THE EFFECTS OF HAY AND STRAW MULCHES ON SOIL MICROCLIMATES.

THE EFFECTS OF HAY AND STRAW

MULCHES ON SOIL TEMPERATURES AND

MOISTURE VALUES.

By

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Measurements of soil temperature and soil moisture values beneath and in close proximity to circular mulches of hay and straw were made. The experiments were conducted to determine whether sub-surface effects vary with mulch diameter, and to acquire information concerning the seasonal changes in such effects produced by a mulch of most favourable diameter. The modification of soil climate increased with a greater mulch size. A circular mulch with a diameter of 60 cms. or less was considered to be of no practical value for winter protection of roots. The mulch with a 240 cms. diameter, provided some winter protection, preventing freezing of the soil, and, in summer caused considerable modification of the sub-surface climate. In the summer, soil temperatures were lowered by values of up to 5°C and 2.5° C at 5 and 100 cms. depth respectively. After a two-month period of dry weather, moisture values at 0-10 cms. depth beneath

the mulch were 20% by volume, whereas, outside the mulch they were 5%. These differences decreased with increasing depth but were over 10% at 100 cms.

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CHAPTER 1

INTRODUCTION

Soil temperatures and moisture contents are known to affect plant growth, and experiments in various parts of the world have demonstrated that mulching practices affect the growth and yield of commercial crops. Jacks, Brind and Smith (1955) describe a mulch as "any material used at the surface of the soil primarily to prevent loss of water by evaporation, to keep down weeds, to dampen temperature fluctuations, or to promote soil productivity. Mulches are commonly applied throughout the Niagara Peninsula and in other parts of southern Ontario, but no detailed study of the effects which a typical mulch may have upon the soil temperature and soil moisture has been undertaken.

1. The Problem

The amount of land suitable for peach tree growth in southern Ontario is limited by the low air temperatures which would cause damage to both buds and woody tissues of the trees (Mercier and Chapman 1956). In the Niagara Peninsula the most favoured area for peach production is a narrow strip of land between Hamilton and Queenston varying in width from one to seven miles. In this strip about 75 percent of Ontario's peaches are grown (Mercier and Chapman 1956).

Whilst efforts are being made to introduce hardier varieties into other parts of the Peninsula (Collin 1967) with varying degrees of success (Mercier and Chapman 1956) the major area for peach production still remains between Hamilton and Queenston. This land, however, is being encroached upon by urban development and the aim of the peach growing industry must be to increase the yield per acre by the adoption of better horticultural practices, one of these could be mulching. With this in mind, the author decided to carry out experiments to determine the sub-surface climatological effects produced by such natural mulches as are commonly used in Ontario's apple and peach orchards. Examples of these are given in Archibald's summary of orchard soil management (1960), and in a paper by Archibald and Bradt (1963). Mulches are also commonly used in the growth of small fruits, vines and other orchard crops. Mulching practices have been found to be successful in this and other areas in increasing the quality and quantity of produce. Very little is known of the effects of a mulch upon the soil climate in all parts of the year. Archibald, Cline and Reissmann (1965) conducted a series of experiments to determine the effects of a mulch on soil temperatures at the Ontario Horticultural Experiment Station and Products Laboratory at Vineland, Ontario. However, they did not specify the size of the mulches that they used in their experimental studies, nor the location of their sensors.

2. Hypotheses

The practice of mulching has a considerable influence on soil temperature and moisture regimes. It is hypothesised that these modifications will vary with:

(a) the size of the mulch

(b) the location of measurement with reference to the centre and perimeter of the mulch.

(c) the percentage of ground covered by the mulch.

The author knows of no other research conducted in the Niagara Fruit Belt which considers these factors. Mulches are generally applied over the soil, extending to the spread of the branches and normally to a depth of fifteen centimeters (Archibald 1960), but there has been no determination of the actual effects of different mulch dimensions in modifying soil climates. It has not been determined whether small mulches are as potentially protective to the small trees as large mulches are to the larger trees. Nor has it been determined to what extent the effects of the mulch spread into the surrounding soil. This could be important since Vuorinen (1958) has observed the roots of young apple trees to extend 1-1.5 meters outside the crown circle. It is hoped that the results of this research will elucidate some of these problems and lead to more efficient and economic use of materials and time.

3. <u>A Review of the literature</u>.

(a) The effects of soil temperature and moisture upon plant growth.

Soil temperature has been observed to affect the plant by the control which it exerts over many vital processes. Some of these are the rate of mineral absorption, (Mack and Barber, 1960, Carlson, 1965); the amount of dissolved carbon dioxide in the soil water which affects the rate of root respiration, (Molga 1962); and the rate of water absorption, (Derlin 1966). Soil temperatures affect different plant types in different ways, and the optimum and critical temperatures for any one plant may depend upon the vigor of the plant and the exposure time to a certain temperature (Nightingale 1935, Willis, Larson and Kirkham 1957, Allmaras, Burrows and Larson 1964, Dinkel 1966, Phatak, Williver and Teubner 1966). Of particular relevance to this study are the effects which low and high soil temperatures have upon plant growth. Kramer (1949) found that the severity of damage inflicted depends upon the temperatures reached, the duration of low temperature and the rates of freezing and thawing. Slow freezing greatly reduced root damage. Also the process of freezing often leads to frost heaving in the soil which may damage fine roots beneath the surface and result in considerably decreased yields (Dechkov 1968). Excessively high soil temperatures prevent root development and since these occur in summer near the soil surface, they prevent root growth in what is often the most fertile part of the soil profile.

Garrett (1944) has shown that the spread and destructive power of various plant diseases is also largely controlled by soil temperature.

As would be expected, the amount of available water is also of vital importance to the growth of the plant. An insufficient supply of soil water at various stages in the development has been shown to be reflected in lower yields (Kimball 1933, Feldstein and Childers 1957, Denmead and Shaw 1960, Haddock 1961, Musick and Grimes 1961, Grimes, Herron and Musick 1962). One of the most critical times for a water shortage to occur is at the stage of flowering and pollination (Robins and Domingo 1953).

(b) The effects of mulching upon plant growth and yield

Tables 1 and 2 present a very brief summary of the beneficial and detrimental effects produced by various mulches upon the yield of certain commercial crops. In all cases of mulches being applied to fruit trees, greatly increased yields were reported. Petroleum mulch appeared to have very beneficial effects on many vegetable and fruit crops in the U.S.A. (Armour Agricultural Chemical Company 1964) though these benefits were not recorded in Ontario (Collin 1962). Many of the decreased yields due to mulch application were attributed to premature application of the material in the spring.

From the large amount of literature published on the subject, a small quantity of which is summarised in Tables 1 and 2, it may be concluded that mulching practices, partly through their effects on the soil climate, have been shown to be of significant commercial importance to the fruit grower, and form a worthwhile topic for investigation.

YIELD INCREASES DUE TO MULCHING

MULCH TYPE	CROP	LOCATION	AUTHOR	MULCH TYPE	CROP	LOCATION	AUTHOR
Alfalfa hulls/straw	Peach	Washington	Proebsting Jr. (1958)	Black polyethylene	Peppers Tomatoes Muskmelon Sweetcorn	Simcoe(Ont) Simcoe Simcoe Simcoe	Collin (1962) Collin Collin Collin
Straw	Apples,	Australia	Selimi et al (1970).				
Straw	Peach	Australia	Baxter (1970)	Black polyethylene	Tomatoes Cantaloupes Pole beans	Oregon Oregon Oregon	Clarkson et al. (1957).
Straw	Peach	Vineland (Ont.)	Archibald (1960)	Petroleum	Cantaloupes	Warmer parts of U.S.A.	Armour Agricultural Chemical Co. (1964).
Straw	Corn	Virginia	Moody et al (1963)		Watermelons Cucumbers	"	
Straw	Strawberries	New Bruns-wick	Collins (1966)		Squashes Snapbeans	"	"
Hay	Peach	Vineland (Ont.)	Archibald (1960)		Carrots Spinach	"	"
Bagasse	Pineapples	Hawaii	Magistad et al (1935)		Sugar beets Tomatoes	" "	" "
Paper	Sugar Cane	Hawaii	Stewart et al (1926)		Cotton	"	"

TABLE 2

DETRIMENTAL * EFFECTS OF MULCHING ON YIELD.

MULCH TYPE	CROP	LOCATIONS	AUTHOR
Corncobs	Strawberries	Iowa	Denison et al. (1953)
Straw	Strawberries	Iowa	Denison et al. (1953)
Straw	Blackcurrents	U.K.	Greenham (1953)
Plant residues	Corn	North-Central U.S.A.	Larson et al (1961).
Petroleum	Corn	Texas	Cochrane et al. (1964).
Petroleum	Peppers Tomatoes Muskmelons Sweetcorn	Simcoe (Ont.)	Collin (1962)

* Also included are reports where no yield increase or decrease was attributed to the mulch.

CHAPTER 2

FACTORS WHICH DETERMINE SOIL TEMPERATURE AND MOISTURE

In order to understand the way in which a mulch changes the soil climate it is necessary to examine the main components of the radiation and energy balances and show how these are modified by the presence of the mulch.

1. Radiation

The net radiation at the soil surface defines the maximum amount of energy which is available for heating the soil. This can be represented as follows:

$$Q_N = (1-\alpha)Q_S + (Q_L\downarrow - Q_L\uparrow) \text{ (cal cm}^{-2}\text{min}^{-1}) \quad (1)$$

where Q_N = net radiation

Q_S = incoming shortwave radiation

$Q_L\downarrow$ = incoming longwave radiation

$Q_L\uparrow$ = outgoing longwave radiation

α = surface reflection coefficient

(a) Shortwave radiation.

The amount of solar radiation absorbed by two adjacent but different surfaces depends only on the difference in their reflection coefficients. Monteith (1959) and Davies and Buttimore (1969) have shown that for green transpiring surfaces when there is complete vegetation cover, the value of α is 0.26. This value has been shown to increase slightly with increasing dessication of the plant material. In the case of a mulch made of hay or straw, the surface is more compact than that presented by a growing crop and there is less chance of solar radiation penetration and trapping within the mulch. This effect should increase α further. Therefore it would seem that when the ground is dry, which is the case for most of the time, the albedo of a straw surface would be higher than that of the surrounding sod. Thus the amount of energy absorbed by the mulch would be less than the surrounding grass. The value of α for a straw mulch surface, measured by Beserve (1968) as 0.21 is disputed in view of the observations made by Davies and Buttimore (1969) which are considered to be more reliable.

(b) Longwave radiation.

As in the case of solar radiation, differences in the net longwave radiation between neighbouring surfaces depend only on differences in the surface characteristics. Incoming longwave radiation must be the same over both. Outgoing longwave radiation from a surface can be written, using the Stefan-Boltzmann and Kirchoff's laws as:

$$Q_L\uparrow = \epsilon\sigma T^4 + (1-\epsilon)Q_L\downarrow \qquad (2)$$

where $Q_L\uparrow$ = outgoing longwave radiation

$Q_L\downarrow$ = incoming longwave radiation

ϵ = emissivity of the surface

σ = Stefan-Boltzmann constant

(8.14×10^{-11} cal cm^{-2}min^{-1}T^{-4})

T_S = surface temperature (°K)

Since practically all surfaces, including snow, have emissivities of between 0.9 and 0.95 (Sellers 1965),

(i) the second term in equation 2 is very small and is usually neglected,

(ii) it is probable that the values for a straw or hay mulch do not differ significantly from those of short grass or a bare soil surface (Van Wijk 1965).

The effect of differences in ϵ and T_S between surfaces can be shown from equation 2 (with the second term neglected). If $\Delta Q_L\uparrow$ is the difference in $Q_L\uparrow$ between surfaces, $\Delta\epsilon$ is the emissivity difference and ΔT is the surface temperature difference, differentiation of equation 2 gives:

$$\Delta Q_L\uparrow = \sigma T^4 . \Delta\epsilon \tag{3}$$

and

$$\Delta Q_L\uparrow = 4\epsilon\sigma T^4 . \frac{\Delta T}{T} \tag{4}$$

Hence, $\Delta Q_L\uparrow$ is proportional to $\Delta\epsilon$ (e.g. a 5% difference in ϵ between the surfaces will produce a 5% difference in $Q_L\uparrow$). The effect of ΔT is not so obvious, but it can be illustrated with a numerical example. If $\epsilon = 1$, $T = 20°C$ (= 293°K), σT^4 = 0.604 cal cm.$^{-2}$ min^{-1} (from black body tables) and ΔT = 10°C

$$\Delta Q_L\uparrow = 4 \times 0.604 \times \frac{10}{293} = 0.08 \text{ cal cm}^{-2} \text{ min}^{-1}$$

$$= 13.4\%$$

This shows that ΔT values have to be large to produce values of $\Delta Q_L\uparrow$ which exceed 10%. Such values could exist between a day mulch and a moist surrounding grass cover. In the absence of experimental evidence, these two effects can only be inferred. If both the mulch and grass surfaces are moist (as would be the case after rainfall or irrigation) $\Delta \epsilon$ and $\Delta T \rightarrow 0$ and $\Delta Q_L\uparrow \rightarrow 0$. In the more usual case where the mulch surface is drier than the surrounding grass, its emissivity should be lower (ϵ increases with moisture content) and T is greater. The effect of the latter is to increase $\Delta Q_L\uparrow$. There is, therefore, a tendency towards conservation, but the absence of empirical information prevents any firm conclusion. However, if we assume that $\Delta \epsilon$ is 5% at T = 20°C, ΔT must be 3.7°C for $\Delta Q_L\uparrow$ = 0. Under strong summertime irradiance, ΔT should exceed this value since there will be no surface cooling due to transpiration losses over the mulch. Hence different conditions. For example, if a surface is wet the evaporation rate may be high, and this will reduce the amount of energy available for heating the soil and its overlying air layers. Conversely, when less evaporation takes place under drier surface conditions, the soil and its overlying air layers will be more strongly heated.

(a) Sensible heat

By day a proportion of the net radiation absorbed by the ground surface heats the overlying air by convection and conduction. At night, sensible heat is transferred downward from the air layers to the colder ground surface.

(b) Latent energy.

Evaporation is the most important process involved in the dissipation of energy from a moist surface. As the net radiation absorbed by the surface increases, the soil temperature will rise and so also will the vapour pressure of its moisture content. As the humidity gradient between the soil air and the air above the surface increases, water vapour will be transferred into the atmosphere through the process of evaporation. The evaporation rate increases with an increasing humidity gradient and also with increasing atmospheric turbulence.

When the ground surface cools considerably at night, the air immediately above it may in turn be cooled, by radiation, convection and conduction, to its "dew point", the temperature at which its contained water vapour is sufficient to cause saturation. Any further cooling of the air will then result in the condensation of dew on underlying surfaces. "Invisible condensation" may also take place within the soil's inter-granular spaces (Ramdas 1958).

Large quantities of energy are involved in these processes of evaporation and condensation. The transformation of one gram of water into water vapour at a temperature of 15°C necessitates the absorption of 589 calories of heat, the latent heat of evaporation. This comes mainly from the surface upon which the water rests, and this energy will be released if subsequent condensation occurs.

(c) Heat flux into the ground

When the temperature of the soil surface rises by day consequent upon the absorption of some of the total net radiation, heat from the surface flows downward into the soil. Conversely, when the surface of the soil cools at night, heat flows upwards towards the surface. If temperatures at various depths are plotted throughout a 24-hour period, a series of waves results, whose amplitudes decrease with depth. On the Grimsby fine sandy loam of the McMaster campus, the amplitude of this diurnal wave becomes zero at a depth of about 75 cms. (Oke and Hannell 1966). The amplitude of the annual temperature wave decreases less rapidly with depth, and the depth at which it becomes zero can be represented as follows:

$$Aa = \sqrt{365.25}\ Ad \quad (6)$$
$$= 19.1\ Ad.$$

in which Aa and Ad are the depths at which the amplitudes of the annual and diurnal temperature waves, respectively become zero (Sutton 1953).

On the McMaster campus, the depth at which the amplitude of the annual temperature wave became zero in 1963-64 was 12 metres which was 16 times the corresponding depth for the diurnal wave (Oke and Hannell 1966).

A hay or straw mulch will exert a considerable modifying influence upon those factors in equation 5. The high air content of the mulch results in a low thermal conductivity. Thus incoming radiation which is absorbed by the surface of the mulch is not transferred readily to the ground beneath and the surface will heat up more slowly than the surrounding sod. Under these conditions more sensible heat will be transferred to the overlying air layers than to the air layers above the sod. Conversely at night, the mulch surface will cool more quickly than the sod and more sensible heat will be transferred to it from the atmosphere. However, because of the low conductivity of the mulch, little sensible heat will pass upwards from the warmer soil beneath. Thus the mulch will keep soil temperatures down during periods of positive net radiation, and up when the net radiation balance is negative.

The mulch also exerts an important influence upon the amount of latent energy exchanged at the surface. The vapour pressure of soil water increases with an increase in temperature, thus by day the warmer sod will normally have a steeper vapour pressure gradient with the air above, than will the cooler sub-mulch soil. Also the air within the mulch moves only very slowly, and would quickly become saturated, inhibiting further evaporation from the soil beneath.The freely moving air above the sod generally removes the more humid air from the near surface layers, and keeps the humidity gradient steep. In these two ways, the mulch significantly decreases evaporation from the surface of the soil beneath it.

Whilst Archibald et al (1965)have stated that light rain may be intercepted by a mulch, many workers have reported the increased infiltration rate, and reduced runoff, due to the presence of a mulch (Denisen et al. 1953, Tukey and Schoff 1963, Archibald et al. 1965, Adams 1966, Greb, Smika and Black 1967). Thus more latent energy will be supplied to the sub-mulch soil than to the surrounding sod under these conditions.

3. Some additions to the energy balance

(a) Advected energy

Air which moves into an area has characteristics which are determined partly by the type of air mass of which it is a portion, and partly by the nature of the surface over which it has travelled. Warmer air overlying a cooler surface is an additional energy source for surface processes. In general, a laminar flow of air has very little effect on the temperature of the soil surface, but a turbulent flow may change that temperature by as much as 2°C in less than one minute (Chang 1958). Wind may also have a considerable effect on the rate of evaporation as explained in the previous section.

Because of its low thermal conductivity, and because it acts as a barrier between the freely moving air and the soil surface, the mulch reduces, delays or eliminates the effects produced by wind. Thus short term energy variations attributable to advected sources may not affect the sub-mulch soil at all, whilst they exert a considerable influence upon the surrounding sod.

(b) Energy transfer by precipitation.

The transfer of energy by the process of evaporation is dependent upon the wind. Thus the energy lost by evaporation in one area will be released in another where the water vapour, after transportation by the wind, condenses.

The temperature of a soil may be very considerably affected by that of the rainwater which percolates into it. If the temperature of the percolating water is higher than that of the soil, the latter may be quickly warmed. Conversely, percolating water whose temperature is lower than that of the soil will exert a cooling effect (Geiger 1965).

The mulch may exert very little influence upon the temperature of rainwater percolating into the soil beneath it, and in this respect will not change soil temperature significantly.

(c) Effect of freezing and thawing.

When one gram of water at 0°C turns into ice, 79.7 calories of heat are liberated, this is the latent heat of fusion. Conversely, one gram of ice at 0°C cannot change into liquid form until that same quantity of heat has been absorbed.

The liberation of latent heat of fusion slows down the freezing process, particularly in a soil, where the liberated heat can be transported away from the freezing site only by conduction. Thus, when the surface temperature of a soil falls to 0°C, it tends to remain at that temperature for some considerable time before falling to some lower value. Conversely, a frozen soil will thaw slowly, since, having first raised the soil temperature to melting point, the incoming heat must be used to change ice at 0°C into water at the same temperature before any further warming can be effected. When rain falls upon a frozen soil, the temperature of the latter may be raised quickly and very markedly, consequent upon the release of latent heat to the soil as the rain freezes on its surface.

The only way in which a mulch would be of significance in the modification of the energy exchanges involved in the freezing and thawing processes, is by preventing freezing of the soil beneath its surface. By so doing all of the temperature effects outlined above would be eliminated, whilst they still occurred in the unmulched soil.

(d) Heat of wetting.

When a very dry clay soil is wetted, its molecular energy increases and this is reflected by a rise in the soil temperature (Janert 1934). During the writer's laboratory measurements of this effect, made with air-dried Lockport clay at room temperature, an instantaneous rise of temperature of 2.5°C was frequently recorded, but this was soon followed by cooling due to evaporation.

It is considered that the heat of wetting is of very minor importance, as sufficiently dry soil conditions would be rarely encountered in situ.

4. The physical properties of the soil.

The physical properties of a soil which are most important in any consideration of temperature regimes are its thermal conductivity, thermal capacity and thermal diffusivity.

(a) Thermal conductivity.

The thermal conductivity of a substance is the amount of heat in calories which flows in one second across an area of one square centimeter when there exists, perpendicular to that area, a temperature gradient of one degree centigrade per centimeter.

The thermal conductivity of a soil is mainly determined by its texture, structure and moisture content and by the nature of its constituent materials. The term "texture" is used to describe the sizes of the soil particles, and these vary from coarse sand to small particles of clay. The thermal conductivity of a soil is always less than the parent rock from which it was derived (Geiger 1965). It thus follows that, for a given type of parent material, the larger the soil particles, the greater will be the soil conductivity.

The term "structure" is descriptive of the shape into which large numbers of soil particles are arranged. During times of dry weather, when such shapes tend to become separated by voids, the structure of a soil will have a considerable influence upon the rate at which heat can pass through it.

The thermal conductivity of a particular soil is very largely dependent upon its moisture content. The spaces between adjacent particles of soil are filled either with air or with water. The thermal conductivity of still water is 0.0014 cal cm^{-1} $sec^{-1} deg^{-1}$ (Geiger 1965), whereas the corresponding figure for still air is only 0.00005. As the quantity of water in the inter-particle spaces increases, Whilst the thermal capacity of still water is 1.0 cal cm^{-3} deg^{-1}, the corresponding value for still air is only 0.00024-0.0034 (Geiger 1965). Hence, an increase in moisture content of the soil will result in an increase in its thermal capacity, as is evident from the figures in Table 4 (Geiger 1965). For this reason, it must be

TABLE 4

THERMAL CAPACITIES OF SAND AND CLAY

Material	Thermal capacity (cal cm^{-3} deg^{-1})	
	Dry State	Wet State
Sand	0.1 - 0.4	0.2 - 0.6
Clay	0.1 - 0.4	0.3 - 0.4

concluded that the soil beneath the mulch will have a higher thermal capacity than the drier soil beneath the sod.

(c) Thermal diffusivity.

The thermal diffusivity of a substance is an indication of the facility with which a substance will undergo temperature change, and its value is obtained by dividing the thermal conductivity of a substance by its thermal capacity. There are a large variety of possible combinations of values for determining the diffusivity of a clay or sandy soil in a dry or wet condition, and there is little point in calculating any typical values as the diffusivity of any soil will depend upon the balance between its thermal conductivity and capacity at the time of measurement.

An increased soil moisture content will result in an increase in both thermal conductivity and capacity, thus the thermal diffusivity tends towards conservatism, and should not vary from that of the outside drier soil as much as the individual values of capacity and conductivity would indicate. This should result in a similar heat flow properties beneath and outside the mulched area.

5. The factors which determine soil moisture.

The water balance at a particular point in a soil can be expressed as follows:

$$W = P + Li + Fu - (E + Lo + Fd) \tag{7}$$

where W = net change in soil moisture content

P = total receipt from precipitation and irrigation

Li = incoming horizontal flow

Fu = incoming vertical flow from below

E = Loss by evaporation

Lo = outgoing horizontal flow

Fd = outgoing vertical flow (percolation loss).

No elaboration of the P and E terms is considered necessary. With regard to the L and F terms, it must be appreciated that water and water vapour within a soil move in response to the following energy potentials (Rose 1966):

(a) the gravitational potential

(b) the submergence potential

(c) the pneumatic potential

(d) the osmotic potential

(e) the temperature potential.

Each of the above potentials contributes to that net total of energy which determines the rate and direction of flow through the soil of both water and water vapour. At different stages of drying-out, different potentials become dominant. For example, when the soil is very wet, the gravitational potential is the most important, though the submergence potential is also significant. As the soil dries, the matric and thermal potentials become increasingly more important, and the rate of change of soil moisture content is entirely dependent upon the balance between supply and depletion.

The application of a mulch changes the effect of some of those factors which might otherwise have contributed to an increase in moisture values within the underlying soil. For example, as has been cited before, it may intercept light summer rains (Archibald et al. 1965) and increase the infiltration rate (Moody et al. 1963, Jones, Nick, Moody and Lillard 1969). The former should reduce P but the latter should increase it to a greater extent. E will be reduced beneath the mulch, as has been discussed previously. Undoubtedly, because of the increased moisture content beneath the mulch, the potentials as described will be altered. In particular the thermal gradients resulting from the presence of the mulch will lead to a change in direction of the thermal potential, i.e. water will tend to be driven into the cooler soil beneath the mulch.

Table 5 summarises a few observations of the effects which a straw mulch has upon soil temperatures. It can be observed that the mulches produced a considerable decrease of soil temperature in summer, and a small increase in winter. These observations agree with the conclusions presented in this chapter.

Table 5

EFFECTS OF A STRAW MULCH UPON SOIL TEMPERATURES IN SUMMER AND WINTER

Depth of measurement (ins.)	Temperatures beneath straw mulch (cf. those of unmulched areas)		Temperature specification or tonnage of straw per acre.	Location	Authors
	Decrease in summer	Increase in winter			
4	Significant	-	Mean temp.	Virginia	Moody et al. (1963)
1	10 - 17^{o}C	-	8 tons/acre	Nebraska	McCalla et al.
1	6 - 9^{o} C	-	2 tons/acre	"	(1946)
1	4^{o} C	-	Mean temp. 4 pm. Aug.	Iowa	Denisen et al.
3	5^{o} C	-	Mean temp. 4 pm. Aug.	"	(1953)
1	7^{o} C	2.5^{o} C	Max. diff.	Vineland, Ont.	Archibald et al.
24	4^{o} C	2^{o} C	Max. diff.	" "	(1965)
1	13^{o} C	7^{o} C	Max. diff.	Simcoe, Ont.	Archibald et al. (1965)

CHAPTER 3

EXPERIMENTAL METHODS AND INSTRUMENTATION

1. Location of the experiments

The selection of experimental sites was determined by their availability, their suitability for mulching experimentation, their proximity to McMaster University and the fact that a 115-volt supply of electricity was essential for the operation of recording instruments.

The experiments were divided into two major groups: a "pilot study" followed by a more detailed investigation, which will be referred to as the "second phase".

At the time of the commencement of the pilot study, a suitable site became available just to the north of Cootes Paradise, which is located at the western end of Lake Ontario. The one disadvantage of this site was that the soil was heavy, and consequently not typical of the soils used for agriculture and horticulture in the area. However, for a pilot study, designed mainly to assess the proposed methods of instrumental layout, it was considered to be adequate.

The second phase of the experiments was located to the south of Cootes Paradise on lighter soil, comparable with those mainly devoted to agriculture and horticulture in the

Niagara Peninsula and southern Ontario. Both sites had once been woodland which, subsequent to clearing, had been replaced by a regularly-mown grass cover.

2. The nature of the mulching materials employed.

Mulching materials of many different types have been introduced into agricultural and horticultural practice. These range from petroleum products, stones and powders, to organic materials such as corncobs and straw. Some materials, however, are prohibitively expensive, or are difficult to obtain in the Niagara Peninsula and the adjacent portions of southern Ontario. Two of the more commonly used mulching materials in these areas are hay and straw. For this reason, the pilot study was conducted using hay, and the second phase involved the use of straw.

3. Shape and size of the mulch.

Mulches are generally applied either in circles around trees or in lines between rows of small plants. It was decided to study the effect of a circular patch of mulch since this is the pattern which is applicable to the local fruit growing industry.

Throughout the Niagara Peninsula and the adjacent portions of southern Ontario, the relative merits of circular patches of mulch of different diameter have received no consideration. The general practice is to apply a mulch in a circle, the diameter of which corresponds to the spread of the branches of the tree which is to be protected. However, it seemed probable that the diameter of the ring of mulch would influence the extent to which it modified this microclimate of the covered soil. It was with this particular probability in mind that the pilot study was initiated.

