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ANNUAL AND SEASONAL MARCH OF SOIL TEMPERATURE ON SEVERAL SITES UNDER A HARDWOOD STAND

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

IV. Annual and Seasonal March of Soil Temperature on Several Sites under a Hardwood Stand[1]

Project P-375

by

D. A. Fraser[2]

INTRODUCTION

This is the fourth contribution in a series of broad ecological studies of forest trees at Chalk River, Ontario. In contrast to the previous papers (Fraser, 1954, 1956, 1957) discussing ecological conditions on an eight-acre experimental plot during only the summer period from May to September, this one includes soil temperature variations on the same plot during all seasons for the last three years of the 1949-55 period. These data thus provide not only changes of soil temperatures on different sites (delimited according to soil moisture regimes) at various depths as observed through the so-called active growing season, but also supply information on conditions during the more adverse part of the year.

While summer measurements of soil temperatures are of great interest, particularly in relation to the theories of birch dieback as evinced by Pomerleau (1953) and Redmond (1955), the winter data might prove to be of special importance in extending knowledge of root growth and frost damage. Although it has been suggested that root growth does not cease simultaneously with crown development (Ladefoged, 1939, 1952; Richardson, 1954), too little is known about winter conditions of the soil to postulate any theories for the climate of Canadian forests. The available data on soil temperatures for Canadian winters are those of Legget and Crawford (1952), and while they give some indication of extremes, they cannot be applied to an undisturbed, usually snow-covered forest terrain.

Crawford (1952) considers that the variation in moisture content of the soil is important in affecting soil temperature changes. In the present study, the higher moisture content on the wetter sites would be expected to increase the specific heat of the soil and probably decrease the rate of change in soil temperatures. Density of snow cover influences the penetration of frost as was observed by Bouyoucos (1913), when he found the minimum temperatures at the 3-inch depth were 7.5°F. under bare soil, 15.6°F. under compact snow cover, 27.0°F. under uncompacted snow cover, and 32.3°F. under uncompacted snow and a layer of vegetation. Data presented in this paper simulates the last-mentioned condition of Bouyoucos.

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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. Part III appeared as Forest Research Division Technical Note No. 55, 1957.

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Christy (1952), in a study of vertical temperature gradients in a central Ohio beech forest from April to December, 1950, found the temperature regimes beneath the canopy and above the ground nearly uniform because of canopy influence on weather beneath it. Summer soil temperatures were higher near the surface (54° to 66°F.) than at a depth of four feet (51° to 61°F.). Fitton and Brooks (1931) reviewed soil temperatures in the United States and indicated that air and soil temperature near the surface vary in a fairly parallel manner. They state that the annual range in soil temperature is apparent at a depth of ten feet, the greatest depth for which a record is obtainable in the United States. The lag of maximum and minimum soil temperatures increases with depth. At Davis, California, the lag varies from less than one hour at the half-inch depth to approximately eight hours at the 36-inch depth. In the winter, northerly stations where the snow cover is more or less permanent show higher mean monthly soil temperatures than stations somewhat farther south but lacking a good snow cover.

MATERIALS AND METHODS

Various investigators (Keen and Russell, 1921; Fowells, 1948; Christy, 1952; and Shanks, 1956) reported that average daily range of soil temperature at the 6-inch depth was rarely more than one or two degrees. Beneath a forest canopy, the results of the present study agreed with this and spot readings were therefore considered representative. To minimize any temporary effect of sunlight penetrating the occasional opening in the canopy, the readings were taken in the morning, usually between 8.00 and 9.00 a.m.

The observations started in 1949 using glass thermometers inserted laterally in walls of covered soil pits to a depth of 18 inches. From 1950 onwards, thermistors incorporated in fiberglas soil units were used to measure soil temperature at the 2-, 3-, 12-, 36-, and 108-inch levels where depth of soil permitted. The thermistors were useful in measuring temperatures between 32°F. and 100°F. Outside of this temperature range, the change in resistance of the thermistors in proportion to temperature changes was either too small (below 32°F.) or too great (above 100°F.). Since the thermistors do not record below the freezing point, no records of sub-freezing soil temperatures are available, and this accounts for the "flat valleys" in Figure 2 and the break in the correlation diagram of Figure 3.

