 1969, $x_{d_{69}}$ is the measured soil moisture within the d^{th} distance region in 1969, and $x_{40\ to\ 60_i}$, x_{d_i}, and y_i are as defined earlier. These two adjustments allow us to more clearly see the relationships between soil moisture and vegetation removal and between soil moisture and distance from the study tree. For example, if soil moisture depletion throughout the plot in 1969 is considered to be equal at all distances from the stump, then, at the end of the 1965 depletion season, there was 1.73 feet more soil moisture depletion within 2 feet of the study tree than in the region 40 to 60 feet from the tree. Whereas soil moisture was about equal within 10 feet of the study tree in Tables 7 and 8, when we account for the soil moisture variability in the bare plot in 1969, we now find a progressive decrease in soil moisture depletion with increasing distance from the tree (Fig. 29, 30).

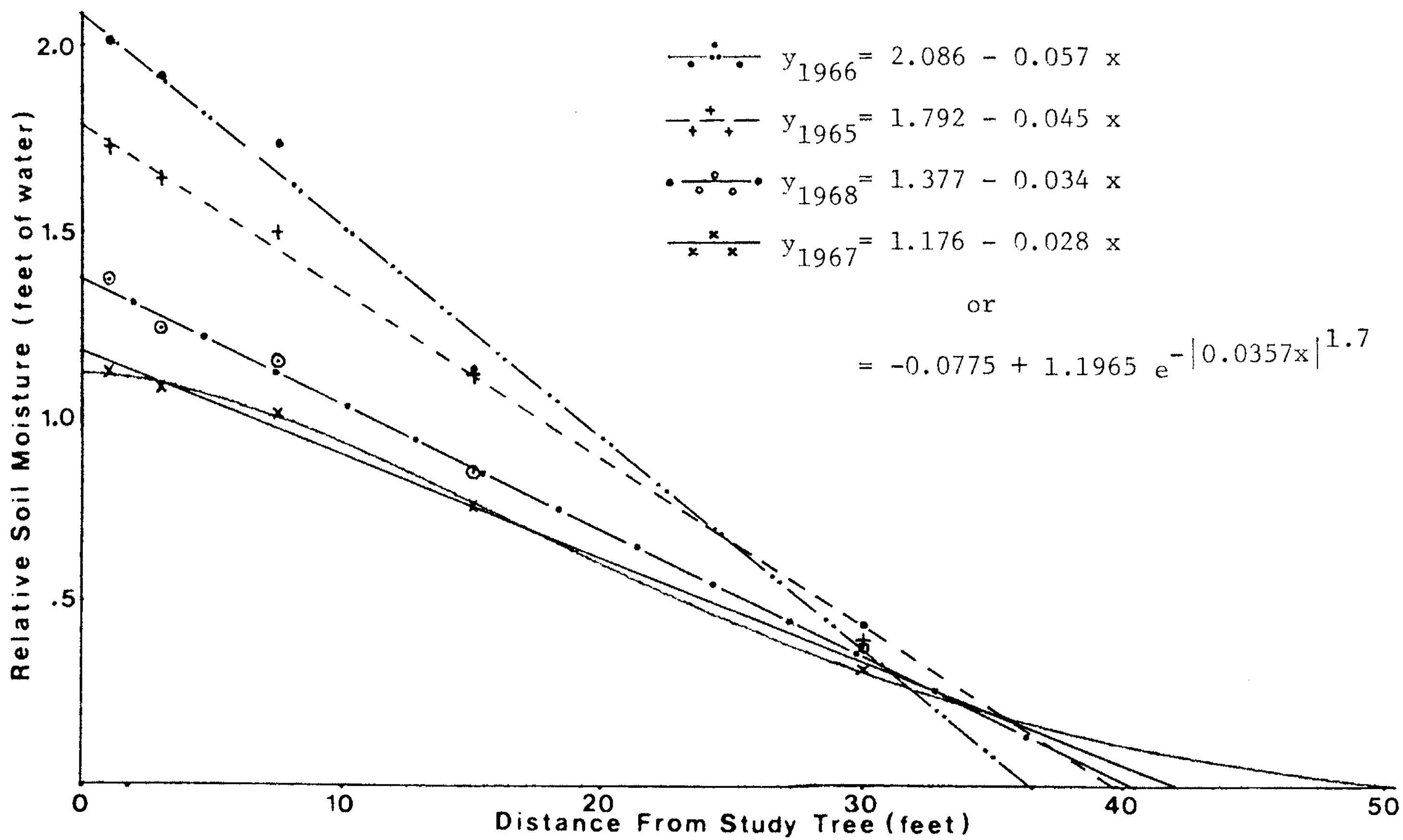

Figure 30. Relationship between distance from the study tree and relative soil moisture at the end of the 1965, 1966, 1967, and 1968 depletion seasons from Table 9.

A sigmoid curve can be fitted by least squares to the adjusted soil moisture at the midpoint of each distance strata, that is, at 1, 3, 7.5, 1.5, 30, and 50 feet from the study tree, for each year of the study, with excellent results.

The general form of the sigmoid equation is:

$$Y = \beta_0 + \beta_1 \frac{e^{-\left|\frac{x}{c-1}\right|^d} - e^{-\left|\frac{-1}{c-1}\right|^d}}{1 - e^{-\left|\frac{-1}{c-1}\right|^d}}$$

where β_0 and β_1 are the regression coefficients, c and d are shape parameters, and e is the base of the natural system of logarithms. The shape parameters were obtained using the method described by Jensen and Homeyer (1970).

At least squares fit to the 1967 data (Table 9) yields a simplified form to the general equation,

$$\hat{Y}_{1967} = 0.0775 + 1.1965\ e^{-|0.0357x|^{1.7}}$$

where Y is the predicted adjusted soil moisture at the end of summer 1967 in feet of water and x is the midpoint of each distance strata in feet. The explained variance (r^2) is 0.9995. Similar equations could be developed for the other years. However, we can approximate the sigmoid relationship to a high degree for the area within 40 feet of the study tree with a linear least squares fit.

$$\hat{Y}_{1965} = 1.792 - 0.045\ x \qquad r^2 = 0.998$$

$$\hat{Y}_{1966} = 2.086 - 0.057\ x \qquad r^2 = 0.990$$

$$\hat{Y}_{1967} = 1.176 - 0.028\ x \qquad r^2 = 0.993$$

$$\hat{Y}_{1968} = 1.377 - 0.034\ x \qquad r^2 = 0.995$$

For most applications of estimating water use and the degree of influence of adjacent trees upon one another, the subtle shape of the curve at the extreme limits of influence, that is as Y approaches 0, is of minor interest. For example, using the linear relationships, in 1966, the year of greatest soil moisture depletion, we would predict the influence of the tree to extend to about 37 feet and in 1967, the year of least soil moisture depletion, to 42 feet.[2] Thus, though it is artistically and theoretically preferable to use a sigmoid relationship, in practice a linear fit to those data points where Y is positive (not 0) is just as good. Given only six data points and explained variances of 0.9995 and 0.993 for the sigmoid and linear relationships, respectively, for the 1967 data, as a general rule, the simpler linear form should be selected.

The total water use by the vegetation within 40 feet of the study tree can now be estimated, relative to the soil moisture depletion in the bare area 40 to 60 feet from the tree (Table 10). The difference

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[2] It is not statistically correct to assign a value to the dependent variable, Y, and calculate the value of the independent variable, x. One should recalculate the least squares fit to the observed data, reversing the dependent and independent variables. However, in the case where the explained variances are quite high, an adequate approximation can be made even though the statistical rules are violated. For example using the 1967 data (Table 9), if distance is the independent variable, the calculated influence of the tree extends to 41.82 feet, and if distance is the dependent variable, the calculated influence extends to 41.60 feet.

Table 10. Volume of soil moisture depleted within 40 feet of the study tree in excess of that depleted 40 to 60 feet from the study tree when adjusted for equal soil moisture in the plot after the tree was cut.

Distance from study tree (feet)	0-2	2-5	5-10	10-20	20-40	Total
Area in region (ft^2)	13	66	236	942	3770	5027
Date of survey	cubic feet of water					
10-19-65	22	108	354	1055	1659	3198
10-25-66	26	127	411	1064	1508	3136
10-30-67	15	71	238	716	1206	2246
10-9-68	18	82	271	801	1433	2605

in the volume of water depleted is calculated by multiplying the area within each concentric region by the average soil moisture difference in that region from Table 9. In 1965 and 1966, the period prior to isolating the study tree, the area within 40 feet of the study tree used 3198 and 3136 cubic feet more soil moisture than the area 40 to 60 feet from the tree. After removing all vegetation surrounding the study tree, these values were reduced to 2246 and 2605 cubic feet of water for 1967 and 1968, respectively. Thus, the residual vegetation which was removed in 1967 in order to isolate the study tree used from about 550 to 900 cubic feet more soil moisture than the isolated tree depending on the year of measurement.

Depletion During Fall Recharge

With the beginning of the rainy season in the fall, a distinct wetting front could be observed which eventually progressed through the soil profile. The presence of this wetting front defined the initiation of the fall recharge period. Summer rainfall was not large enough to produce an observable or persistent wetting front. As fall rains continued to wet the surface soil layers and the wetting front progressed deeper, soil moisture below the wetting front continued to be depleted by the vegetation. Unfortunately this study was not designed to measure depletion during the recharge period. Most of the literature, models, and students of evapotranspiration have implied that the extraction of soil moisture does not occur in the drier soil below a recharge wetting front because more energy is required to remove soil water from these deeper and drier levels. The vegetation, it is often argued, would preferentially satisfy its evapotranspirational

requirements from the more moist zones above the wetting front. Thus, these observations of soil moisture depletion during the fall are incomplete. Since no tensiometers or thermocouple psychrometers were installed and no direct measure of soil water potential was made, the following comments must be viewed with caution.

In some years the period between successive soil moisture measurements was too great to observe depletion below the wetting front because recharge had progressed throughout the 20-foot depth of measurement. However, in most years soil moisture depletion was observed below the wetting front on successive measurements as the wetting front progressed in depth. The depth of recharge at the time of measurement was quite variable between years as well as between access tubes. The rate of recharge was some complex function of the amount, duration, and intensity of antecedent rainfall and the characteristics of the location of each of the soil moisture access tubes. In most of the access tubes, soil moisture recharge and depletion progressed consistently each fall. For example, in the uncut control plots Cl and C2, tube 42 gained some moisture throughout the entire 20-foot access tube depth following the first major storm of the fall--even in 1968 when only 3.16 inches of rain fell between the October 8 and October 22 measurement (Table 11, Fig. 31, 32, 33, 34). In other access tubes, such as tubes 8 and 64, there was an abrupt wetting front with an increase of soil moisture above and a decrease below relative to the previous measurement. In a third case, such as in tubes 2 and 22, there was a distinct wetting front with increased soil moisture above, an intermediate zone where soil moisture neither increased nor decreased, and a deeper zone where soil moisture decreased. None of the access

Table 11. Changes in soil moisture in the uncut control plots C1 and C2 during the fall recharge period.