4. Instrumentation.

Thornthwaite (1958) stated that "instrumentation remains the basic problem in microclimatic research", and this view is shared by many research workers in the subject. Richards (1952) said that "to adequately measure, record and make use of soil temperature records in one localised area is a major undertaking".

Problems of instrumentation were certainly encountered but each of these was eventually solved. In addition to those of an electrical or mechanical nature, there were problems arising from human interference, the most serious of which involved the damage or theft of instruments. On one occasion, a completely staked and well tied-down circle of mulch disappeared without trace.

Oke (1964) presented an analysis of the merits and defects of various methods of temperature measurement, and any further statements on this subject would be repetitious.

(a) Pilot Study

(i) Temperature Sensing Equipment.

The only instrument available when the pilot study was undertaken was a 40-point recording system, whose sensors were small platinum resistance coils connected to the instrument by 75 meter leads. This instrument was designed by the Thermo-Electric Company at Brampton for the industrial measurement of very high temperatures when no great accuracy is required. The modification of the instrument to make it suitable for the recording of soil temperatures to a much greater degree of accuracy involved many changes in the circuitry, including the provision of a greater degree of amplification and a completely re-designed switching system. Many of the necessary modifications were only determined after the earliest attempts to use the instrument failed. The individual resistance pad built into each of the long leads to ensure uniformity of response also created some problems. Nevertheless, after all of these deficiencies and faults had been corrected, the instrument became a very efficient and accurate piece of equipment for the collection of soil temperature data.

At the end of each of the long leads, there was a protective metal sheath, which enclosed a ceramic-covered platinum coil. The resistance of this coil was a function of its temperature, which was in turn determined by the temperature of the surrounding soil. When required, the resistance of each coil in turn was recorded on a strip-chart, from which a direct measurement of temperature could be obtained.

(ii) Calibration of temperature sensing equipment.

The manufacturers, upon request, incorporated into the instrument two calibrating resistance coils. The resistance of each of these coils was known, as also was the temperature which each of these values would represent. Depending upon the temperature range in which the instrument was directed to record, one of these calibration values would be printed out whenever a set of readings was obtained. In this way the accuracy of the temperature reading obtained from each of the buried sensors could be assessed. It was always within 0.2°C.

(iii) Soil moisture.

During the pilot study it was hoped that measurements could be made to determine the effects of the mulches upon soil moisture. However, repeated attempts to calibrate the twenty Bouyoucos blocks were unsuccessful. It was consequently decided to omit soil moisture measurements from the pilot study and to obtain better soil moisture measuring apparatus for the second phase of the experiments.

(iv) Additional observations.

Observations were also made of grass minimum temperature, the air temperature at 135 cm. as indicated by an Assmann psychrometer, and other pertinent variables such as snow cover, precipitation and cloud cover.

(b) Second phase

(i) Temperature sensing equipment

When compared with platinum resistance coils, copper-constantan thermocouples have several important advantages as sensors of sub-surface temperature. In particular, large numbers can be made both quickly and cheaply, and, when coated with epoxy resin, problems which might arise as a result of the oxidation of the copper wire are eliminated. Moreover, all thermocouples made from a 650 meter length of constantan wire conform to the same calibration curve, which remains unchanged through time, and they can be more precisely placed in position at defined depths.

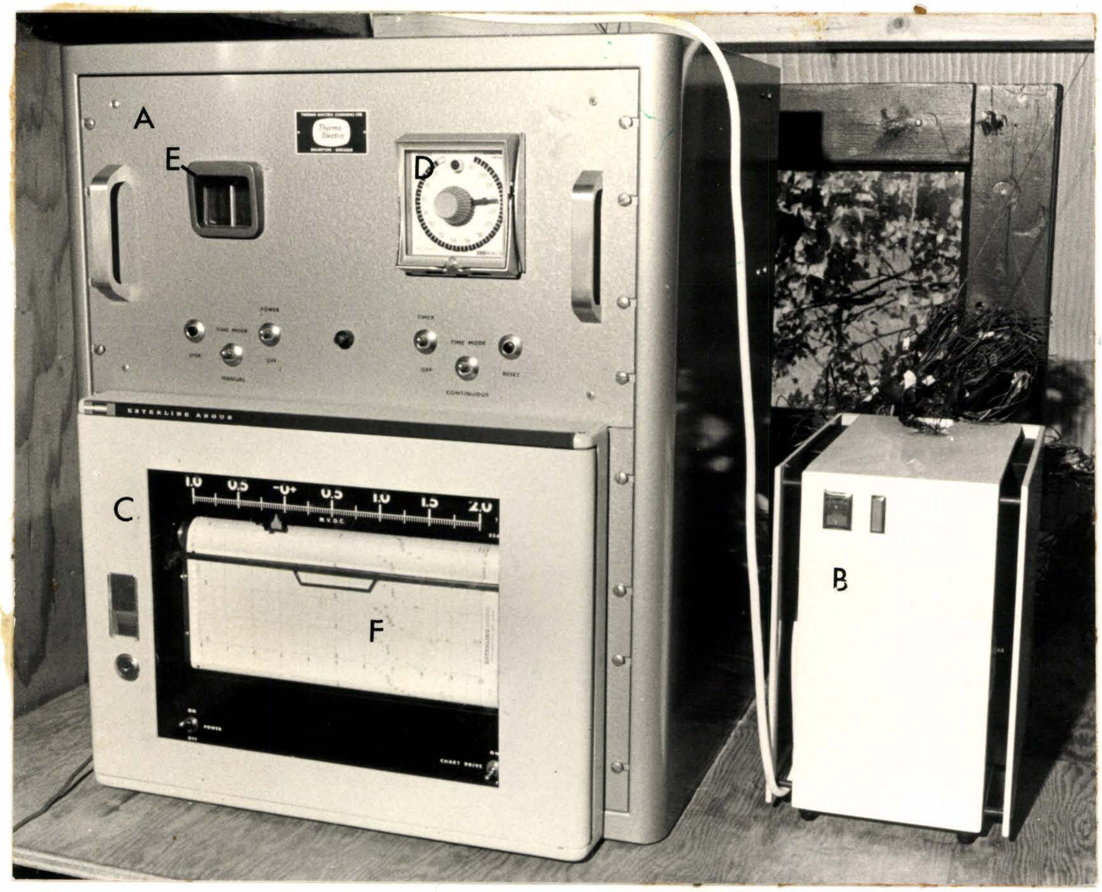
It was therefore decided that during the second phase of this investigation sub-surface temperatures would be measured by means of copper-constantan thermocouples.

The wire selected for use was 24-gauge copper-constantan, as supplied by the Thermo-Electric Company. In the manufacturing process, the copper and constantan wires are separately covered with polyvinyl and the pair is then similarly sheathed. Such a covering is preferable to nylon for, although more liable to damage by abrasion, it does not crack when exposed to low temperatures.

Plate 1 shows one of the two 96-point thermocouple recording systems (A) which now became available, each equipped with an I-cell constant temperature reference unit (B) which was electrically maintained at 0°C. The two recording systems each incorporated a 24-point thermocouple recorder (C), one manufactured by Esterline-Angus (shown in Plate 1) and the other by Texas Instruments. Each of the recording systems, built by Thermo-Electric of Brampton to handle 96 sensors at the request of Dr. F.G. Hannell, the writer's original supervisor, was equipped with a timing device (D), made by Davis Instruments of Toronto, by means of which the system could be activated at any specified interval between 1 and 30 hours. In the window (E) the sensor numbers were indicated as these became activated in sequence (1-96), and a dot with the appropriate sensor number was automatically printed on the chart (F).

PLATE 1

ONE OF THE TWO 96-POINT THERMOCOUPLE RECORDERS, WITH ITS I-CELL REFERENCE UNIT



A. 96-point thermocouple recording system.

B. I-cell constant temperature reference unit.

C. 24-point recorder.

D. Electrically operated time switch.

E. Sensor indicator.

F. Chart.

(ii) Calibration of the temperature sensing equipment.

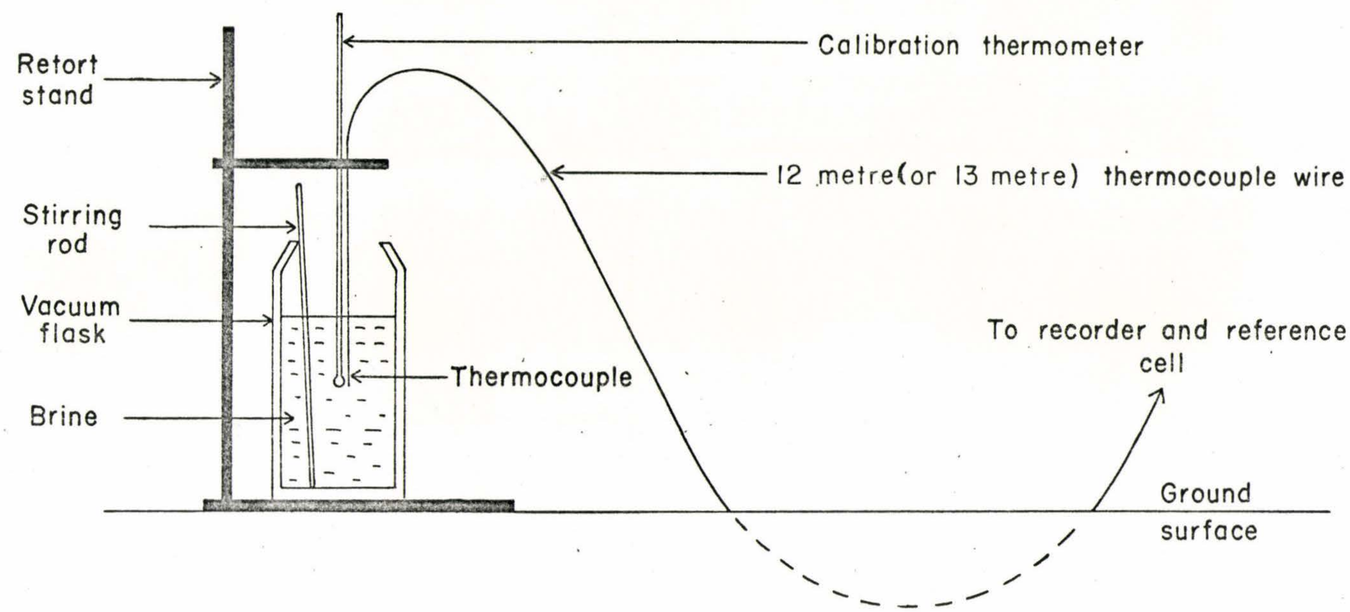
The 96 copper-constantan leads which led to a recording system at the experimental site were approximately of the same lengths, 13 meters in the case of those which led to the first recording system and 12 meters in the case of those which led to the second. The lengths of the wires used in the making of the thermocouples which were to be used for the calibration of the two recording systems were 13 and 12 meters respectively, and during the process of calibration these were buried on the experimental site to the same depths as those which led from each system's thermocouple sensors.

One could have calibrated a copper-constantan thermocouple and tested each of the two 24-point recorders for zero error and linearity of indication in two quite separate operations. Instead of so doing it was decided to perform both tasks simultaneously, by determining the temperatures which corresponded to closely-spaced print-positions on the recorder chart.

A brine solution was placed in a vacuum flask (Fig. 1), in which were submerged a thermocouple and the bulb and lower stem portion of a calibration thermometer, graduated in tenths of degrees centigrade and previously tested by the National Physics Laboratory in England. By

Figure 1

CALIBRATION EQUIPMENT FOR 96-POINT RECORDERS



means of rubber bands, the thermocouple was held in position very close to the bulb of the calibration thermometer, in an effort to reduce any temperature gradients between them to quite insignificant values. The initial temperature of the brine was -15°C, and water was added periodically to raise this through successive intervals of about 3°C. When the temperature of the brine, as indicated by the calibration thermometer, became steady after stirring, a mark was made on the chart paper coincident with the position of the recorder's indicator. In this way, sufficient observations were made to calibrate the system from -5°C to +45°C. The results for each recorder were plotted as in Figure 2, by reference to the scales of temperature and chart-position shown along its left-hand and upper margins respectively, and a best-fit curve was thendrawn through the plotted positions of the points. Horizontal lines were then drawn from the vertical axis to the curve, and from the intersections vertical lines were drawn to the lower margin to give thereon a resulting temperature scale. This was duplicated on a strip of card which, when subsequently applied to a series of printed points on the recorder's chart paper, permitted these to be converted into a series of temperatures.

The calibration data for that recording system which incorporated the Esterline Angus recorder are shown in

Figure 2

CALIBRATION OF THAT RECORDING SYSTEM WHICH INCORPORATED THE TEXAS INSTRUMENT RECORDER

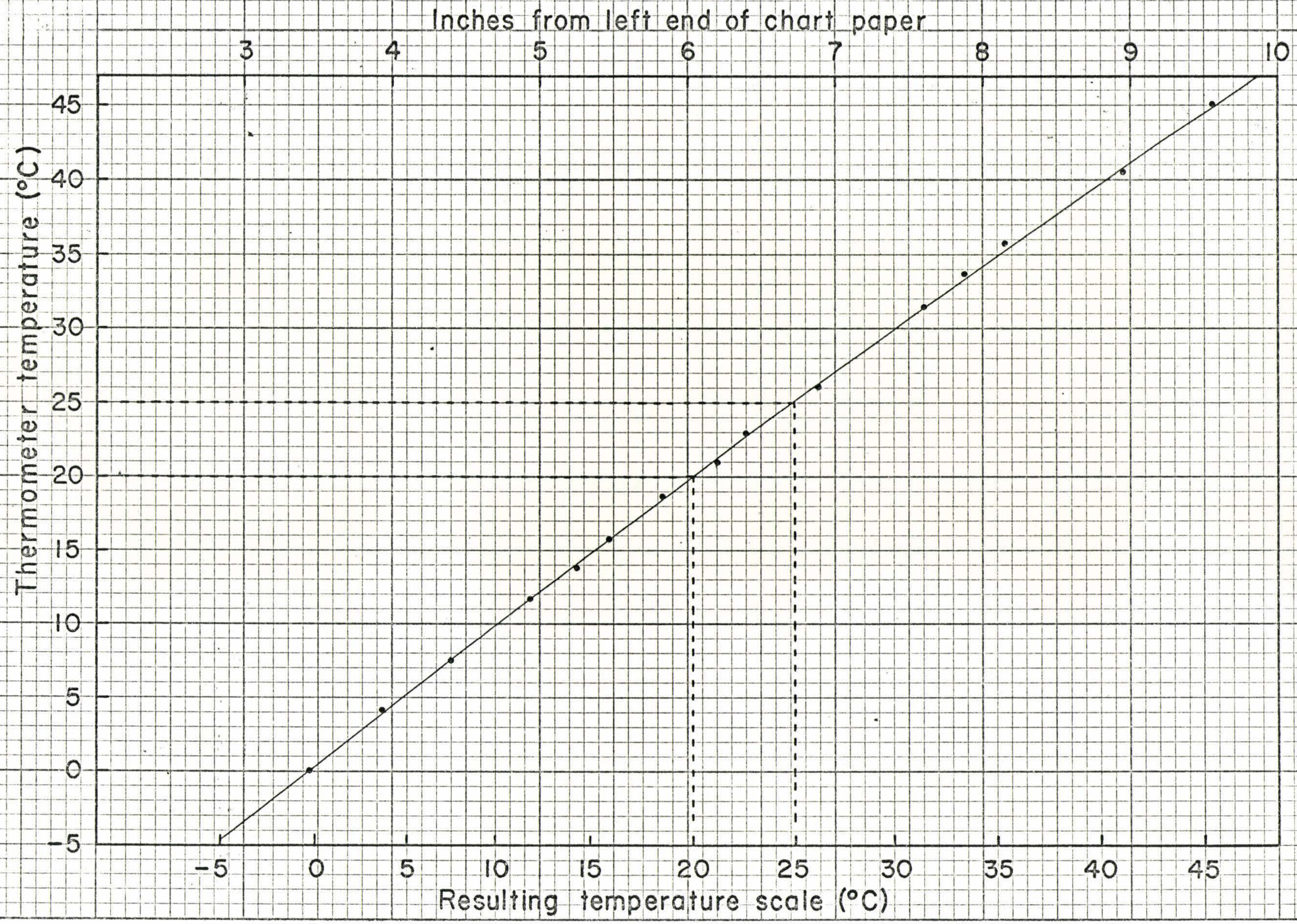


Figure 3. It can be observed that the calibration curves are non-linear and of opposite curvature.

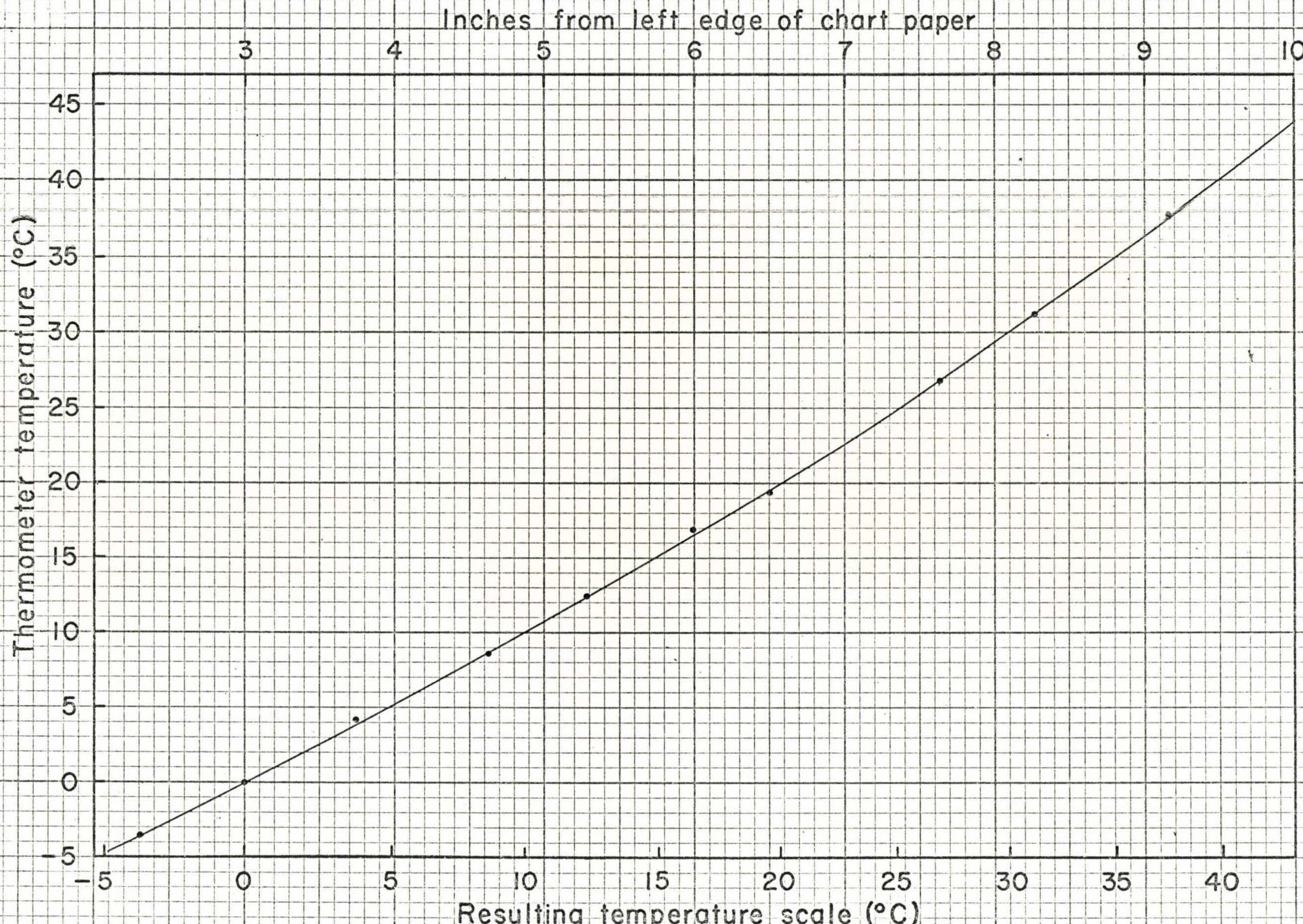
(iii) Soil moisture equipment.

Initially, some near surface observations of soil moisture were made using the gravimetric method. A sample was obtained from the soil, enclosed in an airtight container and weighed in its moist state. It was then oven-dried at 105°C, first for 24 hours and then for 48 hours. After each of these periods of drying, the sample was cooled in a dessicator and re-weighed to determine the amount of water lost during drying. A calculation of the percentage of water by weight which had been present in the original sample was then possible.

The purchase of a Nuclear-Chicago neutron probe, (Model number 5810), for the determination of the amount of moisture contained within a soil as a percentage of volume, made it possible to obtain data from greater depths. Basically, a source of high-energy neutrons, in this case radium-beryllium, is lowered from its shielded container, through an access tube, to those depths at which successive readings of soil moisture are to be taken. The high-energy neutrons pass out into the soil, where they are scattered by hydrogen atoms, contained mainly in the soil water, to produce much

Figure 3

CALIBRATION OF THAT RECORDING SYSTEM WHICH INCORPORATED THE ESTERLINE ANGUS RECORDER



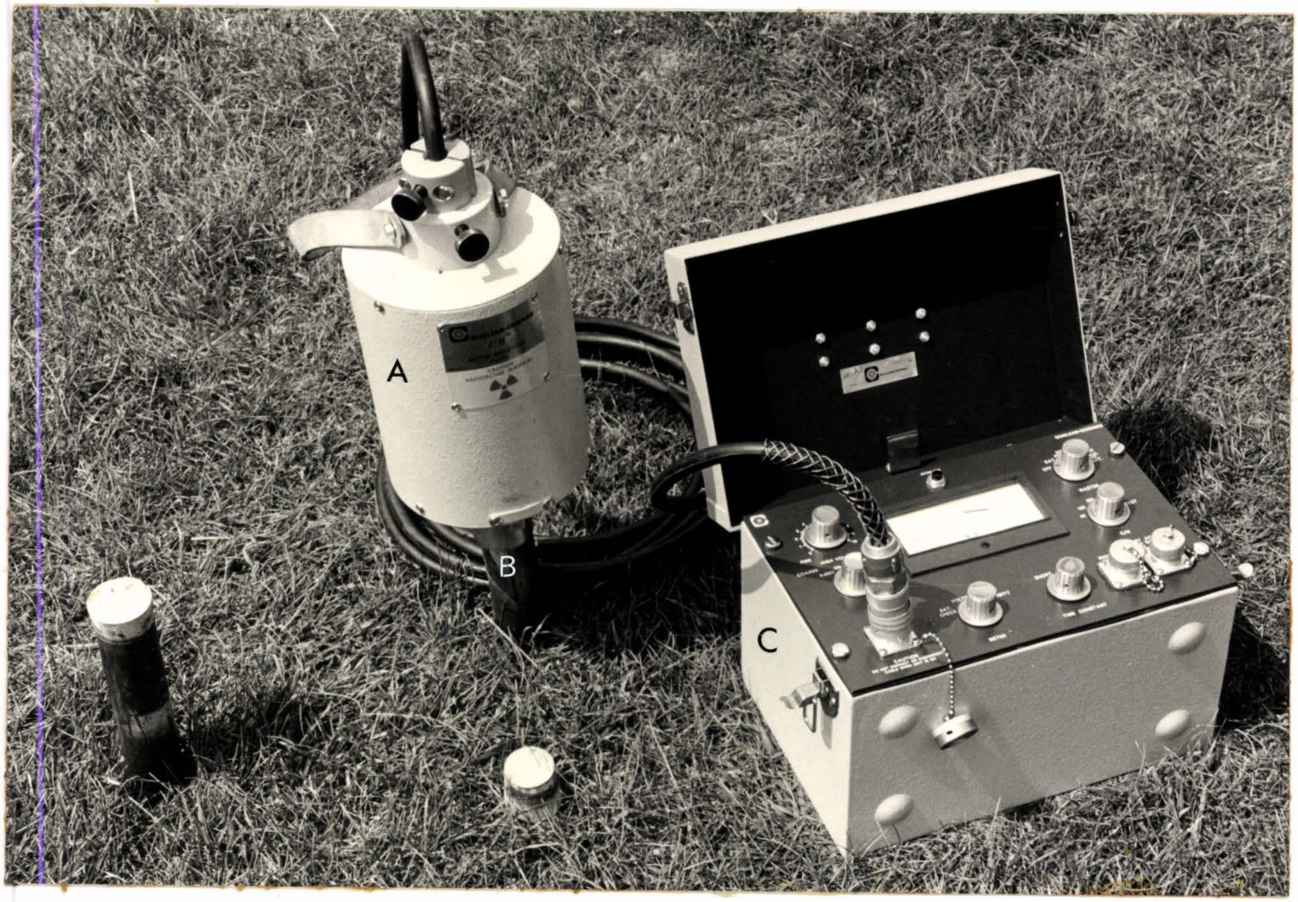
slower moving neutrons. Some of these are intercepted by a detector which is an integral part of the source unit, and this detector is connected to a ratemeter at the surface. The rate at which these slower moving neutrons reach the detector is determined by the amount of hydrogen present in the soil, which in turn is a function of the percentage of soil moisture by volume. Plate 2 shows the unit (A) which houses both the shielded source of high-energy neutrons and the slow-neutron detector when not in use, supported by a tubular steel sleeve which fits on to the projecting end of an access tube (B) down which the source has been lowered.

A heavy cable connects the slow-neutron detector to the ratemeter (C), from which the count of the number of slow-neutrons received per minute (C.P.M.) is obtained. The calibration of the instrument, which is outlined below, permits these C.P.M. values to be converted into soil moisture values, expressed as percentages of volume.

The access tubes used in the collection of soil moisture data for this dissertation were made of steel. Tubes made of many other materials including plastic, brass, aluminum, copper and glass have been used by other workers, and numerous suggestions have been made concerning methods of insertion. In the method adopted, which resulted from considerable experimentation, a steel tube was hammered into

PLATE 2

THE NEUTRON PROBE AND RATEMETER



A. Unit which houses the source of high-energy neutrons and the slow-neutron detector.

B. Access tube into which the neutron source and detector have been lowered.

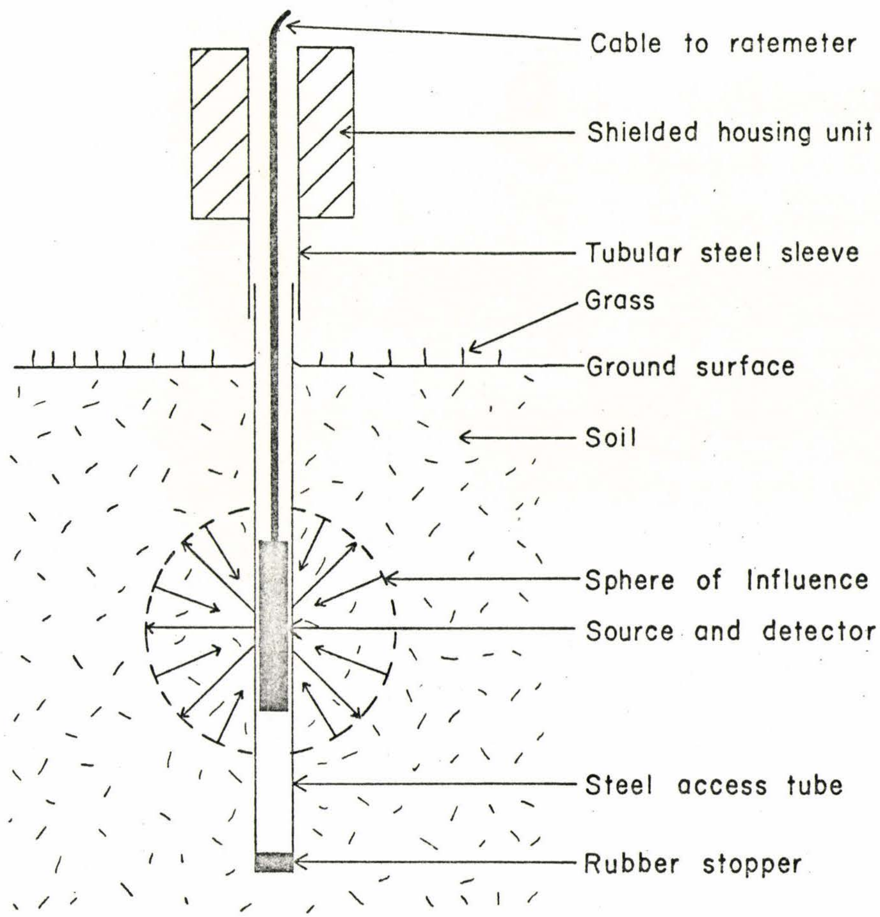
C. Ratemeter.

the soil in stages to reach an eventual depth of 1 meter. It was removed after each 15 cms of additional penetration in order that the soil core contained within it could be forced out. When the hole thus made had attained a depth of 100 cms, a new steel tube was tightly fitted within it, and the soil surface around the outside of this tube was raised slightly to prevent the downward channelling of rain water along it. Prior to final insertion, the lower end of each access tube was sealed by means of a tightly-fitting rubber stopper to prevent the ingress of soil water, and, when not in use, its upper end was closed by a tightly-fitting cork to prevent the entry of rain water. For a concise summary of the theory, calibration and use of the neutron probe, the reader is referred to Wilson (1971).

