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ANNUAL AND SEASONAL MARCH OF SOIL MOISTURE UNDER A HARDWOOD STAND

by
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Ecological Studies of Forest Trees at Chalk River, Ontario, Canada

III. Annual and Seasonal March of Soil Moisture Under a Hardwood Stand[1]

Project P-375

by

D. A. Fraser[2]

INTRODUCTION

This is the third contribution in a series of broad ecological studies of forest trees at Chalk River. The first paper (Fraser, 1954) described site types and tree distribution on an eight-acre experimental plot at the Petawawa Forest Experiment Station. The second paper (Fraser, 1956) presented the results of radial increment studies in relation to certain physical factors of the environment. These factors included canopy, air and soil temperature, rainfall, and soil moisture. The present contribution includes data on variations of soil moisture on this same experimental plot during the 1949-54 period. The plot was chosen partly because it included considerable variations in topography in a small area on a similar parent material, but the complicated drainage pattern resulting from it necessitated the grouping of the soil moisture indices into site groups (Fraser, 1954), for it was not practical to divide the plot into a large number of smaller areas.

The important influence of soil moisture on tree growth is generally recognized but comparatively little work has been done in this field in Canada. Various soil moisture regimes were delimited by Hills (1945, 1953) and Bushnell (1942) in their evaluation of site, but little quantitative information on seasonal and annual variations of soil moisture have been obtained. Recently, Thames *et al.* (1955) followed soil moisture changes on forested and non-forested soil in northern Wisconsin. They concluded that the forest depleted soil moisture more rapidly than a grass cover. Wilcox and Spilsbury (1941) applied the soil moisture value of field capacity to soil survey data in apple nutrition studies. This value was expressed in inches of water and provided information of water reserves on different sites. Rutter (1955) observed fluctuations of the water table in an English heath and correlated it with the composition of the vegetation. Thornthwaite and Hare (1955) approached the problem from a climatological point of view and "expressed the hope that the conceptual framework of forest ecology will approach that of the climatologist more closely in the future."

The contention that changes in soil moisture (Pomerleau, 1935) has been a major cause of the "dieback of birch" suggests an increasing awareness of the importance of this factor. The present paper considers a detailed treatment of seasonal and annual changes of soil moisture on four sites and their relation to calculated potential evapotranspiration (Thornthwaite, 1948) during the

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[1] Parts I and II of this series were published in *Ecology* 35:406-414, 1954; and *Ecology* 37:777-789, 1956.

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1949-54 period. Water deficits calculated by Thornthwaite's method are compared with soil moisture status established through use of fiberglas soil units, which were calibrated by wilting experiments using yellow birch (*Betula lutea* Michx. f.) and white birch (*Betula papyrifera* Marsh.) seedlings, and sunflowers (*Helianthus annuus* L.).

Soil moisture has been studied primarily in agricultural soils, especially where irrigation practices are employed. Investigations in forest soils present a different problem with the wider range of soil texture, slope, and proximity of bedrock to the surface, all of which increases the annual and seasonal variability in soil moisture conditions.

In site classification of Ontario, moisture regimes have been recognized through the development of the horizons in the soil profile (Hills, 1945, 1953; Fraser, 1952, 1954). The entire range of soil moisture has been arbitrarily divided into eleven soil moisture regimes, ranging from θ (theta) (extremely dry), 0, through to 9 which represents a state of almost continuous saturation. Although the development of the soil profile in any one climatic region is attributed largely to the soil moisture conditions, only reconnaissance obeservations have, in the past, been reported on variation in moisture content and position of the water table on different sites under climatic fluctuations. The depth and characteristics of the glei horizon are usually considered indicative of the position and variations of the table (Fraser, 1954). Soil moisture regimes 0 to 6 were represented on the Loamy Sands of the experimental area, and the study was restricted to this range of moisture conditions.

METHODS AND MATERIALS

Two methods of measuring soil moisture, gravimetric and electrometric, were employed in this study to follow periodic variations in soil moisture on several moisture regimes. The gravimetric method was used at first because of its simplicity and the immediate availability of scales and oven. It consists of weighing a soil sample in a closed container. The container and sample are then brought to a constant oven-dry weight at 220°F. The loss of weight, representing the water content, is reported as a percentage of the weight of the oven-dry soil. This method was used to follow the seasonal march of soil moisture in the various soil moisture regimes of the experimental plot at Chalk River during 1949 and 1950. The method involves the collection of many soil samples and is not suitable for accurately recording day-to-day changes in soil moisture.

The electrometric method involves the measurement of electrical resistance between two electrodes (placed in the soil) which are usually embedded in gypsum (Bouyoucos and Mich, 1940) nylon (Bouyoucos, 1948), or fiberglas (Colman, 1948; Colman and Hendrix, 1949). This proved to be the most satisfactory method for our studies.

From 1950, moisture units of the nylon and fiberglas type were used to follow periodic changes in soil moisture at different depths. The fiberglas units were found superior to the nylon units because of greater uniformity in their manufacture and the incorporation of a thermistor for temperature measurements. The behaviour of the fiberglas units in different soils has been investigated by Farrar (1955).

The units were placed in vertical stacks at 2-, 3-, 6-, 12-, 36-, and 108-inch depths where bedrock permitted. Nine stacks were distributed over the eight-acre plot, three stacks in each soil moisture regime group. Since there was close agreement between the readings of each stack of soil units on the same site, only data for representative stacks are presented in this paper. One additional stack was placed in a nearby plot on a southern slope which represents a warmer and drier site of moisture regime 0. The fiberglas soil units are supplied with three six-foot leads in three colours. Neoprene-covered three-conductor cable is used between the soil unit and meter connection via a three-place seven-gang switch which facilitated measurement of the resistance of each unit in the buried stack. The moisture units are dependent on close contact with the soil for reliable reading. Therefore the units were inserted at least 12 inches laterally from the side of an auger hole or pit so that they were parallel to the movement of gravitational water. This prevented a damming-up of free water after rainfall. The units required up to two weeks before their resistances indicated that they were in equilibrium with the surrounding soil moisture.

The resistance of the electrode sandwich varies with the temperature as well as with soil moisture content. For this reason it is necessary to convert the resistance measured at field temperature to the resistance that would have been measured at some standard reference temperature. Colman (1948) recommends 60°F. as the standard temperature, and he has worked out a correlation chart based on laboratory studies with soils representing a wide range of texture.

The thermistors incorporated in the fiberglas units gave very uniform readings and were accurate in measuring temperatures between 32°F. and 100°F. The aforementioned variability of the electrode fiberglas sandwich, as influenced by temperature, ranges from a resistance of 1,250 ohms at 32°F. to 650 ohms at 90°F when the unit is kept immersed in distilled water. At a standard temperature of 60°F., a fiberglas soil moisture unit saturated with water filtered through a loamy sand from the experimental plot gives a resistance of about 900 ohms and a wilting point from 100,000 to 300,000 ohms depending on the batch of soil units used.

The calibration of the fiberglas units used in the study consisted of a check for uniformity at field capacity conditions before installation, and then after removal from the plot in 1954, they were calibrated as to wilting point in the following manner. A known amount of soil (dried at 220°F.) from the B_2 horizon of the plot was placed in weighed glass jars. Distilled water was added and seeds of yellow birch, white birch, or sunflowers were planted. The young birch seedlings were successfully grown under a 16-hour photoperiod with four 200-watt incandescent lamps at a two-foot distance giving a light intensity of 200- to 250-foot-candles. On July 6, 1955, jars with four-month-old white and yellow birch seedling were sealed with a mixture of paraffin and vaseline which had a melting point of 120°F. Resistance of fiberglas units and weight of the jars were observed daily until the birch seedlings were permanently wilted, i.e. the seedling did not recover in a 100 per cent relative humidity. Recovery of the seedlings was effected by injecting water through the paraffin-vaseline layer into the soil with a hypodermic syringe. Four drying cycles were run through in this manner. Figure 1 shows the relation between the resistance of the fiberglas soil unit and percentage water content of the soil on semi-log paper. The curve has the form of a hyperbola, with minor changes of water content reflecting large changes in resistance at the dry end of the scale, the reverse being true at the wet end.

The daily changes in moisture content of the soil in the sealed jars with yellow birch seedlings were expressed in percentage moisture and in resistance in ohms of the fiberglas units. These are shown in Figure 2. The line with dashes represents the course of soil moisture, as indicated by the fiberglas soil units, in the pots containing plants under test for wilting point. The dotted lines show the corresponding course of moisture calculated as per cent of oven-dry weight of soil.