	1964-65		1965-66				1967-68		1968-69			
	10/22 to 11/20		10/18 to 12/8		12/8 to 1/10		11/2 to 1/24		10/8 to 10/22		10/22 to 1/10	
Hole no.	Soil moisture change (in.)	Depth (feet)	Soil moisture change (in.)	Depth (feet)	Soil moisture change (in.)	Depth (feet)	Soil moisture change (in.)	Depth (feet)	Soil moisture change (in.)	Depth (feet)	Soil moisture change (in.)	Depth (feet)
2	+8.64 -.60	0-16 16-20	+8.70 -.18	0-11 11-20	+12.66 -.70	0-13 13-20	+12.94 —	0-20 —	+2.63 —	0-20 —	+13.88 —	0-20 —
8	+10.13 -1.50	0-7 7-20	+10.32 -.76	0-8 8-20	+8.22 -.68	0-11 11-20	+14.18 -.76	0-11 11-20	+3.61 -.75	0-6 6-20	+13.26 -.70	0-13 13-20
22	+9.42 -.53	0-7 7-20	+9.84 -.37	0-12 12-20	+10.45 -.82	0-13 13-20	+14.98 -.52	0-14 14-20	+5.47 —	0-20 —	+12.38 -.16	0-17 17-20
38	+11.30 -.64	0-14 14-20	+10.75 -.32	0-16 15-20	+10.40 -.58	0-14 14-20	+14.83 -.19	0-14 14-20	+2.34 —	0-20 —	+14.69 -.40	0-14 14-20
42	+10.57 —	0-19 —	+8.48 —	0-19 —	+13.50 —	0-19 —	+15.48 -.10	0-18 18-19	+2.20 —	0-19 —	+16.46 —	0-19 —
64	+11.44 -1.31	0-12 12-19	+12.37 -1.04	0-10 10-19	+9.12 -.53	0-14 14-19	+16.64 -1.25	0-12 12-20	+1.07 -.22	0-4 4-20	+17.18 -1.16	0-12 12-20
Average increase decrease	10.25 -.76		10.08 -.44		10.72 -.55		14.84 -.47		2.89 -.16		14.64 -.40	
Precipitation (in.)	11.26		13.23		17.12		22.02		3.16		24.49	

CALCULATED WATER BALANCE (inches)

	1964-65 10/22 to 11/20	1965-66 10/18 to 12/8	1965-66 12/8 to 1/10	1967-68 11/2 to 1/24	1968-69 10/8 to 10/22	1968-69 10/22 to 1/10
Thornthwaite evapotranspiration	1.01	2.59	.33	2.00	.77	1.96
Change in soil moisture storage	+10.25	+10.64	+8.52	+17.32	+2.39	+19.18
"Runoff"	0	0	8.27	2.70	0	3.35

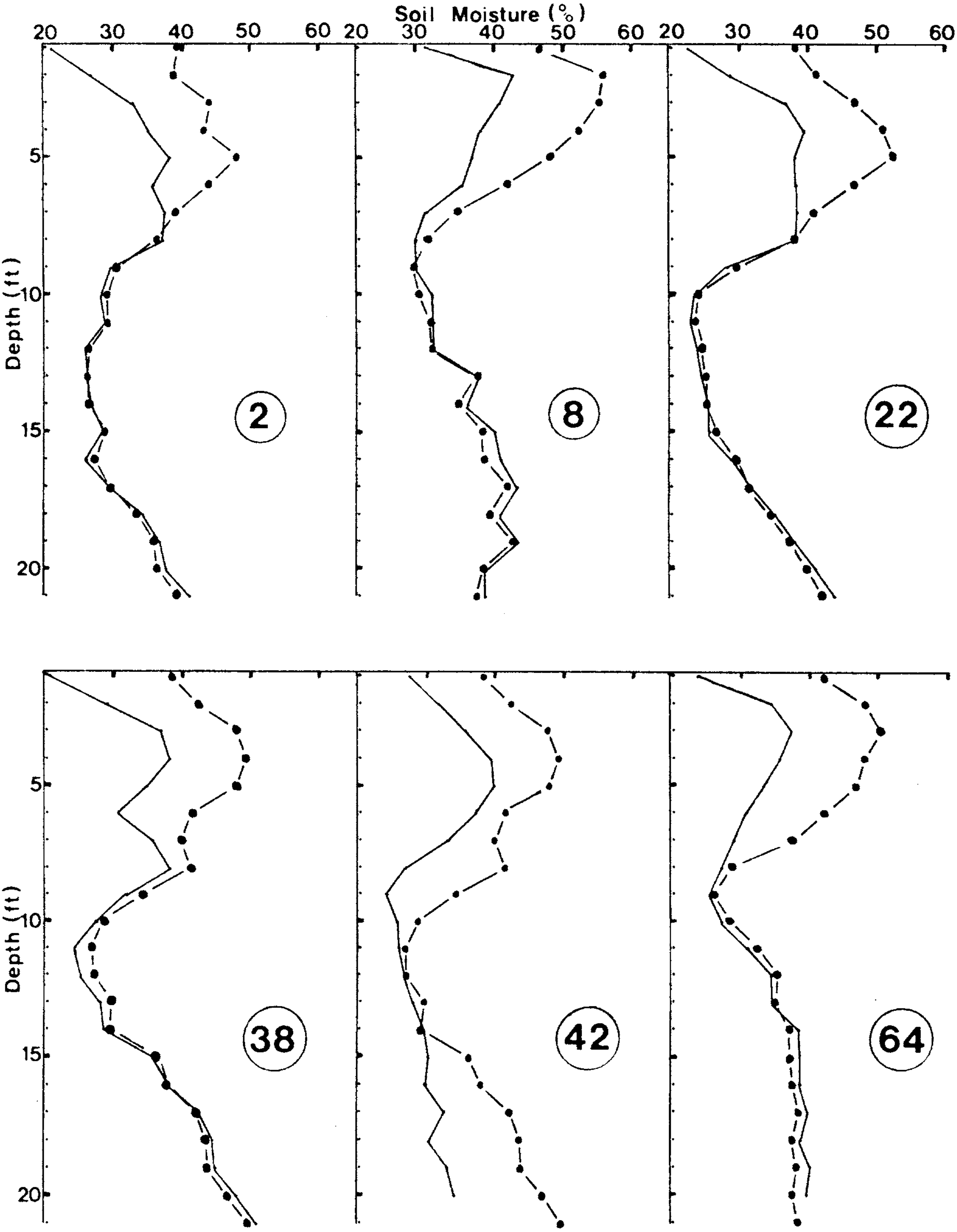

Figure 31. Profiles of soil moisture content with depth at each of the six access tubes in the uncut control plots during the 1964-65 fall recharge period. ——— 10/22/64; •———• 11/20/64

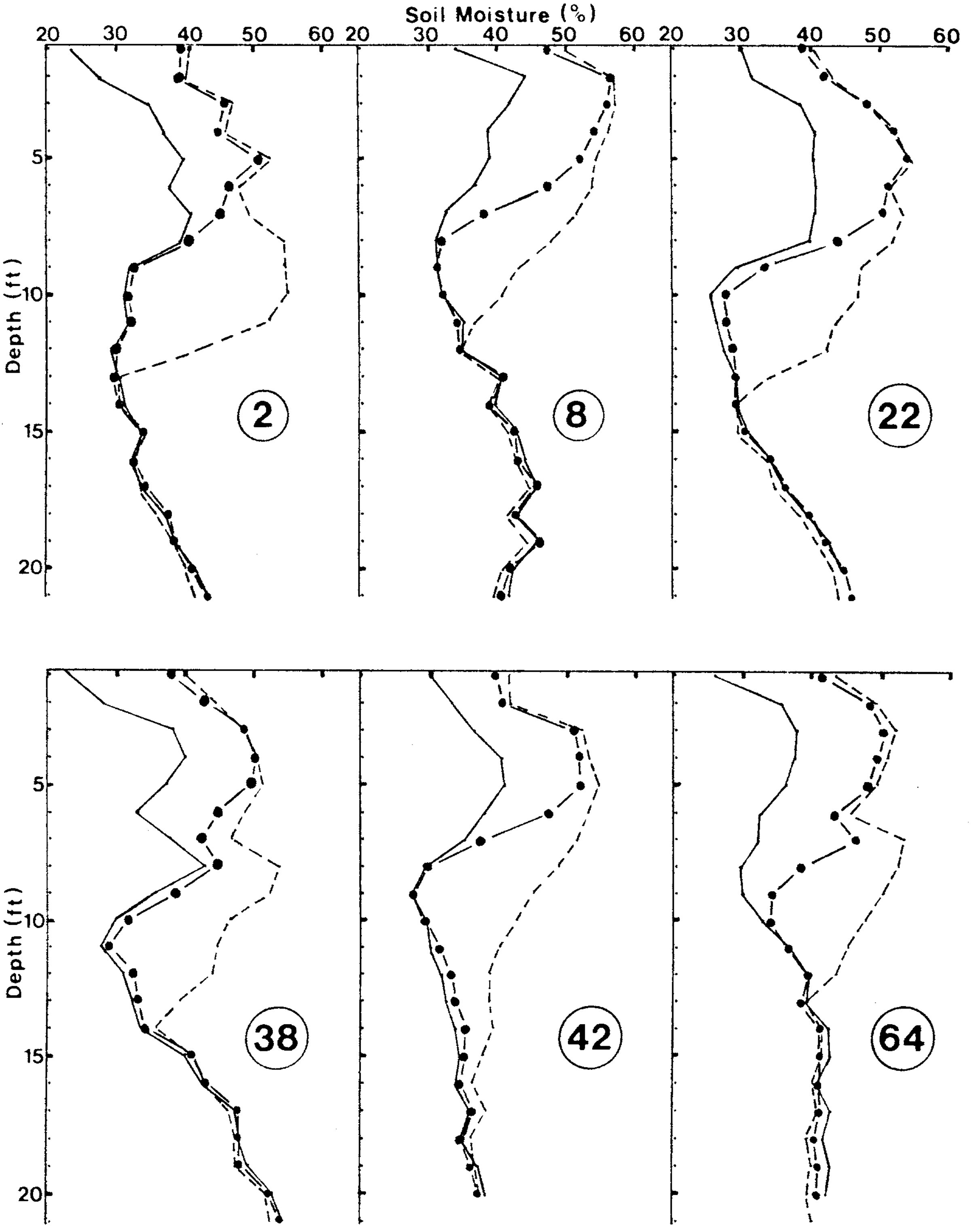

Figure 32. Profiles of soil moisture content with depth at each of the six access tubes in the uncut control plots during the 1965-66 fall recharge period. ——— 10/18/65; •——• 12/8/65; — — — 1/10/66