The sites studied were delimited according to soil profile characteristics and moisture conditions following the soil moisture regime classification of Hills (1945). In this system the complete range of soil moisture conditions from extremely dry to almost continuously saturated is represented by eleven indices, ϑ (theta) (extremely dry), 0 (zero), to 9 (extremely wet).

Details of soil profile, tree growth and general ecological conditions on the experimental area have been described earlier (Fraser, 1954, 1956, 1957). Because of the variation of topography in the small experimental area of eight acres, some of the soil moisture regimes were grouped into pairs where it was not practical to divide the plot into a large number of smaller areas. The soil temperatures were measured on a 0 (very dry) moisture regime located on a south slope of a sandy till under a cover of red oak (*Quercus rubra* var. *borealis* (Mich.f.) Farw.), white birch (*Betula papyrifera* Marsh.), and white pine (*Pinus strobus* L.); and on moisture regimes 1-2 and 3-4 under a nearby hardwood stand consisting chiefly of yellow birch (*Betula lutea* Mich.f.) and sugar maple (*Acer saccharum* Marsh.). The soil was derived from a common parent material but due to moisture variations the profiles had an organic horizon ranging from one-half inch on the driest site studied (0 moisture regime) to eight inches on the wet 3-4 moisture regimes. Air temperatures were recorded by hygrothermographs mounted on a shielded stand four feet above the ground and located on the 1-2 and 3-4 moisture regime groups. Observations were made only during the summers until 1953, when the author was stationed permanently at the Petawawa Forest Experiment Station. Periodic measurements of soil temperature have been made throughout the year since that time.

RESULTS

The seasonal variations of soil temperature, although dependent on air temperatures, shows decreasing fluctuations in proportion to increasing depth. For instance, the annual range of soil temperature at the 2-inch depth varied between sub-freezing temperatures to more than 70°F., whereas at the 9-foot depth, temperatures vacillated between 38°F. and 50°F. during the year. The May-September soil temperatures on the various sites (except for 0 site in 1949) for the 1949-54 period are shown graphically in Figure 1. In 1949 the soil temperatures at the 6-, 12-, and 18-inch depths on moisture regimes 1-2 fluctuated from 45°F. in mid-May to a high of 64°F. in July and August; from then on, temperatures decreased gradually to about 50°F. at the end of September. The soil at corresponding depths was one to two degrees cooler on moisture regimes 3-4. In 1950 temperatures on the same sites indicated a similar trend. Soil at the 36-inch depth had greater uniformity in its seasonal march of temperature. The year 1951 was the first year when temperature observations were made as early as May 1. Variations between sites were greatest in the spring (Table I).

TABLE I—SOIL TEMPERATURES (°F.) TAKEN AT DIFFERENT DEPTHS ON MAY 1st IN THREE SOIL MOISTURE REGIME GROUPS, 1951-1953

Moisture Regimes	Depth in Inches	Year		
		1951	1952	1953
0	2	51	54	55
	3	49	49	48
	12	42	43	46
	36	—	—	—
1–2	2	50	46	46
	3	47	44	41
	12	44	44	37
	36	37	40	36
3–4	2	47	42	41
	3	40	40	37
	12	37	39	36
	36	35	38	36

The spring temperature differences on the three sites were attributed largely to the insulating organic layer which was thicker on the wetter sites and which consequently retarded the spring warm-up. This temperature difference was considered as the cause of delayed initiation of radial growth in the boles of trees located on these cooler sites (Fraser, 1956). The greater near-surface temperatures on the 0 moisture regime were due partly to the more open stand and the southern aspect of this site.