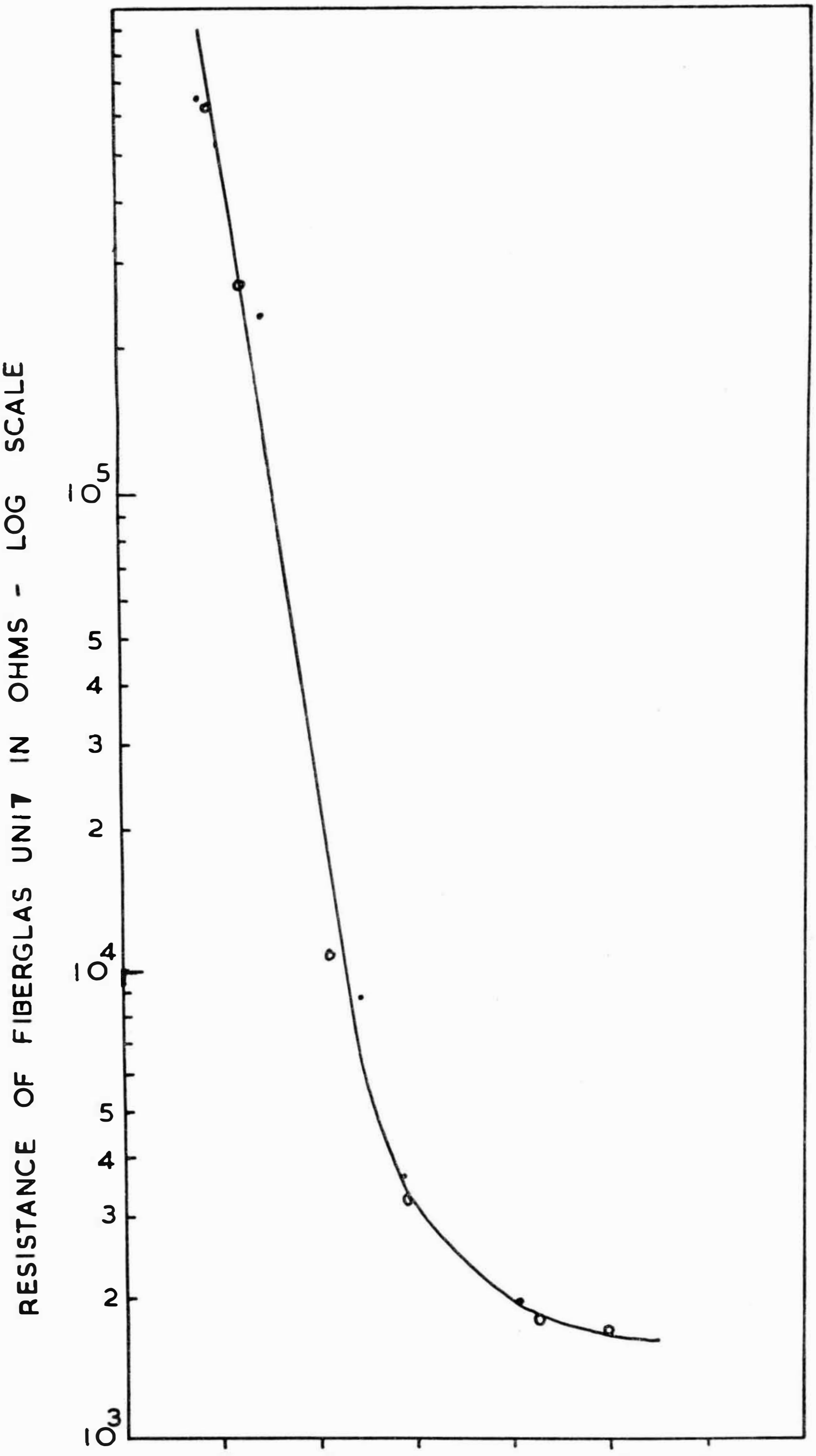

FIGURE 1.—The per cent moisture in soil of experimental plot in relation to resistance in ohms of Colman fiberglas units. Circles and dots represent two separate calibration tests.

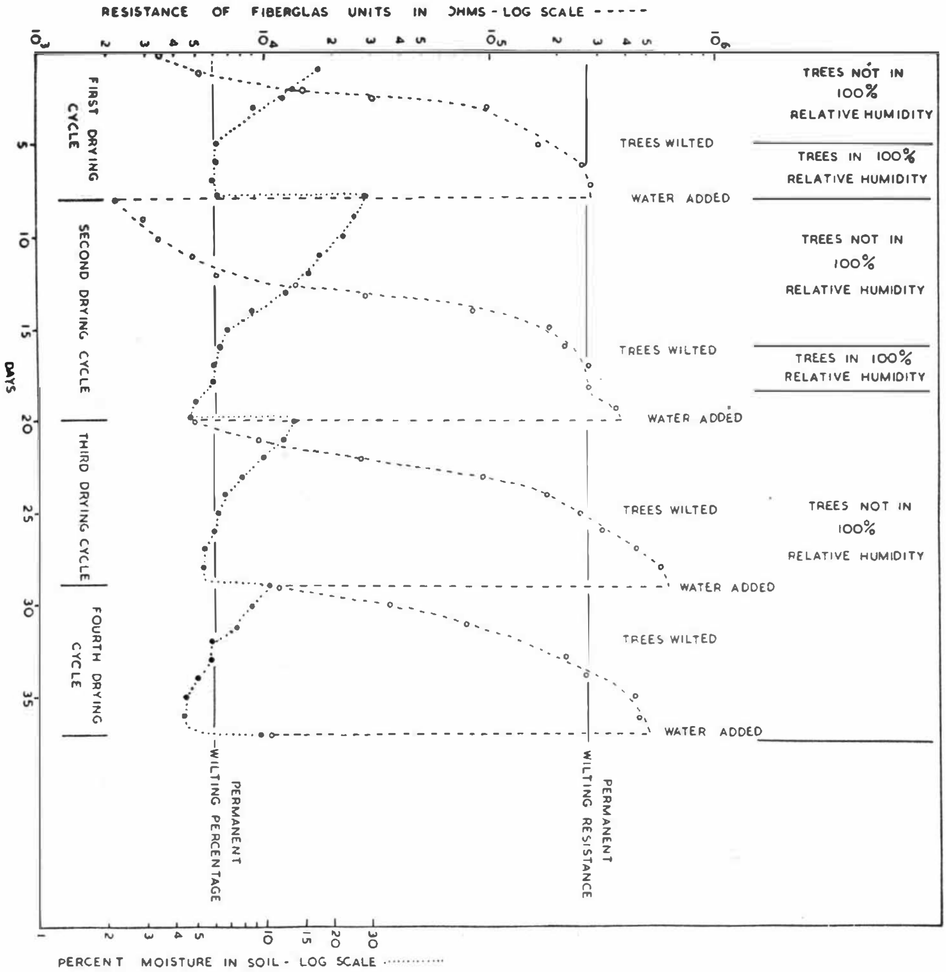

FIGURE 2.—Permanent wilting calibration of soil from experimental plot. Dotted line indicates gravimetric calibration with six per cent soil moisture indicating the permanent wilting percentage. Line of dashes indicates changes of soil moisture as measured by resistance of fiberglas unit with permanent wilting represented by 275,000 ohms. Yellow birch was the test plant for permanent wilting experiments.

The pots were wax-sealed on July 6 (first day on graph). As water was lost through transpiration, the progressive drying of the soil was observed by resistance measurements of the fiberglas units in the test soil, as well as by the decreased weight detected through successive weighings of the pot, soil, and birch seedlings. Resistance in the fiberglas units increased rapidly from the first to the fifth day when permanent wilting occurred at 250,000 ohms and a water content of six per cent. Resistance of the units gradually increased to 275,000 ohms, with the plant in the wilting chamber at 100 per cent relative humidity, as moisture equilibrium was established throughout the soil.

No moisture change was noted by the gravimetric method while moisture equilibrium was established throughout the soil mass. When water was injected through the paraffin-vaseline seal into the soil, the plant recovered and another drying cycle was run through. This time, after the plant was permanently wilted at 275,000 ohms fiberglas resistance or six per cent moisture content, it was left in air below 100 per cent relative humidity. Water continued to be drawn from the soil as indicated by the increasing resistance of the soil unit to 360,000 ohms. Water content of the soil decreased from six per cent to five per cent in the same period.

After two days of wilting, water was once more injected through the paraffin-vaseline seal into the soil. Although the seedling recovered, some of the leaves suffered injury, as evinced from the formation of an abscission layer at the base of their petioles, and they were lost to the plant. In the third and fourth drying cycles the plants were left in air below 100 per cent relative humidity after wilting. The resistances of the fiberglas units then continued to increase past the permanent wilting resistance and, similarly, the soil moisture continued to decrease past the permanent wilting percentage. This indicated that water was removed from the soil and lost through the plant even though permanent wilting had taken place. This experiment provided data for the interpretation of the periodic measurements of the fiberglas units in the field.

OBSERVATIONS AND RESULTS

The seasonal march of soil moisture, 1949-54, on the various sites in the experimental plot underwent considerable variations during the summer months. Following the melting of the winter's snow in March and April, the soil throughout its depth on all sites was close to field capacity. The soil moisture condition thereafter was dependent on summer rainfall as well as on evaporativity, both direct and as influenced through the loss of water by vegetative transpiration. Direct data on the evaporativity were not available, but the potential evapotranspiration was calculated. The rainfall for the May-September periods is shown in Table 1.

TABLE 1.—RAINFALL AT THE PETAWAWA FOREST EXPERIMENT STATION, 1949-1954

Year	May	June	July	August	September	Total
1949	2.32	4.00	2.33	3.34	2.73	14.72
1950	1.60	2.78	2.98	6.32	1.22	14.90
1951	1.54	3.26	3.01	3.00	3.48	14.29
1952	5.18	2.73	2.37	4.11	1.93	16.32
1953	1.30	2.82	2.08	1.29	3.90	11.39
1954	3.76	7.16	3.07	3.60	5.12	22.71

The yearly fluctuations in summer rainfall ranged from 11.39 inches in the dry year of 1953 to almost twice that amount during the wet year of 1954. Although in the other four years (1949-52) the amount of rainfall was nearly equal, the soil moisture conditions were not identical because the pattern of the rainfall from May to September was different. The soil is near or at field capacity due to the melting snows in the spring, and, for this reason, heavy rainfall at this time may inhibit plant growth by causing soil saturation. This gravitational water then runs off into streams and is no longer available for future utilization in tree growth. Rainfall has a more positive effect on growth later in the season because the soil has the capacity to absorb water at that time.