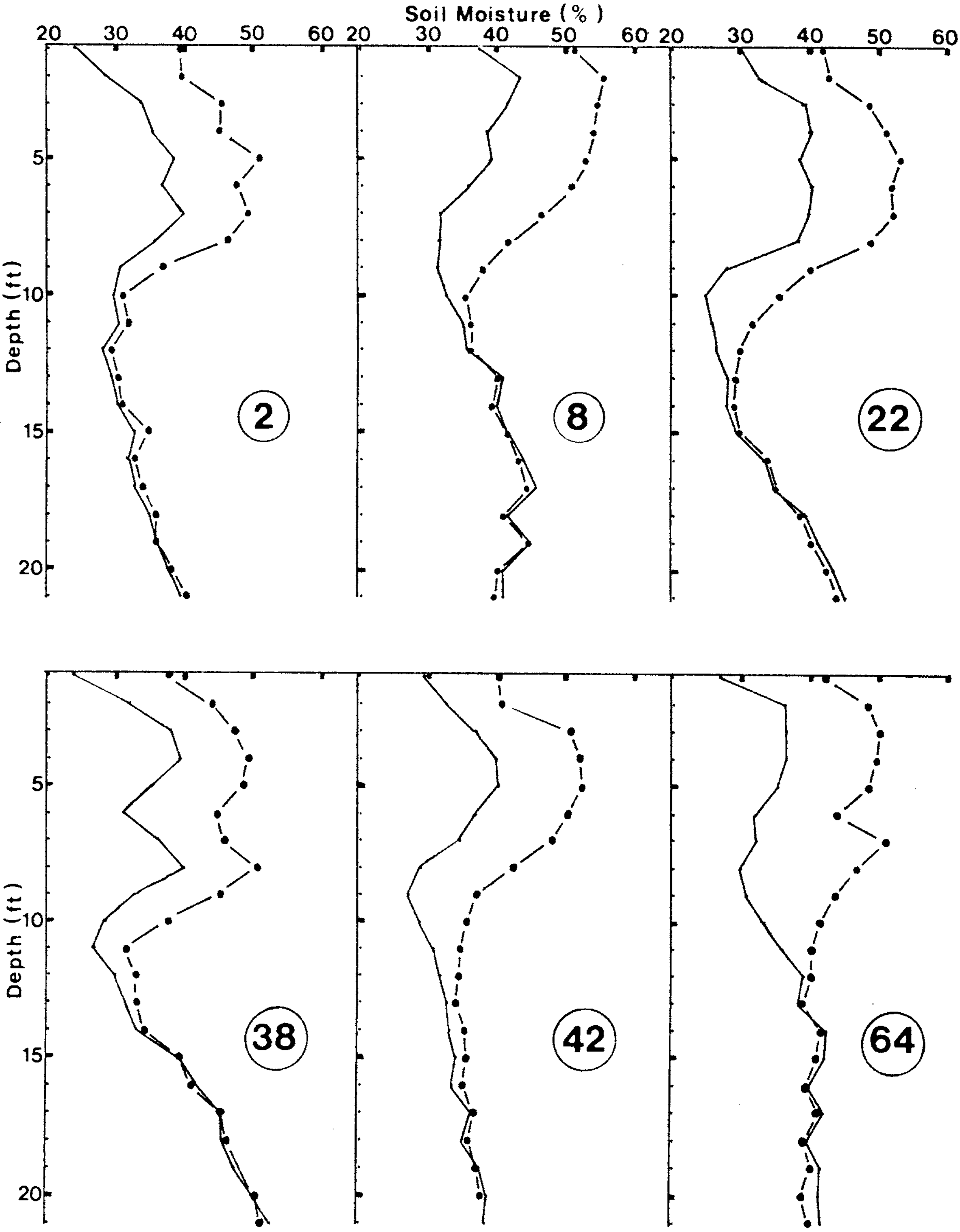

Figure 33. Profiles of soil moisture content with depth at each of the six access tubes in the uncut control plots during the 1967-68 fall recharge period. ——— 11/2/67; •——• 1/24/68

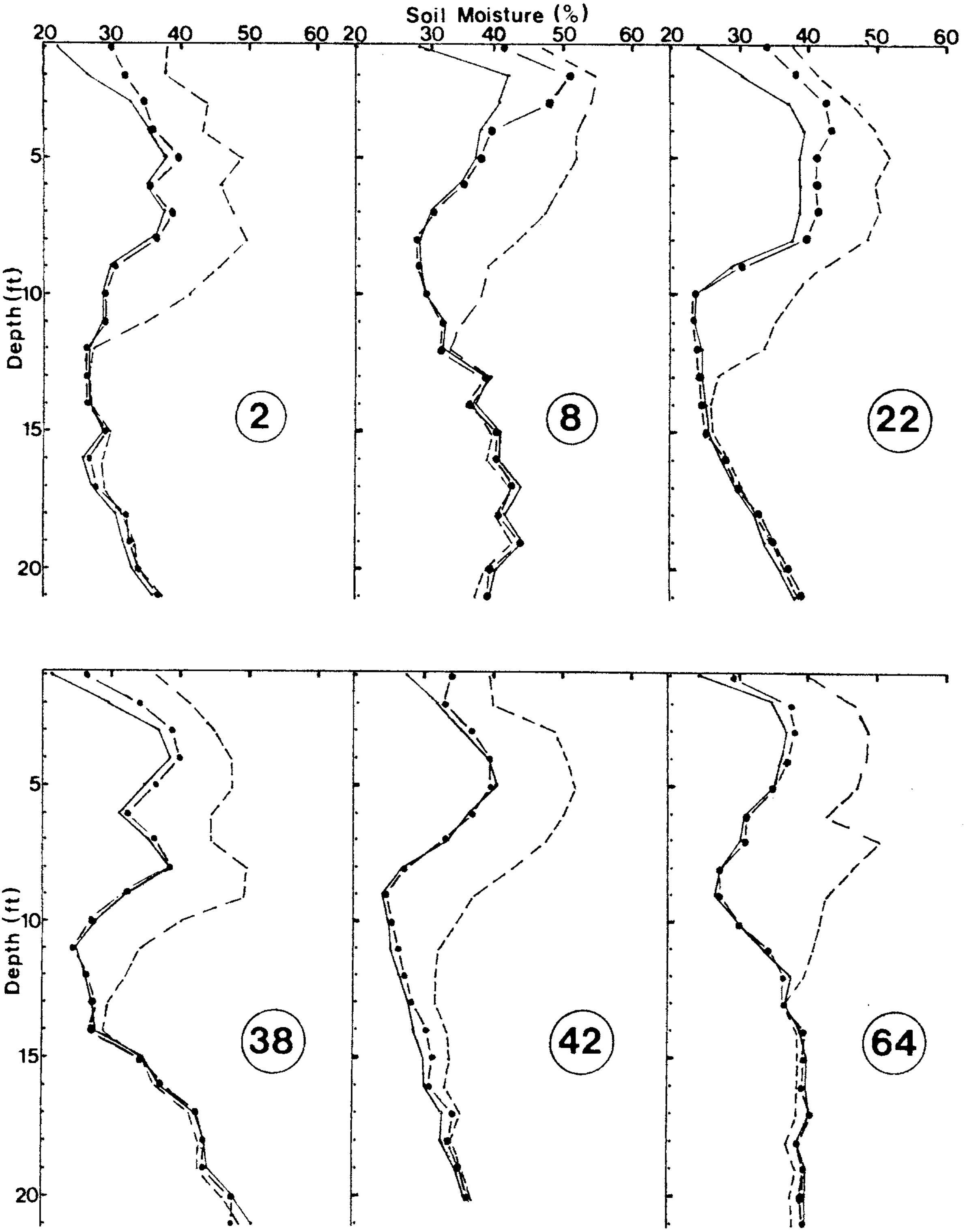

Figure 34. Profiles of soil moisture content with depth at each of the six access tubes in the uncut control plots during the 1968-69 fall recharge period. ——— 10/8/68; •———• 10/22/68; — — — 1/10/69

tubes showed an increase in soil moisture which was greater than the measured rainfall, except in the October 22, 1968 measurement when two of the access tubes showed an increase greater than the measured 3.16 inches of rainfall.

Because of the variable depth of soil moisture recharge among the access tubes, it is not meaningful to average the soil moisture data if one is interested in following the progress of wetting and depletion with depth. In the fall of 1964, 11.26 inches of rain fell between the October 22 and November 20 measurement (Table 12). The principal zone of soil moisture recharge was found to be within the surface 6 to 8 feet for all six access tube locations (Fig. 31). Soil moisture depletion was measured below a depth ranging from 7 feet at tube 8 to below 19 feet--the bottom of the access tube--at tube 42. The variability in the depth of measured soil moisture depletion is related to the depth of the region of partial wetting, which would obscure any actual soil moisture depletion by the trees. Thus, the quantity of soil moisture depletion in the fall can not be taken as the total water use by the trees, but is simply an indication of the soil moisture dynamics below the zone wetted by the infiltration of rainfall.

In 1965 (Fig. 32) and in 1968 (Fig. 34), the progress of the wetting front can be observed on two successive measurements. Between October 18 and December 8, 1965, 13.23 inches of rain fell (Table 13). The principal wetting front can be found at a depth of about 7 feet in all tubes, although there was some soil moisture recharge below 7 feet in some of the tubes. All of the tubes, except tube 42, showed some soil moisture depletion at the deeper depths. Some of this depletion most certainly occurred in the 20 rainless days following the

October 18 measurement and before the moderate storm of November 8. Thus, this observed depletion may simply be a residual of evapotranspiration prior to wetting. The measured depletion ranged from 1.04 inches in tube 64 to 0.18 inches in tube 2 (Table 11). The average depletion for the six tubes was 0.44 inches. The average measured recharge was 10.08 inches. Measured recharge ranged from 8.48 inches in tube 42 to 12.37 inches in tube 64. A calculation of daily evapotranspiration based on the Thornthwaite method indicated a potential evapotranspiration for the period of 2.59 inches and a calculated increase in soil moisture of 10.64 inches (Table 11).

Another soil moisture measurement was made on January 10, 1966. An additional 17.12 inches of rain had fallen since the December 8 measurement. Within this interval the principal wetting front progressed 3 to 4 feet deeper--about 11 feet from the surface. Measured recharge ranged from 8.22 inches to 13.50 inches and averaged 10.72 inches for the six tubes. Soil moisture depletion was observed for this period also. Measured depletion below the wetting front ranged from 0.53 inches to 0.82 inches and averaged 0.55 inches for the six tubes. Potential evapotranspiration was calculated to be 0.33 inches for the period. Soil moisture storage was calculated to increase by 8.52 inches based on the Thornthwaite water balance and 8.27 inches was calculated as runoff for the period. For this measurement period, depletion below the wetting front cannot be attributed to a remnant of evapotranspiration which occurred prior to wetting the surface soil layers. In this case, depletion did occur below the wetting front.

A similar scenario occurred in 1968, although the initial wetting was less than that in 1965. Between the October 8 and October 22

measurement, 3.16 inches of rain fell at the Challenge Ranger Station (Table 16). This storm was characterized by a number of localized convection cells which resulted in a highly variable precipitation pattern. Perhaps an additional inch of rain fell in the uncut control plots than at the Ranger Station. Nevertheless, measured soil moisture recharge for the 14-day period ranged from 1.07 inches to 5.47 inches and averaged 2.89 inches for the six access tubes (Table 11). The principal zone of wetting following this moderate storm occurred within the surface 2 to 3 feet, although small soil moisture increases were found throughout the 20-foot measurement depth in four of the six access tubes (Fig. 34). Only in tube 8 was there a substantial decrease in soil moisture during this period. In this access tube, the rainfall wetted only the surface 6 feet.