A diagrammatic representation of the shielded housing unit and an access tube when the source and detector are lowered into a reading position is presented in Figure 4. It is an unfortunate fact that the soil unit whose water content is measured varies both in size and shape depending upon the amount and distribution of water present. In general, this sampled unit is a sphere whose estimated radius is about 30 cms. However, the wetter the soil the smaller will this radius become, because the energy of the fast-moving neutrons will then be dissipated over a shorter distance.

Figure 4

NEUTRON SOURCE IN POSITION IN THE SOIL



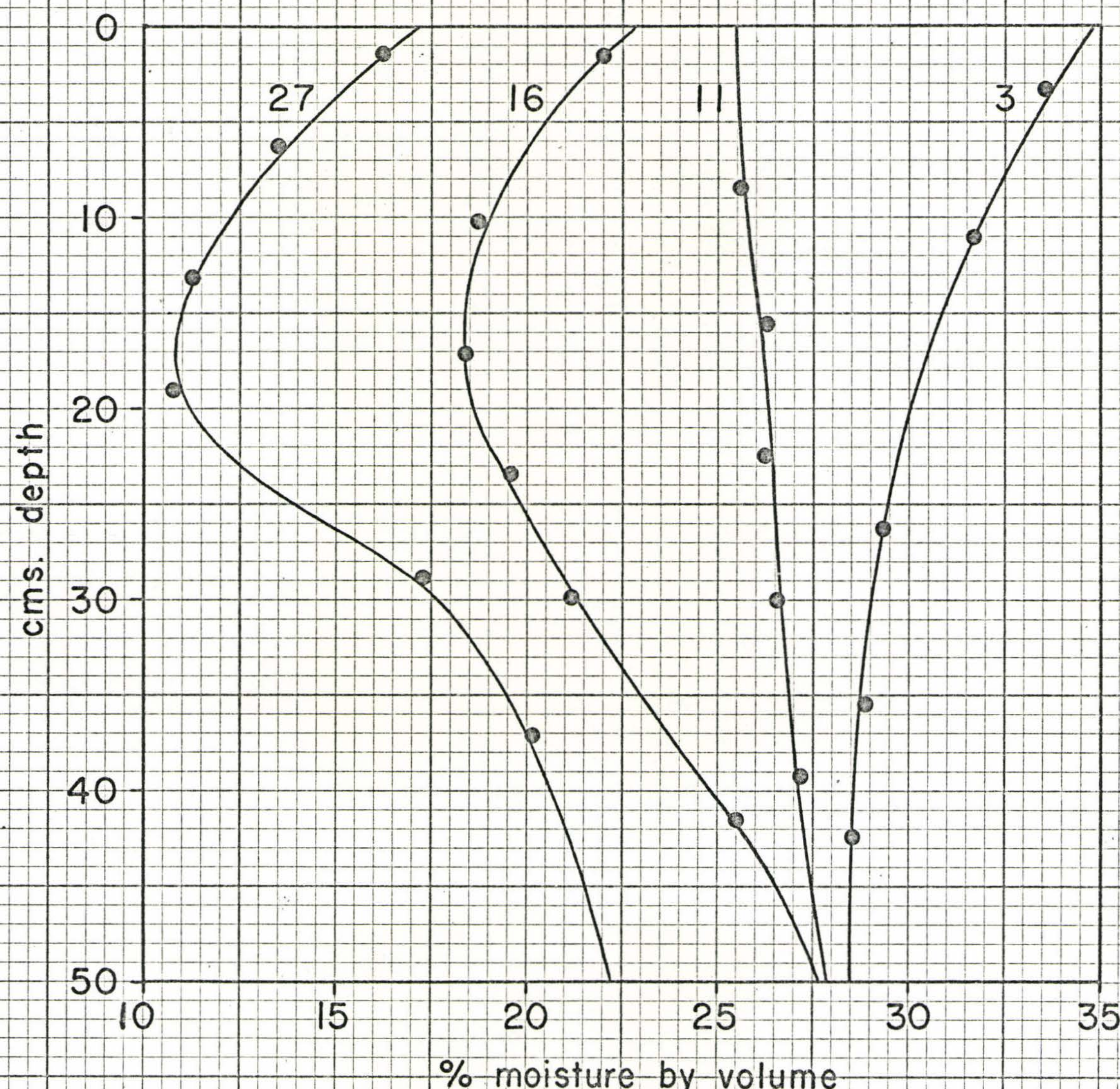
If there is any very distinct difference in the moisture conditions at different depths within the soil, the generally spherical shape of the soil unit whose water content is measured will become very distorted.

(iv) Calibration of the neutron probe.

The calibration of the neutron probe was carried out at the experimental site, within 6 meters of the mulched plots. For this purpose, four access tubes were inserted at the corners of a 1 meter square so that a set of four separate readings of soil moisture content at a depths of 30 cms could be taken in quick succession on any date. Following 6.4 cms of rain on June 25-26, 1968, a set of such readings was taken on each of four later dates as the soil dried out (July 3, 11, 16 and 27). Immediately after each set had been taken, an undisturbed soil core was obtained from within the square at whose corners the access tubes were located. In the laboratory, sections of the core, each 2.5 cms in length, were then removed intact from the containing tube, and these were weighed, dried in an oven at 105°C and then re-weighed. The internal diameter of the sampling tube was 4.8 cms., making each soil sample 45.26 cu.cm. The weight of water lost on drying was converted to a percentage loss by volume of soil and a curve for each of the four dates was drawn (Fig.5) in which each value of this variable was plotted against the appropriate depth. These curves show that the vertical gradients

Figure 5

CURVES OF SOIL MOISTURE VALUES
JULY 3-27, 1968.



of moisture content were notably different on the four dates in question.

Values of the average number of counts per minute (C.P.M.) obtained when the neutron probe was lowered to a depth of 30 cms. in each of the four access tubes on each of the four dates are shown in Table 6. Also shown therein are the corresponding values of soil moisture on each date expressed as a percentage of volume, which were obtained by the gravimetric method from a section of a soil core 2.5 cms in length centred at a depth of 30 cms.

TABLE 6

AVERAGE OF FOUR VALUES OF C.P.M. AT A DEPTH OF 30 CMS AND THE SOIL MOISTURE (% BY VOLUME) AT THAT DEPTH AS DETERMINED BY THE GRAVIMETRIC METHOD

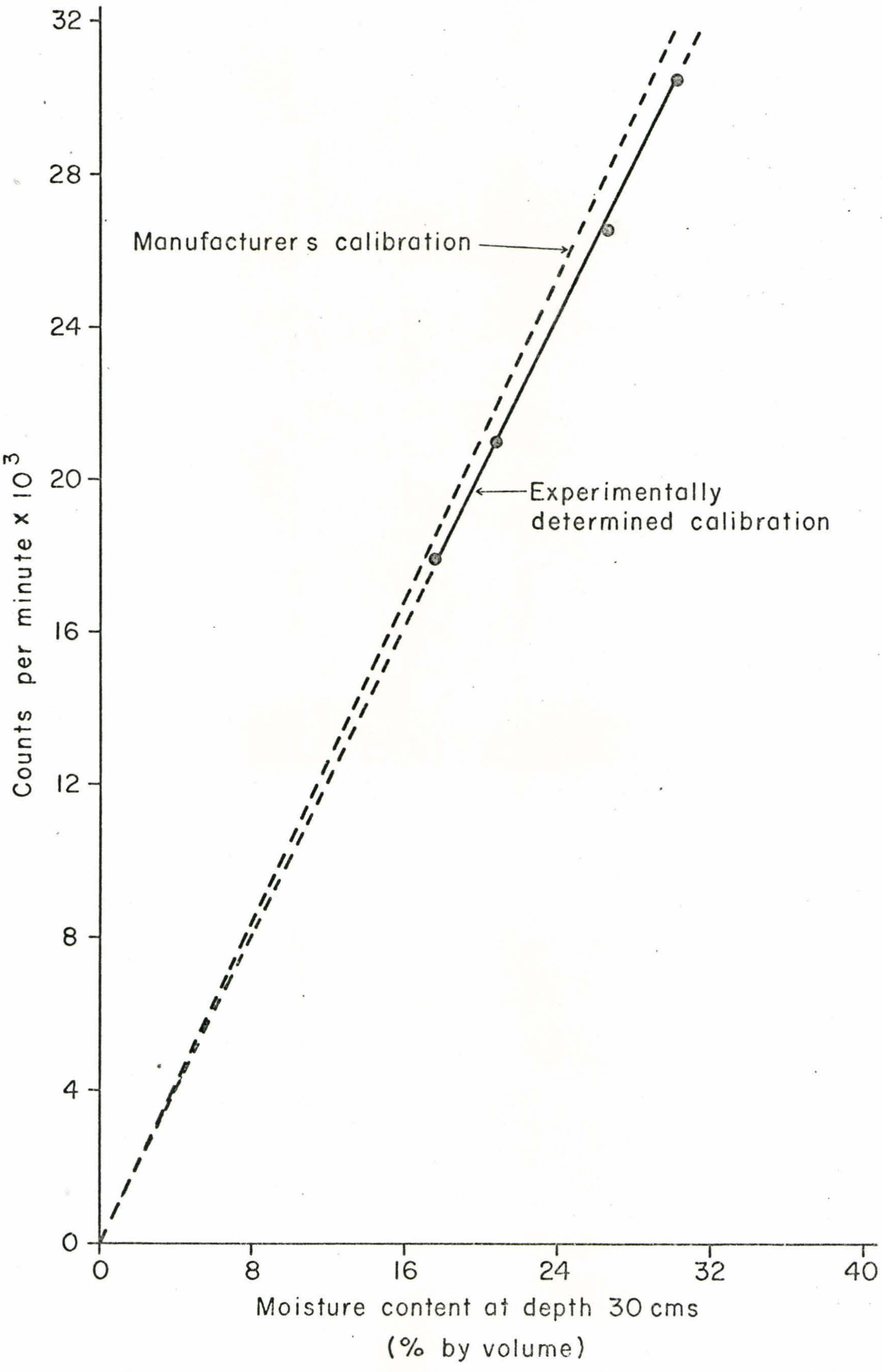
Date	Average value of C.P.M. x 10^3	Soil moisture (% by volume)
July 3, 1968	30.5	29.08
July 11, 1968	26.5	26.55
July 16, 1968	21.0	20.70
July 27, 1968	18.0	17.50

The values given in Table 6 were plotted in Figure 6, and the best-fit line drawn between the four points gave

Figure 6

CALIBRATION OF NEUTRON SOIL MOISTURE METER

(Depth probe)



the "determined calibration" line, which diverged only slightly from that drawn by reference to data supplied by the manufacturer of the neutron probe.

This close agreement between the two lines shown in Figure 6 covered four separate days during which the vertical gradients of moisture content within the soil were notably different (Figure 5). It was therefore concluded that, the "determined calibration" line shown in Figure 6 could be used with confidence to convert values of C.P.M., obtained with the source at a depth of 30 cms, into corresponding values of soil moisture expressed as a percentage of volume at that depth.

(v) Additional observations.

Routine measurements of rainfall, air temperature and snow depth were made and cloud cover was observed.

Since soil water does not necessarily turn into ice when the temperature falls below freezing point, attempts were made to determine the temperature at which this transformation occurs in the soils on which the experimental mulches were located. In the preliminary laboratory experiments, two electrodes, which were connected to a resistance bridge, were inserted into three samples of soil which had been allowed to drain freely for 16 hours. A thermocouple was inserted midway between the electrodes and, whilst the soil samples were subjected to sub-zero temperatures, measurements of electrical resistance within the soil and soil temperature were made at five minute intervals. By this means it was observed that after the soil temperature had fallen to freezing point or to some lower value, the resistance reading increased very sharply, and the temperature then indicated by the thermocouple was clearly that at which the soil water turned into ice.

Similar pairs of electrodes were buried at depths of 10 cms and 20 cms in the soil at the experimental site, and from resistance measurements made when the soil temperature fell to freezing point or below, it was possible to determine whether or not the soil water had been converted to ice.

5. Experimental Layout

(a) Pilot Study.

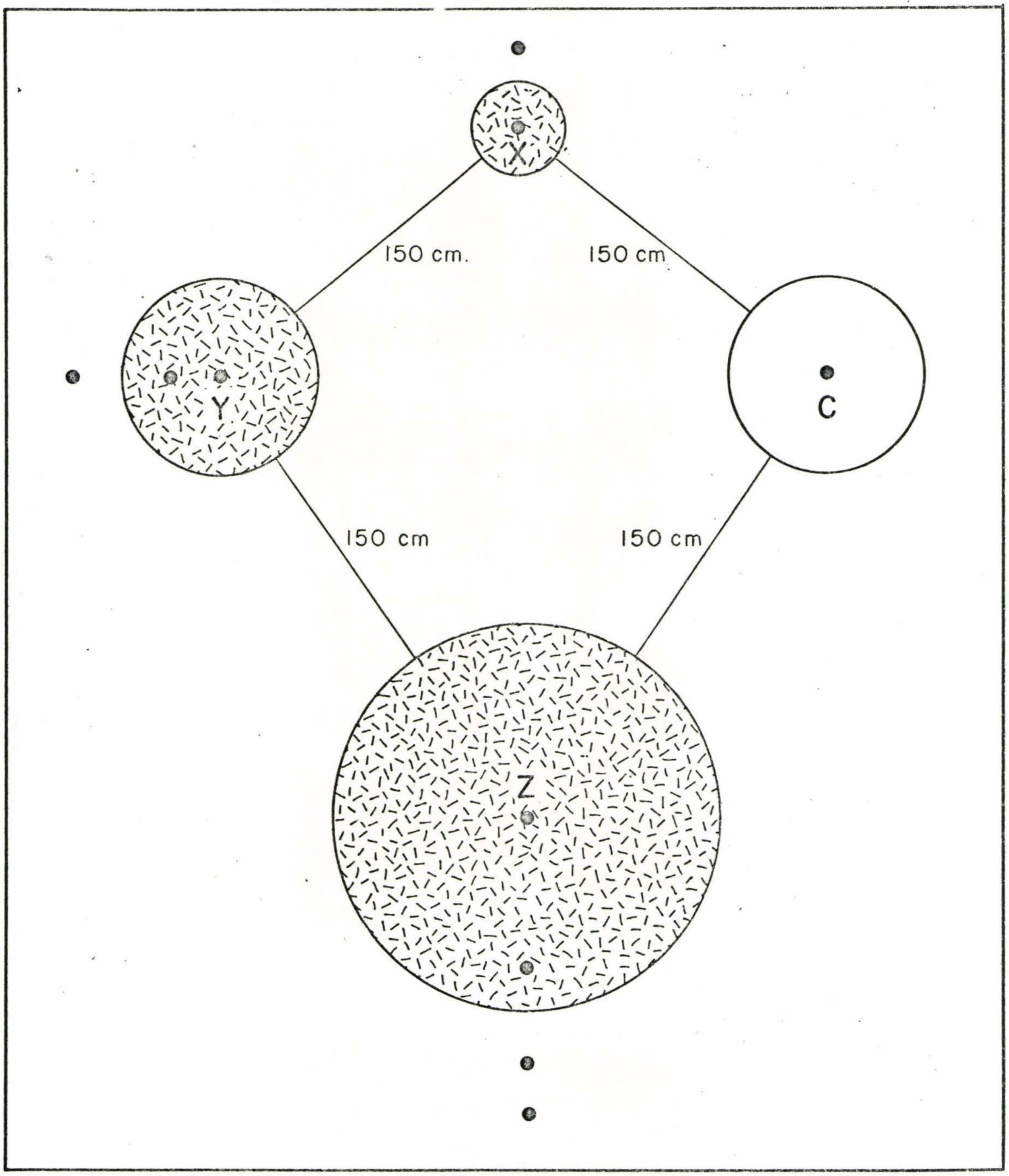
No information is available concerning the extent to which the modification of soil temperature induced by a circular patch of mulch may be dependent upon its diameter, and the pilot study was undertaken in an effort to test such an hypothesis. It was decided to use old hay as a mulching material and to lay this 15 cm thick to conform with general practice throughout the Niagara Peninsula. Three circular patches of mulch were used whose diameters were 60 cms, 120 cms and 240 cms respectively, and these, together with a non-mulched control plot of diameter 120 cms, were laid out such that the circumference of each was nowhere nearer than 150 cms from that of its nearest neighbour (Figure 7). It was hoped that this separating distance of 150 cms would be sufficient to ensure that temperatures beneath one circular plot would not be affected by the lateral flow of heat from another.

Only one recorder, which was capable of handling forty platinum resistance bulbs, was available for the pilot study. Since it was decided that four such bulbs were to be used to give measurements of the differences in soil temperature with depth at each point, the number of such points are shown in Figure 7. One set of four bulbs was placed vertically beneath the centre of each of the four circular plots. In each plots X, Y and Z, an additional set of bulbs was inserted 30 cms. out from the respective circumference, and another set was inserted 60 cms. out from the circumference of Z, the largest plot. The remaining two sets were placed in position 30 cms. inside the circumferences of plots Y and Z.

Two of the platinum resistance bulbs in each set of four were inserted at depths of 20 cms and 50 cms respectively

Figure 7

PLOT LAYOUT FOR THE PILOT STUDY



X — Mulched plot of diameter 60 cm

Y — Mulched plot of diameter 120 cm

Z — Mulched plot of diameter 240 cm

C — Control plot of diameter 120 cm

● — Positions of the sets of platinum resistance bulbs to accord with two of those depths at which the Canadian Department of Agriculture has recommended that soil temperatures be taken (Canada Department of Agriculture 1962). The remaining two bulbs in each set of four were inserted at depths of 2.5 cms and 5 cms to provide near-surface data (Figure 8). The bulbs were inserted horizontally into undistrubed soil through a distance of 30 cms from the sides of trenches, 60 cms in depth, each of which was dug 30 cms to one side of the line (Figure 7) joining those points at which the sets of bulbs associated with each circular plot were to be located. The small auger which was made to facilitate the horizontal insertion of the resistance bulbs is visible in Plate 3. This horizontal method of insertion was selected to avoid errors which would have arisen from the downward conduction of heat and percolation of rain water along the cables, such as would doubtless have occurred if these had been disposed vertically.

The cables from each vertical set of four resistance bulbs were pinned horizontally to the side of the trench, from one corner of which they passed beneath the sod to the recorder (Plate 3). Plate 4, a general view of the site at which the pilot study was conducted, shows some of the reels of resistance bulb cable and the bales of old hay which were later applied as a mulch.

Figure 8

THE PLACEMENT OF PLATINUM RESISTANCE BULBS

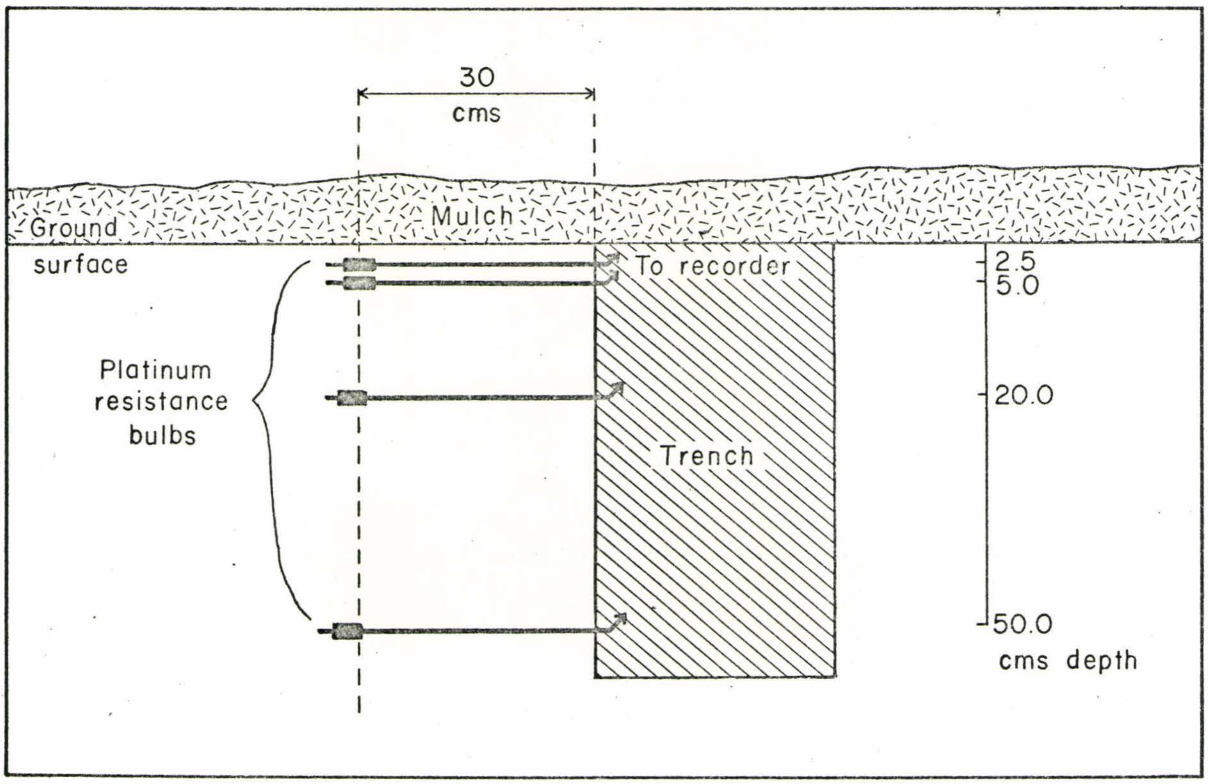


PLATE 3

AN OPEN TRENCH INTO THE SIDE OF

WHICH SOME OF THE PLATINUM RESISTANCE

BULBS WERE INSERTED

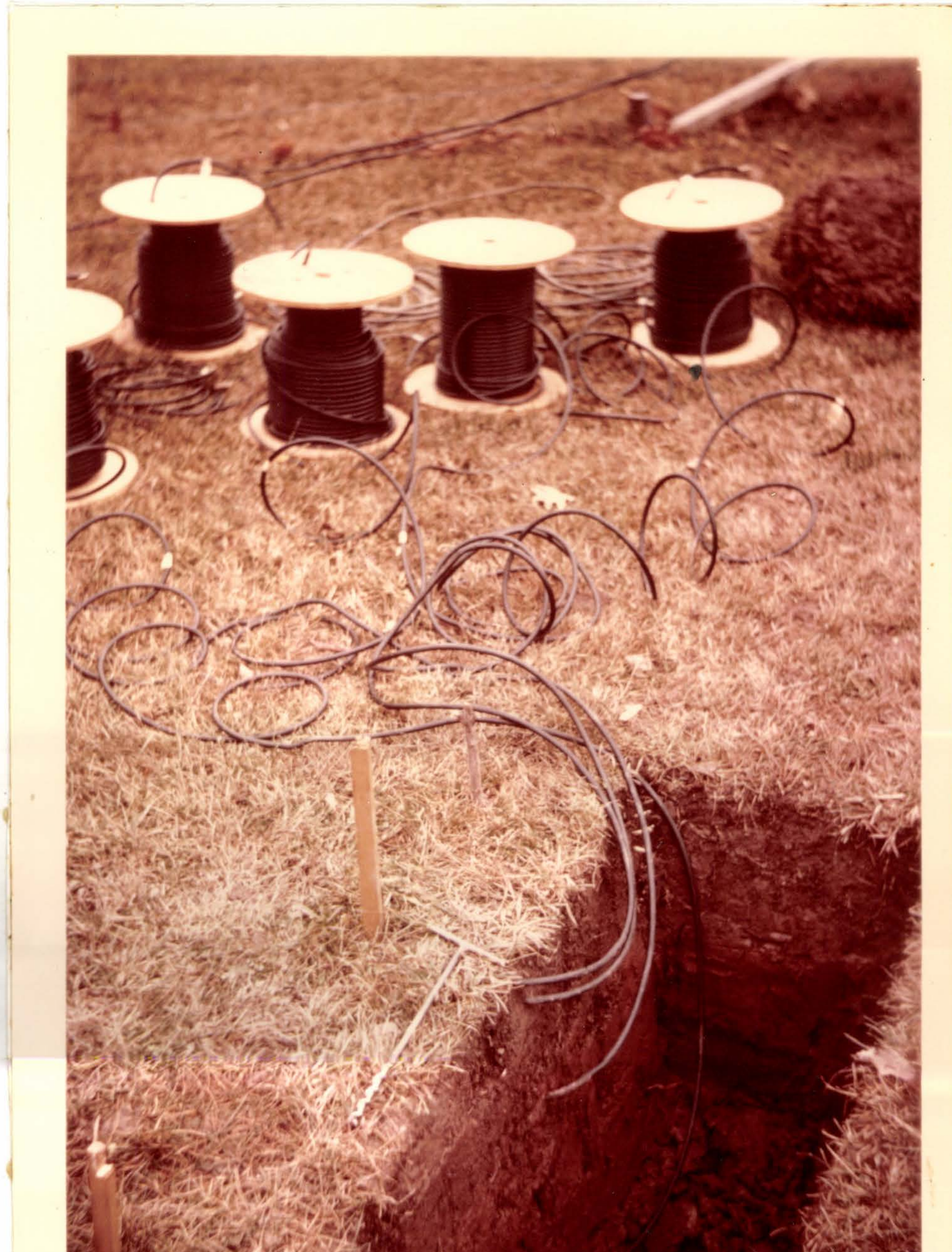


PLATE 4

VIEW OF THE EXPERIMENTAL SITE AT WHICH
THE PILOT STUDY WAS CONDUCTED

Subsequent to the insertion of the 40 platinum resistance bulbs, each trench was re-filled with soil which was then compacted in an effort to ensure that its former location did not become a site at which soil water collected. The compacted in-fill was then re-sodded, and after the subsequent lapse of one week the former positions of the trenches were hardly discernable. Furthermore, the complete absence of any later subsidence along the trench lines indicated that the in-fill had been satisfactorily compacted.