Potential Evapotranspiration and Soil Water Storage

Moisture in the soil is dependent on slope, soil texture, soil structure, vegetation, and climatic conditions. An integration of the climatological and forest ecological techniques was deemed advantageous in this study. In recent years, Thornthwaite (1948) has developed a method of calculating evapotranspiration in his classification of climate which appears to be suitable for the present investigation. His empirical method calculates the potential evapotranspiration from meteorological temperature records using nomograms and tables which he has found satisfactory. Potential evapotranspiration is the combined evaporation from the soil surface and transpiration from plants. It represents the movement of water from the soil back into the air. This value, combined with precipitation and water-holding capacity of the soil, will determine the availability of water to plants.

Soil moisture of forest soils is influenced by slope and consequent run-off, seepage, and depth of soil over bedrock. Thornthwaite's system is usually applied to temperatures averaged over a number of years so that a station may be classified accordingly. In this study, Thornthwaite's potential evapotranspiration values were calculated from temperature records for each month over the 1949-54 period. This provides an index for measuring variations in climate and comparison with actual moisture conditions as measured by the fiberglas soil units and observed from the permanent water table.

The potential evapotranspiration for the 1949-54 period (Table 2) was calculated together with the precipitation data for the same period. It provides an estimate of current water deficit or surplus. If a deficit is indicated, then this will have to be compensated from stored soil water, and drought conditions will prevail once this supply is exhausted. It was mentioned earlier that the soil on the experimental plots was always at maximum water-holding capacity in spring, when the melting snows provided a surplus of water. The moisture content varied between 25 and 35 per cent because of the heterogeneous composition of the till soil. These figures were checked experimentally. Soil particles less than one-twelfth of an inch in diameter from the B horizon were oven-dried at 220°F. and then packed into a long glass tube. The tube was tapped continuously for several hours to promote adequate packing. Distilled water was then gradually poured into the top of the tube and its progress downwards noted by change of soil colour. It was found that one cubic inch of oven-dried soil held 0.36 cubic inch of water. The water content of this soil at field capacity was about 30 per cent and at wilting point it was six per cent as determined in experiments described earlier.

If x equals the volume of water between oven-dry weight and wilting point, then x over 6 equals 0.36 over 0.30, or x equals 0.07 cubic inch. Therefore the volume of water available to the plants when one cubic inch of soil is at maximum water-holding capacity is 0.36 minus 0.07 which equals 0.29 cubic inch.

Let us now consider the amount (depth) of soil available to the roots of trees on the different sites. Moisture regimes 3 and wetter have seepage water, and as this influences the moisture conditions, these sites will be considered separately. On sites with moisture regimes 2, 1 or 0, that is, those at the drier end of the moisture scale, drought conditions will be more common. Although the soil on moisture regime 2 was about ten feet deep, the roots were concentrated in the upper three feet; hence this depth of soil will be arbitrarily chosen for moisture reserve calculations. Since one cubic inch of soil at maximum water-holding capacity has 0.29 cubic inch available water, 36 inches will hold 36 × 0.29 or $10\frac{1}{2}$ cubic inches. Similarly, moisture regime 1 on the experimental plot had, on the average, two feet of soil over bedrock, and will

TABLE 2.—MOISTURE DATA AND SOIL WATER STORAGE IN INCHES ON THREE MOISTURE REGIMES AT THE PETAWAWA FOREST EXPERIMENT STATION, CHALK RIVER, ONTARIO

—1949—

—	J	F	M	A	M	J	J	A	S	O	N	D	T
P.E.	....	....	....	1.65	3.06	5.04	5.19	4.94	3.22	1.81	....	....	24.91
Precipitation	4.10	1.91	1.42	2.54	2.32	4.00	2.33	3.34	3.73	1.01	1.69	2.36	30.75
Deficit	....	....	....	....	0.74	1.04	2.86	1.60	0.49	0.80	....	....	....
Surplus	4.10	1.91	1.42	0.89	....	....	....	....	....	....	1.69	2.36	12.37
Run-off	0.78	0.78	0.83	4.14	3.52	1.56	0.88	0.39	0.25	0.22	0.20	0.28	13.83
Water Storage M.R. 2	10.50	10.50	10.50	10.50	9.76	8.72	5.86	4.26	3.77	2.97	4.66	7.02	....
Water Storage M.R. 1	7.00	7.00	7.00	7.00	6.26	5.22	2.36	0.76	0.27	−0.53	1.16	3.52	....
Water Storage M.R. 0	3.50	3.50	3.50	3.50	2.76	1.72	−0.84	−0.84	−0.84	−0.84	0.85	3.21	....

—1950—

	J	F	M	A	M	J	J	A	S	O	N	D	T
P.E.	....	....	....	0.03	3.08	4.62	5.21	4.23	2.68	1.65	0.08	....	21.58
Precipitation	1.95	2.24	1.56	2.67	1.60	2.78	2.98	6.32	1.22	3.32	4.83	1.74	33.21
Deficit	....	....	....	....	1.48	1.84	2.23	....	1.46	....	....	....	7.01
Surplus	1.95	2.24	1.56	2.64	....	....	....	2.09	....	1.67	4.75	1.74	18.64
Run-off	0.48	0.64	0.56	1.81	2.33	1.34	0.69	0.47	0.48	0.46	0.95	1.38	11.59
Water Storage M.R. 2	8.97	10.50	10.50	10.50	9.02	7.18	4.95	2.[illegible]4	5.58	7.25	10.50	10.50	....
Water Storage M.R. 1	5.47	7.00	7.00	7.00	5.52	3.68	1.45	3.54	2.08	3.75	7.00	7.00	....
Water Storage M.R. 0	3.50	3.50	3.50	3.50	2.02	0.18	−0.84	1.25	−0.21	1.46	3.50	3.50	....

—1951—

	J	F	M	A	M	J	J	A	S	O	N	D	T
P.E.	....	....	....	1.22	3.46	4.45	5.10	4.25	2.79	1.49	....	....	22.76
Precipitation	2.59	2.53	3.94	3.56	1.54	3.26	3.01	3.00	3.48	3.82	3.78	2.26	36.77
Deficit	....	....	....	....	1.92	1.19	2.09	1.25	....	....	....	....	6.45
Surplus	2.59	2.53	3.94	2.34	....	....	....	....	0.69	2.33	3.78	2.26	20.46
Run-off	1.08	0.84	0.92	5.82	5.00	1.54	1.16	0.61	0.44	0.73	1.42	1.54	21.10
Water Storage M.R. 2	10.50	10.50	10.50	10.50	8.58	7.39	5.30	4.05	4.74	7.07	10.50	10.50	....
Water Storage M.R. 1	7.00	7.00	7.00	7.00	5.08	3.89	1.80	0.55	1.24	3.57	7.00	7.00	....
Water Storage M.R. 0	3.50	3.50	3.50	3.50	1.58	0.39	−0.84	−0.84	−0.15	2.18	3.50	3.50	....

—1952—

	J	F	M	A	M	J	J	A	S	O	N	D	T
P.E.	...	...	...	1.38	2.51	3.14	5.31	4.34	2.87	0.95	0.23	...	20.73
Precipitation	2.58	1.93	1.75	2.48	5.18	2.73	2.37	4.11	1.93	1.25	3.46	2.32	32.09
Deficit	...	...	...	...	...	0.41	2.94	0.23	0.94	...	...	...	4.52
Surplus	2.58	1.93	1.75	1.10	2.67	...	...	...	...	0.30	3.23	2.32	15.88
Run-off	1.15	0.93	0.82	3.63	3.80	1.76	0.78	0.52	0.39	0.29	0.26	0.52	14.85
Water 2	10.50	10.50	10.50	10.50	10.50	10.09	7.15	6.92	5.98	6.28	9.51	10.50	...
Storage 1	7.00	7.00	7.00	7.00	7.00	6.59	3.65	3.42	2.48	2.78	6.01	7.00	...
M.R. 0	3.50	3.50	3.50	3.50	3.50	3.09	0.15	−0.38	−0.84	−0.54	2.69	3.50	...

—1953—

	J	F	M	A	M	J	J	A	S	O	N	D	T
P.E.	...	...	...	0.99	3.03	4.14	5.20	4.76	2.88	1.46	0.47	...	22.93
Precipitation	2.13	0.68	3.21	2.58	1.30	2.82	2.08	1.29	3.90	0.83	1.93	0.76	23.51
Deficit	...	...	...	...	1.73	1.32	3.12	3.47	...	0.63	...	...	10.27
Surplus	2.13	0.68	3.21	2.58	...	...	...	...	1.02	...	1.46	0.76	11.84
Run-off	0.53	0.47	1.30	2.67	1.71	0.85	0.50	0.29	0.22	0.20	0.38	0.38	9.50
Water 2	10.50	10.50	10.50	10.50	8.77	7.45	4.33	0.86	1.88	1.25	2.71	3.47	...
Storage 1	7.00	7.00	7.00	7.00	5.27	3.95	0.83	−1.68	−0.66	−1.29	0.17	0.93	...
M.R. 0	3.50	3.50	3.50	3.50	1.77	0.45	−0.84	−0.84	−0.18	−0.45	1.01	1.77	...