No additional soil moisture measurements were made until January 10, 1969. Within this 80-day period, an additional 24.49 inches of rain was recorded. A distinct wetting front had progressed partially through the profile. The pattern of soil moisture content with depth was essentially identical with that observed on January 10, 1966. This would be expected since about the same amount of rain fell prior to the January 1966 and January 1969 measurements--30.35 inches and 27.65 inches, respectively. As in fall 1965, soil moisture depletion was measured below the wetted zone--ranging from 0.16 inches to 1.16 inches and averaging 0.40 inches for the six tubes. Potential evapotranspiration for this period was calculated to be 1.96 inches.

Thus, soil moisture depletion continued below the wetted soil created by substantial rains in the fall. In 2 of the 4 years in which measurements were made, a second soil moisture survey was made

before the wetting front progressed below the depth of measurement. Depletion of soil moisture was again observed. The most plausible explanation for this continued depletion is that it is the result of continued evapotranspiration by the trees. An alternative hypothesis is that this depletion is due to continued drainage rather than evapotranspiration. The probability of continued drainage seems to be very small. The soil moisture retention data for these plots indicates an average retention of 69 percent moisture by volume at 1/3 atmospheres and 21 percent moisture by volume at 15 atmospheres using the average bulk density of 1.7 for these depths (Table 5). The average field soil moisture content below 15 feet for these tubes was 40, 43, 41, and 38 percent by volume in October 1964, 1965, 1967, and 1968, respectively. Gravitational water held in the soil at this depth following 30 days of drainage without rain appears to be about 52 percent by volume. In addition, at the end of the depletion season, soil moisture content generally increases with depth. Thus, drainage of soil moisture toward a more moist soil after 200 or more days without rainfall input seems to be a very remote explanation for the measured soil moisture depletion below the wetting front. However, since no measurement of soil water potential was made, we can neither prove nor disprove the drainage hypothesis.

The depletion of soil moisture by vegetation below a wetting front can be clearly seen in figures published by Butcher and Havel (1976). Profiles of soil moisture were shown for 7-meter deep profiles under native woodland and *Pinus pinaster* stands in Western Australia. The authors, however, did not identify these changes nor discuss the process. The profiles showed progress of the wetting front at monthly intervals

through one winter season and closely resemble the pattern observed at Challenge. Butcher and Havel found almost identical patterns under open native woodland and in low-density pine stands which had been periodically thinned to maintain a basal area of 7.1 m^2/ha. By comparison, under a densely stocked pine stand, maintained at a basal area of 24.6 m^2/ha, the wetting front was slightly delayed and soil drying was greatly accelerated in the summer. Soil moisture was exhausted to a depth of 7 m by mid-November in the dense stand as compared to March under the more open stands. Thus, in the densely stocked stand, there could be no continued soil moisture depletion by the vegetation below the winter wetting front since the available soil moisture had been exhausted in midsummer. In the more open stands, some soil moisture continued to be available to the vegetation below the wetting front and depletion continued into the early winter. Unfortunately, interpretation of the soil moisture data by the authors was very limited. The rate of soil moisture depletion below a wetting front in the fall was, of course, much slower than earlier in the summer before the wetting front existed. This is to be expected since the potential evapotranspiration is also lower in the fall, and the vegetation has, in many cases, entered winter dormancy. In the Butcher and Havel data, the hypothesis of drainage accounting for the soil moisture depletion below the wetting front can be clearly rejected. The vegetation had depleted nearly all of the available soil moisture in the profile and the water potential most certainly would not have permitted drainage.

Groundwater Variation

The response of groundwater levels to precipitation in forested mountainous terrain of the western U. S. is an area of study in which little significant progress has occurred though a great deal of work has been conducted. The blocks to progress are related to the enormous variations in groundwater depth and response observed within a small geographical area imposed by steep slopes, shallow soils, and fractured bedrock. Overland flow rarely occurs on undisturbed forest soils in the west, but streams rapidly respond to precipitation on areas having steep slopes and highly permeable surface soils. The importance of rapid, shallow subsurface flow to streamflow response has been repeatedly documented by a number of authors, the most recently being Harr (1977) working in the Oregon Cascades.

Harr and others have reported that only a small part of a watershed produces storm runoff. This area expands and contracts according to changes in rainfall intensity and soil water conductivity. Field studies have demonstrated the interaction between unsaturated and saturated flow and streamflow. In other studies, subsurface water has been shown to move rapidly through piping channels and other non-capillary biologically created channels in otherwise unsaturated soil.

As discussed earlier, the study tree plot (L1) and the uncut control plots (C1 and C2) were selected for study only after it was determined that no water table could be found within 50 feet of the surface at any time of the year. The reason for this selection criteria was to eliminate the probability of capillary recharge from a water table to the surface 20 feet of soil where soil moisture depletion was being measured. Any such capillary recharge would obscure

actual soil moisture depletion by the vegetation. Several of the original 21 plots did not meet this criteria and a free water table appeared in the observation wells during at least a portion of the year. In three plots, there was a persistent water table throughout the duration of the study and the water levels seasonally fluctuated between a depth from about 10 to 40 feet below the soil surface.

In August 1965, Leupold-Stevens FW-1 water level recorders were installed on the water table observation wells in plots 5, 7, and 16. Fluctuations in the depth of the water table was continuously monitored from August 1965 through March 1970 (Fig. 35-39). In April 1969 a wood rat drowned in the observation well in plot 16. Repeated efforts to remove the carcass from the well failed and subsequent data from that well was rendered useless.

Recession. The general pattern of the water table fluctuations at Challenge was similiar from year to year. Water table levels began to fall at the end of the winter rainy period and continued to drop through the rainless summer until the beginning of heavy fall rains. Each of the three wells produced similar recession curves (Fig. 35-39). The shape of these recession curves was slightly concave with the water levels dropping an average of 0.082 feet per day in June to 0.067 feet per day in September. The maximum depth to the water table usually occurred in late November or early December. The maximum water table depth attained each year corresponded closely to the pattern of the total minimum soil moisture found in the well-drained uncut control plots at the end of each summer (Fig. 40).

The minimum depth to the water table was indicative of the relative wetness or dryness of the winter. For example, 1965-66 and

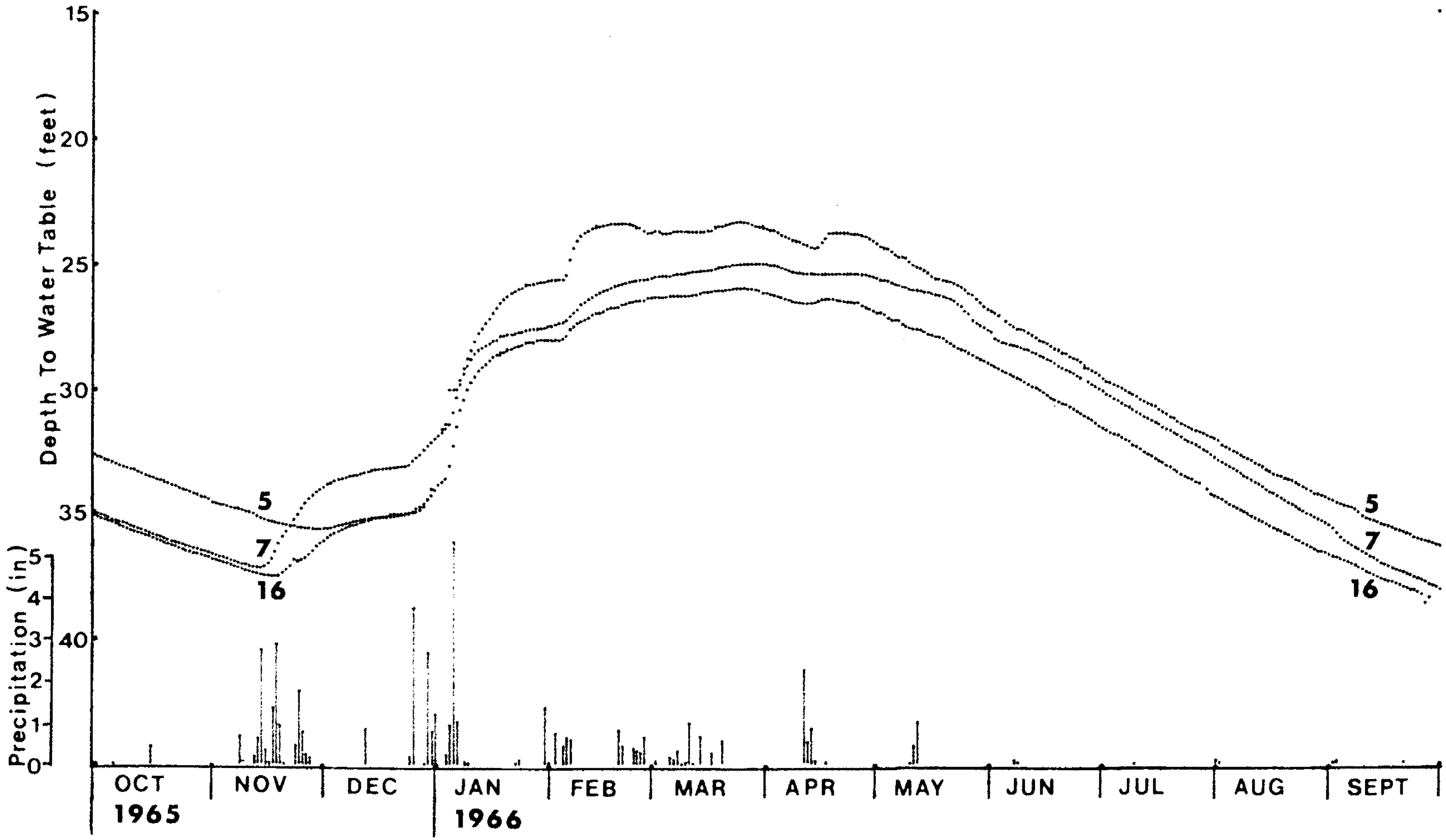

Figure 35. Fluctuations in depth to water table during water year 1966 in plots 5, 7, and 16.