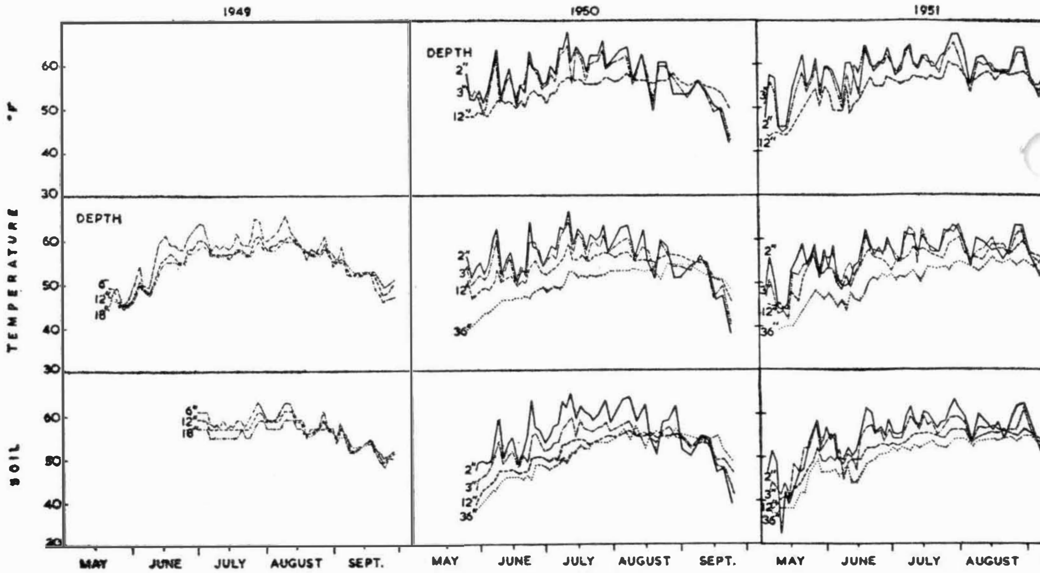


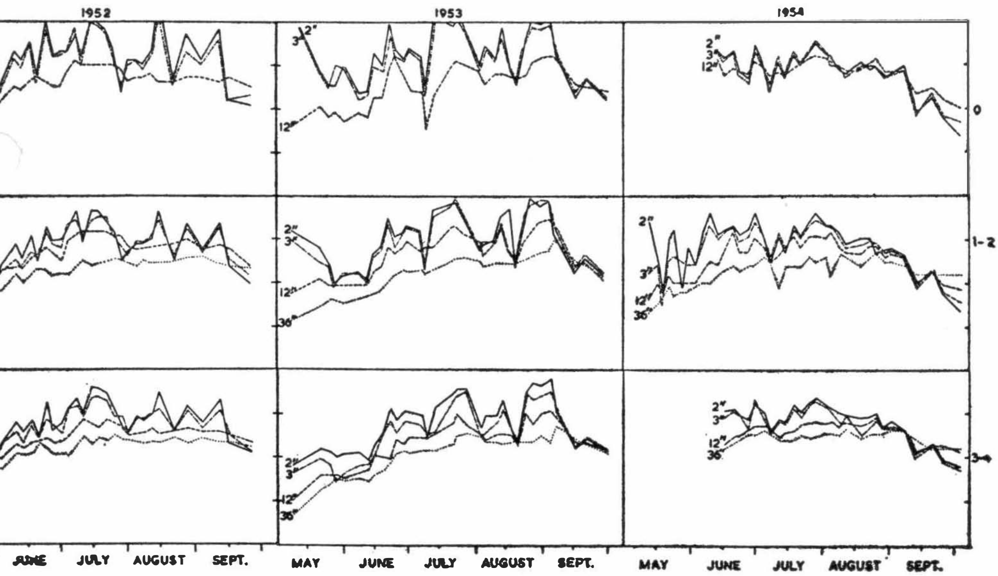
Figure 1. Soil temperatures at various depths on three sit

The very warm dry summer of 1953 and the comparatively cool wet summer of 1954 are reflected in the soil temperature data for these two years (Figure 1). In 1953 soil temperature at the 2-inch depth on the 0 moisture regime reached 70°F. for periods up to one week from July to September, with 73° and 74°F. maxima on three different occasions. Maxima were some five degrees lower on moisture regimes 1-2 and about seven degrees lower on the wet sites of moisture regimes 3-4. The summer of 1954 was cooler and had soil temperatures on moisture regimes 1-2 ranging around 62°F., or some ten degrees lower than soil temperatures on the same site one year previously.

On soil moisture regimes 1-2, soil temperatures were measured throughout the winter as well as summer months since 1953. Because of the low water table and deep soil it was possible on this site to insert thermistors to a depth of 108-inches. The march of soil temperatures at the 2-, 3-, 12-, 36-, and 108-inch depths, together with average air temperatures at the 4-foot height, are shown in Figure 2.

Legget and Crawford (1952) state that there is no appreciable variation in soil temperature below a depth of approximately 20 feet. The temperature at this depth at Ottawa, Ontario, is about 48°F. At the Petawawa Forest Experiment Station, which is 120 miles northwest of Ottawa, the mean air temperature is 39.4F. (Anon. 1952), or about two and one-half degrees lower than at Ottawa.