—1954—

	J	F	M	A	M	J	J	A	S	O	N	D	T
P.E.	...	...	...	0.63	3.34	4.77	4.82	4.35	2.44	1.65	...	...	22.00
Precipitation	1.97	0.71	2.90	3.70	3.76	7.16	3.07	3.60	5.12	1.73	2.58	3.52	39.82
Deficit	...	...	...	...	...	...	1.75	0.75	...	...	...	...	2.50
Surplus	1.97	0.71	2.90	3.07	0.42	2.39	...	...	2.68	0.08	2.58	3.52	20.32
Run-off	0.52	0.45	0.77	2.77	2.85	2.56	1.40	0.92	0.76	1.59	1.68	1.37	17.64
Water 2	5.44	6.15	9.05	10.50	10.50	10.50	8.75	8.00	10.50	10.50	10.50	10.50	...
Storage 1	2.90	3.61	6.51	7.00	7.00	7.00	5.25	4.50	7.00	7.00	7.00	7.00	...
M.R. 0	3.50	3.50	3.50	3.50	3.50	3.50	1.75	1.00	3.50	3.50	3.50	3.50	...

* M.R. = Moisture Regime.

therefore hold 24 × 0.29 or 7 cubic inches of water. Likewise soil moisture regime 0 with an average of 12 inches of soil over bedrock will hold 12 × 0.29 or 3½ cubic inches of water. These three moisture regimes thus have unequal water-reserves when the soil is at field capacity.

It must be realized that the deeper soils in times of critical drought can lose additional water (referred to as non-available water) between the wilting point and oven-dry weight (assuming the soil could reach this level of dryness in the field). If such a condition should occur, then it could conceivably require a greater rainfall to satiate this soil moisture deficit in the deeper soils than in the shallower ones. This total possible non-available water deficit is as follows:

Moisture Regime 2: 36 × 0.07 or 2.52 cubic inches
Moisture Regime 1: 24 × 0.07 or 1.68 cubic inches
Moisture Regime 0: 12 × 0.07 or 0.84 cubic inch

Table 2 shows the results of these calculations with potential evapotranspiration listed in the first line. From this the rainfall (line 2) was subtracted to give the water surplus or deficit as income or outgo from the soil (lines 3 and 4). The run-off, calculated as depth in inches on the Petawawa drainage area (Anon. 1952, Wood 1956) is shown in line 5. The suitability of Thornthwaite's formula for calculating potential evapotranspiration will show if there is agreement between the water surplus (line 4) and run-off (line 5). There is good agreement in all years except 1950. The variation in that year is attributed to the fall of 6.74 inches precipitation as snow in November and December; this would not melt (and consequently show as run-off) until the following spring.

In the last three lines of Table 2, the water storage on moisture regimes 2, 1 and 0 is tabulated with the different water-storage capacities indicated in early spring as dependent on the depth of soil. Since the moisture reserves are less on the shallower soils, these will reach the wilting percentage during the summer more frequently with consequent influence on plant growth.

The annual and seasonal march of water storage in moisture regimes 2, 1, and 0 is shown in Figure 3. The increase in water reserve due to snowfall is shown as a progressive change although during winter months this reserve is on top of the soil as snow and ice rather than in the soil mass as water. Some of this may be lost as run-off and evaporation if a rapid thaw occurs with the ground still in a frozen and impermeable condition. Although water in the form of snow is usually sufficient to bring the soil up to field capacity by December, the occasional year occurs, as exemplified by 1953, when summer drought causes a large depletion of soil water. In this instance the water reserve to field capacity condition was not replaced by current precipitation until April of 1954.

The seasonal march of soil moisture will be discussed separately for the moisture regimes studied. In the presentation of field data, no resistance of the fiberglas units greater than 50,000 ohms is shown, because when the graph exceeded this resistance it usually reached 100,000 to 300,000 ohms within a day or so (as shown by the steep slope of the lines in Figures 4 to 8). To facilitate graphic representation of the data, 50,000 ohms was then taken as the base line. For practical purposes, resistances of the soil units greater than this figure may be taken as good indications of extreme drought conditions.

Moisture Regime 0

On soils with a moisture index of 0, there is little profile development. The characteristics of this regime were studied on a south slope close to the main experimental plot. The depth of soil averaged one foot, so that there

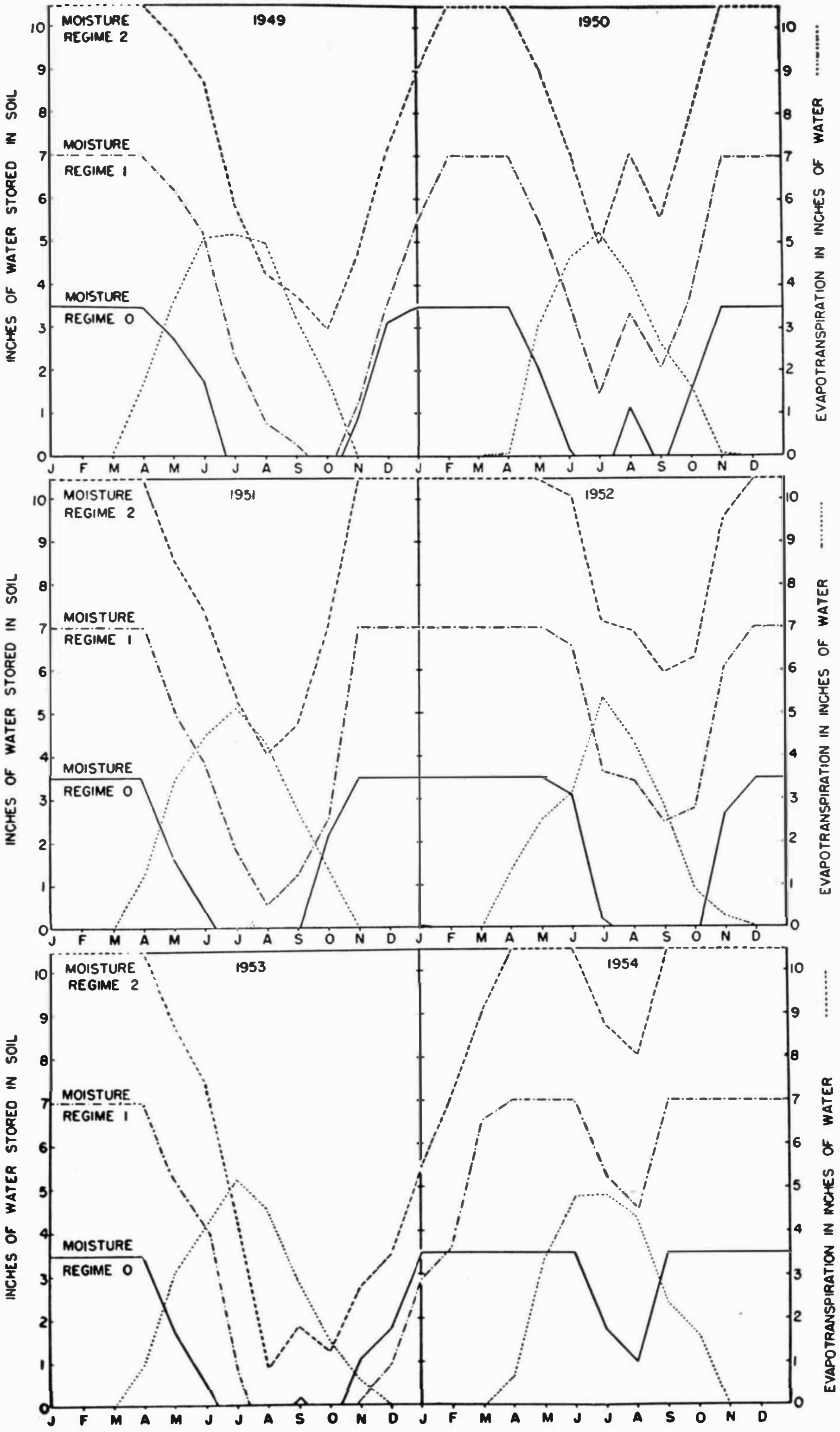

FIGURE 3.—Annual and seasonal march of water storage on moisture regimes 0, 1, and 2, with current changes in potential evapotranspiration expressed in inches of water, 1949-1954.