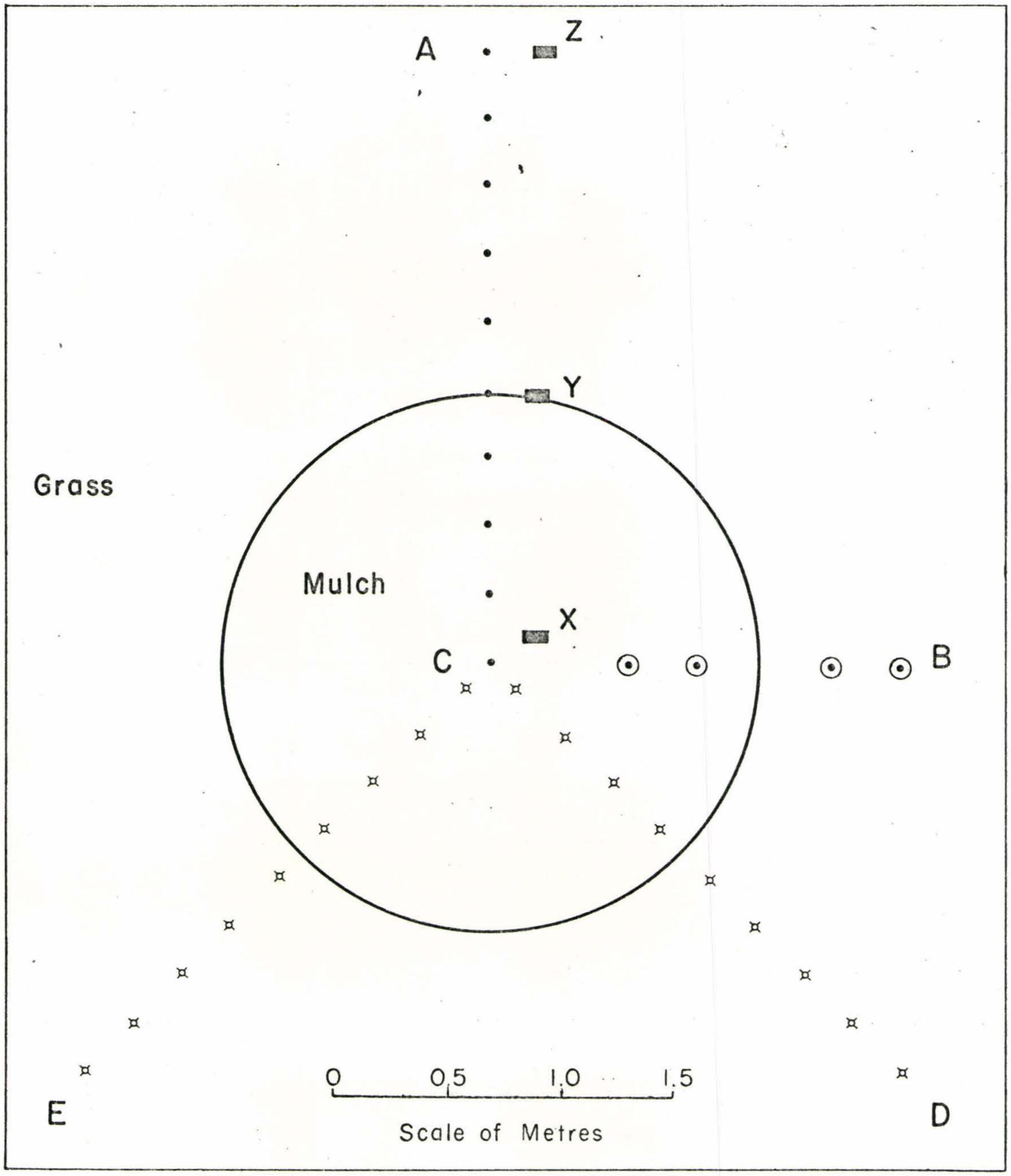
(b) Second Phase

(i) General Layout.

Following a study of the data obtained in the pilot study it was decided that, throughout the second phase, attention should be confined to two circular patches of mulch of diameter 240 cms. Figure 9 shows, in plan, the instrumental layout of one such circular patch. The sensors were all arranged along radii and the continuation of these beyond the circumference. Along one such line (CA), ten thermocouple rods were inserted vertically, and details concerning the design of these follow on page 62. In an effort to achieve some measure of replication, four thermocouple check-rods were inserted along the line CB in the positions shown. It had been hoped that a much greater measure of replication might have been possible, but the two recording systems, which

Figure 9

INSTRUMENTAL LAYOUT (SECOND PHASE)



• — Thermocouple rods

⊙ — Thermocouple check-rods

¤ — Access tubes for the neutron probe

▬ — Electrodes for the measurement of electrical resistance were the only ones available, could not handle more than a total of 192 thermocouples, and this was less than the number required adequately to equip twenty-eight rods, fourteen for each of the two circular patches. If the number of thermocouples with which each rod was to be equipped had been reduced in an effort to provide for an increased measure of replication, this would have reduced the number of levels within the soil from which temperature readings were to be obtained to less than the acceptable minimum. Moreover, since particular attention was to be paid to horizontal gradients of temperature and soil moisture outside the mulched patch, it was not possible to reduce the number of thermocouple rods along the line CA (Figure 9) in order to increase the number along the line CB.

Nine steel access tubes for the neutron probe, each 80 cms in length, were inserted along the line CD as shown in Figure 9 and, to provide for replication, an additional set of nine was disposed along the line CE. Readings of soil moisture were obtained by lowering the neutron source to depths of 30, 45 and 60 cms within each of these tubes.

Two pairs of electrodes were inserted at each of the points X, Y and Z shown in Figure 9; one pair at a depth of 10 cms and the other at a depth of 20 cms. Between

December 6, 1968 and April 25, 1969, these electrodes were used to determine whether or not soil water at a temperature at or below freezing point had turned into ice.

Plate 5 is a photograph of the instrumental layout of one of the mulched patches used in the second phase of the investigation. The copper-constantan wires which led from the thermocouple rods to the recording systems were buried beneath the sod.

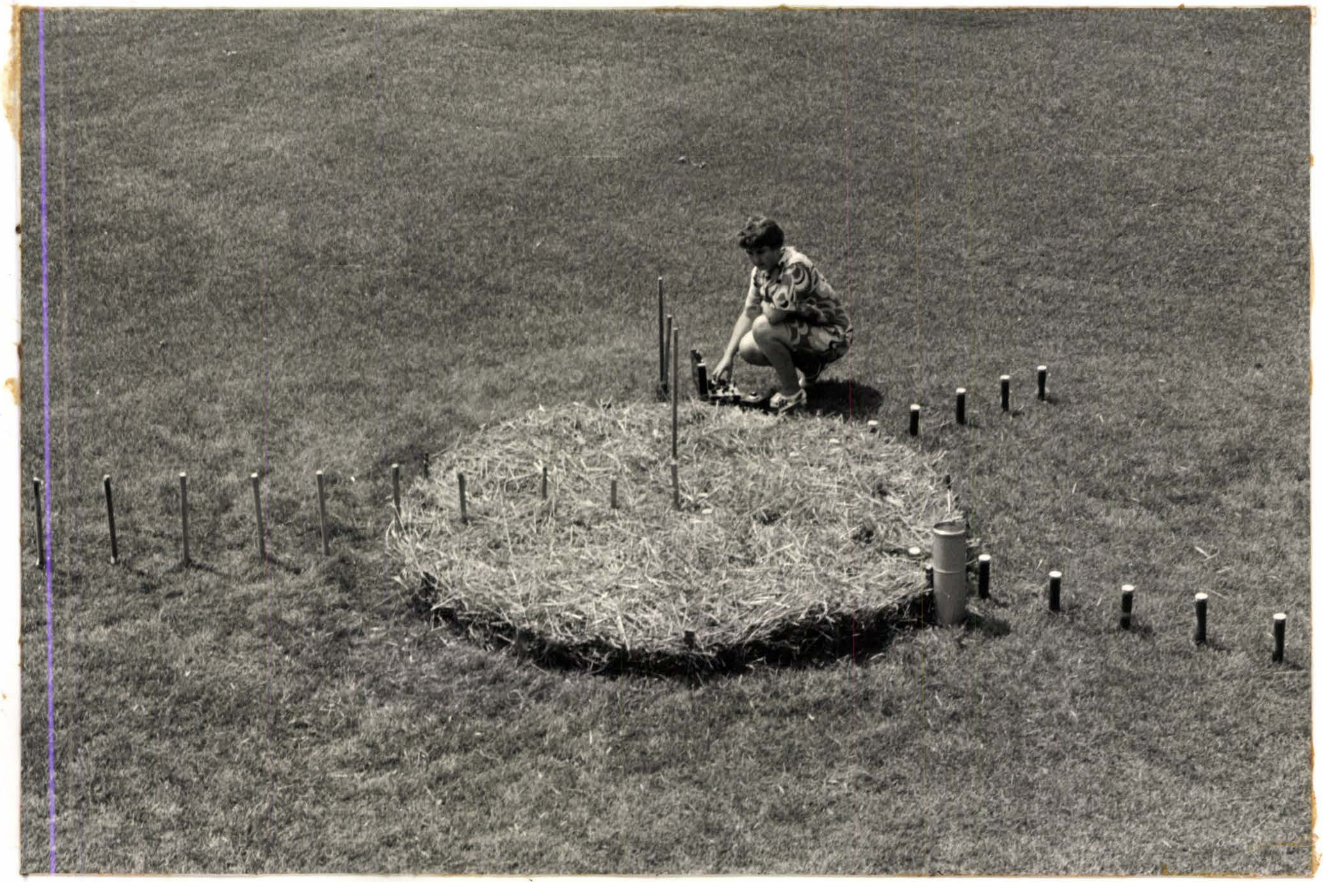
(ii) Thermocouple rods

It was decided that throughout the second phase of the study, sub-surface temperatures were to be measured by means of copper-constantan thermocouples. No additional platinum resistance coils and resistance recorders could be purchased, but two microvolt recording systems became available, and a large number of thermocouples could be made for comparatively little cost. Moreover, the experience gained during the pilot study had proved conclusively that, as sensors of sub-surface temperatures, platinum resistance coils are inferior to thermocouples.

Although thermocouples have often been used for the measurement of sub-surface temperatures, they have normally been inserted horizontally from one of the undisturbed walls of an excavated trench, [e.g., Oke and Hannell 1968]

PLATE 5

THE INSTRUMENTAL LAYOUT OF ONE OF THE MULCHED PATCHES USED IN THE SECOND PHASE OF THE INVESTIGATION



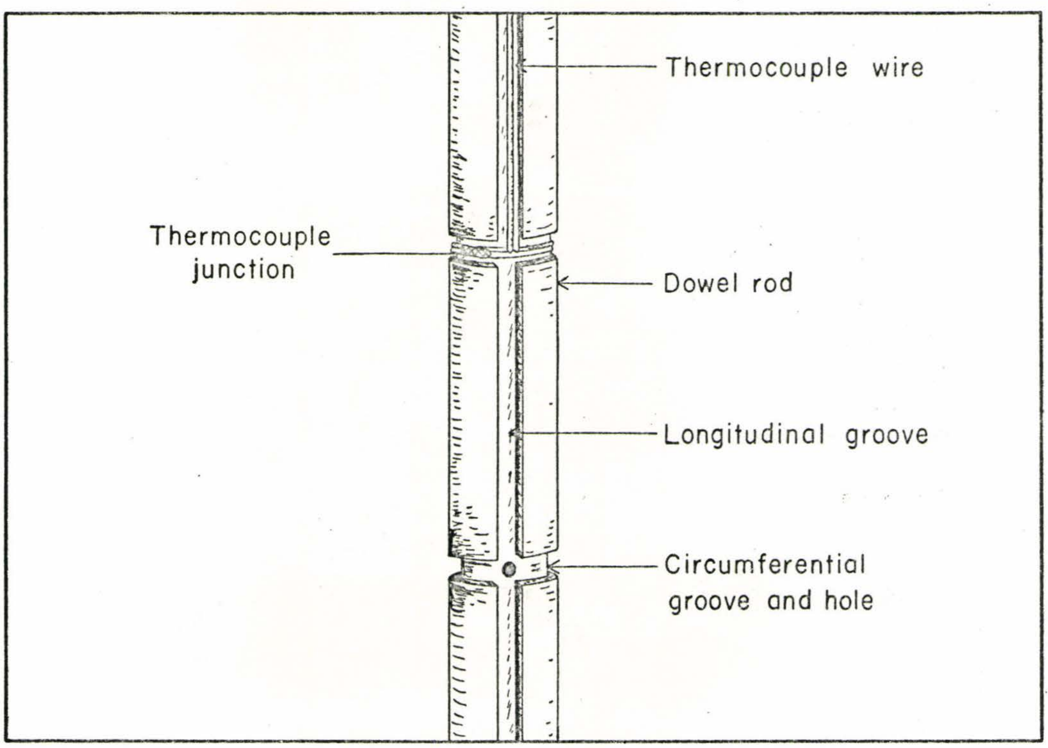
This method of insertion is open to criticism, since no matter how carefully the trench is subsequently filled, it destroys the natural environment considerably. It was therefore decided that the thermocouples to be used during the second phase of this study should be inserted into the soil vertically, using a method devised by the author for the measurement of sub-surface temperatures in areas of muskeg and permafrost, where the digging of trenches is difficult.

It was appreciated that when thermocouple wires are inserted vertically into a soil, the conduction of heat along them might well falsify the indicated temperatures. For this reason, a series of laboratory tests was undertaken. A wooden trough 60 cms. in length was filled with sand and, during the filling process, thermocouples (T_1), which were introduced through one end of the trough, were laid such that they extended into this medium for distances which increased successively by 2.54 cms. Other thermocouples (T_2) were passed through holes in the side of the trough such that each lay very close to one in the T_1 series. At the end of the trough through which the wires of the T_1 series passed, and insulated from it by a thick asbestos pad, a container was placed to hold water, and the wires of the T_1 series passed through this. By varying the temperature of the water, various temperature gradients were established along the wires of the T_1 series, and for each of these gradients simultaneous readings of temperature were obtained from all the thermocouples in both series until such time as those of the T_1 series indicated steady values. It was thus established that even under the steepest temperature gradients which were likely to be met in the field, heat conducted along the wires of the T_1 series was entirely dissipated within 12.7 cms of their hotter ends.

Thirty thermocouple rods were then made for use in the field (Figure 10). In each case, a longitudinal groove was cut in a dowel rod of diameter 2.54 cms and length 120 cms., and a surface mark was inscribed to indicate the depth to which the rod was eventually to be driven.Circumferential grooves were then cut at distances of 5, 10, 20, 30, 40, 50, 75 and 100 cms from the surface mark, these being the depths at which sub-surface temperatures were to be measured. Within each of these grooves a hole was bored diametrically through the rod. A thermocouple junction was pushed through the hole and 12.7 cms of the copper-constantan cable was then wrapped around the rod such that it filled the circumferential groove. leaving the thermocouple on the outside. The thermocouple was then twice coated with epoxy resin to reduce the risk of oxidation of the copper wire at

Figure 10

PART OF A THERMOCOUPLE ROD



the soldered junction, thus increasing the length of that period over which the junction could be expected to give reliable readings.

To facilitate the insertion of each thermocouple rod at its designated position, a vertical hole was bored to a depth of about 105 cms. by means of a gas-driven Cobra Drill and tungsten-carbide bits of diameter 2.56 cms. When the bit was withdrawn, a tightly fitting thermocouple rod was hammered into the hole. The wires from the top of the rod were led to the small hut which housed the two recording systems, and these wires were then buried beneath the sod to avoid damage. Every effort was made to ensure that the surface of the experimental plot was not damaged whilst the thermocouple rods were being inserted.

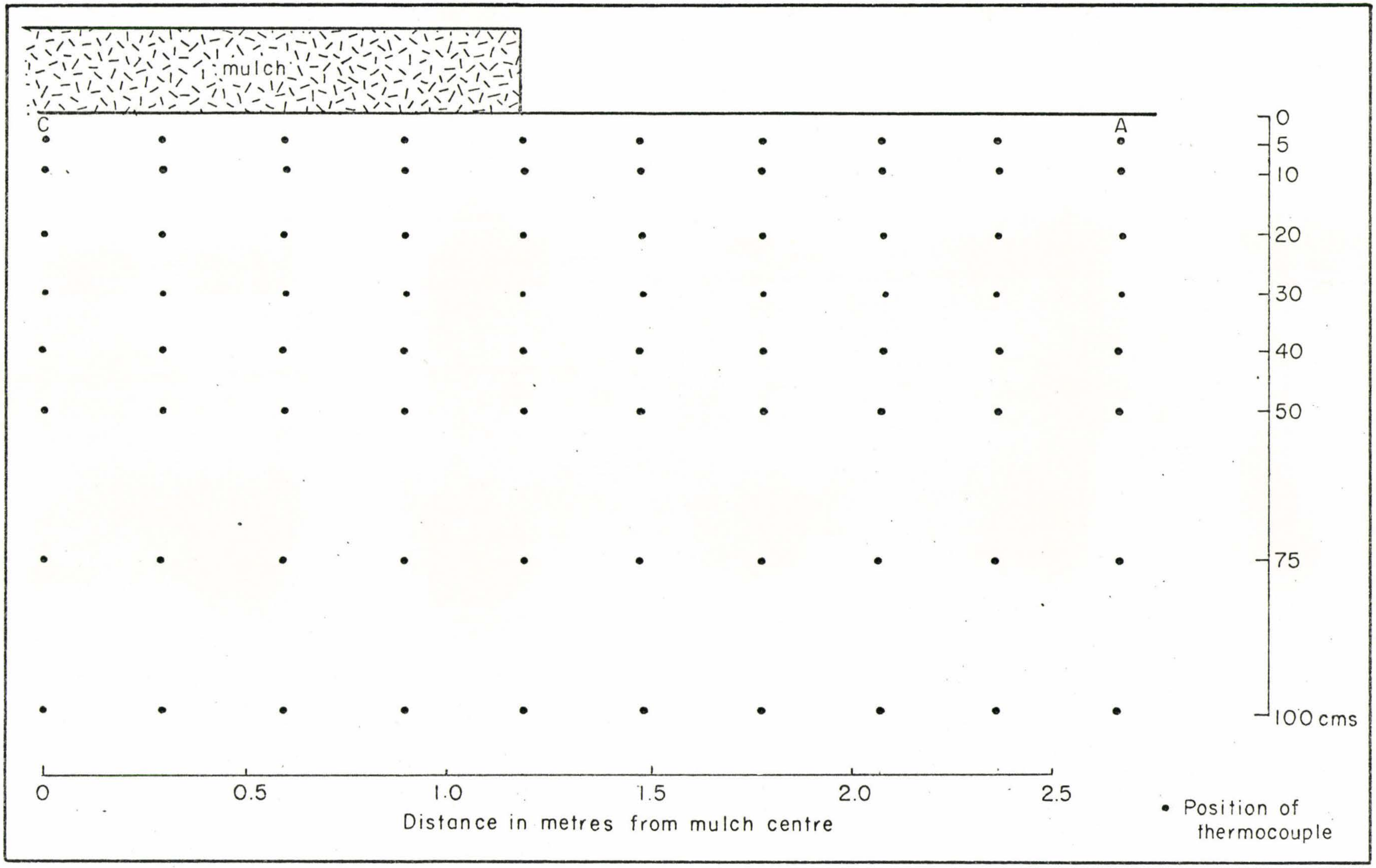
Figure 11 shows the dispositions of those thermocouples which were arranged in a vertical plane through the line CA in Figure 9.

6. Application of the mulches

Subsequent to the delineation of the four circular plots which were to be used in the pilot study (Figure 7), a grass killer, whose commercial name is "Paraquat", was watered on to the surface of each. The surfaces of these plots were covered with short grass. Since the application

Figure 11

VERTICAL ARRANGEMENT OF THERMOCOUPLES



of the mulch would certainly kill the grass on three of these plots, it was decided to kill the grass on all four, in order that the differences between readings obtained from the mulched plots and the one which was to be used as a control could be ascribed solely to the effects of the mulch. No such grass killer was used in the second phase of the investigation since no grass-covered control plot was then involved.

Around the circumference of each of those plots which were to be mulched, pegs were driven into the soil such that the tops of these stood 15 cms. above the general level. After the mulching material had been fluffed-up and laid to a uniform depth of 15 cms it was held in position by strings which passed both diametrically across the circular plot from one peg to another and from peg to peg around the circumference. These strings very effectively prevented the mulching material from being blown away by strong winds.

As the thickness of the mulch was slowly reduced by compaction, more was added to maintain a thickness of 15 cms. Alternatively, the compacted material could have been fluffed-up to restore its thickness to 15 cms., but local horticultural practice includes no such procedure.

7. Dates of mulch application and removal

For the pilot study, the mulching material was applied in December 1965 and it remained in position until the relevant observations were completed in the summer of 1966.

During the second phase of the investigation it was planned to compare the effects of a mulch which remained in position throughout two summer seasons and the intervening months with those produced by another, which was in position for the winter months only. Thus the first mulch was applied in early May 1968, and this remained in position until observations were completed in September 1969. The second mulch was applied in November 1968 and removed in April 1969.

8. Site descriptions

(a) Pilot study.

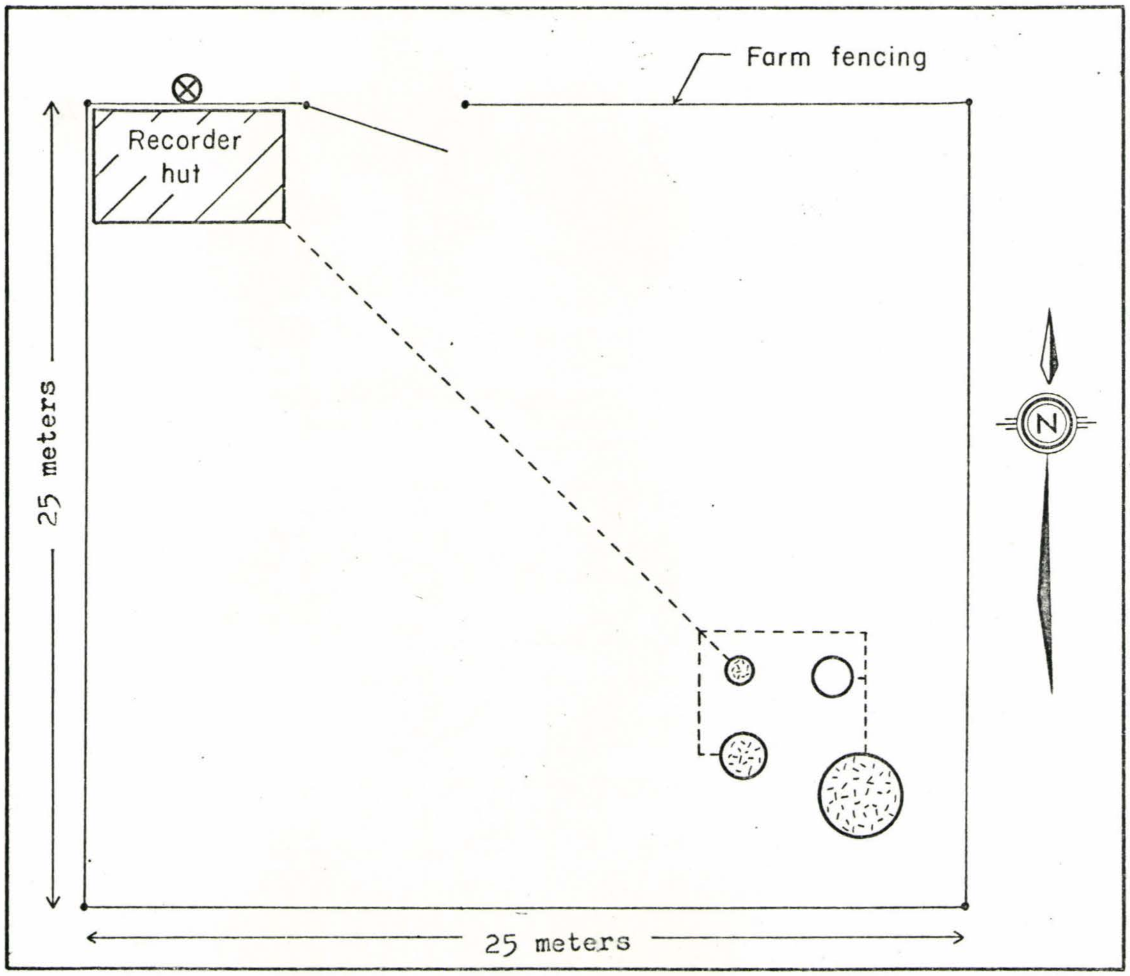
The experimental site for the pilot study was located on gently sloping grassed land in the Royal Botanical Society's arboretum to the north of Cootes Paradise at the western extremity of Lake Ontario. A general plan of the site is presented in Figure 12.

(b) Second phase

After exploratory sets of readings at certain other sites, and notably several at the Simcoe Horticultural Re-

Figure 12

PLAN OF SITE USED FOR PILOT STUDY



Location : Royal Botanical Society's arboretum (43° 17'N ; 79° 54'W)

Elevation : 350 feet above mean sea level

— mulched plots

— control plots

-------- buried cables from sensors to the recorder

⊗ — hydro pole

search Station, had proved these to be unsuitable on account of pronounced inhomegneity of the soil, the site selected for the second phase of the investigation was one located on a level grassed area near the south shore of Cootes Paradise and immediately to the west of the residence occupied by the President of McMaster University. The only defect of this site arose from the fact that, under sunny conditions, some of the surrounding trees caused the experimental plots to lie in shade until about 1030 hours. A general plan of this site is shown in Figure 13.

9. Soil descriptions

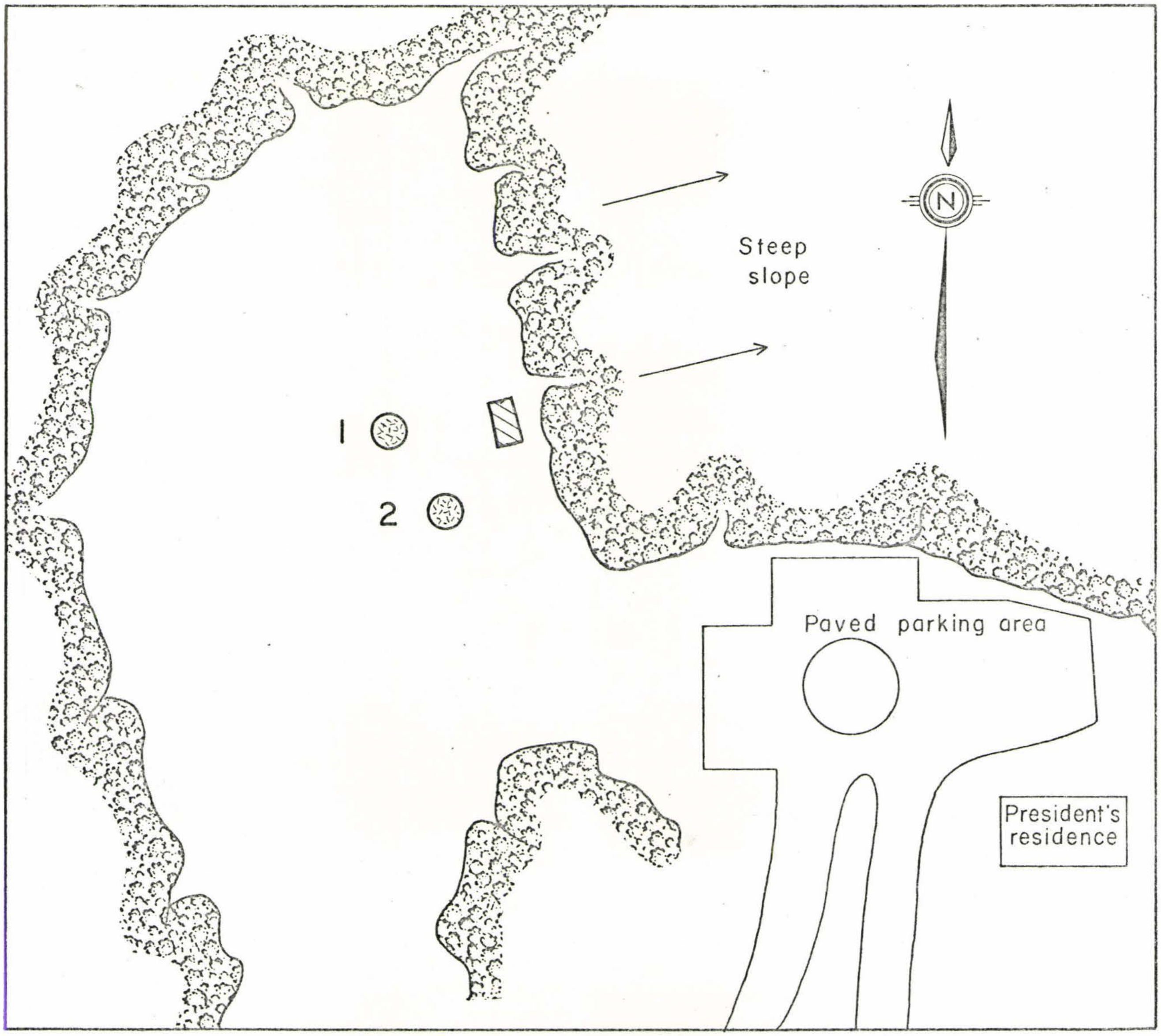
Detailed soil descriptions are given in the Appendix and the two which follow are to be regarded as very brief summaries.

(a) Soil at the site used for the pilot study.

Although the soil at the site used for the pilot study was classed by the Ontario Soil Survey (1965) as a Lockport clay, textural analysis of its topmost 10 cms revealed that it was a sandy clay loam (Beserve 1968). At depths below 10 cms. the clay content increased, and bands of hard grey shale were present at various depths. Although the surface of short grass sloped southwards at an angle of about 5 degrees it was poorly drained.