At the commencement of continuous measurements on moisture regimes 1-2 on May 1, 1953, the temperatures at the 2-, 3-, 12-, 36-, and 108-inch depths were 47°, 41°, 37°, 35° and 35°F. respectively. As expected, the layers nearest the surface warmed up first. Within one week, the temperatures at the 2-inch depth increased to 65°F., followed closely by 62°F. at the 3-inch depth. The deeper levels warmed up more slowly. In the third week of May, 1953, a cold period occurred with average air temperatures of 47°F. The



erimental plot during the May-September periods of 1949-54.

soil at the 2- and 3-inch depths showed an immediate response with temperatures falling to 45° and 46°F. The deeper soil, at the 12-inch depth, showed a gradual lowering of temperatures from 52° to 48°F. extending over a twelve-day period. At the 36-inch depth a mere drop of two degrees from 47° to 45°F. was recorded, whereas the temperature at the 108-inch depth remained colder than the current air temperature and levelled off at 39° to 40°F. Soil temperatures at the 2- and 3-inch levels reached a maximum of 70°F. for two periods of one to two weeks in July and August, 1953. This was about three to ten degrees lower than corresponding average air temperatures. At the 12-inch depth the maximal temperatures were five degrees lower and at the 108-inch depth about 20 degrees lower than those at the 2- and 3-inch depths during the latter part of the summer. The temperature at the 108-inch depth reached its maximum of 49°F. in early September.

The soil temperature inversion (i.e. when temperature curves of the upper layers cross those of the lower layers) occurs twice a year, usually around the beginning of April and again in October. In 1953 the autumn inversion occurred in the first week of October when falling air temperatures cooled the upper layers of the soil. The temperature at the 12-inch depth remained steady at 40°F. for the first three weeks of October and then decreased until by mid-November this layer had reached the same temperature as the above layers, namely 36°F. Temperatures at the 36-inch depth were more uniform, remaining steady at 49°F. until mid-November, and then decreasing to 36°F. by early January. The snow which covered the ground continuously from December 27, 1953, onwards throughout the rest of the winter, provided an insulating layer. The temperature at the 108-inch depth reached its maximum of 49°F. in September, remaining constant until early December, then decreasing slowly until it reached a low of 39°F. in late April of the following year. Frost was limited to the upper few inches of soil throughout this winter.