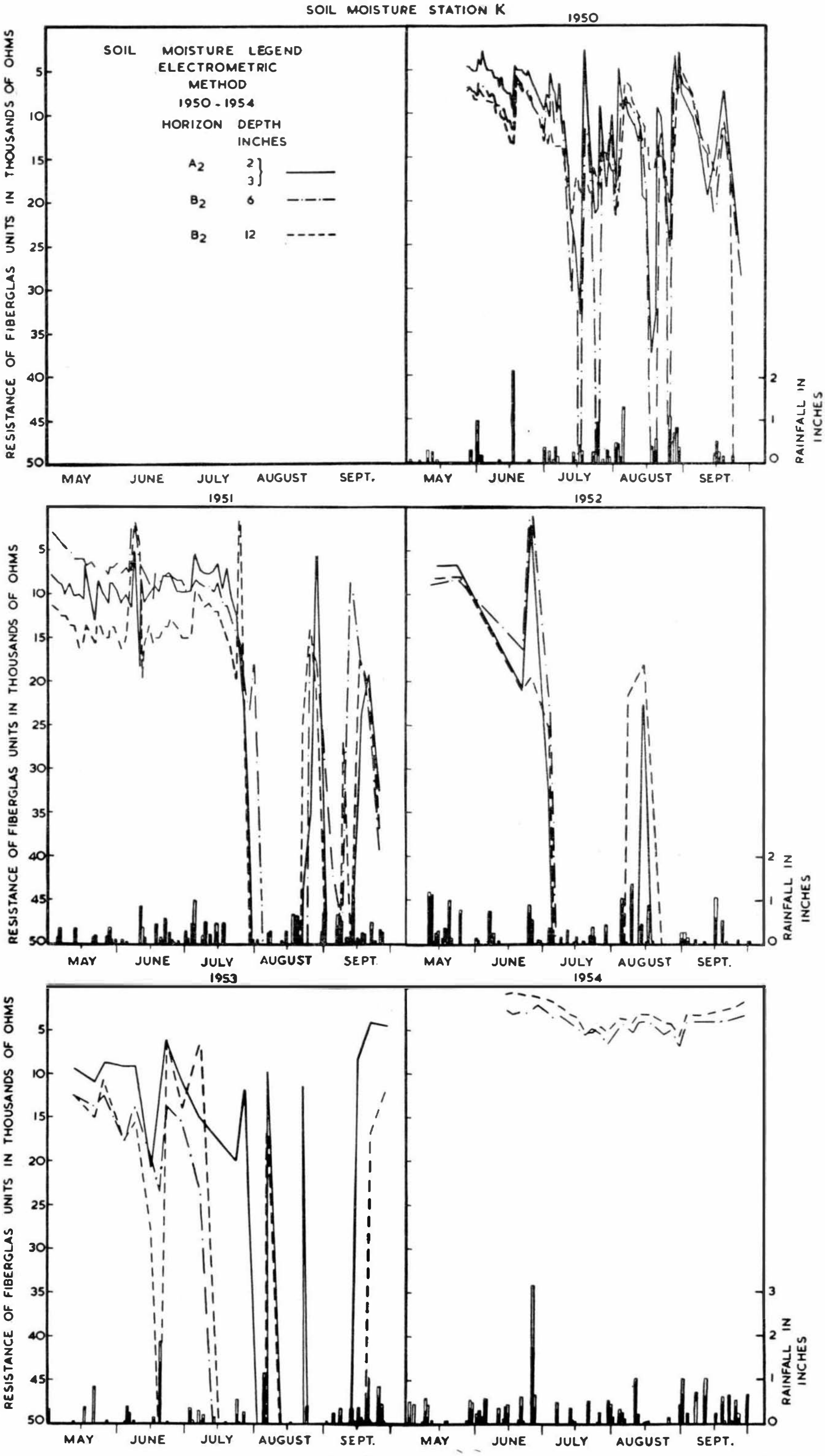

FIGURE 4.—Annual and seasonal march of soil moisture on moisture regime 0 (Station K—one foot of soil over bedrock) as measured with fiberglas units; the lower the lines, the drier the soil. Drought (wilting percentage) begins to occur when the lines indicating moisture changes drop below the bottom of charts for each year. Histograms indicate current rainfall; solid bar shows part of rainfall penetrating canopy.

was less reserve soil moisture than in the deeper soils. The A horizons were very thin and were underlain by a light-brown, poorly developed B horizon which extended to bedrock. This site was excessively drained because of its slope and shallow soil. One stack of soil moisture units (Station K, Figure 4) was located here. The 1950-54 electrometric measurements of soil moisture are shown in Figure 4. This station was established one year after the commencement of studies to provide data for a soil of a drier index than any found on the main plot.

In every year of the studies, with the exception of very wet 1954, wilting conditions or drought occurred in some part of the soil profile. In 1950, drought occurred for only one or two days at a time during July and August because of the intermittent rains of the summer. The following year had a week of drought at the beginning of August, and similar conditions extended for a longer period of two to three weeks in both 1952 and 1953. Only in the very wet year of 1954 was there no lack of soil water at any time. Thus on moisture regime 0, wilting conditions may be expected almost every year. This is substantiated by soil water storage calculations (Table 2). The frequency of drought on this site will limit the establishment of species to those able to withstand extended periods of drought. There was no permanent water table on this site.

Moisture Regimes 1 and 2

Three soil moisture stations (A, B, and C) with stacks of fiberglas units were established along the upper part of the ridge on the western side of the plot on moisture regimes 1 and 2; observations thereof are shown in Figure 5 (Station B), Figure 6 (Station A), and Figure 7 (Station C). This was the driest site studied on the main plot, yet wilting conditions occurred, for the most part, only in the upper two or three inches of the soil. The depth to bedrock varied on these three stations, ranging from two feet at Station B, five feet at Station A, and more than 15 feet at Station C. The proximity of the bedrock to the surface at Station B, with the resultant shallowness of the soil in that area, reduced the water-holding capacity on that station so that extremes of moisture conditions occurred more frequently than on the deeper soils. There was no permanent water table on Stations A or B. On Station C the water table was usually more than nine feet below the surface.

In 1949, moisutre content in the upper 18 inches of soil on this site fluctuated around 15 per cent, decreasing gradually from July onwards. The upper layers of the soil dried out more rapidly due to the proximity to the outer air and the abundance of plant roots. The solid lines in Figures 5, 6, and 7 represent the seasonal march of soil moisture at the three-inch depth and portray the rapid drying and wetting (after rain), more effective here than in the deeper layer. During the course of the 1949 summer this layer fluctuated between 22 and 6 per cent moisture. Conditions during 1950 were wetter due to the greater precipitation during August (6.32 inches) when soil moisture usually is rapidly decreasing. In 1949, appreciable rainfall (4.00 inches) in June when the soil was already wet resulted in considerable run-off laterally. This was reflected by a temporary rise of the water table on the lower parts of the plot.

In 1950, the difference in the gravimetric and electrometric methods of measuring soil moisture is apparent. Daily readings were possible with the electrometric method but the time-consuming gravimetric technique permitted only a weekly sampling on similar horizons. In addition, the depth of gravimetric sampling was limited by the occurrence of stones in the soil which interfered with the penetration of the auger for removal of the sample. The drier part of this site, with the bedrock closest to the surface (Station B,

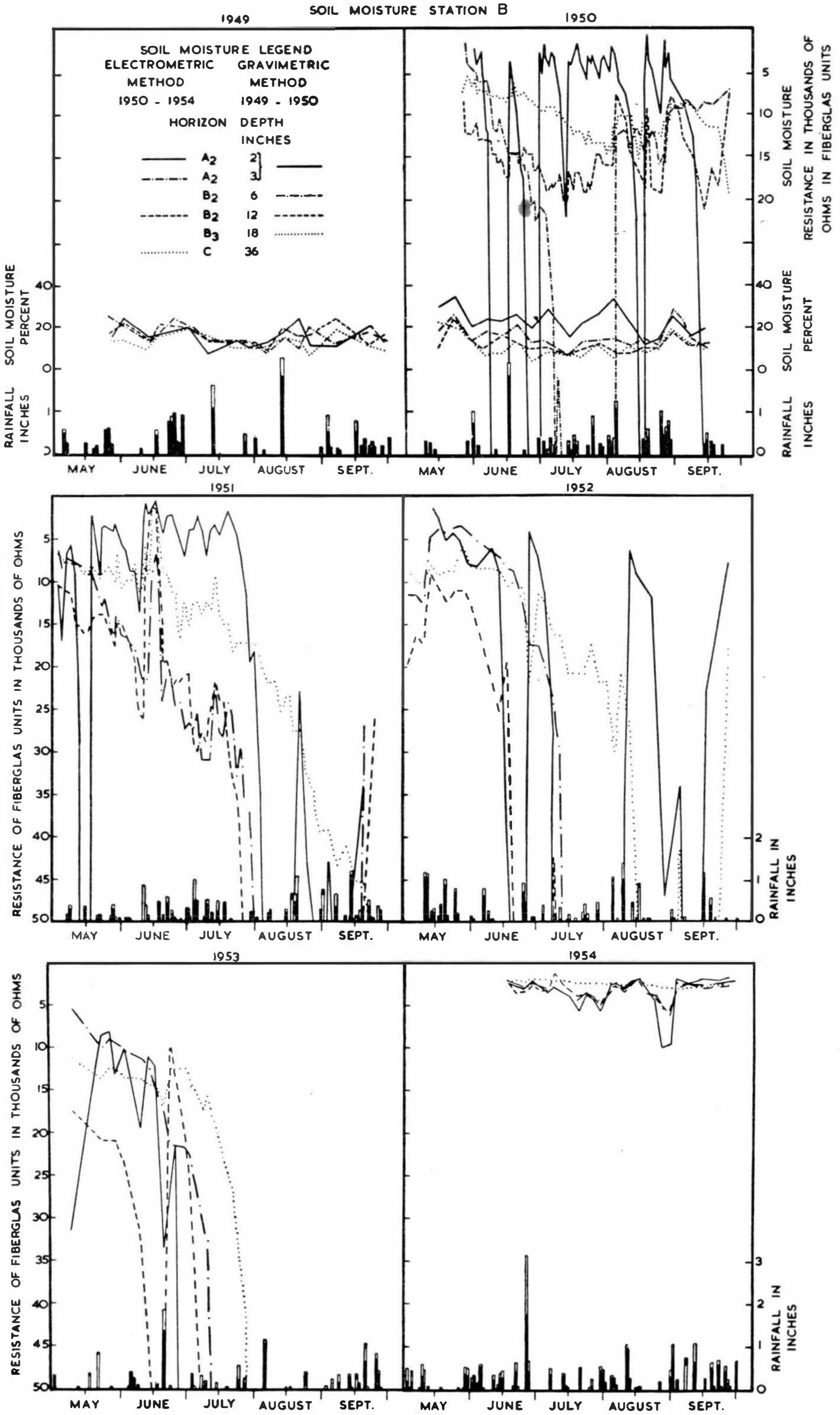

FIGURE 5.—Annual and seasonal march of soil moisture on moisture regime 1 (Station B—two feet of soil over bedrock), as measured gravimetrically 1949-50, and with fiberglas units 1950-54. Histograms indicate current rainfall; solid bar shows part of rainfall penetrating canopy.