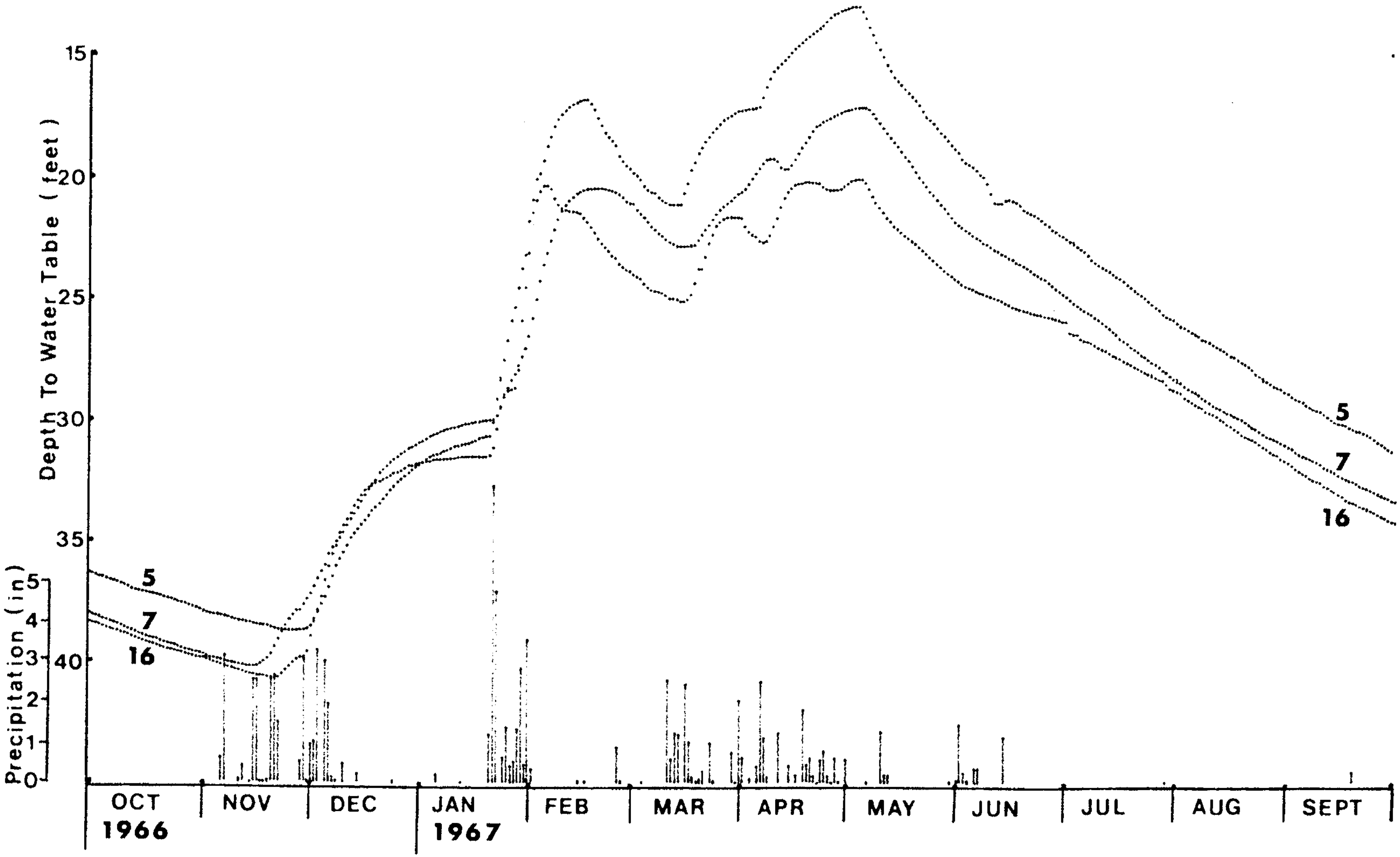

Figure 36. Fluctuations in depth to water table during water year 1967 in plots 5, 7, and 16.

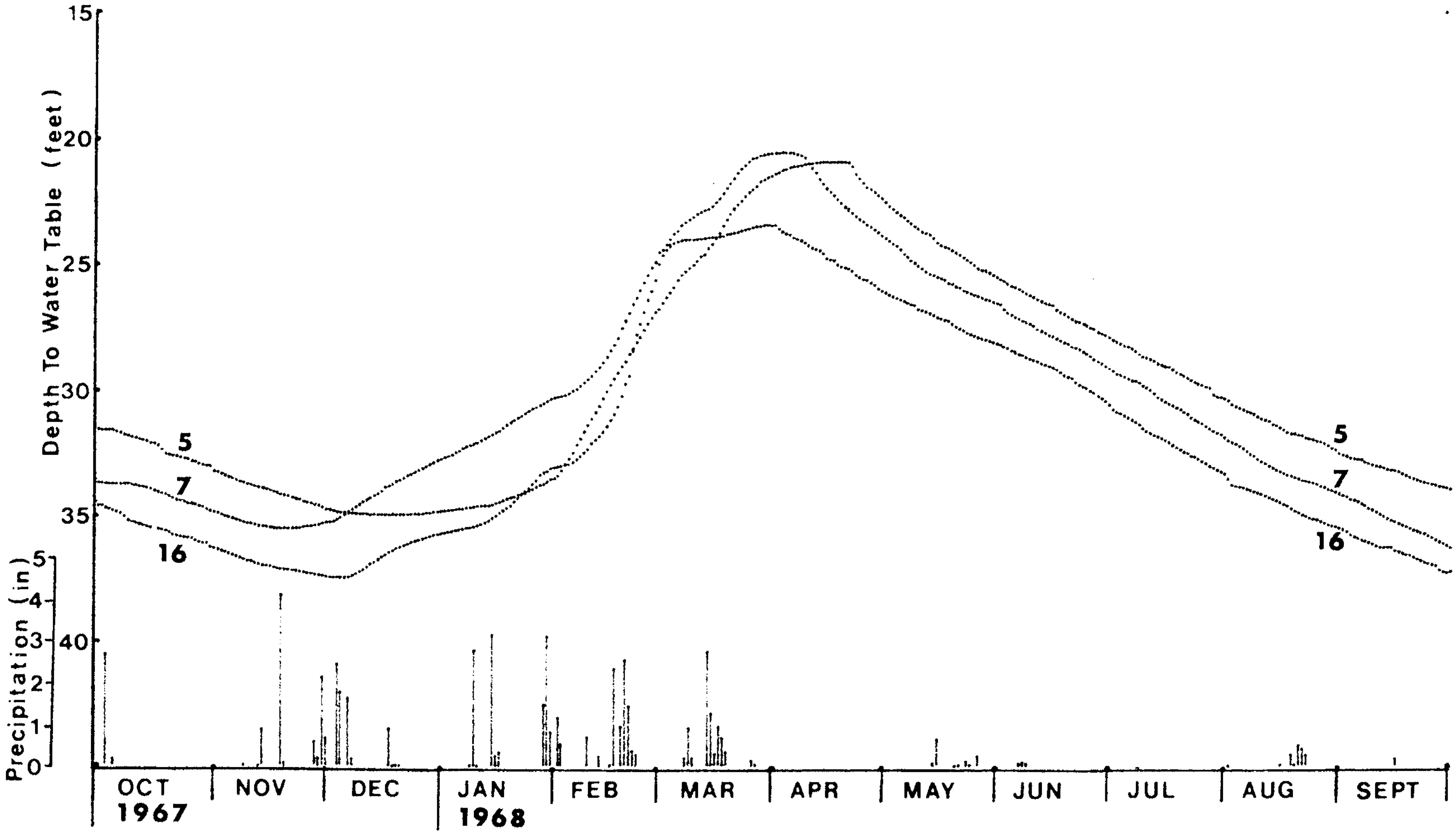

Figure 37. Fluctuations in depth to water table during water year 1968 in plots 5, 7, and 16.

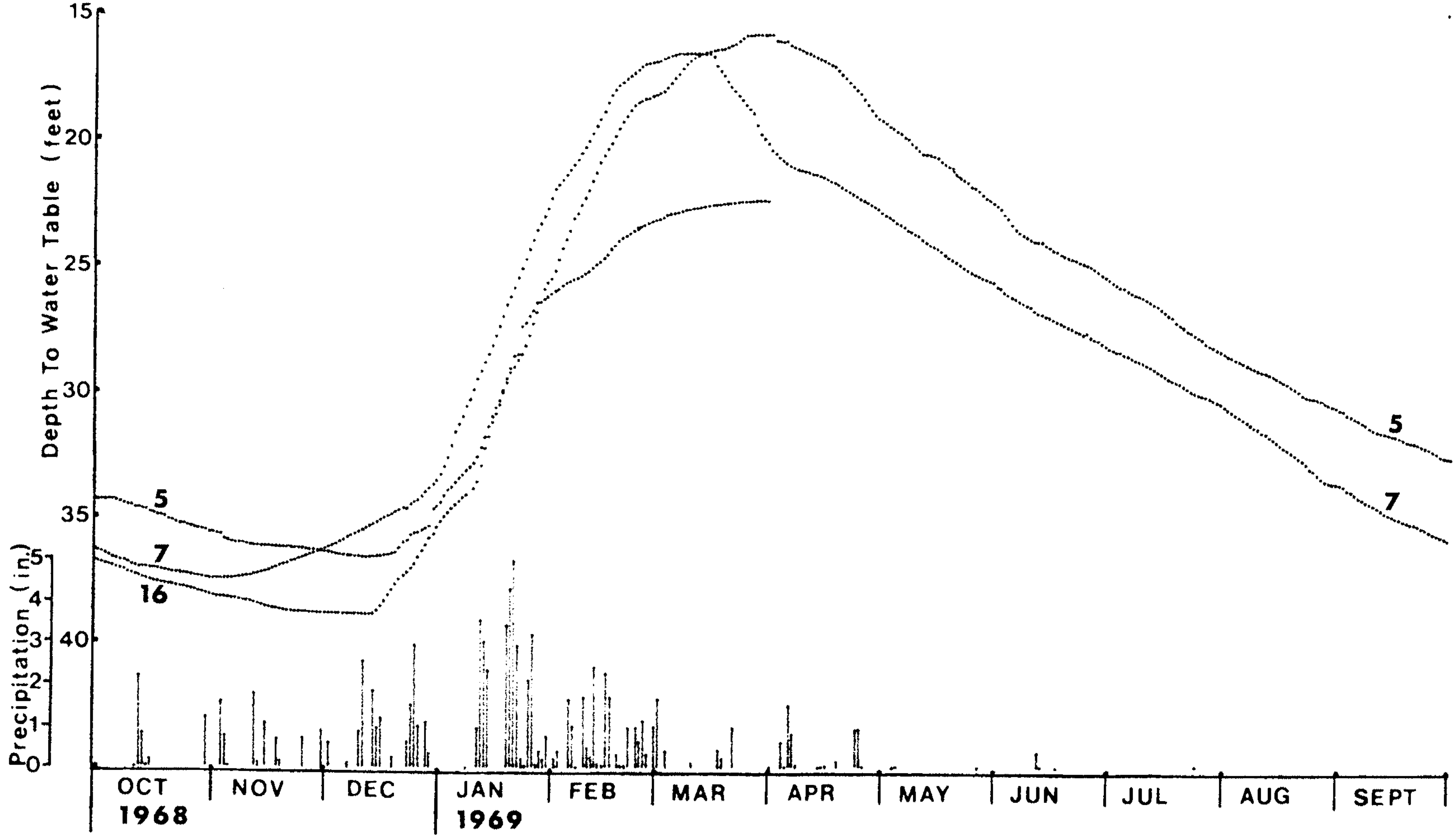

Figure 38. Fluctuations in depth to water table during water year 1969 in plots 5, 7, and 16.