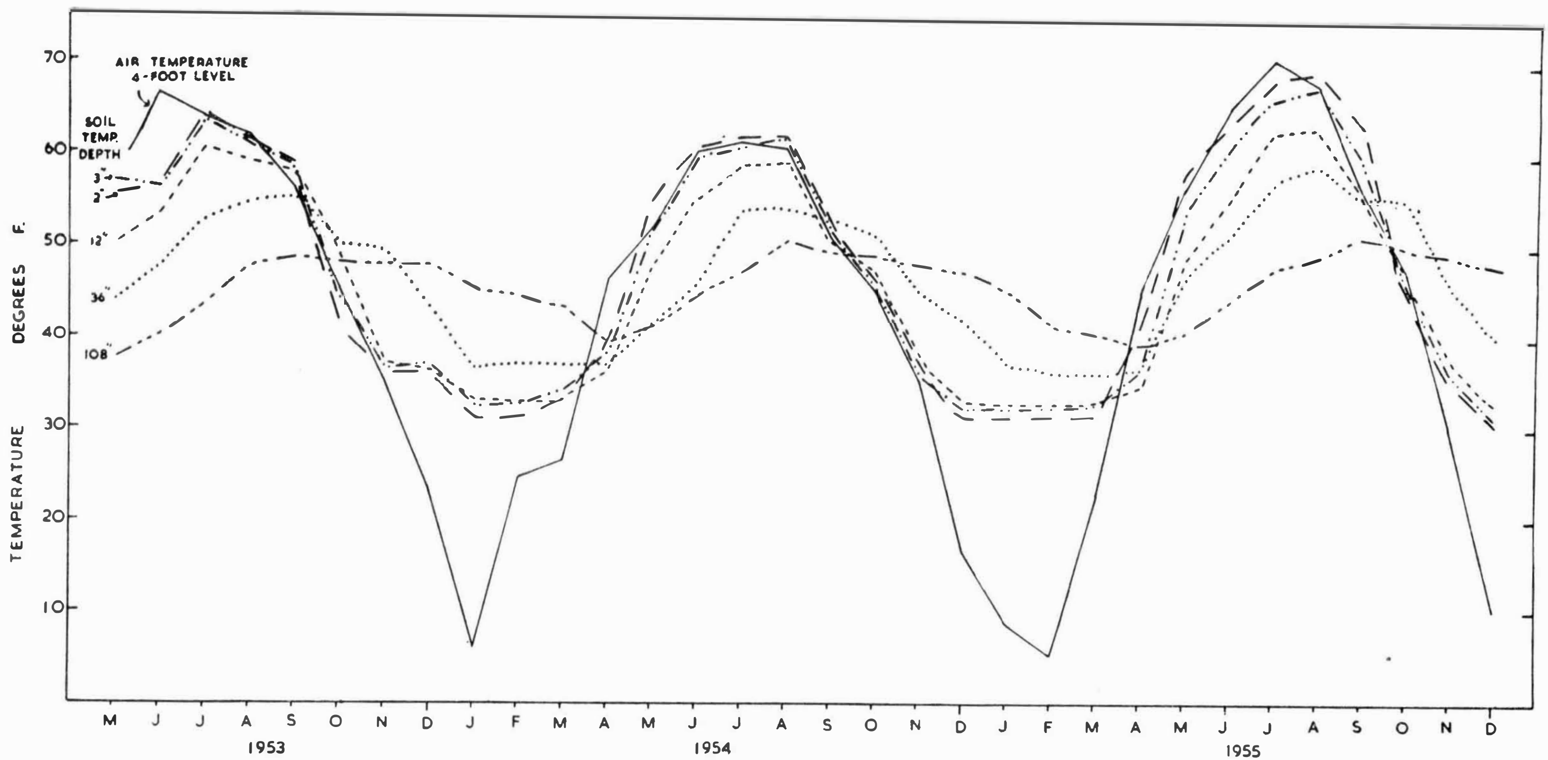


Figure 2. Mean monthly soil temperatures at depths of 2, 3, 12, 36, and 108 inches on moisture regime 1 (Station C in the experimental plot), and mean monthly air temperatures at the 4-foot level.

The spring temperature inversion of 1954 occurred in mid-April when air temperatures averaged 40°F. The soil at the 2- and 3-inch levels started to thaw April 6. These strata followed a straight-line warm-up until 50°F. was reached by May 7. Thereafter they followed air fluctuations very closely, with July-August temperatures much cooler than the previous summer. The 12-, 36-, and 108-inch levels were more gradual in their temperature responses with summer maxima of 61°, 55° and 50°F. respectively.

The autumn soil temperature inversion of 1954 occurred on September 22 when the temperatures at the 2- and 3-inch depths fell below the 50°F. of the 108-inch level. This was two weeks earlier than the previous year. The upper three inches of soil reached freezing temperatures on November 15, 1954, and did not thaw until April 15, 1955, when the spring temperature inversion took place within a few days. It accompanied the rapid rise in air temperature.

The early part of the 1955 summer was similar to the preceding two years with soil temperatures at the 2- and 3-inch levels reaching close to 70°F. for short periods in mid-May. The 2-inch level reached a maximum of 82°F. for a few days at the end of July and was above 70°F. for longer periods in August and September. The soil temperatures at the 12-, 36-, and 108-inch levels reached peaks of 65°, 63° and 55°F. which were about five degrees higher than maximal temperatures the previous year at the same levels.

DISCUSSION

A forest tree extends through a series of "temperature regimes" from the microclimate of a root tip where temperature fluctuations are gradual and limited in their range, to that of a twig where the range in temperature may extend from —40°F. in winter to over 100°F. in summer. Siminovitch and Briggs (1949) noted that the mechanism for adaptation of trees to cold is elaborated annually and alternately in response to the seasonal periodicity of climate. This is evident from the fact that trees may be killed by a temperature of 25°F. in mid-summer, but the same trees can withstand subzero temperatures during the winter months. Thus the importance of soil temperatures may be realized when it is known that it influences the metabolic activity of tree roots and soil micro-organisms, the availability of soil moisture (Barner, 1951; Bohning and Lusanandana, 1952; Kramer, 1942), and the rate of disintegration of soil particles with subsequent release of plant nutrients.