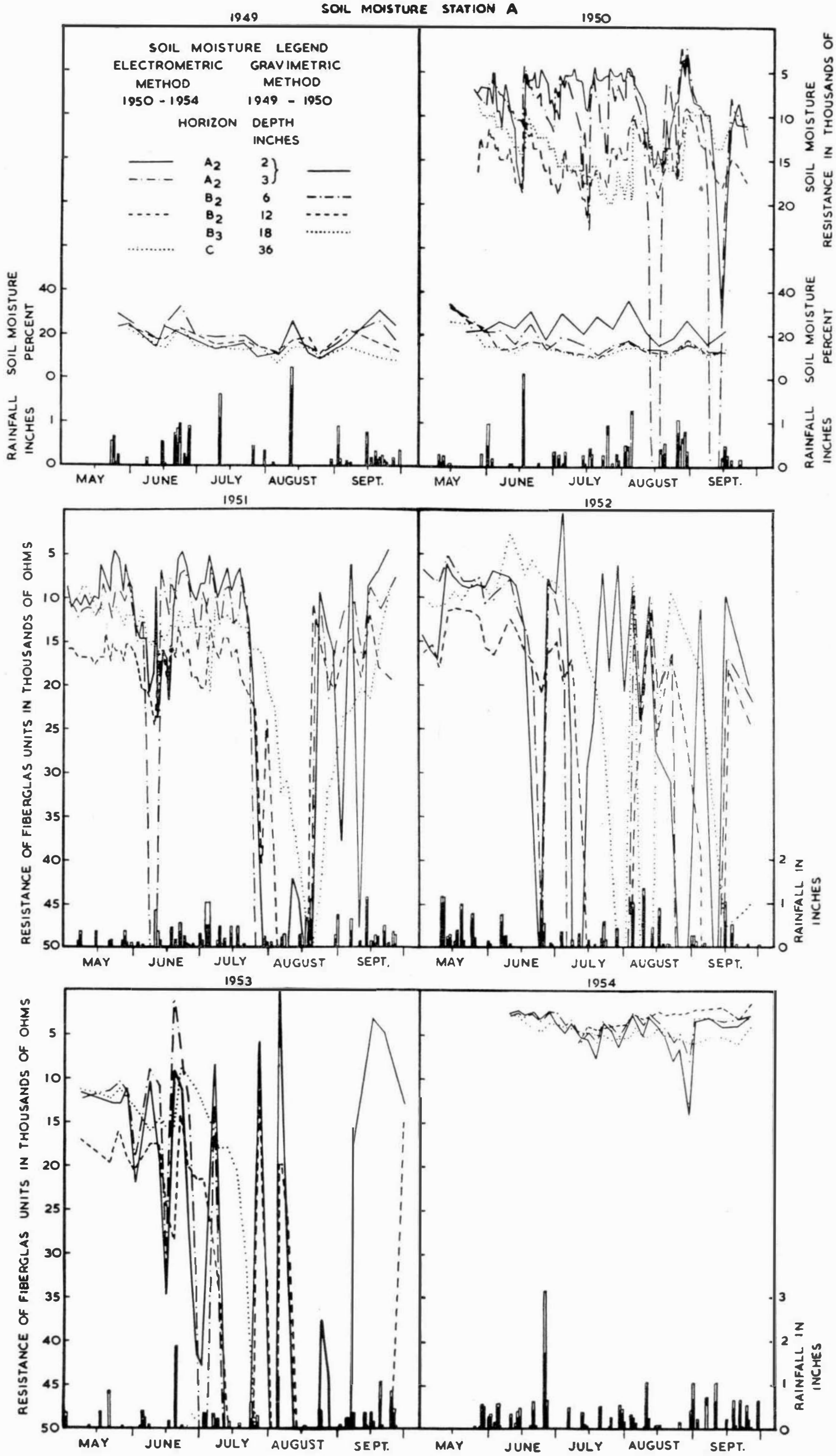

FIGURE 6.—Annual and seasonal march of soil moisture on moisture regime 2 (Station A—five feet of soil over bedrock), as measured gravimetrically 1949-50, and with fiberglas units 1950-54. Histograms indicate current rainfall; solid bar shows part of rainfall penetrating canopy.

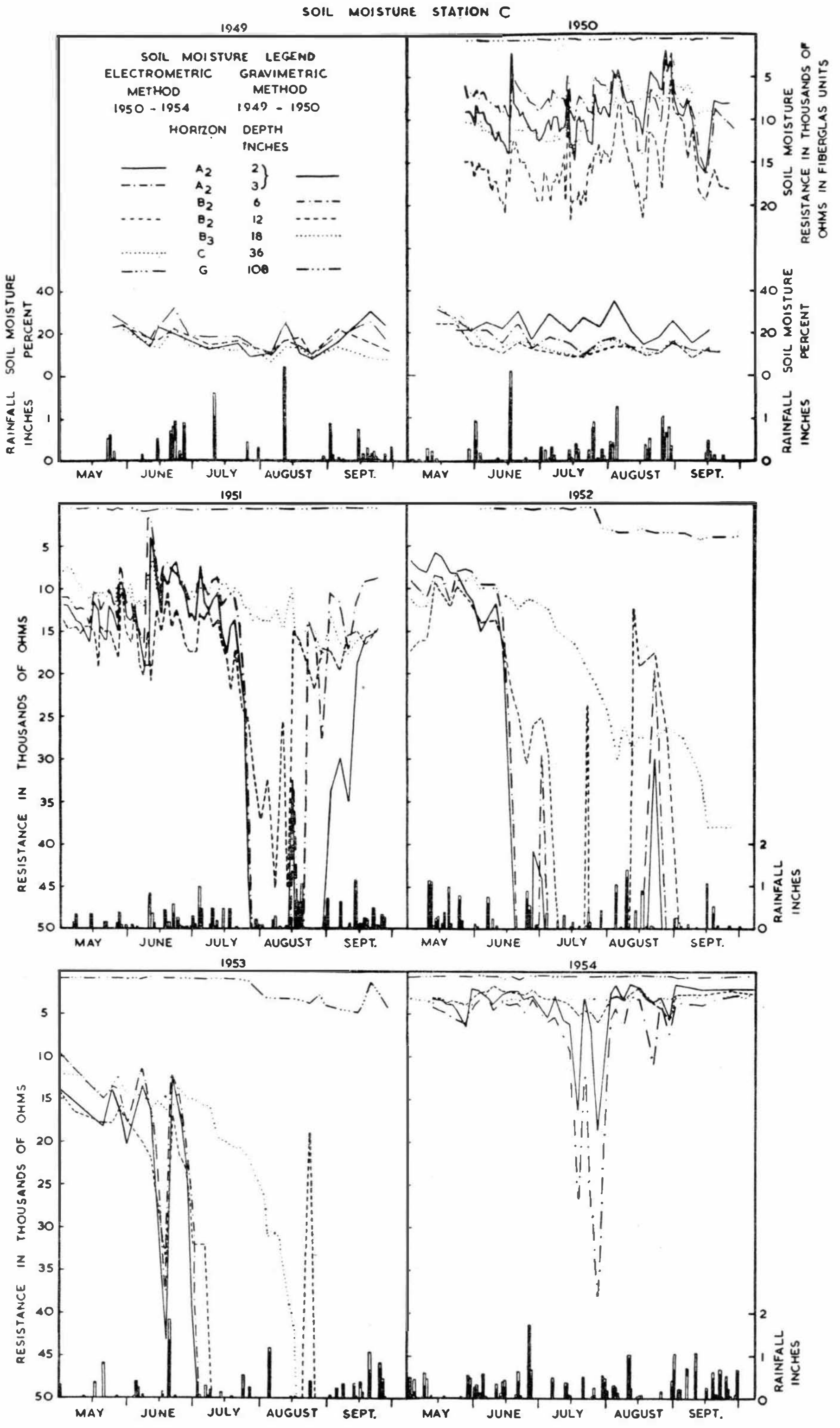

FIGURE 7.—Annual and seasonal march of soil moisture on moisture regime 2 (Station C—ten feet of soil over bedrock), as measured gravimetrically 1949-50, and with fiberglas units 1950-54. Histograms indicate current rainfall; solid bar shows part of rainfall penetrating canopy.

Figure 5), had wilting conditions occur in the upper two- and three-inch levels for short periods during the 1950 summer. Moisture conditions at the lower levels indicated water content always above the wilting percentage.