Figure 13

PLAN OF SITE USED FOR THE SECOND PHASE OF THE INVESTIGATION



Location : McMaster University Campus (43°15'N; 79°55'W)

Elevation : 326 feet above mean sea level

— mulched rings (1 and 2)

— hut in which recording systems were housed

— trees

(b) Soil at the site used for the second phase of the investigation.

The soil at the site used for the second phase of the investigation was classed by the Ontario Soil Survey (1965) as a Grimsby fine sandy loam. Down to a depth of 25 cms. the percentage of fine sand was very high, but below that depth the clay content increased. The surface, which sloped to the N.N.E. at an angle of 1.5 degrees, was freely drained and covered with short grass.

Differences in the texture and drainage characteristics of the two soils undoubtedly resulted in differences in thermal properties and temperature regimes. For this reason, and because the experiments in the two phases of the experiment were not conducted simultaneously, no attempt will be made to compare the results from the two locations.

CHAPTER 4

RESULTS OF THE PILOT STUDY (1966)

1. Weather conditions during the period of observation

Mean climatic figures seldom convey an accurate impression of weather conditions over a period of about six months duration. It is therefore necessary to summarise the extent to which the weather conditions which prevailed throughout the observation period differed from those which might have been inferred from Hamilton's climatic normals.

(a) Temperature

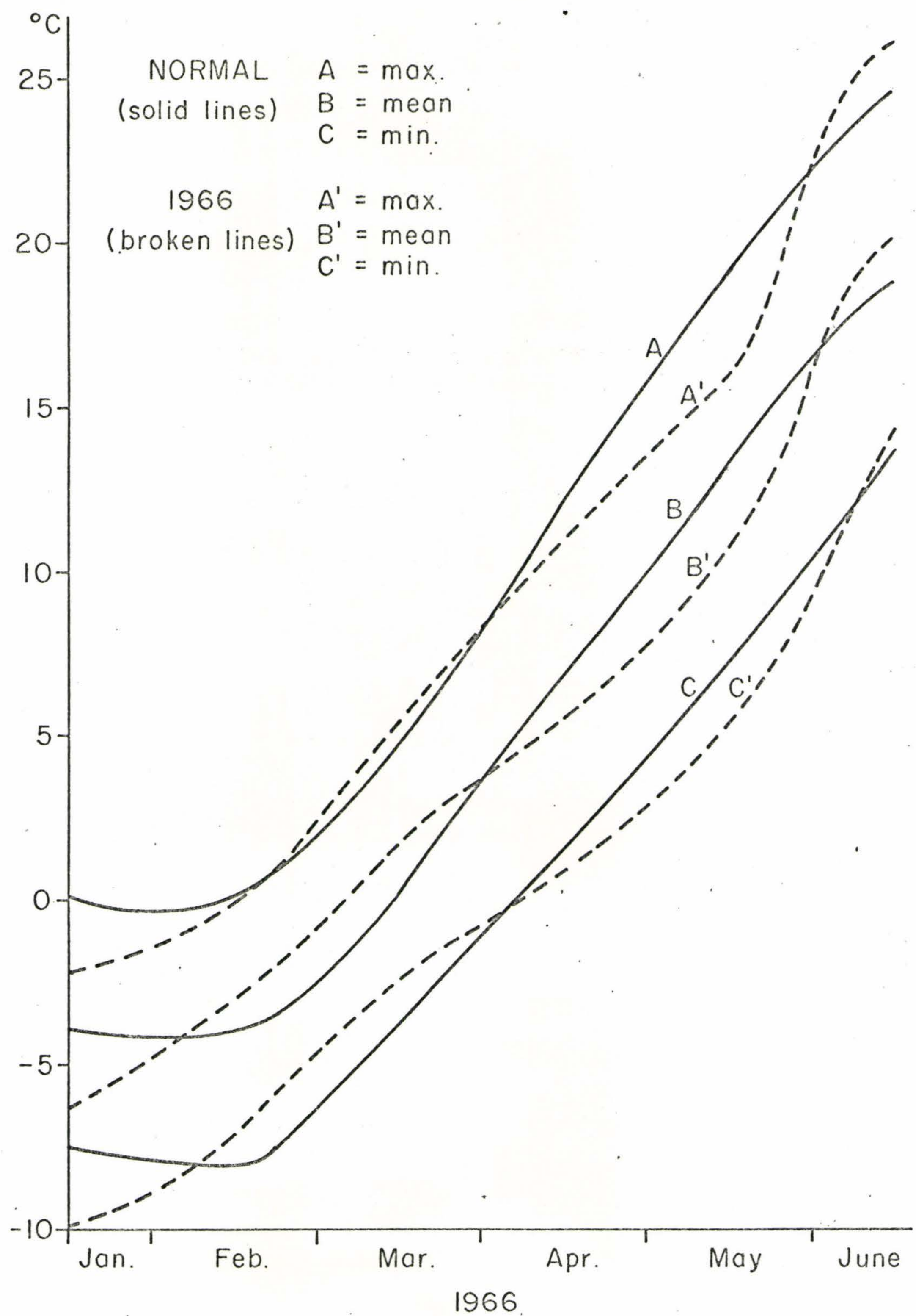
Monthly mean values of maximum, mean and minimum temperatures for Hamilton, issued by the Hamilton Weather Office, over the period covered by the pilot study are shown in Figure 14, together with the corresponding normal values. Minimum temperatures usually reach their lowest level in February, but in 1966 they did so in January which was a particularly cold month. This was succeeded by a period of above-normal temperatures from early February until about the end of March, after which readings again fell below normal until early June.

(b) Precipitation

The figures given in Table 7 show that precipita-

Figure 14

MONTHLY MEAN TEMPERATURES OVER THE PERIOD COVERED BY THE PILOT STUDY



tion totals differed appreciably from their normal values.

TABLE 7

MONTHLY PRECIPITATION TOTALS IN CENTIMETERS

Month	Normal values			1966			Difference from normal
	Rain	snow	Total water equivalent	Rain	Snow	Total water equivalent	
Jan.	3.18	34.3	6.61	0.51	73.7	7.88	+1.27
Feb.	3.23	30.6	6.29	1.46	19.3	3.39	-2.90
Mar.	5.18	20.3	7.21	8.66	5.8	9.24	+2.03
Apr.	7.40	2.8	8.18	7.61	5.1	8.12	-0.06
May	7.77	Tr	7.77	4.29	Tr	4.29	-3.48
June	5.92	0	5.92	6.12	0	6.12	+0.20
						Total	-2.94

Source: Hamilton Weather Office

The snowfall totals in January and April of 1966 were twice the normal values, but the corresponding figures for February and March were well below normal. Over the six months covered by the pilot study, the total water equivalent was 2.94 cms less than is normally recorded.

2. <u>General statement concerning sub-surface temperatures in the control plot throughout the period February to May 1966 inclusive</u>.

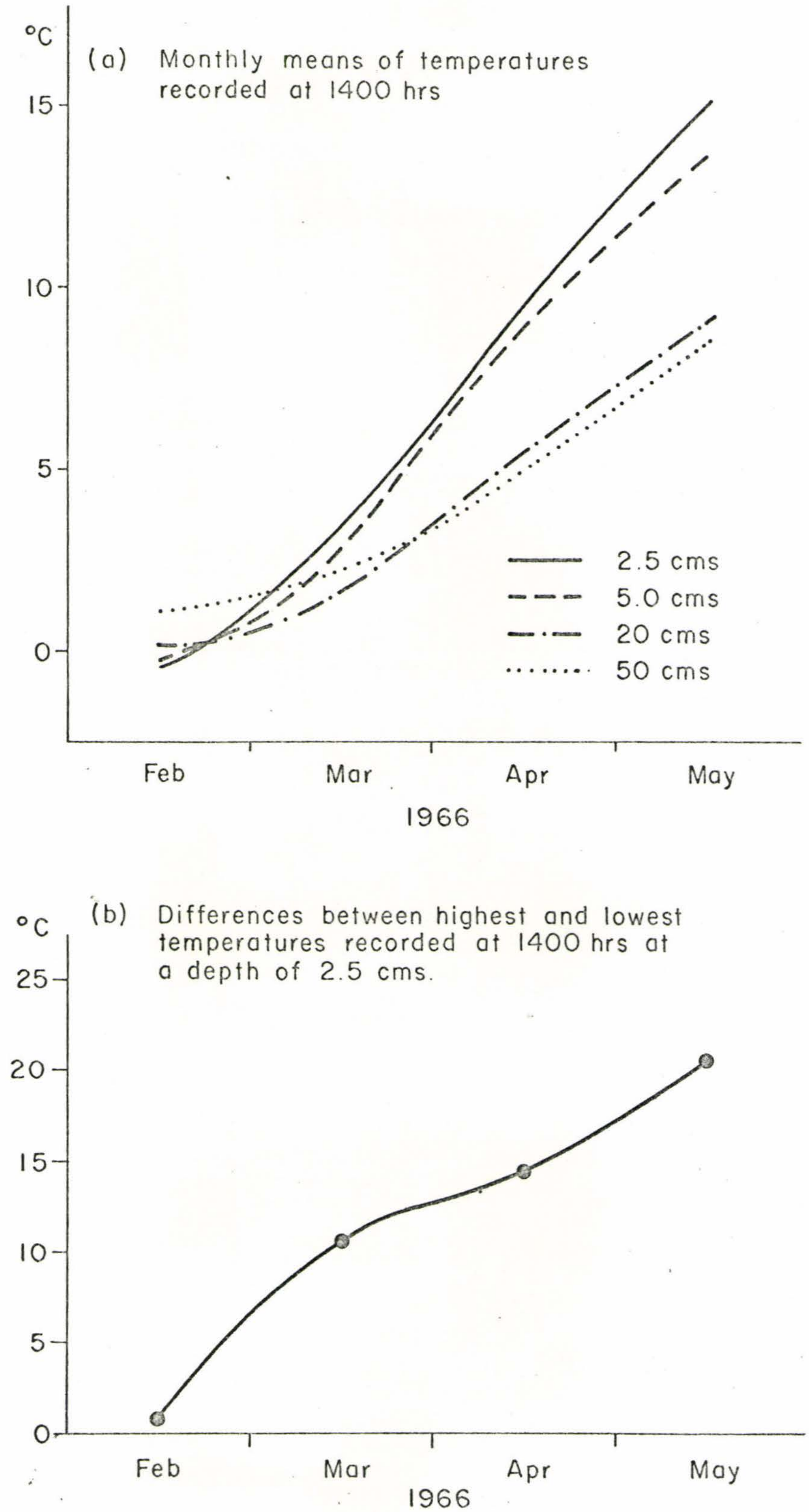
Throughout the February to May period, soil temperatures at depths of 2.5, 5, 20 and 50 cms beneath each of these ten positions shown in Figure 7 were read daily at 1400 hours. On a number of occasions, readings were taken hourly over a 24-hour period. Whenever a set of temperatures was required three runs were taken, and the three values for each of the 40 points never differed from each other by more than 0.2°C. The mean of the three values for each point was then accepted as its temperature.

The selection of 1400 hours as the time for the regular daily observation was made since this is generally the time at which the surface layer of soil achieves its maximum temperature. For the same reason, Oke (1964) and Beserve (1968) both used this time for their daily observations in this locality. At this time, the vertical gradient of temperature within the soil is usually steepest and the thermal effect of a mulch on the gradient will then be most apparent.

The monthly means of temperatures recorded at 1400 hours daily in the control plot are shown in Figure 15(a),

Figure 15

SOIL TEMPERATURES IN THE CONTROL PLOT



and these convey a general impression of the flow of heat through the soil throughout the period of observation. In February, mean temperatures at 1400 hours were very similar at all depths, the difference between those values obtained from the 2.5 cms and 50 cms levels being no more than 1.6°C. During that month, sub-surface temperatures increased with depth, as is normal throughout the winter season.

In late February the near-surface layers of the soil began to warm, and by the end of that month the highest temperatures at 1400 hours within the upper 20 cms of soil were recorded at a depth of 2.5 cms. This was the beginning of the Spring temperature change-over, but the values recorded in mid-March at a depth of 20 cms were still lower than those at the 50 cms level. In late March this changeover was completed throughout all soil layers down to a depth of 50 cms. and thereafter temperatures measured at 1400 hours declined with depth as is normal throughout the summer season. Following the completion of the changeover, soil temperatures rose quickly, but the rates of increase were greatest in the near-surface layers.

The differences between the highest and lowest temperatures in each month recorded at a depth of 2.5 cms in the control plot at 1400 hours daily are represented in

Figure 15(b). In February, during the first half of which the ground was snow-covered, the value of this difference was small, but it increased progressively during the three succeeding months. This increase was correlated with greater day-to-day fluctuations in the intensity of radiation receipts, the effects of which were intensified by the reduced thermal diffusivity of the soil consequent upon its drying.

3. The effects of the mulches on the monthly means of temperatures recorded beneath their centres at 1400 hours daily.

The three mulches (Figure 7) were applied in mid-December 1965, but six weeks were allowed to elapse prior to the commencement of regular observations. It was anticipated that by the end of this period the effects of the mulches on the temperatures of their underlying soils would have become fully established.

The differences between the monthly means of temperatures recorded beneath the centres of the mulched plots at 1400 hours daily and the corresponding figures for the control plot are presented in Table 8 (p.83.). No temperatures could be measured at a depth of 2.5 cms beneath the centre of the 120 cms mulch since the platinum resistance coil which had been implanted at that point ceased to function before mid-February. No spare bulb was available and, in any event, a replacement could not have been placed in position without removing at least a segment of the mulch and disturbing the near-surface layer of soil beneath it.

Those figures given in Table 8 for February demonstrate the effect of a mulch upon soil temperatures during the winter months, when the amount of outgoing radiation from the surface exceeds its total receipt. Consequent upon this net loss, soil temperatures near the surface are lower than those at greater depths [Figure 15(a)], and heat is conducted upwards. A mulch impedes the escape of some of this upward-flowing heat, as a result of which the soil temperatures beneath it are higher than those at equivalent levels beneath an uncovered surface. In the case of a circular mulch, the amount of this temperature gain is a function of its diameter, at least for values up to 240 cms., as is evident from the February figures. Beneath the centre of the 60 cms mulch, the temperature gain did not exceed 0.3°C at any of the four depths, whereas in the case of the 240 cms mulch it exceeded 1.0°C at each.

So far as soil temperatures are concerned, March represents a transitional period during which heat flows downward through the topmost layers, but upward through the

Table 8

AMOUNTS ($^{\circ}$C) BY WHICH THE MONTHLY MEANS OF TEMPERATURES RECORDED BENEATH THE CENTRES OF THE MULCHED PLOTS AT 1400 HOURS DAILY WERE HIGHER (+) OR LOWER (-) THAN THE CORRESPONDING FIGURES FOR THE CONTROL PLOT.

Depth	February			March			April			May		
	Diameter of mulch (cm)			Diameter of mulch (cm)			Diameter of mulch (cm)			Diameter of mulch (cm)		
(cm)	60	120	240	60	120	240	60	120	240	60	120	240
2.5	+0.3	-	+1.2	-1.7	-	-1.1	-3.9	-	-4.6	-6.0	-	-7.0
5	+0.3	+0.9	+1.5	-1.1	-0.4	-1.0	-3.2	-3.2	-4.3	-4.6	-4.6	-6.0
20	+0.1	+0.8	+1.6	+0.2	+0.8	-0.7	-0.4	-0.1	-0.9	-0.3	-0.7	-1.7
50	+0.1	+0.8	+1.1	+0.1	+0.7	+0.7	-0.1	-0.3	-0.7	-0.3	-0.5	-1.2

deeper layers [Fig. 15(a)]. The net radiation balance at the surface of unprotected soil is now positive by day, and a mulch impedes the consequential rise of temperature within the near surface layers. This is evidenced by those negative figures relating to depths of 2.5 cms and 5 cms which are given in Table 8. These do not increase with the diameter of the mulch, whose effect at this time, so far as near-surface soil temperatures are concerned, seems to be restricted to the reflection and absorption of some of the incoming radiation. On the other hand, at depths of 20 cms and 50 cms, heat is still flowing upward through the soil [Figure 15 (a)], and a mulch continues to exert its winter effect upon temperatures at those levels, as is evidenced by the figures given in Table 8. However, in the case of a circular mulch, that effect would no longer seem to be a function of its diameter.

During April, the typical summer effect of a mulch became well established. The flux of heat in the soil was now downwards, at least through all levels down to 50 cms. [Figure 15 (a)], and the mulch reduced the thermal input. The effect was more marked in May, and the figures given in Table 8 testify to the fact that the cooling influence which a circular mulch exerts upon the underlying soil in both April and May increases with its diameter at all depths down to 50 cms.

4. <u>The monthly means of temperatures recorded at 1400 hours daily in the vicinities of the mulches</u>

To acquire information concerning the vertical and horizontal distribution of temperature in the vicinity of each mulch, temperatures at four depths beneath each of the points indicated in Figure 7 were read at 1400 hours daily throughout the months February to May 1966 inclusive. From the daily values for each point monthly means were calculated, and these will now be considered.

(a) February 1966

The monthly mean of air temperature was only slightly above normal, and the weather throughout this month was mainly characterised by a deficiency of precipitation. The total water equivalent of 3.39 cms was only slightly more than a half of the normal figure of 6.29 cms (Table 7). Moreover, since only 19.3 cms of snow fell by contrast with the normal total of 30.6 cms., and more particularly since the amount lying on the surface fell to zero by the middle of the month, the soil was less protected by a snow cover than is usually the case in February.

The monthly mean values of soil temperature read daily at 1400 hours at each of forty points are shown in Figure

16 (a), (b), (c) and (d).[7] In the control plot (a), these values were sub-zero throughout a soil layer whose depth was only slightly less than 20 cms. Beneath the centre of the 60 cms mulch (b) the corresponding figure was only about 4 cms, but this mulch did not extend its protective influence to points lying beyond its perimeter. Moreover, it had very little effect on soil temperature at a depth of 20 cms below its centre and none at a depth of 50 cms.

It is seen from Figure 16 (c) that the 120 cms mulch eliminated all sub-zero temperatures from beneath it, and that it induced the development of an underlying warmer zone whose presence was evident at all depths down to 50 cms.

Beneath the centre of the 240 cms mulch [Figure 16 (d)], temperatures exceeded 1°C at all depths below about 3.5 cms. The underlying warmer zone was now a more prominent feature, and at depths below 20 cms. it influenced points lying more than 60 cms beyond the perimeter of the mulch.

The differences between the monthly mean values of temperature recorded at 1400 hours daily and the corresponding figures for the control plot are shown in Figure 17

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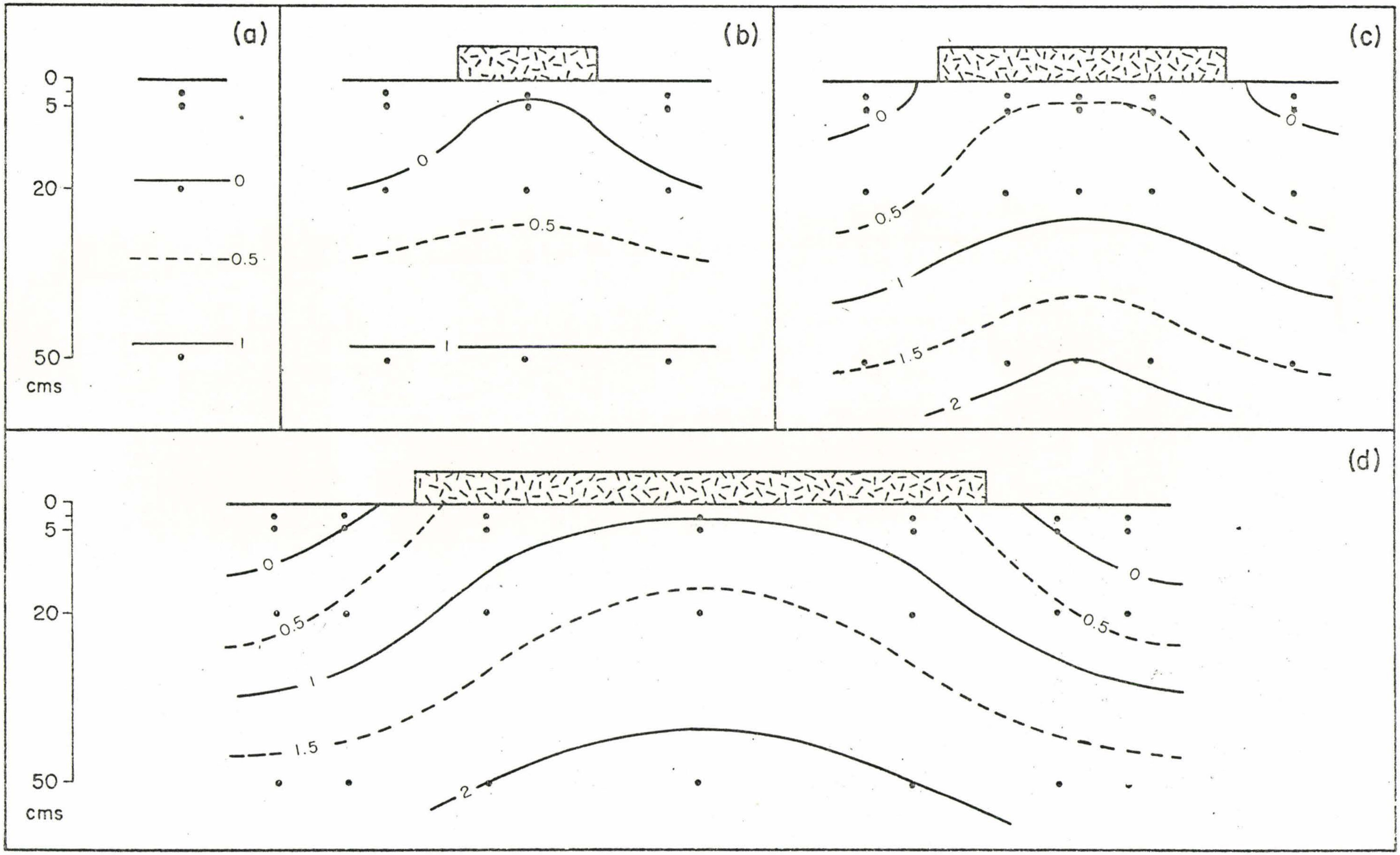
7. In Figure 16 and in each succeeding figure of identical format, temperatures are represented on both sides of each mulch centre although in fact they were measured on one side only.

Figure 16

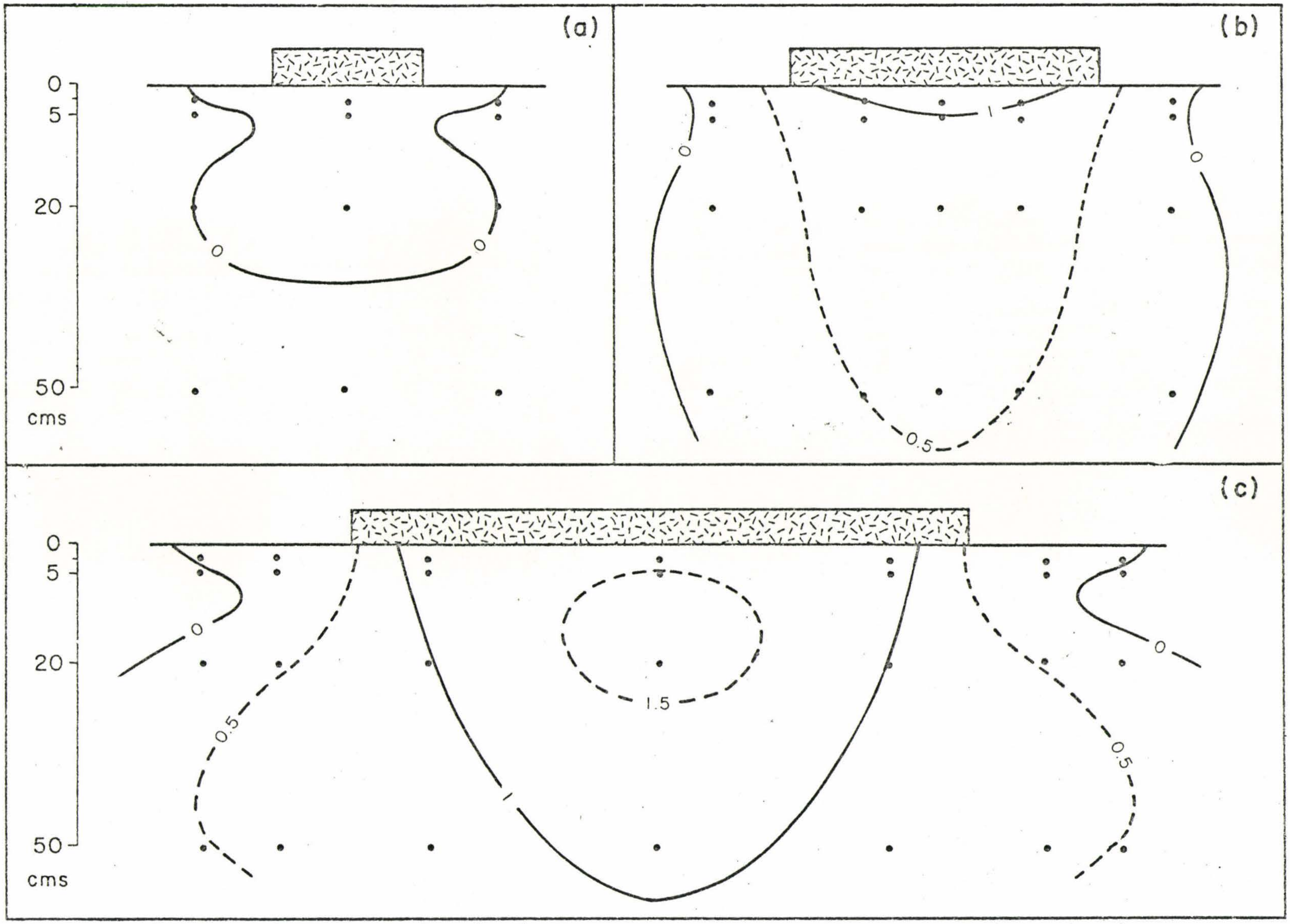
MONTHLY MEAN VALUES OF TEMPERATURES (°C) READ AT 1400 HOURS DAILY THROUGH FEBRUARY, 1966



Horizontal scale 1:24

Figure 17

FEBRUARY 1966. DIFFERENCES (°C) BETWEEN THE MONTHLY MEAN VALUES OF TEMPERATURES RECORDED AT 1400 HOURS DAILY AND THE CORRESPONDING FIGURES FOR THE CONTROL PLOT



Horizontal scale: 1:24

(a), (b) and (c). Nowhere beneath nor in the vicinity of the 60 cms mulch did such differences amount to as much as +0.5°C, and it is evident that a mulch of such small diameter affords no worthwhile protection against low temperatures during the winter season.

Beneath the centre of the 120 cms. mulch [Fig.17 (b)], temperatures at depths down to about 4 cm exceeded the corresponding values in the control plot by 1.0 °C, and the mulch induced a temperature gain of more than 0.5°C through all soil layers down to 50 cm. Moreover, a very slight protective influence spread laterally for about 30 cm beyond the perimeter of the mulch, and this affected all soil layers down to a depth of 50 cm.

Beneath the centre of the 240 cm. mulch [Figure 17 (c)], the soil temperatures at depths between 5 cm. and about 25 cm. were raised by more than 1.5°C above the corresponding values in the control plot, and the temperature gain exceeded 1.0°C at all depths down to 50 cm. Moreover, there were now much clearer indications of the fact that the mulch was extending its protective influence laterally through distances which increased from 60 cm. at the soil surface to a larger figure at a depth of 50 cm. This is shown by the 0°C isoline.

The amount of winter protection afforded by a circular mulch and the extent to which this protection spreads laterally beyond its circumference is controlled by the area covered. When this is small, the warmer zone which develops beneath the mulch is insignificant, and the thermal gradient which is directed outward from the centre of the covered plot is weak. As the area covered by the mulch is increased, the warmer zone which is developed beneath it becomes a more pronounced feature. The horizontal component of the thermal gradient directed outward in a radial direction becomes steeper, and more heat will consequently reach those uncovered areas of soil which lie beyond the perimeter of the mulch.