In the experimental area, soil temperatures fluctuated both annually and seasonally, but even the surface layers did not show large daily variations since the ground was shaded with trees and there was little incident sunlight to give heat from radiant energy. Surface heating was greater on the 0 moisture regime which was on a south slope and did not have the dense cover of trees characteristic of the wetter sites. The various sites showed greatest temperature differences in the spring and this was attributed to the varied thickness of the insulating organic layer which ranged from one-half inch on the 0 moisture regime to eight inches on the 3-4 moisture regimes.

The seasonal soil temperature differences between sites (Figure 1) varied from four to eleven degrees F., depending on the depth and year. The inadequacy of annual average temperature as an expression of temperature difference within the year is reflected in the data of 1954 and 1955 (Table II). The average annual air temperature at the 4-foot level in both these years was 40.6°F. However, the average monthly comparison between these two years showed that 1954 had a relatively mild winter (av. temp. December - February 15.9°F.) and cool summer (av. temp. June - August 61.0°F.), whereas 1955 had a severe winter (av. temp. December - February 8.0°F.) and a warm summer

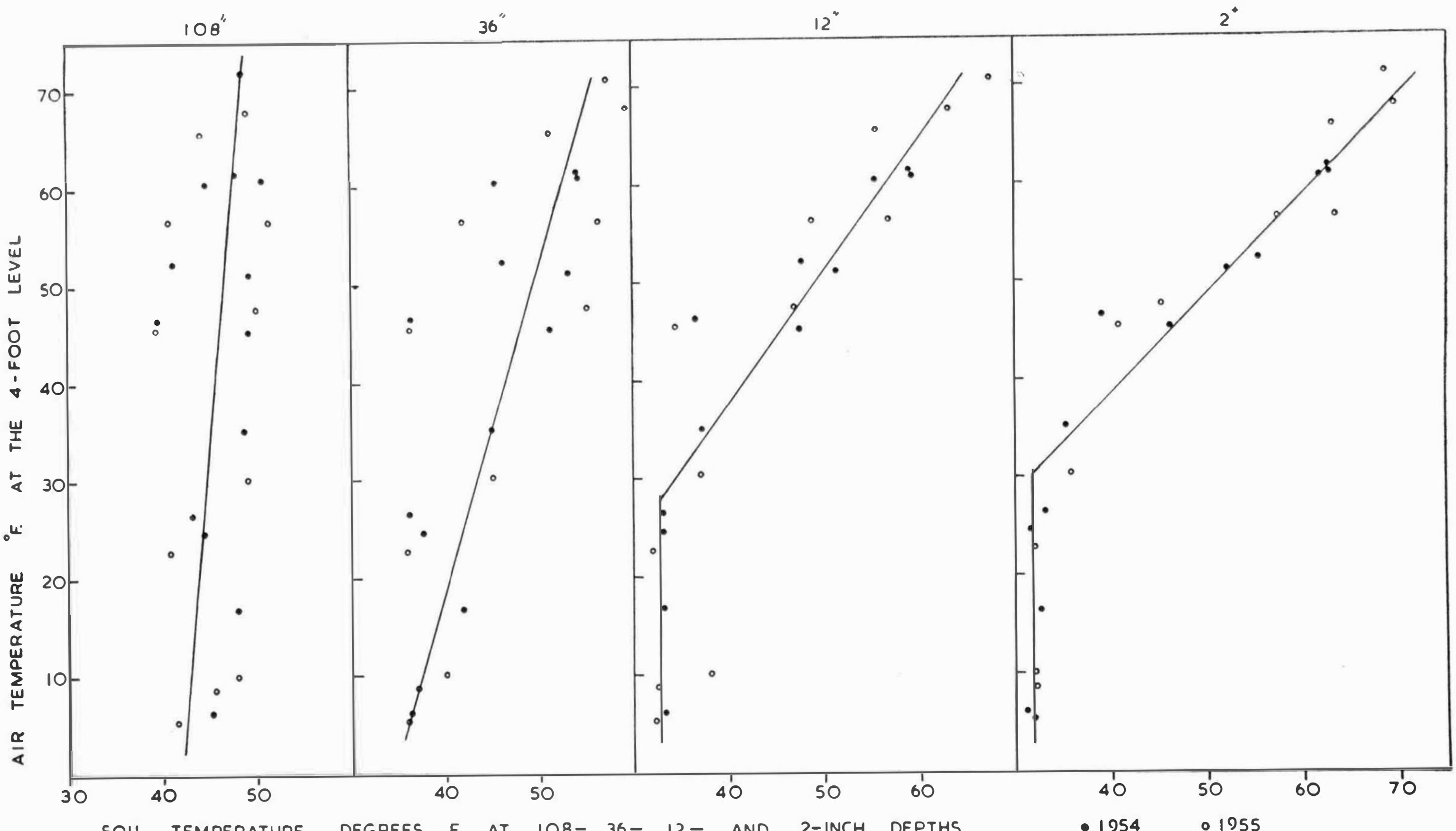


Figure 3. Relationship between mean monthly soil temperatures at depths of 2, 12, 36, and 108 inches on moisture regime 1 (Station C) and mean monthly air temperatures at the 4-foot level, May 1953, to December 1955.

(av. temp. June - August 68.1°F.). The previous four summers of 1949-53 were intermediate in their average air temperatures of 63.5°F., 62.4°F., 62.3°F., and 64.0°F., respectively. The average soil temperatures showed a similar trend.

This study has shown that there are considerable annual and seasonal fluctuations in soil temperature on the three moisture regime groups studied under a hardwood stand at Chalk River. It will form a basis for greenhouse and growth chamber studies for tree species located on this plot. Annual soil temperature variations amounted to as much as 10 degrees (Figure 2). Although Redmond (1955) considers that a 3.6-degree rise in soil temperature will cause a 60 per cent rootlet mortality in yellow birch and cause a dieback condition in the crowns, the 10-degree increase of soil temperature on the experimental plot in 1955, as compared with 1954, was not accompanied by a noticeable change in health of birch trees located thereon.