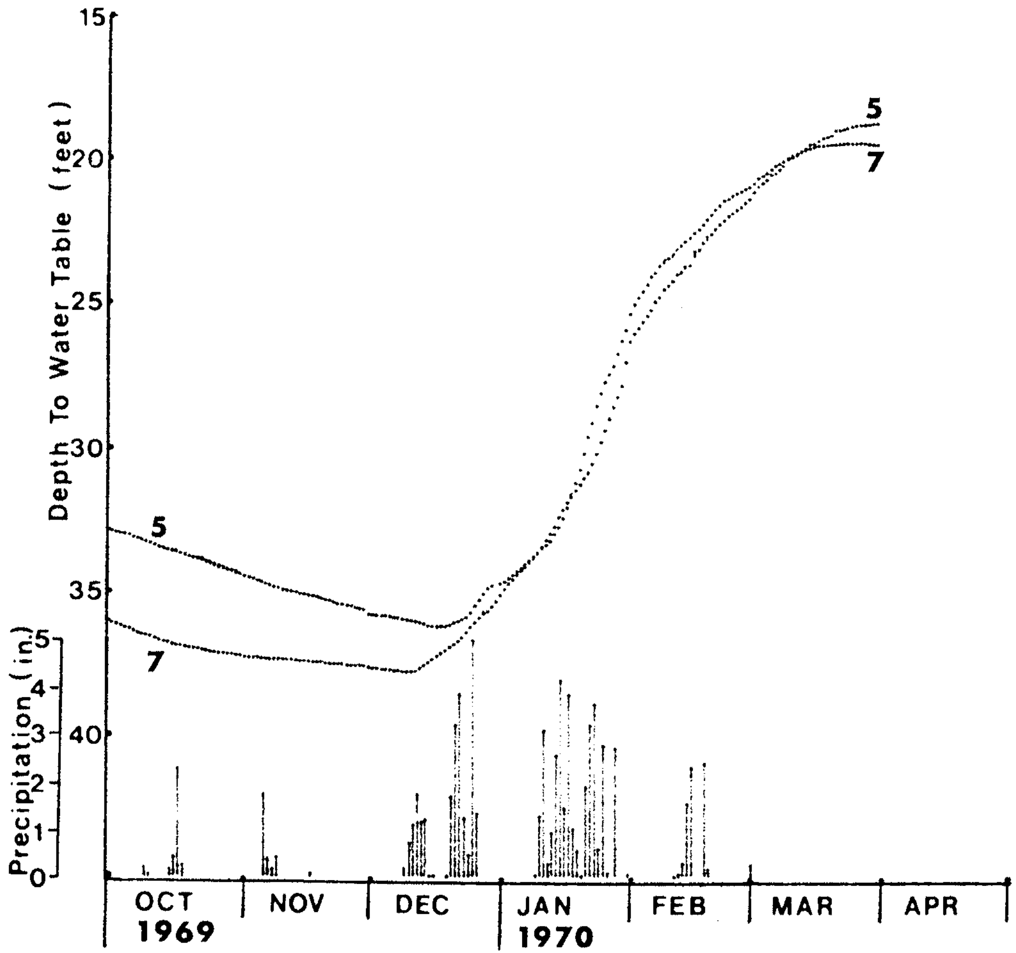

Figure 39. Fluctuations in depth to water table during a portion of water year 1970 in plots 5 and 7.

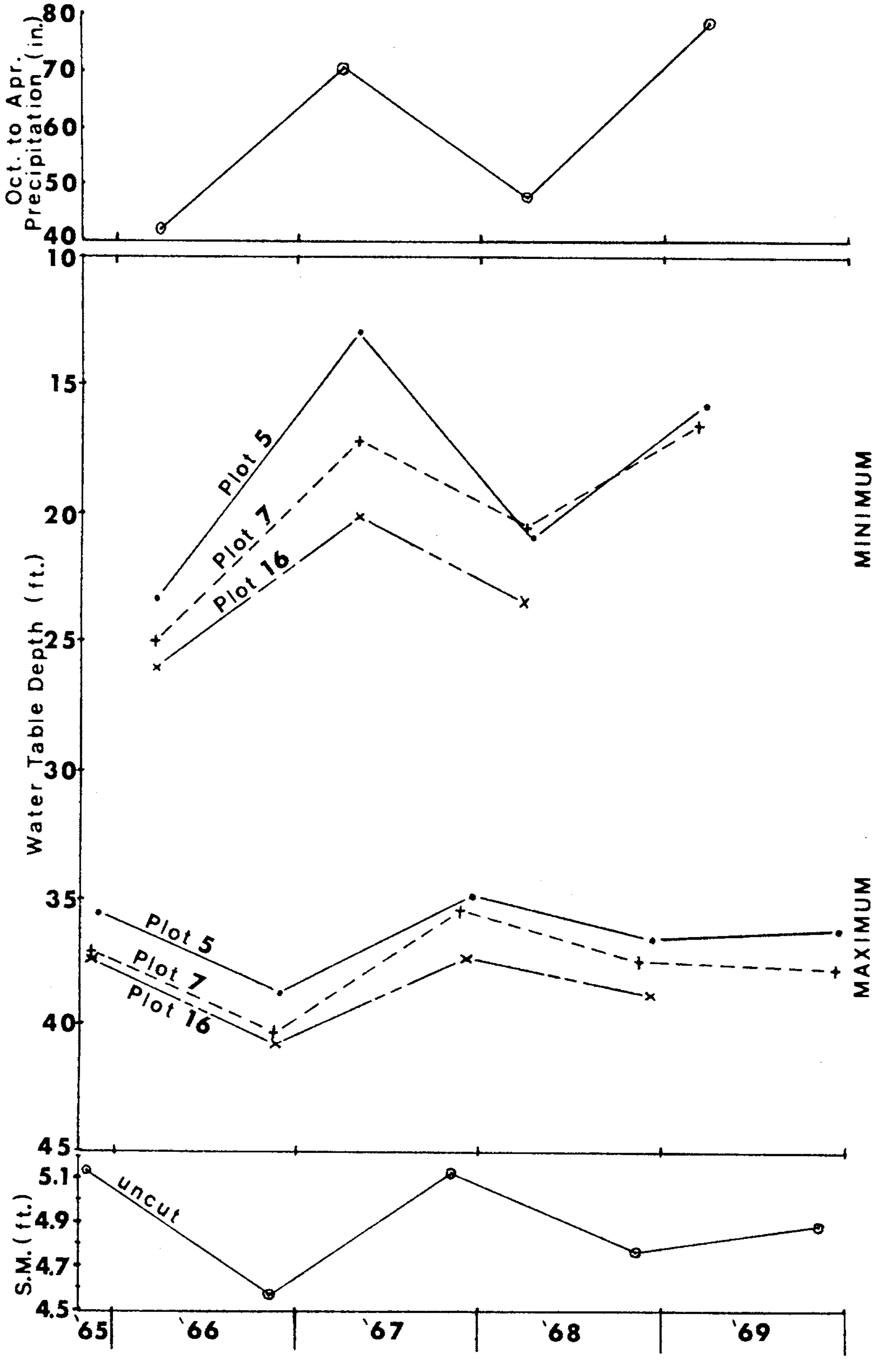

Figure 40. Relationships between precipitation, water table depths in plots 5, 7, and 16, and average end of season soil moisture in the uncut control plots.

1967-68 were dry years with the October to April rainfall being 41.84 inches and 47.72 inches, respectively. The minimum depths to the water table were correspondingly greater during these dry years than during the wetter years, 1966-67 and 1968-69, when the October to April rainfall was 70.51 inches and 78.51 inches, respectively. There was also a carry over to the level of ground water at the end of the summer. That is, a wet winter produced a high minimum water table level which persisted to result in a relatively high water table level at the end of the following summer. Conversely, a dry winter produced a low minimum water table level and, thus, a deeper maximum water table level at the end of the summer. A dry fall and winter tended to be followed by a dry spring and, conversely, a wet fall and winter was followed by a wet spring. For example, March to July rainfall was 7.33, 9.56, 9.11, and 17.80 inches for 1966, 1968, 1969, and 1967 respectively. This order is closely correlated with the order of maximum water table depth found at the end of the summer (Fig. 40). Thus, water levels were not only higher in the wet years, but the recession generally began later in the spring.

The high correlation between minimum soil moisture in the uncut control plots in the late fall and the maximum depth to the water table in plots 5, 7, and 16 may be related to direct use of the water in capillary fringe above the water table by trees as suggested by Lewis and Burgy (1962) for oak trees in their Placer and Hopland watersheds. However, an equally plausible explanation is that both soil moisture depletion and groundwater recession are responding to different processes, but which began later in wet years than in dry years. Consequently, the time available for evapotranspiration from the uncut plot

as well as gravitational recession of the water table was shorter in wet years than in dry years. Thus, it does not necessarily follow that the recession of the groundwater table was directly influenced by vegetation or that the soil moisture depletion within plots where no water table was observed within a depth of 50 feet was influenced by capillary recharge from some deeper water table.

The processes of groundwater recession were not investigated in detail. However, the recession curves are useful in that they provide additional and continuous information of the influence of climatic processes on the soil water regime, particularly in the winter and late spring when the interaction of rainfall on soil moisture content is complex.

Rise. The response of the water table levels in the three observation wells at Challenge to rainfall was greatly delayed relative to that reported by Harr (1977) and others working in forested and mountainous terrain. Harr was working on slopes ranging from 50 to 110 percent whereas the Challenge plots were on gentle 10 to 20 percent slopes. Harr was working in shallow clay loam soils about 3 feet deep underlain by 6 to 20 feet of saprolitic subsoil whereas the Challenge plots were in finer textured silty clays to silty clay loams, which were uniformly deeply weathered from 50 to 100 feet in depth. Harr found only temporary saturated zones whereas at Challenge there was a persistent and perennial water table. Thus, although the amount and pattern of precipitation and the vegetative cover in the Oregon Cascades and at Challenge were similar, the groundwater patterns were certainly dissimilar.

At Challenge no rapid subsurface saturated responses to precipitation could be detected. Where Harr found a piezometric response within hours after rainfall, several days to several weeks were required for the piezometers at Challenge to begin rising. The response of the Challenge wells were more typical of that observed by Lewis and Burgy (1962) on their Placer County watersheds in California. However, the details of water table response in the Placer County watersheds are obscured because water level depths were measured only weekly by Lewis and Burgy.

As mentioned earlier, the processes affecting groundwater response in forested and mountainous terrain are extremely varied and it is difficult if not dangerous to generalize without thoroughly investigating the detailed processes involved.

Even in the relatively uniform soils at Challenge, the groundwater response to rainfall between plots 5, 7, and 16 were varied both in terms of the hydrograph shape and timing of the initial rise (Fig. 35-39). Precipitation patterns during the first storms of fall 1965 and 1966 were similar in that 13 to 16 inches of rain fell within about a 20-day period. The water levels in plot 7 began to rise within 8 to 12 days after the initial rainfall (Fig. 41, 42). In plot 16, water levels began rising within 13 to 18 days and in plot 5 within 23 to 24 days. The shallowest water table, plot 5, required the longest period in which to respond to rainfall. The fall rains of 1967, 1968, and 1969 were spread over a longer period and the rising phase of the hydrographs were more extended in time.