It has been found by Vuorinen (1958), working with apple trees, that their root systems spread more rapidly than the crown of the young tree and may reach 1-1.5 meters outside the crown circle. These roots reach depths of 40-80 cm but in older trees may be 1 meter deep. Thus the significance of the influence of the mulch on the soil outside its perimeter becomes evident.

An attempt was made to investigate the relationship between the diameter of a mulch and the magnitude of warming in February. For this purpose, the magnitude of warming was defined as the extent to which the mean value of the soil temperatures read daily at depths of 5, 20 and

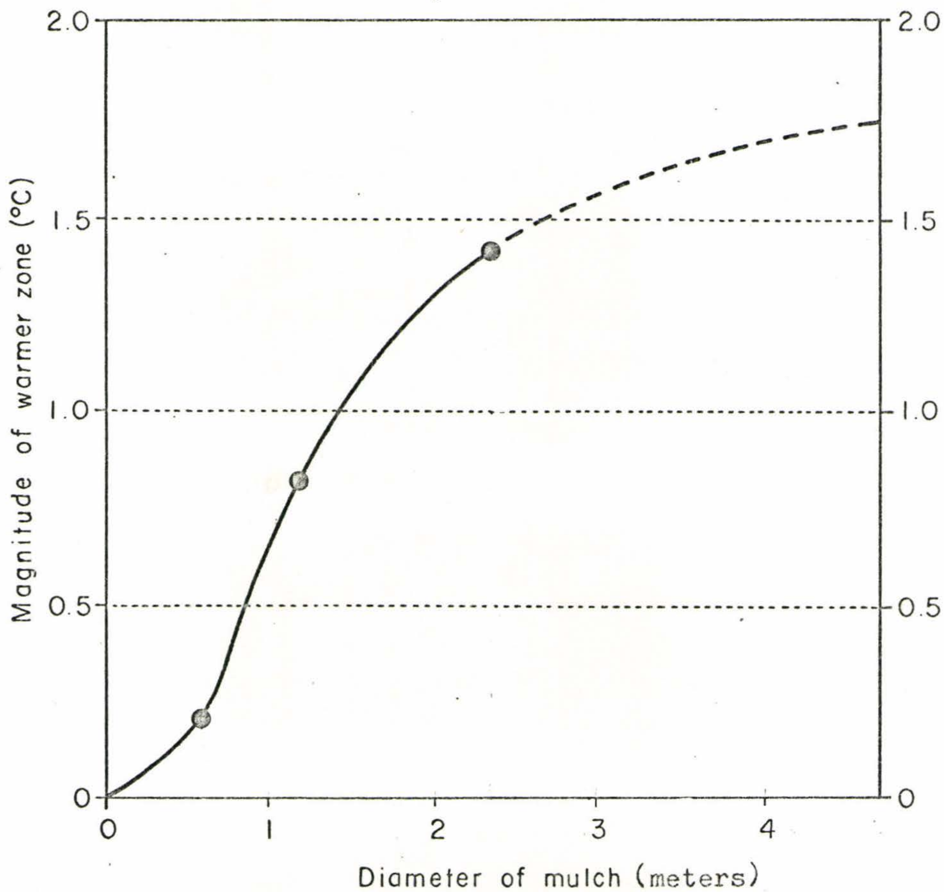
50 cm. beneath the centre of each mulch exceeded the corresponding mean value in the control plot. The data for the 60 cm., 120 cm., and 240 cm. mulches are represented in Figure 18, and extrapolation of the curve shown therein suggests that no sifnificant increase in the magnitude of the warmer zone which develops beneath the centre of a circular mulch in February would result from any increase in its diameter beyond 480 cm. Moreover, since the amount of mulch required to cover a circular plot of diameter 480 cm. is four times the amount required to lay the same thickness on a plot of diameter 240 cm., the extra cost involved may be very uneconomic in view of the small additional gain in the magnitude of the warmer zone. Whilst this gain increases rapidly with diameter up to 240 cm., the increase in diameter beyond that figure would seem to be much less, and it tends to become zero at diameters in excess of 480 cm. It would thus seem that for the winter protection of individual fruit trees, circular mulches of diameter 240 cm. are to be strongly recommended. Mulches of diameter 120 cm. afford much less protection against low soil temperatures, and that afforded by mulches of diameter 60 cm. is insignificant.

(b) March 1966

The air temperatures recorded at Hamilton's weather station during this month were above normal (Figure 14), and

Figure 18

RELATIONSHIP BETWEEN THE DIAMETERS OF THE MULCHES AND THE MAGNITUDES OF THE WARMER ZONES WHICH THEY GENERATED WITHIN THEIR UNDERLYING SOILS IN FEBRUARY, 1966



a high of 20°C was recorded on the 18th. The snowfall of 5.8 cm. was only 29 percent of the normal amount, but the figures previously given in Table 7 (p. 77) show that the total water equivalent of precipitation during this month exceeded the long-term mean by 2.03 cm.

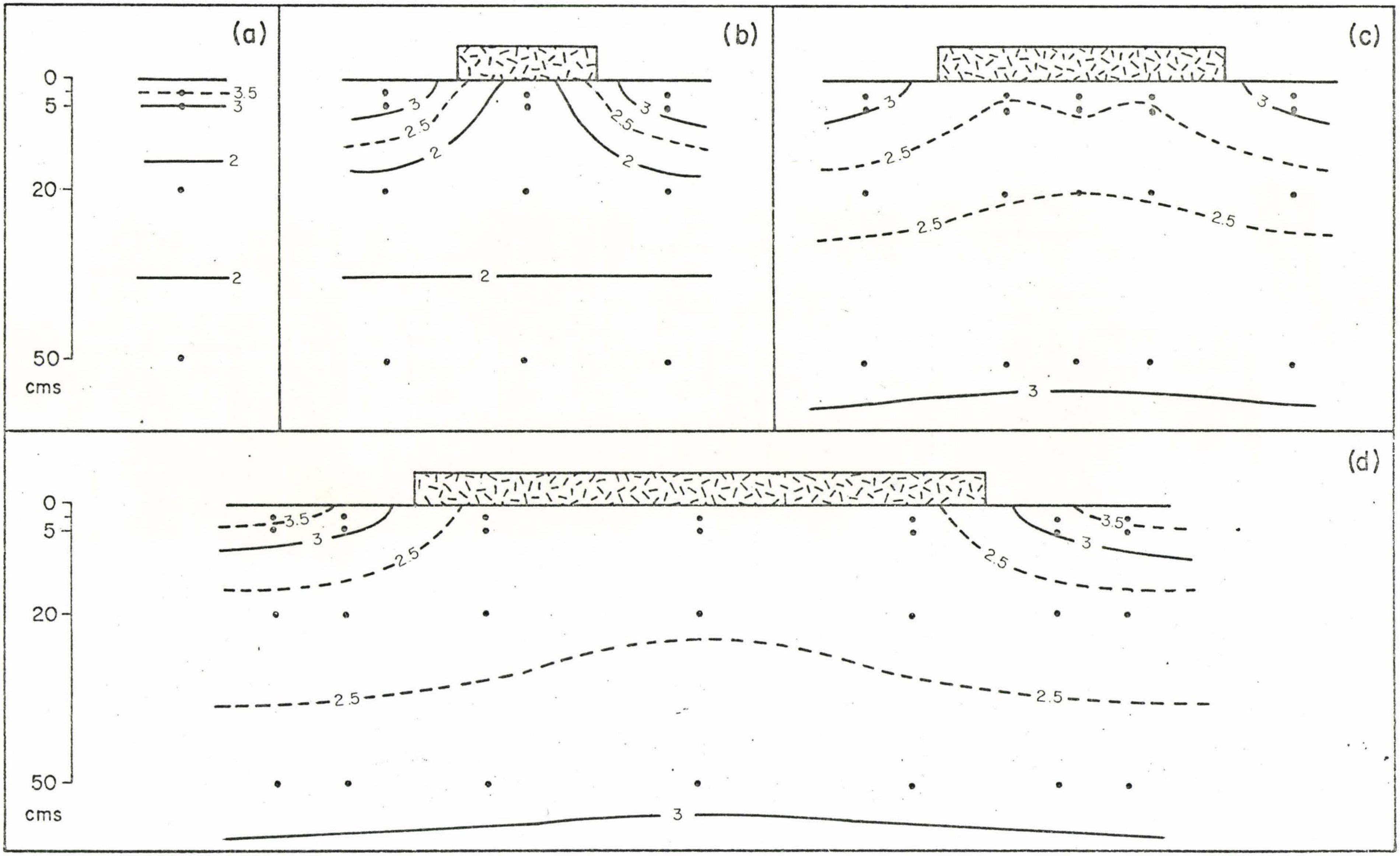
The monthly mean values of soil temperature read daily through March at 1400 hours are shown in Figure 19 (a), (b), (c) and (d). The two-way flux of heat through the soil during this month is evidenced by the fact that on each section of this Figure there are two geotherms[1] of the same numerical value. In the control plot (a) and beyond the perimeter of each of the mulches, heat from the warming surface was flowing downward to a depth of about 20 cm., but a greater depths heat was flowing upwards. Beneath the 120 cm. and 240 cm. mulches, remnants of the warmer zone were still in evidence at depths below 20 cm., but that beneath the 240 cm. mulch was no longer the more pronounced.

The differences between the monthly mean values of temperatures recorded at 1400 hours daily and the corresponding figures for the control plot are shown in Figure 20 (a), (b) and (c). The mulches were now equally effective in

1. "Geotherms" are lines joining sub-surface points of equal temperature. (See Geiger, 1965).

Figure 19

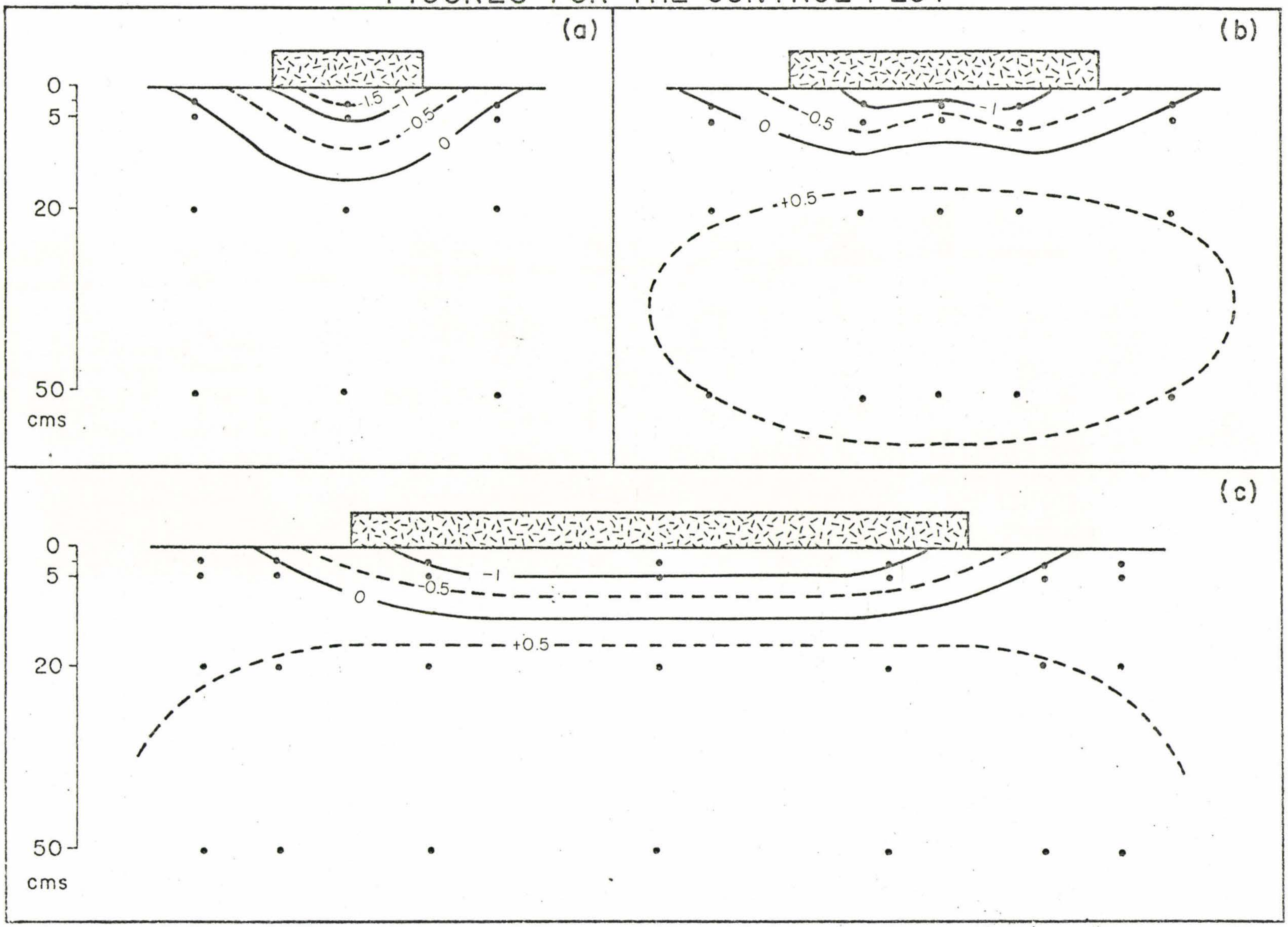
MONTHLY MEAN VALUES OF TEMPERATURES (°C) READ AT 1400 HOURS DAILY THROUGH MARCH 1966



Horizontal scale 1:24

Figure 20

MARCH 1966. DIFFERENCES BETWEEN THE MONTHLY MEAN VALUES OF TEMPERATURES RECORDED AT 1400 HOURS DAILY AND THE CORRESPONDING FIGURES FOR THE CONTROL PLOT



Horizontal scale 1:24

preventing much of the incoming radiation by day from penetrating to the soil beneath. Thus the upper layers of the sub-mulch soil were in each case 1.0 - 1.5°C cooler than the corresponding layers in the control plot, and a slight cooling effect extended to a distance of about 30 cm. beyond the perimeter of each mulch. However, the 120 cm. and 240 cm. mulches also succeeded in preventing the escape of some of the outgoing radiation from the underlying soil at night, and this permitted the retention of an area of small temperature gain beneath each at depths below 20 cm. This remnant beneath the 240 cm. mulch was now no more intense than that beneath the 120 cm. mulch. Thus in March, the two effects of a circular mulch upon soil temperatures are not functions of its diameter.

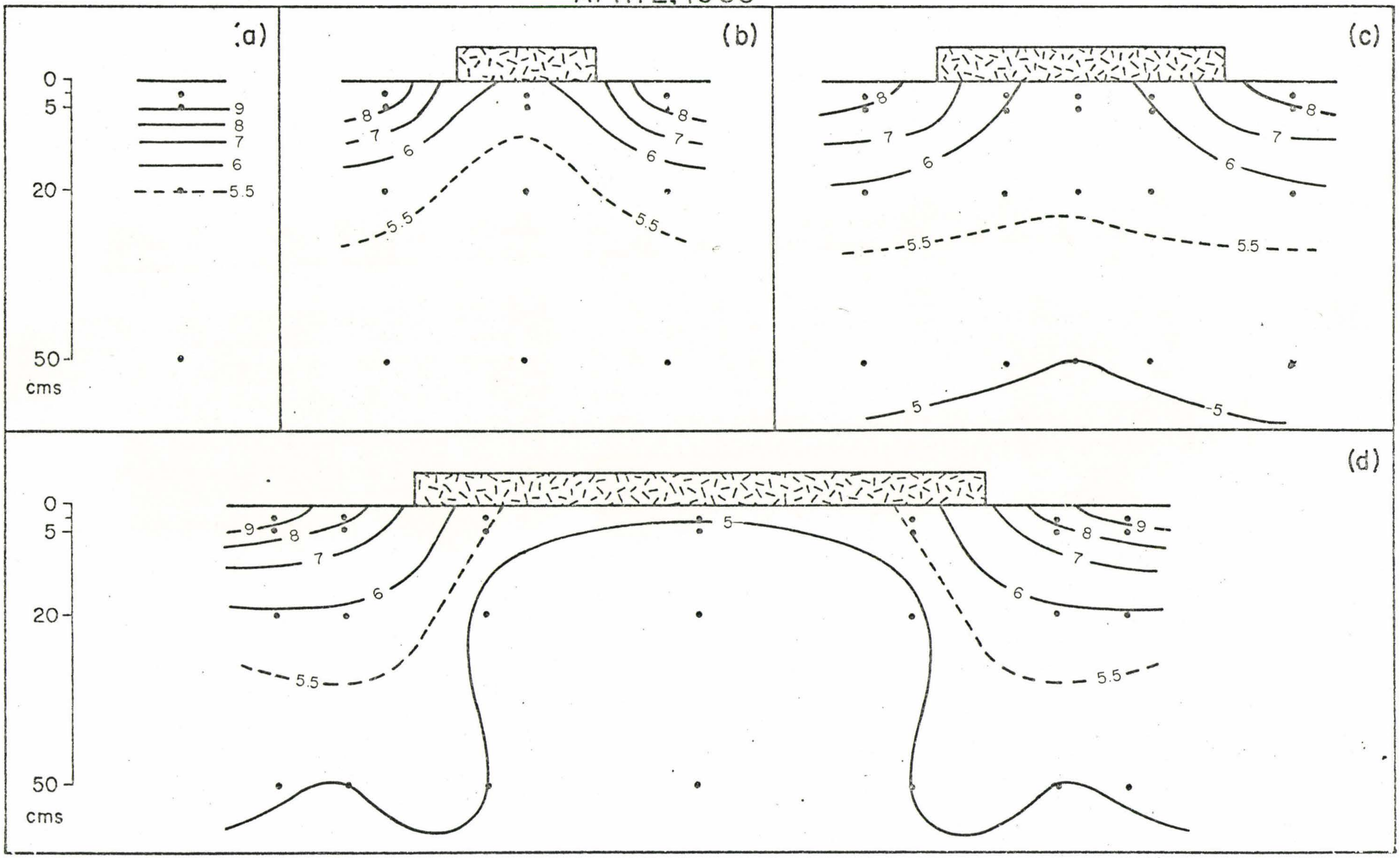
(c) April 1966

In general, air temperatures throughout this month were below average, and the total of snowfall (5.1 cm.) was nearly twice the figure normally recorded. However, the total precipitation in terms of water equivalent was close to the long-term mean. (Table 7. p.77)

The monthly mean values of soil temperature read daily at 1400 hours are shown in Figure 21 (a), (b), (c) and (d).In the control plot (a) the downward gradient of temper-

Figure 21

MONTHLY MEAN VALUES OF TEMPERATURES (°C) READ AT 1400 HOURS DAILY THROUGH APRIL, 1966



Horizontal scale: 1:24

ature from the surface was now steeper than had been the case during the preceeding month, and there was no upward flow of heat from deeper layers to the 20 cm. level in any of the four plots. Thus each of the mulches now served to reduce the amount of heat flowing vertically into its underlying soil. A heat flux with a horizontal component was directed from the warmer near-surface soil layers which lay beyond the perimeter of each mulch to the cooler layers beneath its centre. The ability of this horizontal heat flow to raise near-surface soil temperatures beneath the centre of the mulch was a function of the mulch radius, as is indicated by the distance apart of the two arms of the 6° geotherm measured at the soil surface. A cone of comparatively cool soil extended upwards from greater depths into the sub-mulch layers. This distribution was most pronounced beneath the 240 cm. mulch and least pronounced beneath the 120 cm. mulch. Thus those parts of a fruit tree's root system lying at a depth of 20 cm. beneath the centre of a 120 cm. mulch which had remained in position throughout the winter would, at 1400 hours, be about 0.5°C warmer than would have been the case had the mulch diameter been 60 cm.[1]

---

1. The mean temperature at a depth of 20 cm. beneath the centre of the 120 cm. mulch was 5.6°C, whereas the corresponding figure for the 60 cm. mulch was 5.1°C.

This would seem to be a reflection of the greater protection against low soil temperatures which had been afforded by the larger mulch in preceeding months. Similarly, these same parts of a fruit tree's root system lying at a depth of 20 cm. beneath the centre of a 120 cm. mulch would, at 1400 hours, be about 1.0°C warmer than would have been the case had the mulch diameter been 240 cm.[1] In the case of the 240 cm. mulch, this would seem to be due to less of the lateral heat flux flowing inwards from the warmer soil lying beyond the perimeter of the mulch being able to reach the central portions of the covered soil.

The differences between the monthly mean values of temperatures recorded at 1400 hours daily and the corresponding figures for the control plot are shown in Figure 22 (a), (b) and (c). The lower temperatures beneath the 60 cm. and 120 cm. mulches were very similar, and this would seem to be due to the fact that, although the horizontal component of heat flow from the warmer near-surface layers of soil lying beyond the perimeters was less effective in the case of the 120 cm. mulch, the soil temperatures beneath

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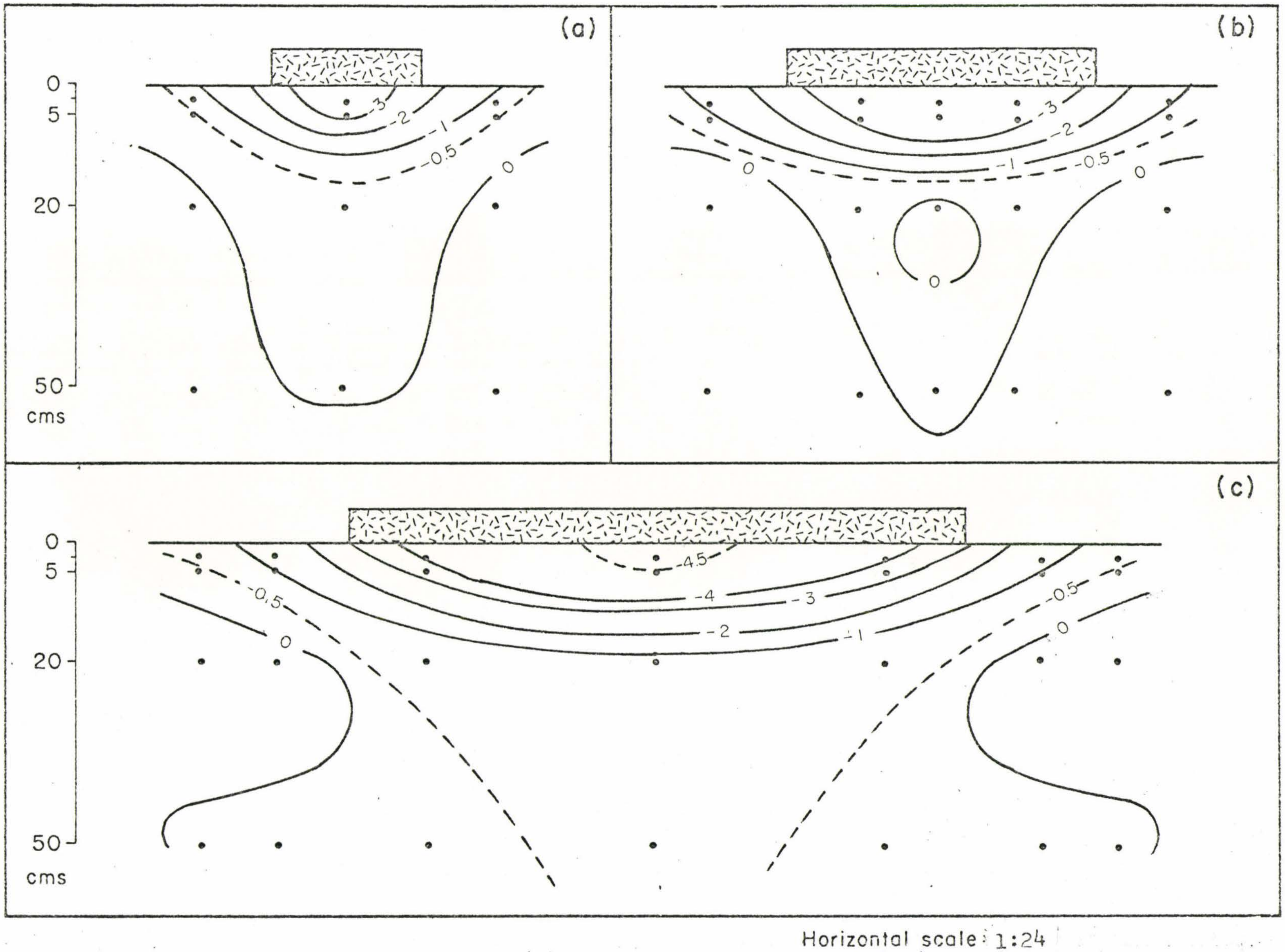
1. Whilst the mean temperature at a depth of 20 cm. beneath the centre of the 120 cm. mulch was 5.6°C, the corresponding figure for the 240 cm. mulch was only 4.6°C.

Figure 22

APRIL 1966. DIFFERENCES BETWEEN THE MONTHLY MEAN VALUES OF TEMPERATURES RECORDED AT 1400 HOURS DAILY AND THE CORRESPONDING FIGURES FOR THE CONTROL PLOT



this were still influenced by their somewhat higher values in the preceeding months. Thus the trend of the line indicating zero difference of temperature as compared with the control plot was very similar beneath the 60 cm. and 120 cm. mulches.

Owing to the larger diameter, the horizontal component of the heat flow from the warmer surface layers of soil lying beyond the perimeter of the 240 cm. mulch was much less effective, and this was not compensated by the higher soil temperatures which had been recorded beneath the mulch during the winter months. Thus the near-surface layers of soil beneath the 240 cm. mulch were cooler than those beneath the mulches of smaller diameter. Moreover, the apex of the inverted cone of cooler soil beneath the largest mulch reached downwards to a greater depth. It would thus seem that the extent to which a circular patch of mulch retards the warming of the soil beneath it in early spring increases with its diameter, but only when that measure exceeds 120 cm.

It is seen from Figure 22, that, in April, each of the mulches maintained lower temperatures in the near-surface layers of soil lying beyond its perimeter. This was due to the heatflow therefrom to the cooler soil beneath the mulch. At a distance of 30 cm. beyond the perimeters of the

60 cm. and 120 cm. mulches, this cooling effect amounted to about 1°C. In the case of the 240 cm. mulch, the corresponding figure was 1.5°C, and a temperature deficit of 0.5°C was experienced more than 60 cm. beyond the perimeter of this largest mulch.

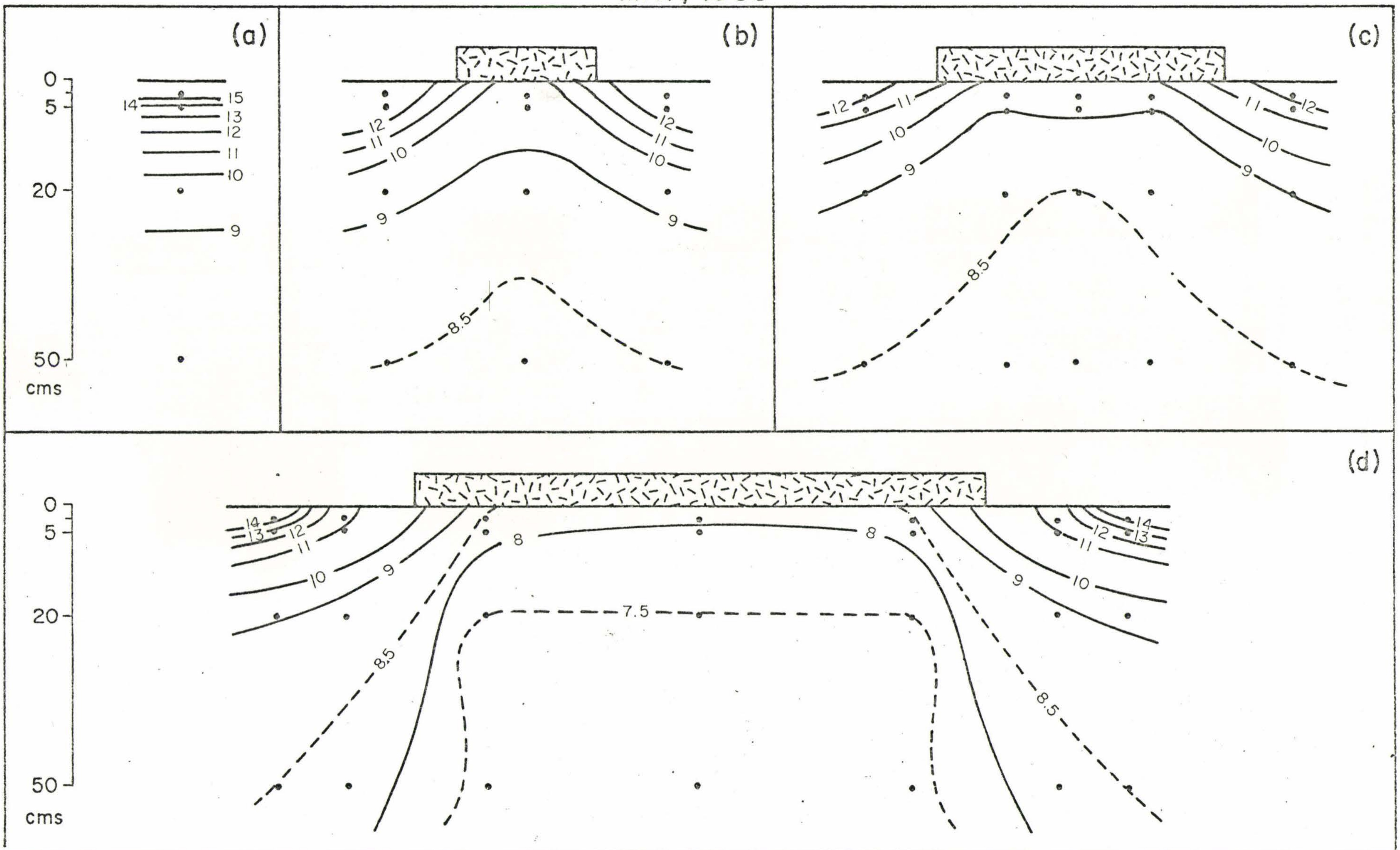
(d). May

This month was characterised by low temperatures, and the last air frost of spring was recorded on the tenth day. The rainfall total of 4.29 cm. was also low, the long term average for this month being 7.77 cm.