Shanks (1956) has suggested the use of soil temperature as a measure of air temperatures. He found better agreement between average air temperatures and soil temperature at the 6-inch depth, than between average air temperatures and average weekly maximum and minimum temperatures. In the present study, monthly average air temperatures (Table II), plotted against average soil temperatures at the 2-, 12-, 36-, and 108-inch depths (Figure 3), show an approximate straight-line relationship, with rates of soil temperature changes, relative to air temperature, greatest at the 2-inch depth and least at the 108-inch depth. The maximum soil temperatures at the 108-inch depth occurred usually in October, or three months after maximum air temperature (Figure 2).

Rates of change of soil temperature relative to changes of air temperature were greatest in the dry site (moisture regime 0) and least in the wet site (moisture regimes 3-4). This was attributed to the thicker organic layer in the wetter sites which would retard changes through its insulating effect as well as through its higher specific heat.

SUMMARY

Soil temperature data from the 2-, 3-, 12-, 36-, and 108-inch depths on three sites under a hardwood stand on the Petawawa Forest Experiment Station are compared with air temperatures at the 4-foot level for the 1949-56 period. Temperature differences between sites were greatest in the spring and amounted to as much as 14 degrees in the upper foot of soil. The maximal soil temperature at the 2-inch depth on the dry sites was 73°F. in the hot dry summer of 1955. During the cold wet summer of 1954 this maximum was about 10 degrees lower. Frost penetration was usually limited to the upper two or three inches of soil since the winter snow cover formed an insulating layer. Maximum and minimum temperatures at the 108-inch depth were 50°F. and 38°F.

TABLE II—MONTHLY AVERAGE SOIL TEMPERATURES (°F.) TAKEN AT DIFFERENT DEPTHS ON SOIL MOISTURE REGIMES 1-2, 1949-55 AND MONTHLY AVERAGE AIR TEMPERATURE AT THE FOUR-FOOT LEVEL