The late summer rainfall in 1951 and 1952 was similar to that of the previous two years, but soil moisture conditions were closer to 1949 since the rainfall was more uniformly distributed during the latter part of the summer. Substantial rainfall variations through May and early June are usually not critical, for the soil has a reserve of moisture obtained from melting snows in March and April. Drought conditions were manifest in the upper soil levels during late August and early September for short periods (Figures 5, 6, 7).

Soil moisture conditions of 1953 and 1954 represent extremes, since the former summer was very dry with 11.33 inches of rain, while the latter had almost twice as much rain. On the shallow soil (Station B, moisture regime 1) wilting conditions occurred at the end of June, and this soil drought had penetrated deeper by the third week of July when the whole stratum above the bedrock was below the wilting percentage and did not recover until early autumn. The deeper soils on this site showed a similar pattern. This drought was indicated by soil water storage calculations (Table 2) for moisture regime 1 during 1953. At the nine-foot depth, relatively drier conditions occurred during the same period. The opposite was evident in 1954 with extreme wetness prevailing throughout the summer. The soil was close to field capacity except for two weeks in mid-August.

Moisture Regimes 3 and 4

Soil moisture regimes represented by indices 3 and 4 are characterized by a higher water table than 1 and 2, together with underdevelopment of both the A and B horizons. The upper parts of the C horizon and the lower part of the B are modified by the fluctuating water table which causes alternating oxidation and reduction of the iron compounds. This reaction is indicated by reddish-brown mottles in the lighter coloured parent material forming the gley horizon. The annual and seasonal march of soil moisture on moisture regime 4 (Station F) is represented in Figure 8, with the position of the water table for the same period on moisture regimes 3, 5, and 6 shown in Figure 9.

In 1949 the moisture content of the upper 18 inches of soil fluctuated around 20 to 30 per cent. On June 1 it was about 20 per cent, rising temporarily to nearly 40 per cent in the upper six inches in response to the June precipitation of four inches. Since the field capacity of the mineral part of this soil is only 30 per cent, the excess water content of a heavy thundershower with almost two inches of rain on August 10, 1949, was apparent in the rise of soil moisture from 18 per cent to almost 30 per cent in the surface layer. The following month was without rain, causing the soil to dry close to the wilting percentage. The September rains brought the three-inch soil depth up to the 40 per cent moisture content.

The May-September amount of rainfall in 1950 was almost the same as during the previous year, that is, about 15 inches, yet the different distribution of rain with only 1.6 inches in May, when the soil was at or near field capacity and could not retain much more moisture, and more than 6.3 inches in August, when the soil was dry and had the capacity to absorb most of the precipitation, resulted in a soil wet throughout the summer. According to the fiberglas units that year, the soil never approached the wilting percentage. Weather conditions were similar in 1951, with a small decrease in soil moisture occurring towards the middle of August and continuing until the end of September.

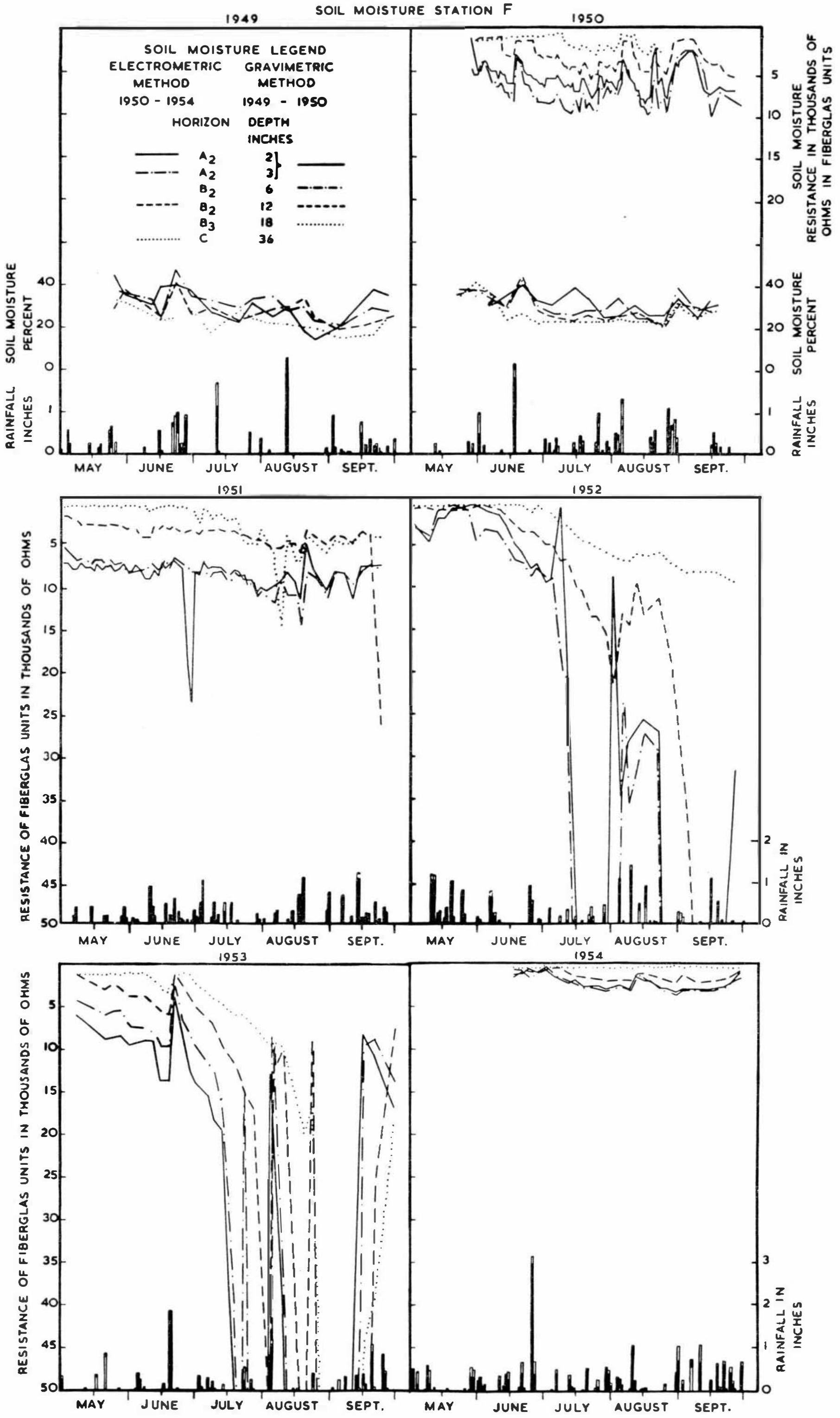

FIGURE 8.—Annual and seasonal march of soil moisture on moisture regime 4 (Station F—ten feet of soil over bedrock-seepage area), as measured gravimetrically 1949-50, and with fiberglas units 1950-54. Histograms indicate current rainfall; solid bar shows part of rainfall penetrating canopy.

Soil moisture was low in 1952 and extremely low in 1953. Although the total May-September rainfall of 1952 was more than that of any one of the previous three years, the distribution of the rain was such that almost one-third (5.18 inches) fell in May when the ground was very wet and could not retain this excess moisture. The four inches of rain in August, 1952, alleviated the soil drought. In August, 1953, rainfall amounted to only 1.29 inches, which was insufficient to satiate the soil's capacity to absorb water, hence the summer drought of that year extended through August into mid-September. Extremely wet conditions in 1954 accompanied the heavy summer rainfall of more than 22 inches.

The seasonal and annual variations of water table level (Figure 9) reflected the overall soil moisture status. The water table in soil moisture regimes 3 and 4 was always about two feet below the surface in April and early May when the soil had its greatest moisture content because of the melting snow. During the dry summers of 1949, 1952, and 1953, the water table gradually fell until a maximum depth ranging from 80 inches (1949) to 95 inches (1953) was reached in early September, at which time it started to rise in response to autumn rains and decreased evapotranspiration. During the wet summers of 1950, 1951, and the very wet summer of 1954, the water table varied between two and four feet below the surface.

Moisture Regimes 5 and 6

The development of the soil profile on this site is controlled largely by the high water table which prevails through most of the year and which retards decomposition of the organic material. The organic horizon ranges here from five to eleven inches (Fraser, 1954), with tree roots forming a tangled mass. The fiberglas soil units do not accurately record soil moisture conditions in organic material because it is difficult to maintain a close contact through the drying cycle, which results in volume changes of the organic matter. Moisture conditions were therefore followed by direct observation of the water table level (Figure 9). Moisture regimes 5 and 6 occupied the lowest part of the valley on the experimental plot; moisture regime 5 was at the southerly end and drained through a small gap in the centre of the plot into moisture regime 6 at the northeasterly end. Moisture regime 5 contained, in addition to the drainage water from the surrounding slope, a small permanent spring with a constant supply of water. This position relative to drainage is reflected in the seasonal variations of water table in these two moisture regimes (Figure 9).

In 1949 the level of the water table on soil moisture regime 6 was eight inches below the surface in May and early June, dropping gradually to 18 inches below the surface in early September, and then rising again in response to the autumn rains. An immediate rise of seven inches was noted in response to a two-inch rain in early August, indicating that seepage accounted for almost four times as much moisture as that due to direct rainfall on this site.