The monthly mean values of soil temperature read daily at 1400 hours are shown in Figure 23 (a), (b), (c), and (d). In the control plot (a), the downward gradient of temperature was notably steeper than had been the case during the preceeding month. In this plot during April, the temperature difference between the soil layers at depths of 2.5 and 50 cm. had been 4.4°C, but the corresponding figure was now 6.6°C. As had been the case during the preceeding month, each of the mulches continued to impede the vertical flow of heat into its underlying soil.. A cone of comparatively cool soil thus extended upwards from greater depths into each of the sub-mulch areas, and this became a more marked feature as the diameter of the mulch increased.

Figure 23

MONTHLY MEAN VALUES OF TEMPERATURES (°C) READ AT 1400 HOURS DAILY THROUGH MAY, 1966



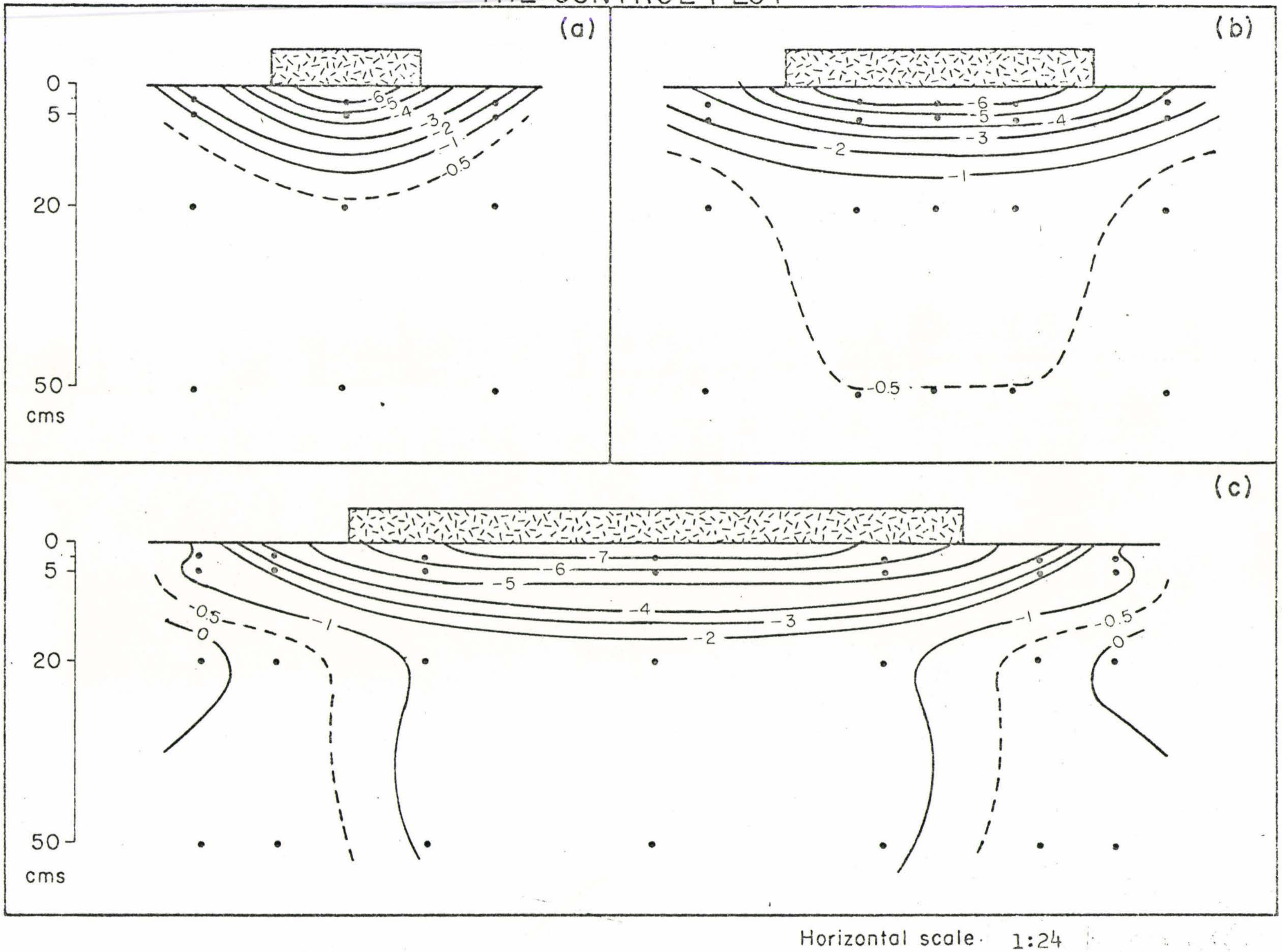
Horizontal scale: 1:24

The differences between the monthly mean value of temperatures recorded at 1400 hours daily and the corresponding figures for the control plot are shown in Figure 24 (a), (b) and (c). In the case of the 60 cm. and 120 cm. mulches, there was no significant difference in the amount of cooling induced at each depth within the upper 20 cm. of the sub-mulch soil, but the corresponding figure beneath the 240 cm. mulch was greater by 1°C. The cooling effect of each mulch on the near-surface layers of soil extended beyond its perimeter, and the amount of such heat deficit increased with the mulch diameter. The near-surface layer of soil at a distance of 30 cm. beyond the perimeter of the 60 cm. mulch was cooler than that of the control plot by 2°C, whereas the corresponding figures for the 120 cm. and 240 cm. mulches were 3°C and 4° C respectively. In the case of the 240 cm. mulch, a temperature deficit of 1°C affected the near-surface layer of soil at a distance of 60 cm. beyond its perimeter.

A comparison of Figures 24 and 17 clearly indicates that within the upper 20 cm. of the sub-mulch soil the cooling effects induced by the mulches in May were much more marked than their warming effects in February. However, at depths between 20 cm. and 50 cm. the cooling induced in May was no more marked than the warming in February.

Figure 24

MAY 1966. DIFFERENCES BETWEEN THE MONTHLY MEAN VALUES OF TEMPERATURES RECORDED AT 1400 HOURS DAILY AND THE CORRESPONDING FIGURES FOR THE CONTROL PLOT



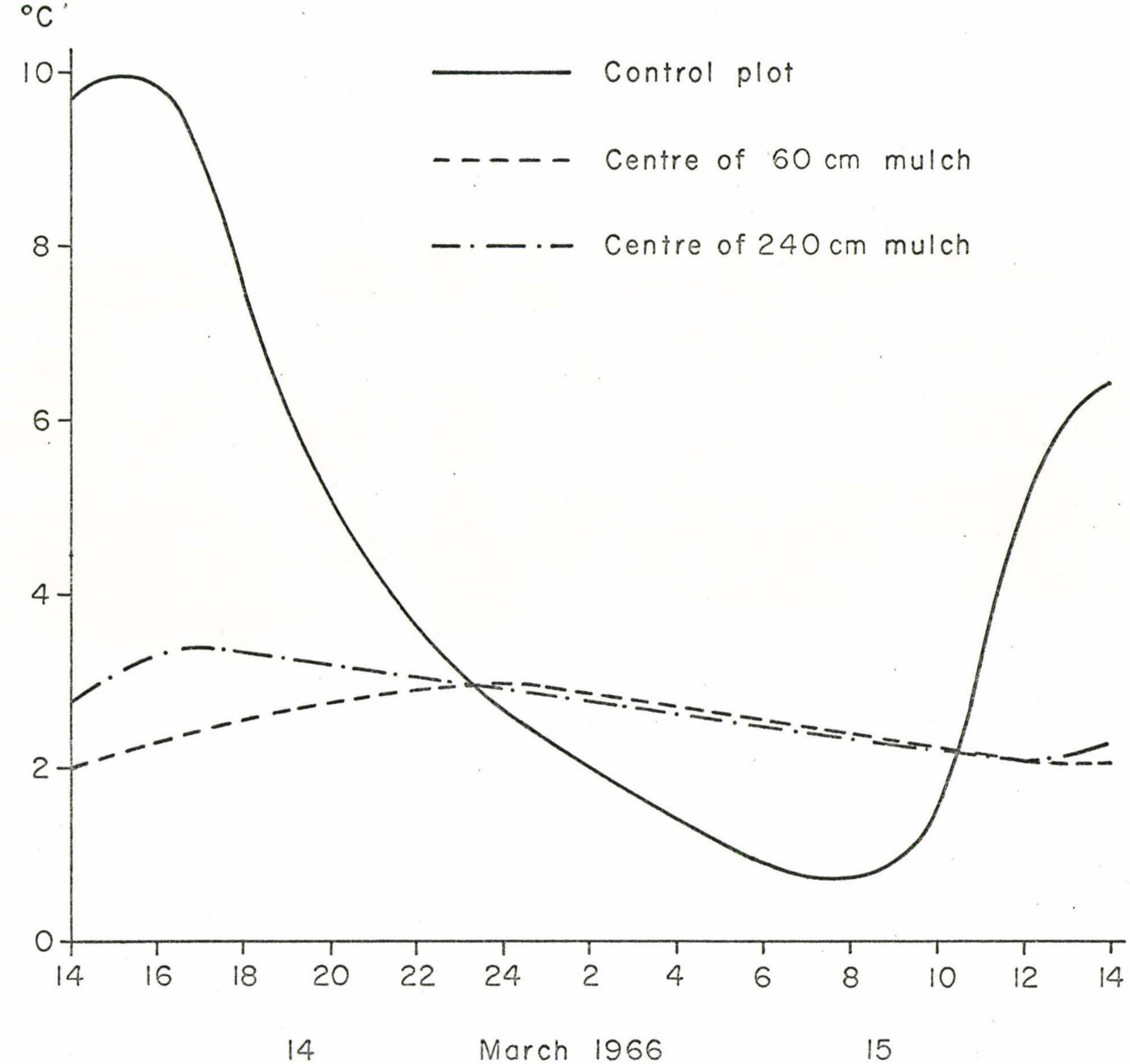
5. <u>The effects of the mulches on the diurnal variation of temperature.</u>

Observations were made hourly from 1600 hours on February 26 to 1700 hours on February 27, a cloudless period during which the soil in the control plot was still below zero to a depth of about 15 cm. These observations showed that there were no significant temperature variations with time at any depth beneath the centre of the control plot. Since there was no snow cover, the lack of temperature variation must have been due to the presence of the frozen layer of soil. By day, energy absorbed by the soil surface was mainly used to thaw the near-surface layer, and little, if any, remained to warm the soil. At night, energy lost from the soil surface resulted in re-freezing, with the consequent liberation of latent heat of fusion. Hence temperature changes with time were very small. It can therefore be safely assumed that only small variations of soil temperature with time will occur at any specified depth during those periods when there is a frozen layer near to the surface.

By mid-March the soil in the control plot had thawed, and there was a particularly warm spell of weather from March 9 to March 19. Readings taken every hour from 1400 hours on March 14 to the same time on the succeeding day demonstrate how soil temperatures respond to cloudless conditions in very early spring. Figure 25 shows the temperatures recorded at a depth of 2.5 cms in the control plot and beneath the centres of the smallest and largest mulches. It is at once evident from this figure that the large diurnal range of temperature which characterised the control plot was greatly reduced by the mulches. In the control plot the maximum temperature was 10°C, but the corresponding figures recorded beneath the centres of the 240 cm and 60 cm mulches were only 3.4°C and 3.0°C respectively. In the control plot the maximum temperature was achieved just after 1500 hours. Beneath the centre of the 240 cm mulch the corresponding time was delayed by two hours, but beneath the centre of the 60 cm mulch the maximum temperature was not attained until midnight. The reason for this unexpected pattern of temperature fluctuation is more easily understood in the light of the findings which are later to be reported in Chapter 5 concerning the horizontal flow of heat beneath the mulches. In brief, the inward flow of heat under the edges of the mulches by day had a strong horizontal component. In the case of the 240 cm. mulch, the distance to be travelled by this horizontal flow was such that it contributed little or no heat to the near surface layers of soil beneath the centre. These only received heat which had moved downwards through the mulching material, see Chapter 5, and thus the

Figure 25

SOIL TEMPERATURES AT DEPTH 2.5 CMS, MARCH 14-15, 1966



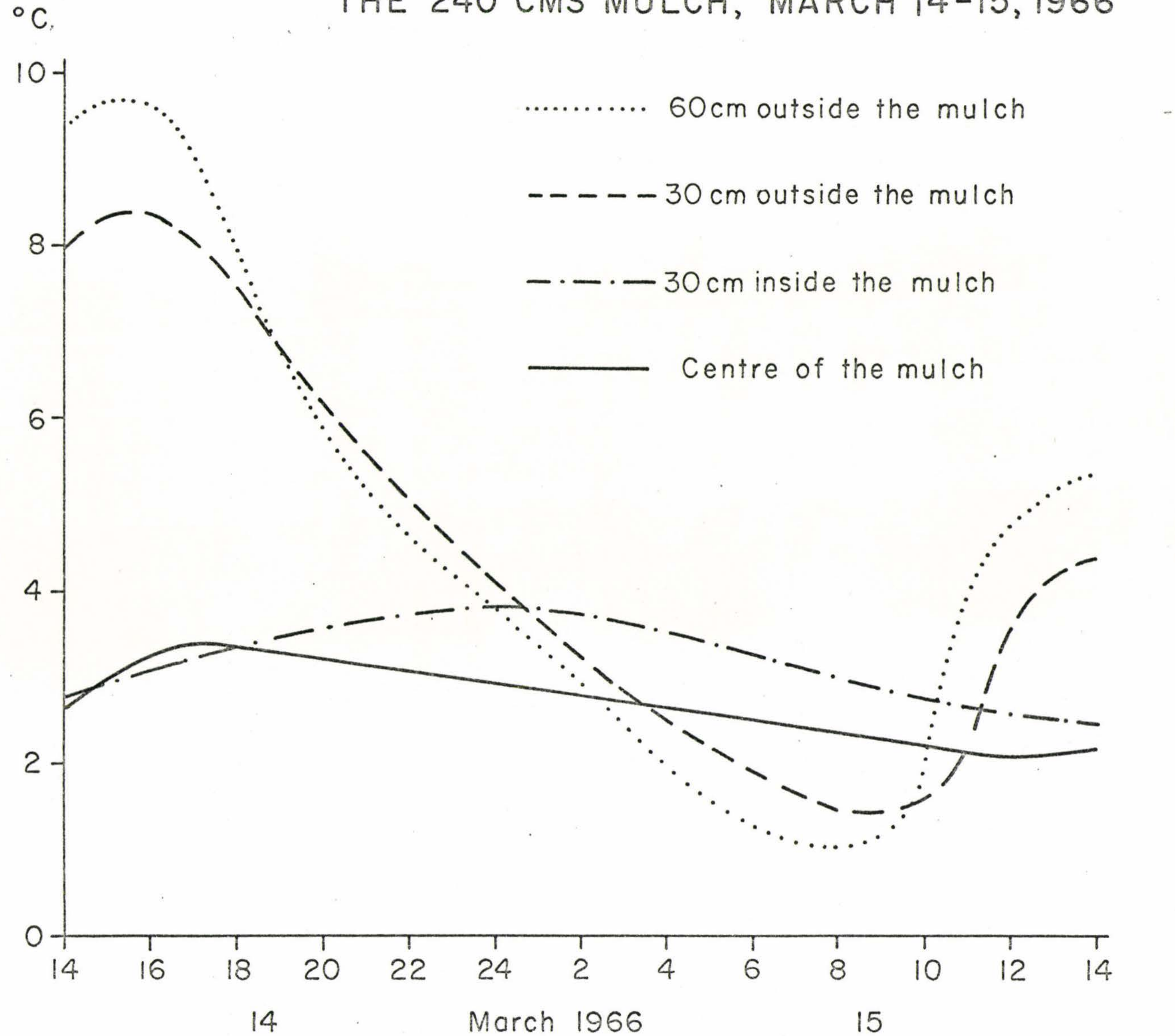
attainment of the maximum temperature was delayed only by the time involved in this movement. At the centre of the 60 cm. mulch, the near-surface layers of soil received heat which had passed downwards through the mulching material plus that contributed by the horizontal component of the inward flow. The latter movement was slower than the former and therefore the attainment of the maximum temperature was delayed.

Throughout the same 24-hour period, (1400 hours March 14 - 1400 hours March 15), a similar investigation of the times at which maximum temperatures at a depth of 2.5 cm. were attained was made for the points lying 60 cm. outside, 30 cm. outside and 30 cm. inside the perimeter of the 240 cm. mulch. The results, which are represented in Figure 26, again show that at a point lying 30 cm. inside the perimeter of the 240 cm. mulch, which corresponds to the centre of the 60 cm. mulch, the maximum temperature was not attained until 2400 hours.

A comparison of Figures 25 and 26 shows that the soil temperatures at a depth of 2.5 cm. beneath the centre of the control plot and at those points lying 30 cm. and 60 cm. outside the perimeter of the 240 cm. mulch achieved their maximum values just after 1500 hours. At those same points, temperature minima were recorded soon after 0800 hours.

Figure 26

SOIL TEMPERATURES AT DEPTH 2.5 CMS BENEATH AND NEAR THE 240 CMS MULCH, MARCH 14-15, 1966



However, an inspection of these two Figures shows that the diurnal range of temperature at a depth of 2.5 cm. beneath the centre of the control plot exceeded that recorded 60 cm. outside the perimeter of the 240 cm. mulch and that this latter, in turn, exceeded the diurnal range recorded 30 cm. outside the mulch perimeter. Thus, the proximity of the mulch reduced the diurnal range of temperature at a depth of 2.5 cm. and this effect became more marked as the perimeter of the mulch was approached.

Figures 25 and 26 both show that, during March, the mulching material greatly impeded the daytime warming of the near-surface layers of soil beneath it. However, at night, the mulch impeded outgoing radiation, with the result that temperature minima beneath it were higher than those at all unprotected points. This marked reduction in the diurnal range of temperature in the near-surface soil layers in late winter and early spring represents one of the chief benefits conferred by mulching.

Other observations of temperature at hourly intervals were made on several occasions during April. For all points at a depth of 2.5 cm. the shapes of the temperature curves during that month corresponded very closely to their counterparts in March, though by late April the recorded temperatures were considerably higher. Furthermore, temperatures beneath the mulches were then lower than those at the unprotected points by night as well as by day; a feature which is typical of the summer season with its high values of incoming radiation. At a depth of 2.5 cm. maximum temperatures at each of the unmulched points of measurement were attained at about 1500 hours; the same time as those in the control plot. As was the case during the preceeding month, the attainment of the maximum temperature at a depth of 2.5 cm. beneath the centre of the 240cm. mulch was delayed by two hours. Beneath the centre of the 60 cm. mulch, and 30 cm. inside the perimeters of the other two mulches, maximum temperatures at a depth of 2.5 cm. were not recorded until 2000 hours. The corresponding time in March had been 2400 hours, and the earlier attainment in April was probably due to the faster inward flow of heat which resulted from the steeper temperature gradient across the mulch perimeters.

CHAPTER 5

RESULTS FROM THE SECOND PHASE OF THE INVESTIGATION (1968-1969)

1. Weather conditions during the period of observation

(a) Temperature.

Monthly mean values of maximum, minimum and mean temperatures for Hamilton, issued by the Hamilton Weather Office, over the period covered by the second phase of the investigation are shown in Figure 27 , together with the corresponding normal values. Whilst April 1968 was a comparatively warm month, temperatures during the succeeding summer months were slightly below normal. The fall months were warm, but winter temperatures were below normal and achieved their minimum values in January, a month earlier than usual.

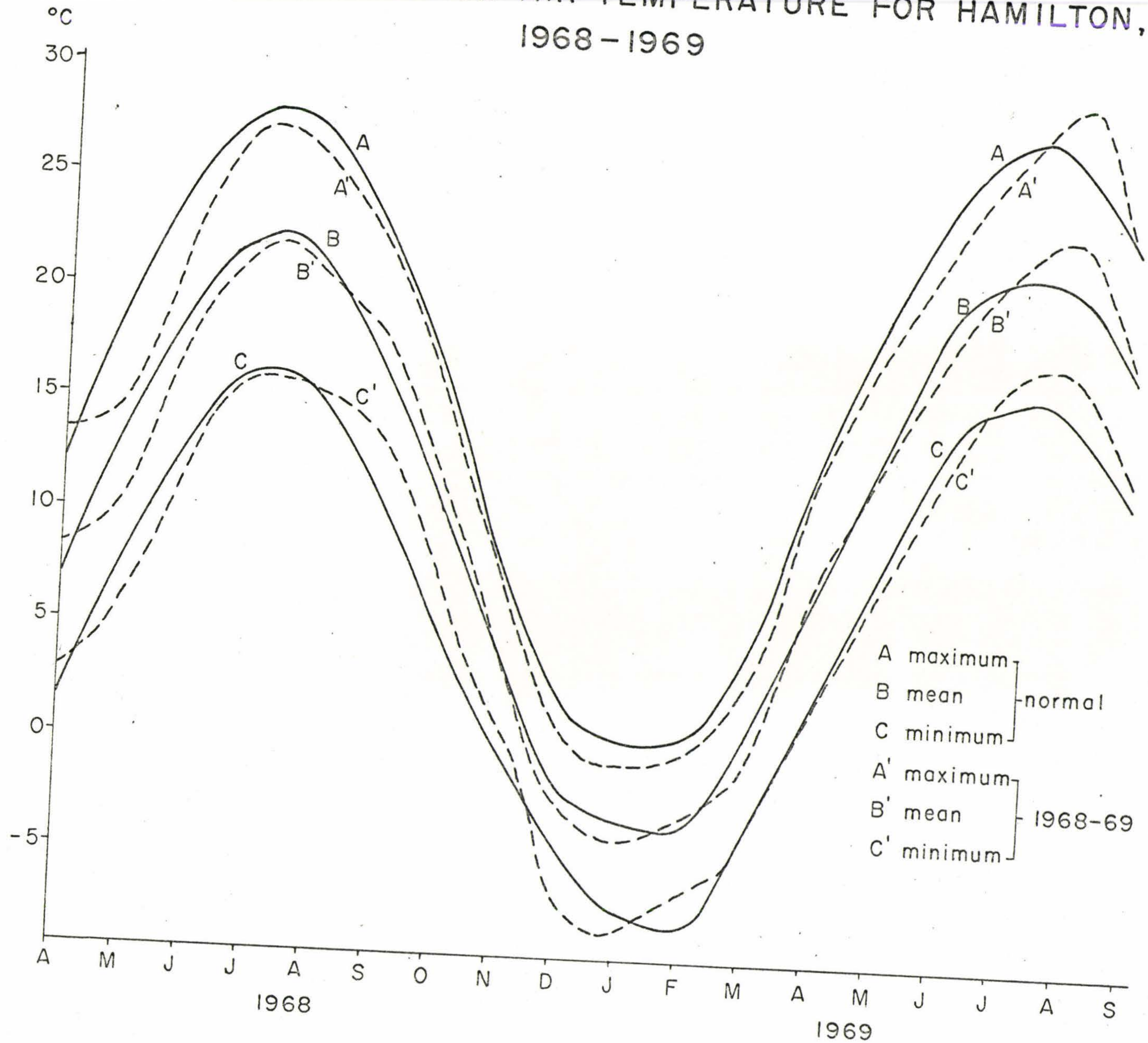
The temperature conditions which prevailed during the spring of 1969 were close to normal, but the early summer months of that year were comparatively cool. August, however, was an exceptionally warm month in which maximum, minimum and mean temperatures reached their highest values, one month later than usual.

(b) Precipitation.

Precipitation totals for the months April 1968 to

Figure 27

MONTHLY AVERAGE AIR TEMPERATURE FOR HAMILTON, 1968-1969



September 1969 varied considerably from their normal values, as can be seen in Table 9. The exceptionally wet months in 1968 were June, August and November, and the snowfall in December approached twice its normal value. The only exceptionally dry months were April and July. On the whole, the period from April to December 1968 was comparatively wet, and its precipitation total exceeded the normal value by 10.14 centimeters.

By contrast, January to September 1969 was a comparatively dry period, and particularly dry conditions prevailed in February, August and September. The total water deficit over this period was 12.64 centimeters.

2. <u>The effects of a mulch upon the annual sinusoidal pattern of temperature variation.</u>

Figures 28 and 29 show the monthly mean temperatures at 1400 hours recorded beneath the centre of the mulch and 150 cm. outside its perimeter at depths of 5 and 50 cm. respectively. The mulch reduced the annual range of temperature from27.1°C to 22.3°C at a depth of 5 cm., and from 21.4°C to 19.5°C. at a depth of 50 cm. Most of this reduction resulted from the lowering of monthly mean temperatures during the summer from maxima of 27.0°C to 22.5°C at a depth of 5 cm., and from 22.2°C to 20.5°C at a depth of 50 cm. During the fall

TABLE 9

MONTHLY PRECIPITATION TOTALS IN CENTIMETERS, 1968-1969.

Month	1968			Normal			Differences
	Rain	Snow[1]	Total[2]	Rain	Snow[1]	Total[2]	(Totals)[3]
April	3.45	Tr	3.45	7.96	2.8	8.18	-4.73
May	7.24		7.24	7.77	Tr	7.77	-0.53
June	9.78		9.78	5.92		5.92	+3.86
July	1.55		1.55	6.15		6.15	-4.60
August	11.76		11.76	7.64		7.64	+4.12
Sept.	8.89		8.89	7.09		7.09	+1.80
Oct.	5.82	Tr	5.82	6.91	0.2	6.93	-1.11
Nov.	12.14	3.0	12.44	5.18	10.7	5.29	+6.25
Dec.	5.72	45.5	10.27	3.88	23.6	5.19	+5.08
				Sum of differences			+10.14
		1969					
Jan.	6.88	33.8	10.26	3.18	34.3	6.61	+3.65
Feb.	0.00	6.6	0.66	3.23	30.6	6.29	-5.63
March	3.94	10.9	5.03	5.18	20.3	7.21	-2.18
April	9.24	2.0	9.44	7.96	2.8	8.18	+1.26
May	9.24		9.24	7.77	Tr	7.77	+1.47
June	5.56		5.56	5.92		5.92	-0.36
July	7.72		7.72	6.15		6.15	+1.57
Aug.	0.53		0.53	7.64		7.64	-7.11
Sept.	1.78		1.78	7.09		7.09	-5.31
				Sum of differences			-12.64

Source: Hamilton Weather Office.