Once the water tables began to rise, they continued rising throughout the winter, generally showing only one peak in early spring,

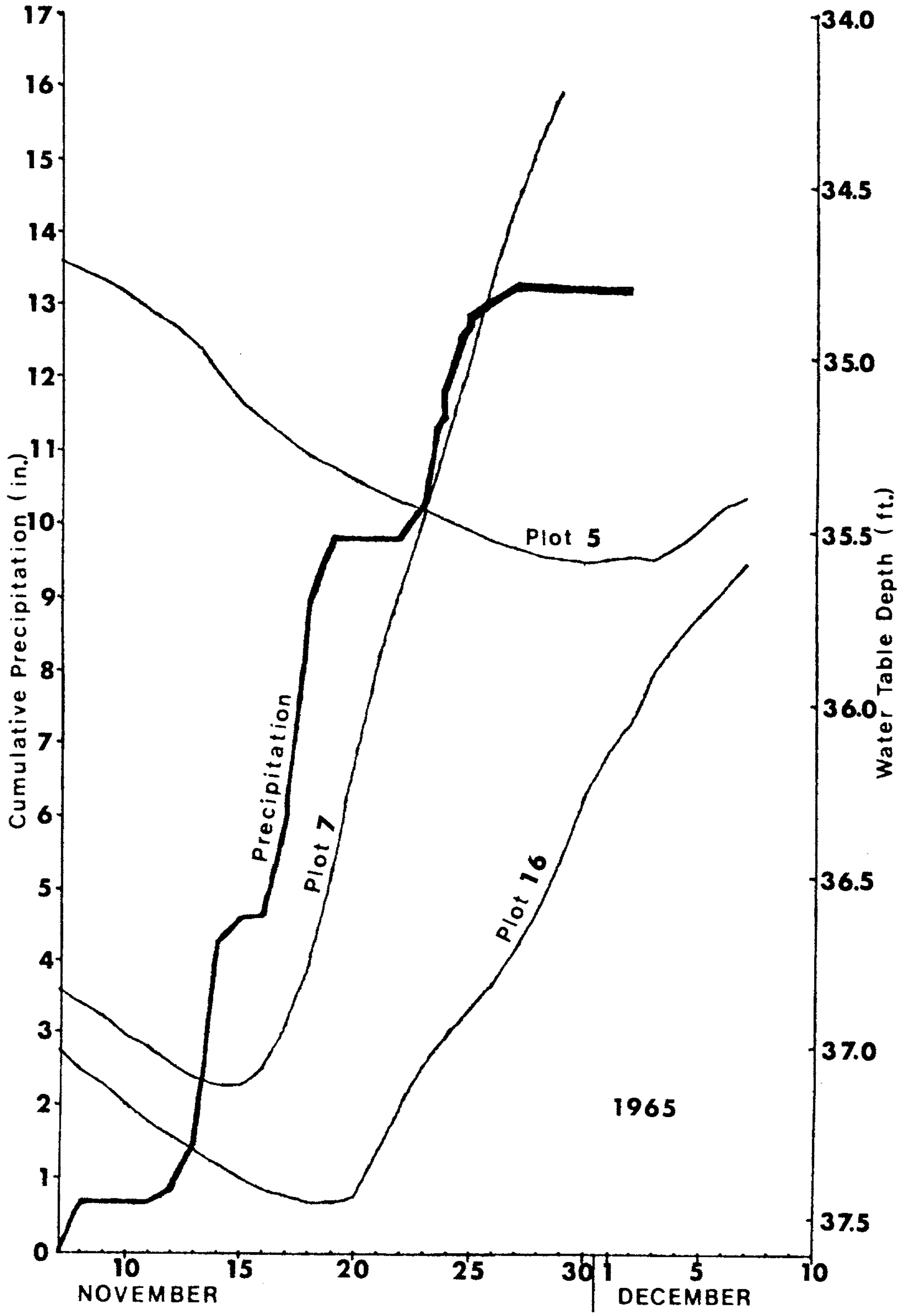

Figure 41. Time lag in the initiation of water table rise in plots 5, 7, and 16 relative to precipitation during fall 1965.

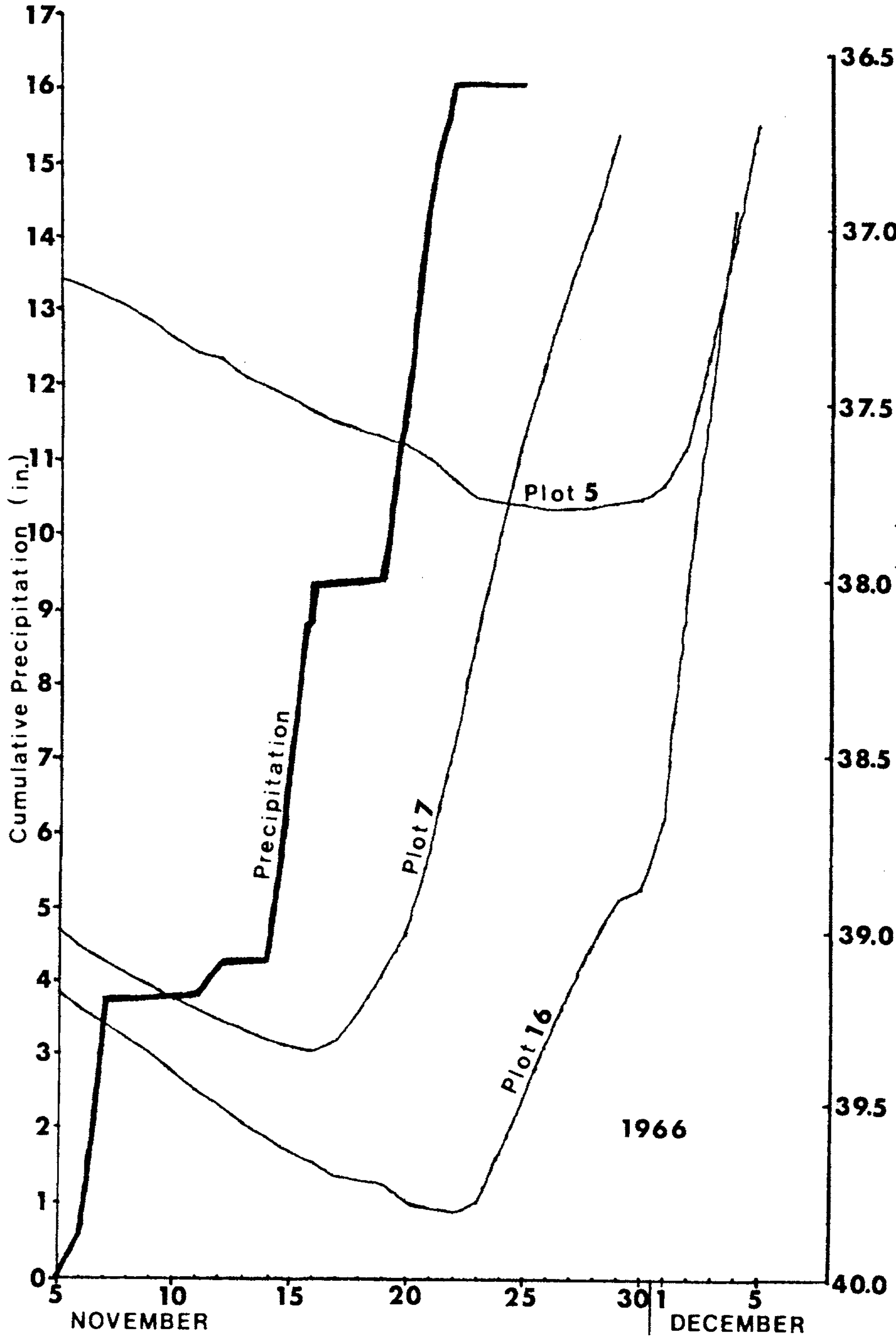

Figure 42. Time lag in the initiation of water table rise in plots 5, 7, and 16 relative to precipitation during fall 1966.

followed by a continued recession of water level through the summer. Occasionally, a heavy burst of rainfall would cause a very rapid rise in water level in all three wells, such as in early January 1966 (Fig. 35) and mid-January 1967 (Fig. 36). In 1966-67, the hydrograph shape deviated from the general pattern of a single peak during the winter and showed two or possibly three distinct peaks. Precipitation during this winter was characterized by three definite heavy rainfall periods, early November through early December, mid- to late January, and mid-March to mid-April. The two intervening periods of about 1 1/2 months duration were essentially rainless. During the other years of the study the frequency of rainfall events were much more uniformly distributed throughout the winter.

CHAPTER V

SUMMARY AND CONCLUSIONS

The soil moisture regime of a 15-foot profile was measured for a 5-year period under a second growth mixed conifer forest which had not been cut for about 80 years and under an adjacent stand in which 88 percent of the stand basal area had been removed 3 years earlier, leaving one dominant residual sugar pine about 30 inches in diameter surrounded by much smaller understory vegetation of fir, pine, and tan-oak. Within this plot, neutron meter access tubes were installed at distances of 2, 5, 10, 20, 40 and 60 feet from the sugar pine in concentric circles of increasing distance from the tree. A total of 23 access tubes were installed in the individual tree plot. In the uncut stand, three access tubes were located at random within each of two 50- by 50-foot blocks. The criteria for plot selection was (1) no water table present within the plots to a depth of 50 feet at any time during the year, (2) a uniform pattern of soil moisture recharge with no indication of lateral subsurface flow, (3) well-drained sites with no surface ponding or water runoff concentration, (4) no unexplained anomalies in soil moisture data during the depletion or recharge measurements, and (5) uniform soil with all access tubes at least 15 feet in depth. These criteria were established to reduce the variability between access tubes and to make comparison of soil moisture depletion data between access tubes within the plot and between plots possible. After 2 years of soil moisture measurement, all of the vegetation surrounding the sugar pine was cut to a distance of 120 feet from the

tree leaving a bare plot with one isolated tree in the center. After an additional 2 years of measurement, the isolated sugar pine was cut leaving the plot bare. Soil moisture was measured in the bare plot for 1 additional year.

By each spring, the soil in the plots was uniformly and completely recharged with moisture. Beginning with a uniform soil moisture content in the spring, there was a dramatic change in the pattern of soil moisture after a summer of evapotranspiration for each of the 2 years when the plot was partially logged and the 2 years when there was an isolated tree. Most soil moisture depletion occurred at a depth between 8 and 13 feet beneath the tree and extended to a distance of approximately 20 feet from the tree. Beyond about 30 feet from the tree, the soil moisture content remained fairly uniform with depth. Surface evaporation was evident within the surface several feet of soil. After the isolated tree was removed, leaving the plot bare, the zone of depletion 8 to 13 feet under the tree disappeared and the soil moisture content remained rather uniform below a depth of 2 feet. The eccentric pattern of low soil moisture adjacent to the tree disappeared.

Within the surface 5 feet of soil, there was no dramatic change in soil moisture content at the end of the summer after isolating the tree, or after removing the isolated tree. There was also no definitive pattern of soil moisture content related to distance from the tree, other than a vague increase in moisture content in the regions closer to the tree. At a depth of 5 to 10 feet, there was a definite correlation between soil moisture content at the end of the summer and distance from the tree. At a distance of 40 to 60 feet from the tree, soil moisture content remained fairly uniform at the end of each summer

throughout the duration of the study with no measurable impact of isolating or later removing the isolated tree. However, for the areas within 10 feet of the tree, there was a definite increase in soil moisture content at the end of the summer in which the tree was isolated and another increase after the isolated tree was cut. At a depth of 10 to 15 feet the soil moisture response to tree cutting was similar to that at a depth of 5 to 10 feet.