In 1950 the water table level was also followed in soil moisture regime 5. Its much greater fluctuation on this site indicated its dependence on rapid seepage into the site after rainfall, followed by a rapid drainage out. This contrasts with the wetter soil moisture regime 6 where without such rapid drainage, a relatively stable water table results. Moisture regime 5 was usually wetter than moisture regime 6 in May and June, when the water table was almost always within a few inches of the surface, but from July onwards the water table on this regime fell as low as six feet during the dry summer of 1953.

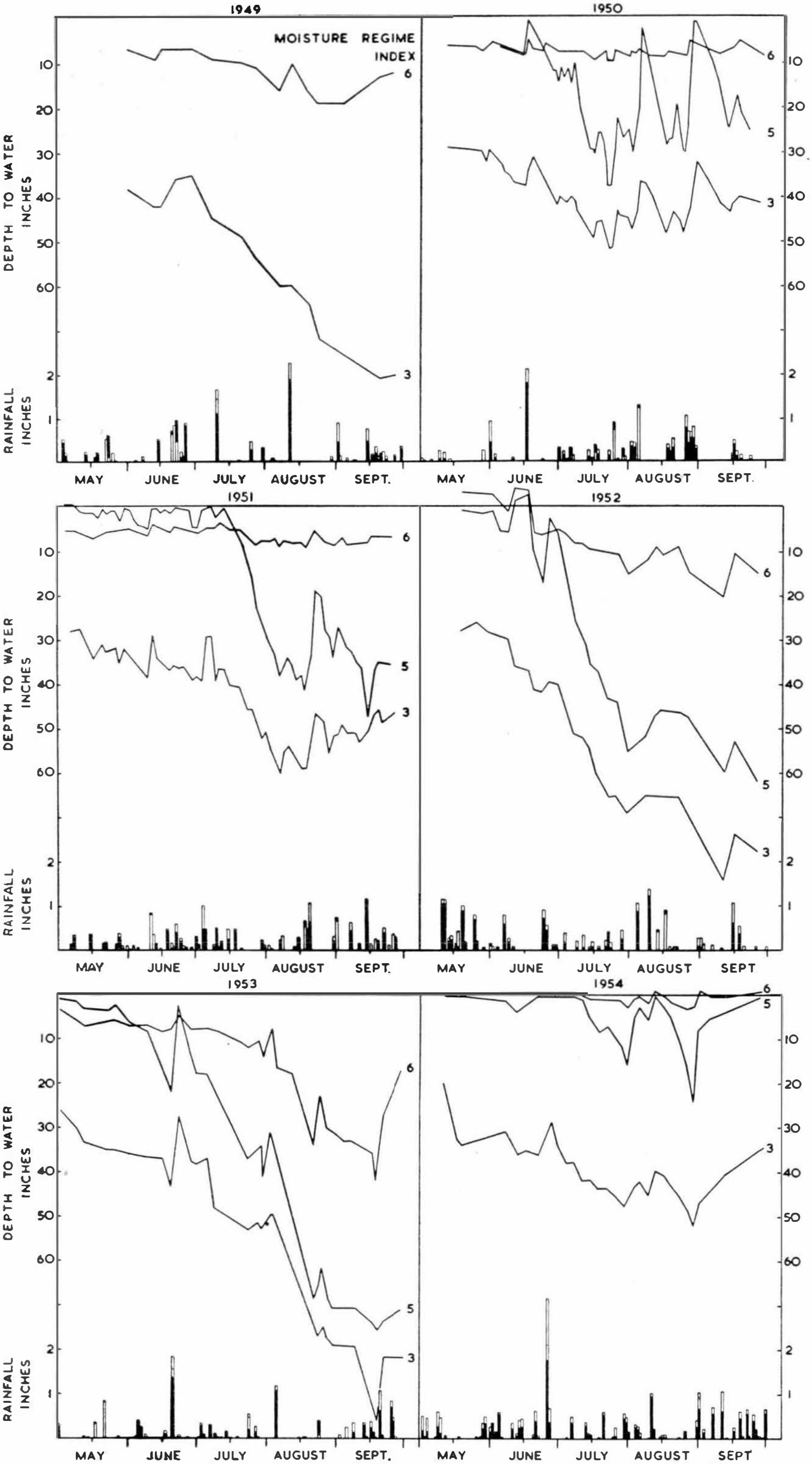

FIGURE 9.—Annual and seasonal march of water table levels on moisture regimes 3, 6, 1949-54; moisture regime 5, 1950-54.

The water table level on moisture regime 6, on the other hand, remained within a foot of the surface for most of the year except in the latter part of August in the very dry year of 1953 when it fell to a low of three feet. In contrast, during the wet year of 1954, the water table remained within three inches of the surface for the whole summer.

DISCUSSION

Moisture is one of the primary factors of both climate and site. It is important to know not only whether a climate and soil is moist or dry, but also the extent of seasonal variations, if the climate and soil are humid one season and dry the next. In this study an attempt was made to integrate potential evapotranspiration calculated according to Thornthwaite's formula (1948) with soil moisture measurements on several sites.

During 1949-1954 the average rainfall at Chalk River, Ontario, was 32.44 inches compared with 22.49 inches of potential evapotranspiration. Theoretically this resulted in a rainfall surplus of almost ten inches. However, the potential evapotranspiration is effective chiefly during the summer months when it frequently exceeds current rainfall and then draws on stored soil moisture. Taking this into consideration the average annual water surplus was 16.58 inches which approximates the average water run-off of 14.72 inches. This agreement indicates the suitability of Thornthwaite's method for calculating evapotranspiration.

The water storage capacity of each site influences the periodicity of wilting conditions or drought. In the six years of study, wilting percentages occurred every summer on moisture regime 0, except in 1954 (Table 2). Measurement of soil moisture with fiberglas units on this dry regime (Station K, Figure 4) was in agreement with calculated occurrence of drought. In addition, the fiberglas units showed the progressive moisture changes and, as was to be expected, drought conditions first occurred in the upper levels of the soil.

Moisture regime 1 had twice the water-storage capacity of moisture regime 0 because of its greater depth of soil; thus it had wilting conditions occurring in only two of the six years, i.e. in 1949 and 1953, both according to measurements of the fiberglas units (Station B, Figure 5) and as calculated water deficits (Table 2). The fiberglas units also indicated that the soil moisture content approached wilting conditions in the upper 18 inches for short periods in 1951 and 1952.

Moisture regime 2, with its deeper soil, had wilting conditions occur only in the upper 18 inches in the very dry year of 1953, for water was still available at the greater depths. This moisture regime was the first one at the dry end of the moisture scale to have a permanent water table which fluctuated at the nine-foot depth.

The wetter moisture regimes 3, 4, and 6, as represented on the plot, had progressively higher water tables (Figure 9). Because these wetter moisture regimes are affected by seepage and run-off from the drier regimes, their moisture content cannot be ascertained from water deficits or surpluses calculated from potential evapotranspiration and rainfall alone. It is on these regimes that observations of the fiberglas units and of the water table levels give a more reliable index as to current moisture conditions. The water table on moisture regime 3 was always about two feet below the surface in spring and dropped progressively throughout the summer in relation to the potential evapotranspiration-rainfall ratio. During dry years, the greatest depth of the water table was 81 inches in 1949 and more than 100 inches in 1953. The water table levels on moisture regimes 5 and 6 were higher, starting each spring on the surface. The water table on moisture regime 5 occasionally dropped as low as 60 inches, with its greatest depth of 80 inches reached in the autumn of the very dry year of 1953 (Figure 9). Here the water table was affected both by seepage and run-off from the drier sites upslope, especially after heavy rain. Moisture regime 6 showed fewer fluctuations and its water table was always within 20 inches of the surface except for one instance, in the autumn of the dry year of 1953, when it reached a depth of 40 inches. This was in contrast to its position during the wet summer of 1954 when the water table was always within two or three inches of the surface.

Growth of most trees will be impeded if the soil is drier than the "permanent wilting percentage" or wetter than "field capacity." In the former, water is no longer available to the tree in sufficient quantity, whereas in the latter, excess water flooding the roots may cause lack of oxygen which adversely influences root growth (Hunt, 1951). The uptake of minerals is also influenced by soil moisture (Hobbs and Bertramson, 1950). Although water is probably not equally available to the tree in the range between permanent wilting percentage and field capacity, the wider the range between these two points, the greater the amount of water at the tree's disposal. The moisture content at permanent wilting percentage depends on soil texture. It is lowest in sandy soils and highest in clays. The total water reserve depends not only on the texture and structure of the soil, but also on its depth (Table 2).

The seasonal and annual variations in moisture conditions in a number of moisture regimes delimited according to a reconnaissance system used in the field (Hills, 1945, 1953; Fraser, 1952; Brown, 1953) indicated the frequency of drought on each site studied. The great variations from year to year in the moisture condition at one place does not indicate that the moisture regime concept is of limited validity but rather emphasizes the complex nature of soil moisture. The Thornthwaite potential evapotranspiration tables are useful in calculating drought conditions on moisture regimes 2, 1, and 0, but additional information on seepage must be available for postulating current soil moisture levels in the wetter moisture regimes.

Although all plants are considered to have the same ability to remove water from the soil, their tolerance and survival under "permanent wilting percentages", "field capacity", or "maximum water-holding capacity", depends on the characteristics of the species. It is probable that occurrence of extreme soil moisture conditions may limit the permanent establishment of a tree species on certain sites or will influence its growth and reproduction.

The information obtained in this study provides a necessary background for tree physiology studies in progress at the Petawawa Forest Experiment Station.

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