Year	Stratum (Inches)	J	F	M	A	M	J	J	A	S	O	N	D	Summer* Average	Annual Average
1949	Air	...	...	...	...	63.9	64.1	62.6	50.1	...	...	...	...	63.5	
	6	...	...	...	...	57.1	61.3	51.8	52.3	...	...	...	...	56.7	
	12	...	...	...	...	53.8	58.7	58.9	52.7	...	...	...	...	57.1	
	18	...	...	...	...	52.6	57.7	58.5	52.8	...	...	...	...	56.3	
1950	Air	...	...	...	...	62.7	64.0	60.5	51.9	...	...	...	...	62.4	
	2	...	...	...	...	55.6	60.2	58.5	51.6	...	...	...	...	58.1	
	3	...	...	...	...	55.6	59.5	57.7	52.6	...	...	...	...	57.6	
	12	...	...	...	...	51.8	56.8	56.8	54.2	...	...	...	...	55.1	
	36	...	...	...	...	52.1	50.8	52.8	52.7	...	...	...	...	51.9	
	108	...	...	...	...	36.5	42.7	44.6	49.0	...	...	...	...	41.3	
1951	Air	...	...	...	56.0	61.0	64.8	61.2	54.9	...	...	...	...	62.3	
	2	...	...	...	52.0	55.8	59.3	58.6	54.8	...	...	...	...	57.9	
	3	...	...	...	51.3	55.7	60.1	59.2	55.7	...	...	...	...	58.3	
	12	...	...	...	49.4	54.0	56.9	57.8	56.2	...	...	...	...	56.2	
	36	...	...	...	41.9	47.9	51.4	53.9	53.0	...	...	...	...	51.1	
	108	...	...	...	38.3	40.4	45.2	47.8	48.3	...	...	...	...	44.5	
1952	Air	...	...	...	51.7	61.8	67.8	62.2	55.9	...	...	...	...	63.9	
	2	...	...	...	48.3	58.8	63.1	60.0	56.0	...	...	...	...	60.6	
	3	...	...	...	48.3	59.4	63.7	60.3	57.3	...	...	...	...	61.1	
	12	...	...	...	47.8	57.4	60.8	58.9	57.0	...	...	...	...	59.0	
	36	...	...	...	42.9	51.3	53.6	53.4	52.5	...	...	...	...	52.8	
	108	...	...	...	...	45.3	44.8	45.6	47.2	...	...	...	...	45.2	
1953	Air	...	...	...	...	57.4	66.4	63.8	61.8	56.0	45.2	35.0	23.7	64.0	
	2	...	...	...	...	55.5	56.6	64.4	61.6	59.0	41.0	36.0	36.0	60.9	
	3	...	...	...	...	57.0	56.2	64.0	61.2	58.6	44.5	36.0	37.0	60.5	
	12	...	...	...	...	50.7	53.6	60.6	59.3	57.4	49.0	36.0	36.0	57.8	
	36	...	...	...	...	44.0	47.6	52.8	54.7	55.0	49.5	49.0	43.0	51.7	
	108	...	...	...	...	38.0	40.2	43.8	47.8	48.8	48.0	48.0	48.0	43.9	
1954	Air	6.1	24.7	26.5	46.5	52.3	60.5	61.5	60.9	51.1	45.2	35.3	16.9	61.0	40.6
	2	31.3	31.5	33.3	39.0	55.4	61.6	62.4	62.7	52.0	46.2	35.0	32.3	62.2	45.2
	3	32.3	32.5	34.0	38.0	51.8	60.2	61.3	61.8	52.2	46.5	35.2	32.7	61.1	44.9
	12	33.3	33.0	33.0	36.5	47.9	55.2	59.0	59.3	51.2	47.5	37.0	33.0	57.8	43.8
	36	36.3	37.5	36.3	36.5	46.1	45.5	54.1	54.2	53.2	51.2	45.2	42.0	51.3	44.8
	108	45.3	44.5	43.3	39.5	41.3	44.8	47.4	50.6	49.2	49.2	48.8	48.0	47.6	45.8
1955	Air	8.7	5.3	22.8	45.5	56.7	65.6	70.8	67.8	56.5	47.7	30.3	10 0.	68.1	40.6
	2	32.2	32.2	32.3	40.8	57.6	63.7	68.4	69.5	63.2	45.2	35.8	32.0	67.2	47.7
	3	32.5	32.5	33.0	36.8	54.2	61.1	66.6	67.0	60.2	45.0	36.2	32.5	64.9	46.4
	12	32.5	32.2	32.0	34.5	48.9	55.3	62.6	63.3	56.8	46.8	37.0	33.0	60.4	44.6
	36	37.0	36.0	36.0	36.2	47.0	51.1	57.2	59.5	56.2	55.2	45.2	40.0	55.9	46.4
	108	45.5	41.5	40.7	39.2	40.8	44.4	47.8	49.2	51.2	50.0	49.2	48.0	47.1	45.6

* June, July and August.

NOTE:—Soil temperatures represent average of all soil temperatures taken during the month. Air temperatures represent average of 2-hourly temperature records ... recorded on a stand at the 4-foot level.

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