There is a linear relationship between distance from the study tree and relative soil moisture content at the end of summer. "Relative soil moisture" was obtained by adjusting the measured total moisture content in the plot by the total soil moisture in the area 40 to 60 feet from the tree and then adjusting to equalize soil moisture throughout the plot after the isolated tree was cut. As distance from the tree increases, the relative soil moisture content decreases, that is, the soil moisture "savings" obtained by removing the tree decreased as distance from the tree increased. There was a different curve for each year. During dry years the slope of the curve was steeper than during wet years, that is, the soil moisture content closer to the tree was lower in dry years than in wet years relative to the soil moisture content in the area outside the influence of the tree. The explained variance, r^2, for each curve is in excess of 0.99. A sigmoid fit to the data was not significantly better than the linear fit. The influence of the tree extended to a distance of 38 to 42 feet from the base of the tree. In the 2 years prior to isolating the tree, the vegetation within 40 feet of the tree depleted about 3200 cubic feet more soil moisture each summer than the area 40 to 60 feet from the tree. After the tree was isolated, the sugar pine depleted about 2200

and 2600 cubic feet more water than the area 40 to 60 feet from the tree in the first and second year after treatment, respectively.

On a number of occasions, soil moisture measurements were made in the uncut control plots after the end of the summer depletion season, that is, after a substantial amount of rain had fallen. The progress of the wetting front can be clearly observed on successive measurements. All of the tubes, with only one exception, showed continued soil moisture depletion below the wetting front. The most plausible explanation for the continued depletion is that it is the result of continued evapotranspiration by the trees. An alternative hypothesis is that this depletion is due to continued drainage rather than evapotranspiration. The probability of continued drainage seems to be rather small. Since no measurement of soil water potential was made, we can neither prove nor disprove the drainage hypothesis or the evapotranspiration hypothesis. However, depletion of soil moisture by vegetation below a wetting front has been clearly shown in figures published by others.

One of the criteria for selecting soil moisture depletion plots was that no water table was to be found within a depth of 50 feet. However, in searching for such plots some areas were found where the groundwater table routinely fluctuated between a depth of about 10 and 40 feet. There was a definite seasonality in the depth of the water table under this precipitation regime. Groundwater depths generally reached a maximum at the end of the dry summer depletion season and began rising shortly after the beginning of fall. precipitation, reaching a minimum level sometime in the late winter or early spring and then beginning to gradually fall as the summer progresses. This general pattern was the same for all three wells measured. In some years, there

was a single broad-crested peak occurring in the winter. In other years, several distinct peaks were observed during the winter, generally in response to large storms. During the interval between these large storms, there was a typical recession curve, followed by another rise as the next series of large storms arrived. When rainfall ceased in the spring, there was a general and gentle recession curve throughout the summer period.

The water table level responded within days and in some cases weeks after the first significant rainfall in the fall. Even in the relatively uniform soils at Challenge, the groundwater response to rainfall within the three plots varied, both in terms of hydrograph shape and timing of the initial rise following rainfall. During the first storms of fall, the water level in one of the wells began to rise within 8 days, in another well within 15 days, and in a third well within 24 days after the initial rainfall. Though the length of time before water table levels began to rise were rather lengthy relative to that which some researchers have reported in mountainous terrain, this time was much shorter than that required for the surface 15 feet of soil to be recharged by precipitation. During the water table recession period in the summer, no diurnal. fluctuations in water table depth could be detected. Such fluctuations would have been indicative of direct depletion or direct access of the water table by vegetation.

This study has provided some insight into the quantity, timing, and pattern of soil moisture storage and depletion throughout the rooting depth of an isolated mature sugar pine. It seems to be a corollary of research that a study designed to answer one question leads to a more basic and detailed question. This study was undertaken because of

an attempt to measure the changes in soil moisture depletion in partially logged forests. In the first year of that study, it became evident that the variance in soil moisture depletion within the plots made an analysis of differences between plots tenuous. A preliminary step, then, was an understanding of the soil moisture depletion patterns around individual trees before it was possible to design a study to evaluate the more complex question of the interaction of individual trees and the influence of selective logging on soil moisture depletion.

This isolated tree study has raised some even more basic questions which reflect the inadequacy of our understanding of soil-vegetation-water interrelationships. Root distribution and biomass studies have shown that roots are concentrated in the upper layers of soil. Many of these roots have a structural function, others have an absorption function. This study has shown the most dynamic depletion of soil moisture by the tree occurs at a depth of 8 to 13 feet. We need to understand the interrelationships between root numbers, biomass, size, and distribution and soil moisture depletion. We also need to understand how the pattern of soil moisture depletion varies by tree size and species.

Unfortunately, many of these basic questions are not being addressed. Interest in forest soil water research has waned considerably within the past decade in favor of "more pressing" problems related to water quality We have not progressed as far as we might like to believe since the early studies of Charmow and Wyssotzky in the late 1800's. Perhaps in another generation a future student of the forest soil moisture regime might also be forced to the same realization.

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APPENDIX

Table 12. Daily precipitation during 1964-65, Challenge Ranger Station.

Date	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1		.83	.47	.02			.40					
2		2.50	.18				.03		.03			
3		.04	.32	1.74			.10		.19			
4				3.60								
5	T		.08	3.59	.87		.02	.18				
6				3.15	.23	.21	.09					
7	T			1.76		.03	.11					.55
8		.11					.76					
9		1.90	.02	.09			2.55					
10		2.17	.04				1.02					
11		.38	1.31	.21		.01	.31				.14	
12		1.44		.11		.62					1.27	
13						.05	.17					
14					.02		.24		T			
15			.05				T					
16							2.98					
17							.02		.10			
18							.17		.19		.05	
19			2.70				.55					
20			1.45	.19			.02	.09				
21			4.10	.02			.51	T				
22		.25	8.65				.04	.13				
23			5.33	.02								
24			1.48	2.17		.24						
25		.34	.22			.25						
26		.25	1.29	.08		.67						
27	T	.01	4.59		.76	2.17						
28	.19	.92	.37			.05						
29	1.37	.35	.80									
30	.33		1.18									
31			.72									
Total	1.89	11.49	35.35	16.75	1.88	4.30	10.09	.40	.51	.00	1.46	.55

Table 13. Daily precipitation during 1965-66, Challenge Ranger Station.

Date	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1						.07						
2					.73							
3				.24								
4				.94	.42							
5	.02			5.35	.63	.16						
6				1.01	.58	.11			.08			
7						.31			.02			
8		.68		.07		T				T		
9				.03		.03		.01				
10						.97	2.24	.43				
11						.01	.51	.01				
12		.19	.85				.83					
13		.64				.65	.07					
14		2.74										
15	.44	.35										
16		.05				.25	.03					
17		1.35										
18		2.87										T
19		.93			.80	.54						
20		.02			.42							
21												
22				.04								
23		.45		.11	.37							
24		1.75	.19		.32							
25		.78	3.77		.27							
26		.26			.64							
27		.17										
28			.01									
29			2.67									
30			.79	1.35						.08	T	
31			1.20	T						.01	.05	
Total	.46	13.23	9.48	9.14	5.18	3.10	3.68	.45	.10	.09	.05	T

Table 14. Daily precipitation during 1966-67, Challenge Ranger Station.

Date	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1			.95		.36		.62		1.44			
2			1.01						.25			
3			3.29				.11		.06			
4						.04						
5			3.03	.21			.41		.36			
6		.61	1.95				2.49	.02	.36			
7		3.15	.15				1.11					
8			.05				.15					
9												
10			.48					1.26				
11		.08				2.53	1.22	.20				
12		.41		.01		.59		.19				
13						1.24			1.13			
14		T	.24		.07	1.20	.43					
15		2.54										
16		2.52			.05	2.43	.20					
17		.02				1.01						
18		.02				.16	1.80					.25
19		.05				.05	.45					
20		2.55		1.19		.11	.61					
21		2.64		7.36		.29	.17					
22		1.49		4.75			T					
23						.99	.56					
24			.05	.63		.07	.78					
25				1.37	.89		.17					
26				.41	.06		.01					
27				.53			.61					
28		.53		1.33			.03			.02		
29		3.08		2.82		.76		.02				T
30		.05		.45		.02	.58					
31				3.55		2.03		.07				
Total	.00	19.74	11.20	24.61	1.43	13.52	12.51	1.76	3.60	.02	.00	.25

Table 15. Daily precipitation during 1967-68, Challenge Ranger District.

Date	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1			.66									
2	T				1.16		.59					
3	2.63				.55		.04					
4			2.41									
5	.15		1.76						.05			
6									.09			
7			1.62			.20			.06			
8			.18			.91						
9		.01		.02		.20						
10				2.74	.69							
11				.01								
12												
13		T			.24	2.72		.06				
14		.86				1.25		.63			.01	.16
15				3.15		.29						
16				.25	.03	.93						
17				.34	2.30	.68					.26	
18			.90			.33					.01	
19		4.09	.01		.94			T			.48	
20		.08	.03		2.52			.01			.40	
21			.03		1.43						.25	
22					.37			.10				
23					.27			.02				
24												
25						.13		.23				
26						.04						
27												
28		.57										
29		.20		1.46								
30		2.10		3.12								
31				.81						T		
Total	2.78	7.91	7.60	11.90	10.50	7.68	.63	1.05	.20	T	1.41	.16

Table 16. Daily precipitation during 1968-69, Challenge Ranger Station.

Date	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1					.21	1.63						
2			.60		.39							
3		1.56				.40	.60	T				
4		.74					.02	.02				
5		.03			1.61		1.48					
6					.99		.80					
7			.11		.02		.05					
8				T								
9					1.67							
10			.86		.48	.12						
11	T		2.52	.94	.25				.35			
12	2.16	1.74		3.54	2.39				.02			
13	.79	.10		3.00	.09		T					
14	.03		1.82	2.32	.05		.01					
15	.18	1.04	.94		2.23		.04					
16			1.18		1.68				T			
17						.42						
18		.67			.32	.21	.14					
19		.14	.25	3.41	.05							
20				4.28	.05							
21				4.95	.95	.95						
22				2.90								
23			.61	.22	.95		.90			.02		
24			1.49	.06	.63		.91					
25		.70	2.92	2.08	1.12		.03					
26			.99	3.20	.32			T				
27				.08								
28			1.08	.38	.98							
29			.35	.20								
30	1.18	.87		.75		.01						
31												
Total	4.34	7.59	15.72	32.31	17.43	3.74	4.98	.02	.37	.02	.00	.00

Table 17. Daily precipitation during 1969-70, Challenge Ranger Station.

Date	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1												
2												
3												
4												
5		1.69										
6		.36										
7		.15										
8	.19	.40	.18	.04								
9	.05		.70	1.25								
10			1.07	3.06	T							
11			1.72	.27	.05							
12			1.14	.91	.28							
13			1.20	2.52	1.52							
14	.16		.02	4.11	2.25							
15	.42		.03	1.43								
16	2.24	.06		3.81								
17	.24			1.00	2.35							
18			.01	.53	.15							
19			1.66	.02								
20			3.18	1.85								
21			3.83	3.17								
22			1.22	3.61								
23			.46	.58								
24			4.94	2.72								
25			1.31	.08								
26												
27				2.66								
28					.24							
29												
30				.05								
31												
Total	3.30	2.66	22.67	33.67	6.84							