1 Snow is registered as the actual depth in centimeters.

2 In the determination of total precipitation values. 1 cm. of snow is regarded as the equivalent of 0.1 centimeters of rainfall.

3 1968/1969 totals minus normal totals.

Figure 28

MONTHLY MEAN SOIL TEMPERATURES AT A DEPTH OF 5 CMS, 1968-69

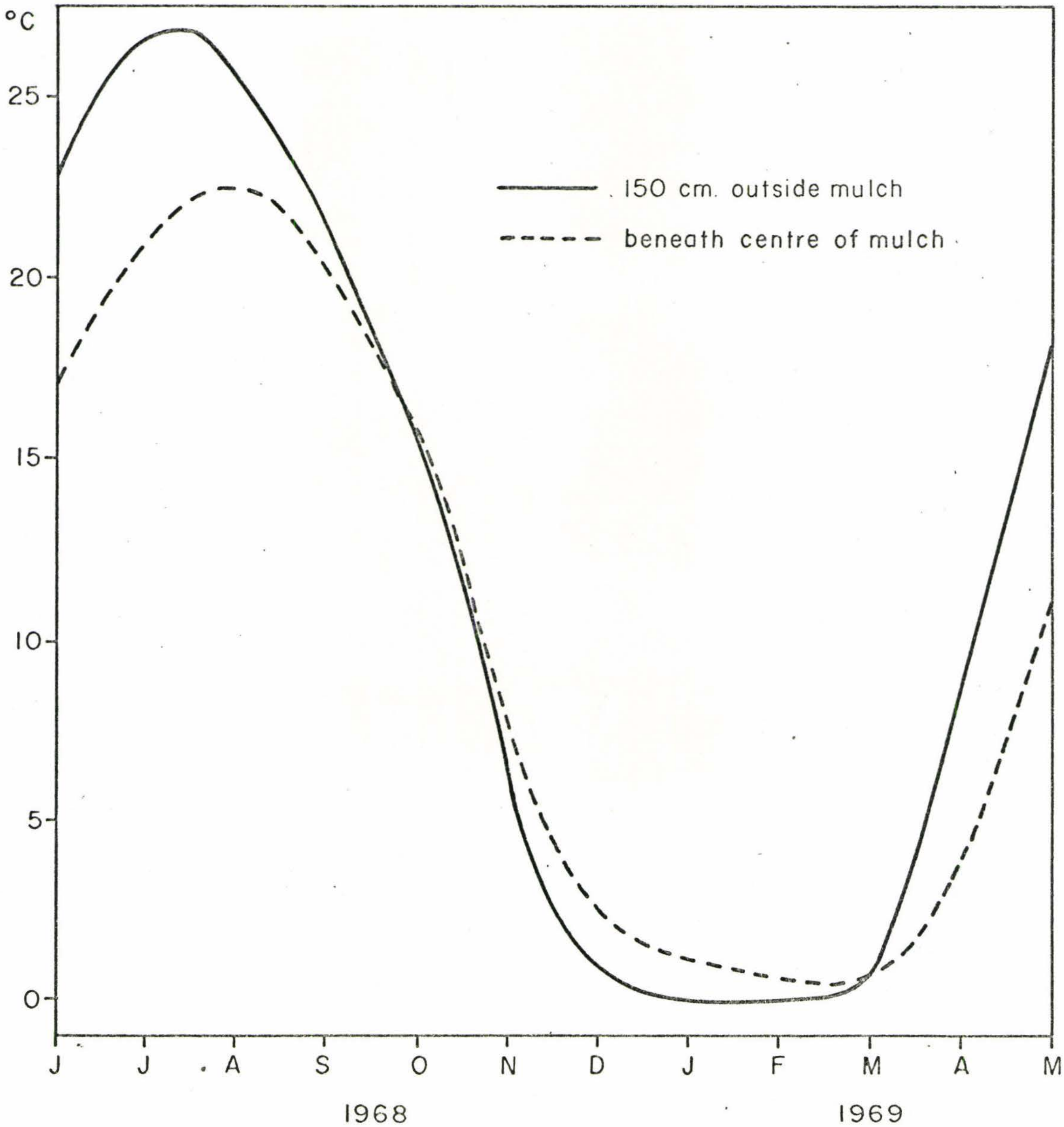
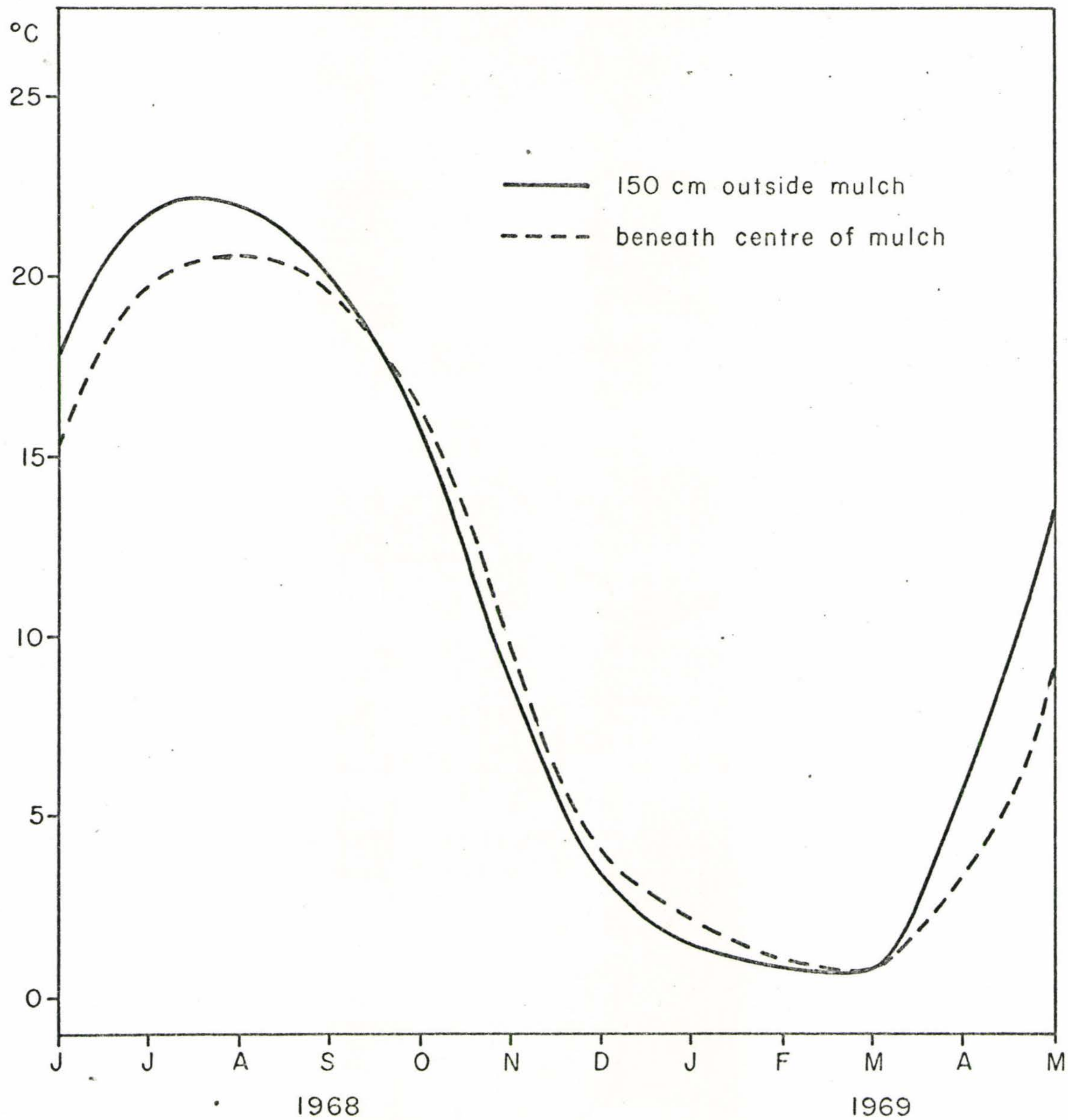


Figure 29

MONTHLY MEAN SOIL TEMPERATURES AT A DEPTH OF 50 CMS, 1968-69



months, the mulch only raised the monthly mean temperatures beneath it very slightly, but in the early winter months the benefits of the mulch increased, when its reduction of outgoing energy losses at night became of greater importance than its exclusion of incoming radiation by day. The benefits attributable to the presence of the mulch gradually decreased during the succeeding winter months. This was largely a consequence of the persistent snow cover, which, being itself a good insulator, minimized the additional protective influence provided by the mulch. Thus, by March, the differences in the monthly mean temperatures beneath the centre of the mulch and at a point lying 150 cm. outside its perimeter were virtually zero at depths of both 5 and 50 cm. However, during the succeeding months, the monthly mean temperatures at both depths beneath the mulch became increasingly cooler than those 150 cm. outside its perimeter.

The mulch retarded the attainment of the soil's highest monthly mean temperature from July to August at both the 5 and 50 cm. depths. However, the lowest monthly mean temperature at each of these depths was recorded in February, both beneath the centre of the mulch and at a point lying 150 cm. outside its perimeter.

A consideration of the monthly mean temperatures during the autumn months (Figures 28 and 29) reveals that the rate of fall of soil temperature at depths of both 5 and 50 cm. was not reduced by the presence of the mulch. However, the later consideration of temperature changes from day to day will show that the mulch induced a marked reduction in the rate of fall of temperature over shorter periods of time.

Using the values for the annual range of temperature within the topmost 20 cm. of soil, both at the centre of the 240 cm. mulch and at a point 150 cm. outside its perimeter, van Wijk's (1965) method of determining the thermal diffusivity of the soil was applied. There were two reasons why this technique could not be used for depths greater than 20 cm.:-

(a) It assumes that heat flows through the soil in a vertical direction only. As will later become apparent, the deeper layers of soil beneath the mulch received substantial quantities of heat in a non-vertical direction.

(b) It assumes that thermal properties are the same throughout the layer under consideration, and this was not the case in the profile which lay 150 cm. outside the perimeter of the mulch, due to considerable moisture variations with depth.

In Table 10 the annual temperature ranges and the natural logarithms of these values are shown for depths of 5, 10 and

20 cm. in two profiles; one beneath the centre of the mulch and one beneath a point lying 150 cm. outside its perimeter. In accordance with van Wijk's method, the natural logarithmic values of the annual temperature ranges were then plotted against depth in Figure 30. In the case of the profile lying beneath the centre of the mulch, the points A, B and C were found to lie on a straight line. This fact indicated that the topmost 20 cm. of soil beneath the mulch centre were similar so far as their thermal properties were concerned, and the thermal diffusivity of this layer was readily calculated from the slope of the line, (Van Wijk 1965). However, in the case of the profile lying 150 cm. outside the perimeter of the mulch,

TABLE 10

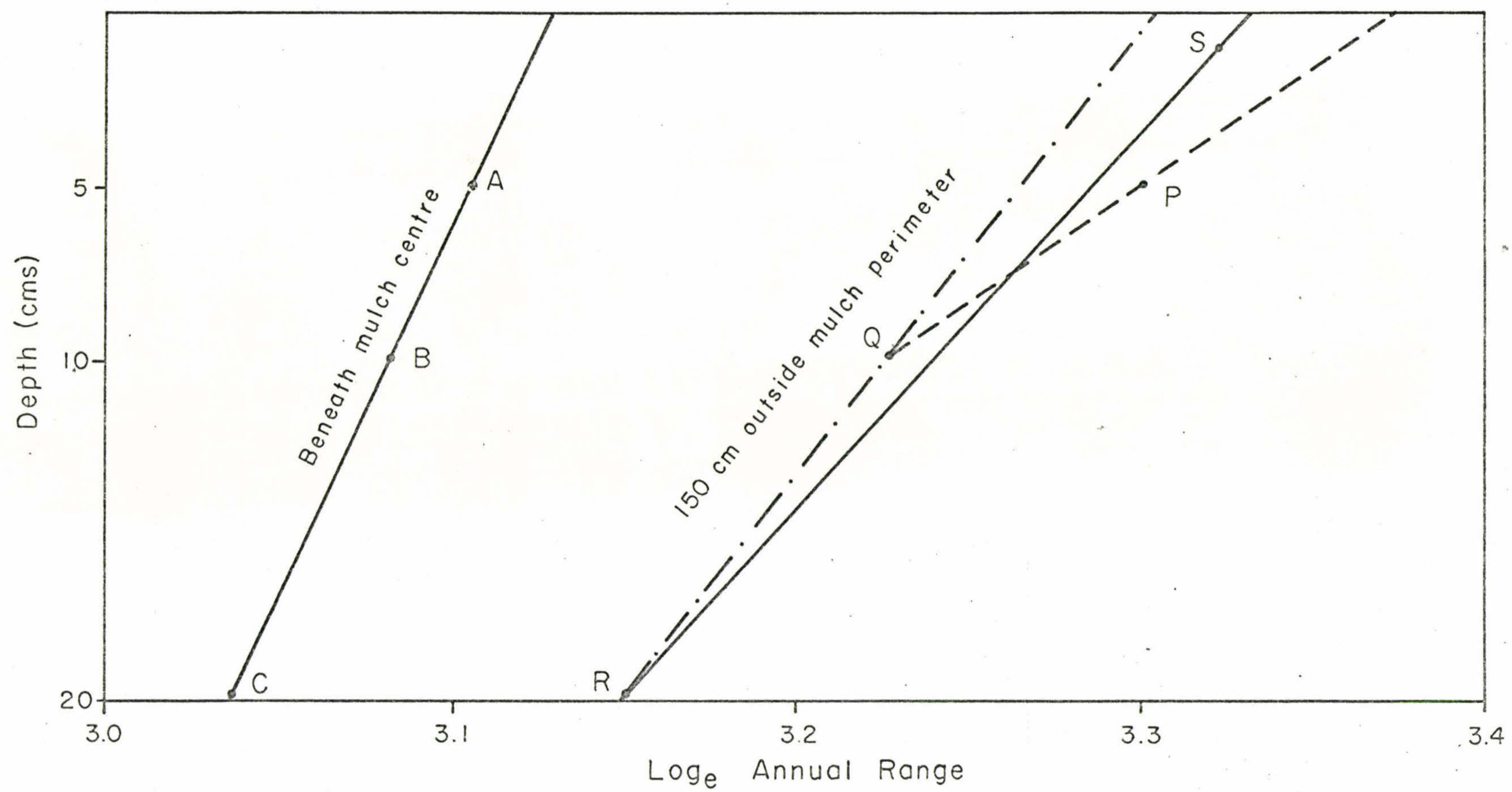
VALUES AND LOG_e VALUES OF ANNUAL RANGE, 1968 - 1969.

Depth (cm)	Centre of mulch		150 cm. outside Mulch	
	Range (°C)	Log_e	Range (°C)	Log_e
5	22.3	3.105	27.1	3.300
10	21.8	3.082	25.2	3.227
20	20.8	3.035	23.3	3.149

the points P, Q and R did not lie on a straight line, and this indicated that the topmost 20 cm. of soil in this profile were

Figure 30

LOG$_e$ VALUES OF ANNUAL RANGE PLOTTED AS A FUNCTION OF DEPTH



not homegeneous in their thermal properties. Approximate values of thermal diffusivity between depths of 5-10 cm., 10-20 cm. and 5-20 cm. were obtained from the slopes of the lines PQ, QR and SR respectively.[1] The values of thermal diffusivity for both profiles are shown in Table 11. The lower values of thermal diffusivity in the profile which lay 150 cm. outside the mulch perimeter indicated that the soil there was considerably drier than that which lay beneath the centre of the mulch. Furthermore, the decrease in the values of thermal diffusivity as the surface layers were approached indicated that the near-surface soil was considerably drier than that at a depth of 20 cms. In that profile which lay beneath the mulch centre, no such differences in soil moisture occurred within the topmost 20 cm.[2]

TABLE 11

VALUES OF THERMAL DIFFUSIVITY ($cm^2\ sec^{-1} \times 10^3$)

Depth (cm.)	Beneath mulch centre	150 cm. outside mulch perimeter
5-10	4.620	0.462
10-20	4.620	1.638
5-20	4.620	1.210

1. The position of the point S was located such that the slope of the line RS was equal to the mean of the slopes of the lines PQ and QR. Van Wijk reported linear relationships.
2. Measured values of soil moisture will later be considered in detail, (p. 182)

3. <u>Sub-surface temperatures beneath and in the vicinity of the mulch.</u>

Readings were obtained at eight depths from each of the fourteen thermocouple rods disposed along the lines CA and CB shown in Figure 9. Thus during those periods in which attention was focussed upon one mulch only, 112 sub-surface temperatures were read at 1400 hours daily. When readings were taken at hourly intervals, the total for a 24-hour period amounted to 2,688. Each of these totals was, of course, doubled during those periods when conditions beneath two mulches were being studied simultaneously.

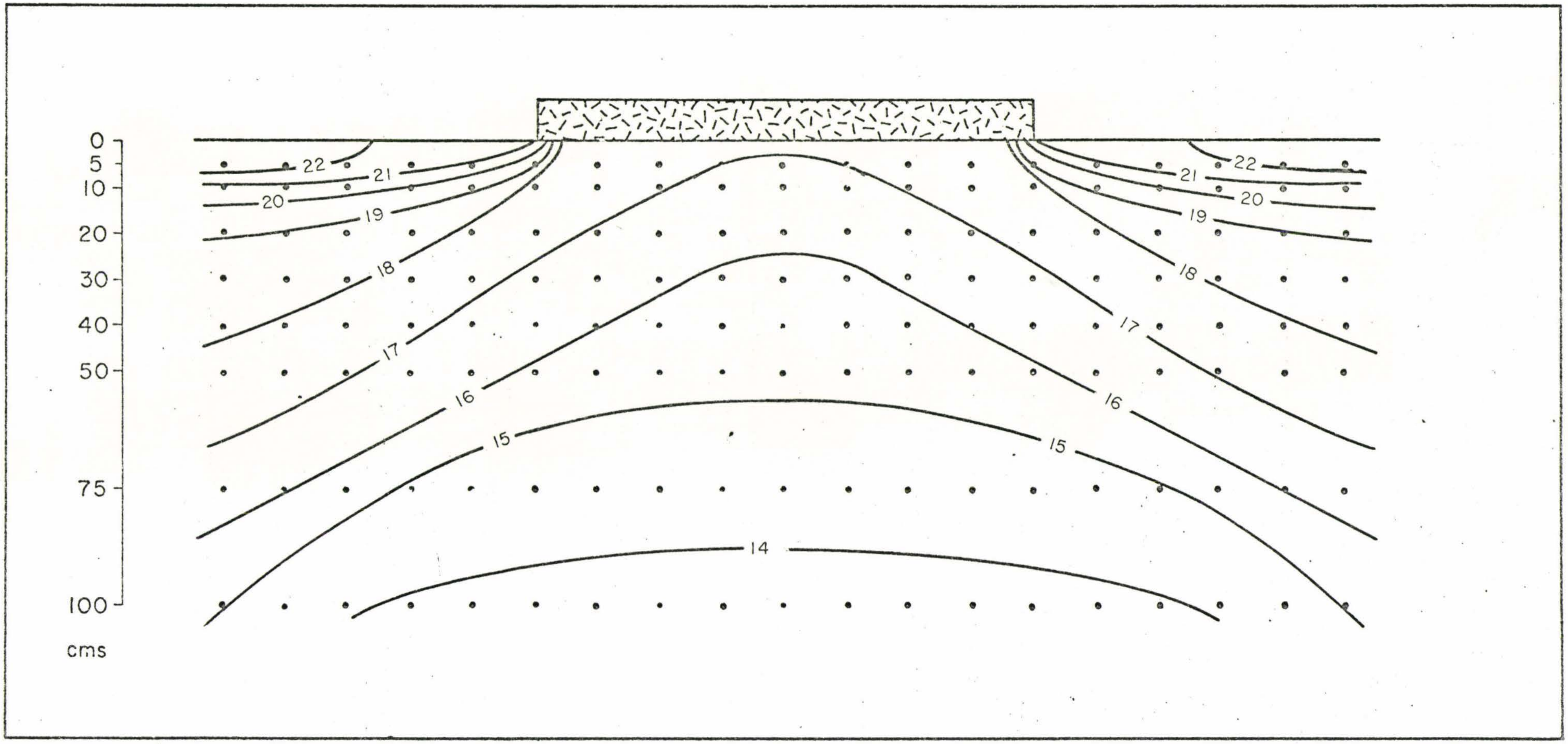
After a very detailed examination of the temperatures which were read daily at 1400 hours and those which were read at hourly intervals throughout many 24-hour periods, it became apparent that certain months in which essentially the same characteristics were displayed could be grouped together. The division as between one group of months and the next coincided, in each case, with fundamental differences in the distribution of sub-surface temperatures.

(a) June to August, 1968.

The distribution of sub-surface temperatures in each of these three summer months is shown in Figures 31, 32 and 33. These clearly indicate the extent to which the mulch impeded

Figure 31

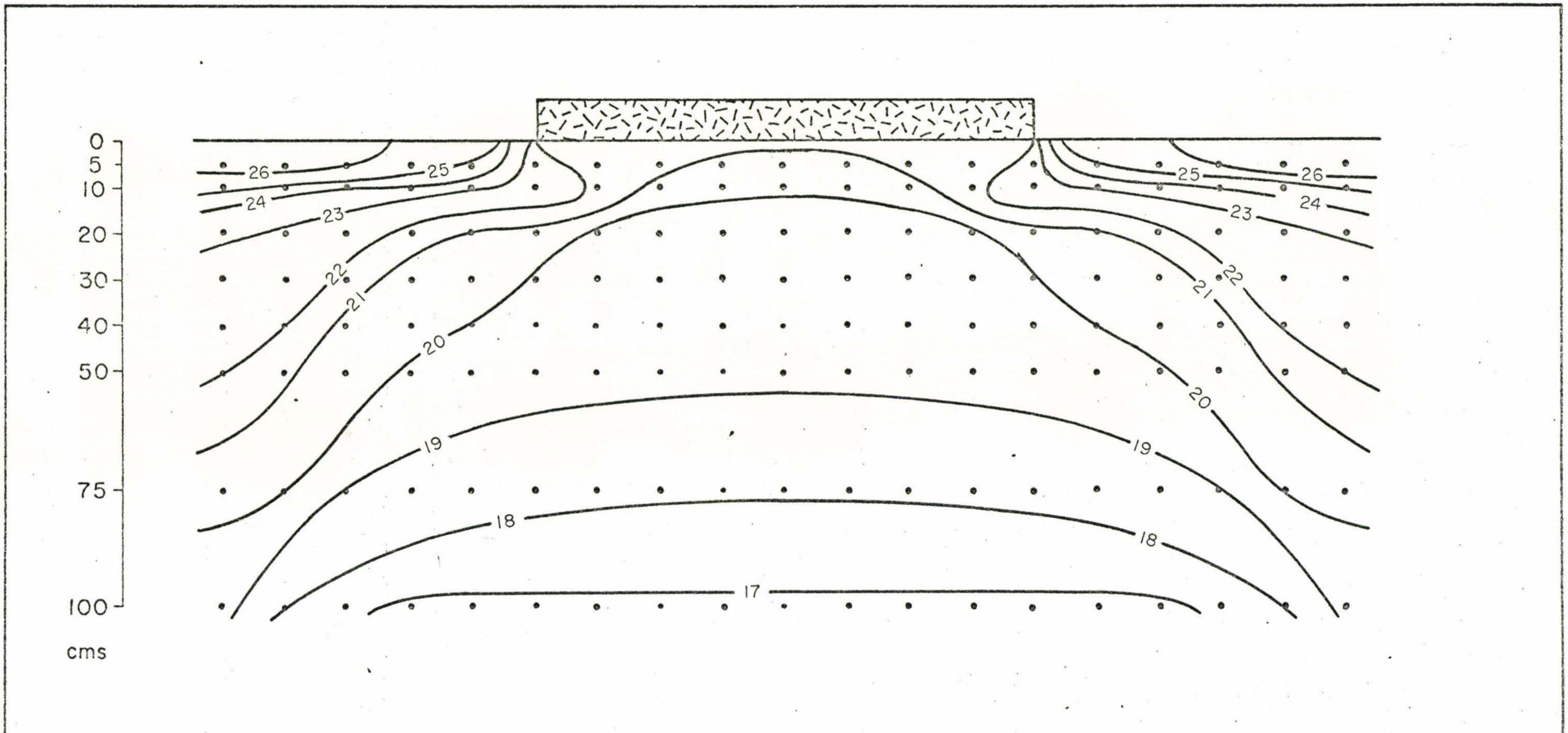
MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH JUNE, 1968



Horizontal scale: 1:24

Figure 32

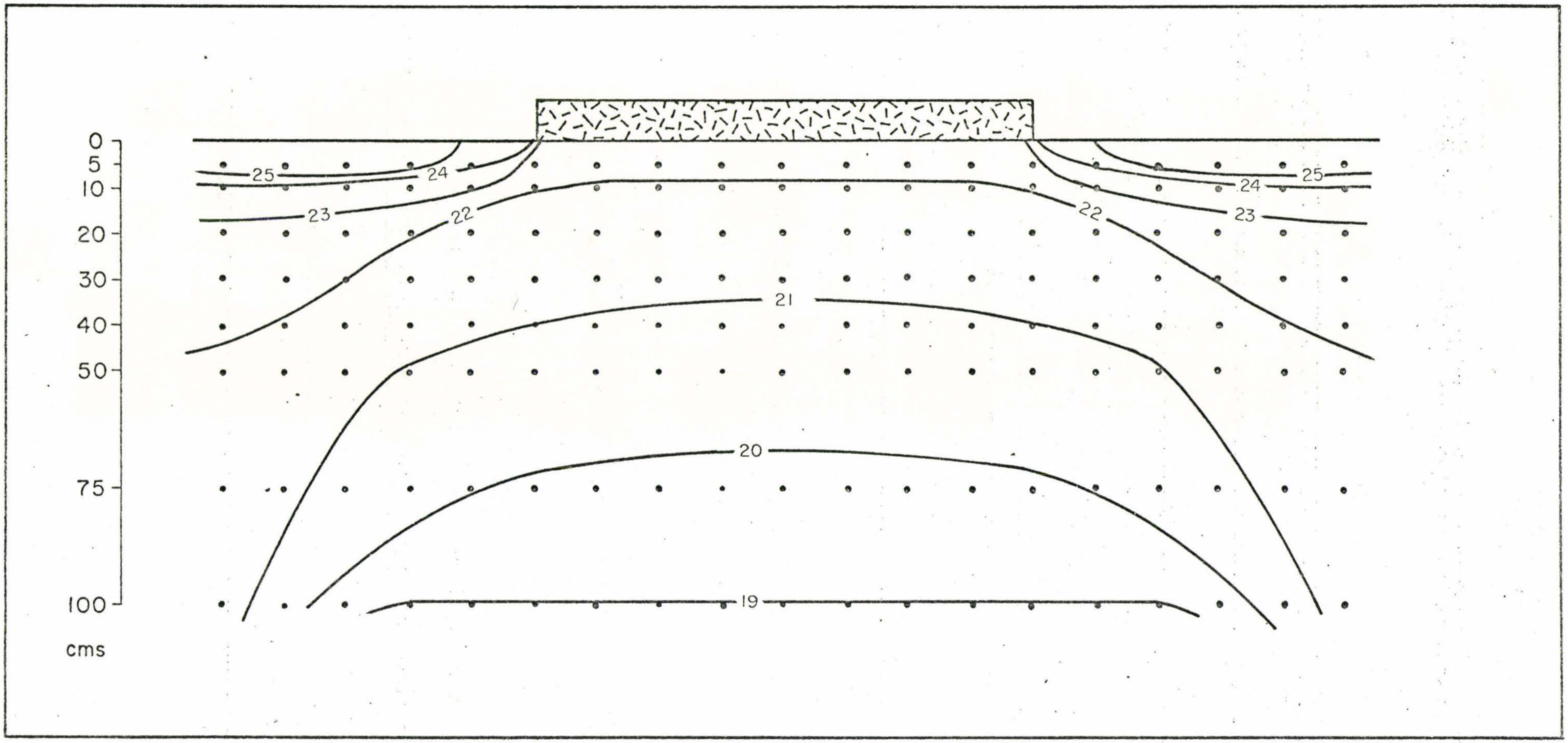
MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH JULY, 1968



Horizontal scale: 1:24

Figure 33

MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH AUGUST, 1968



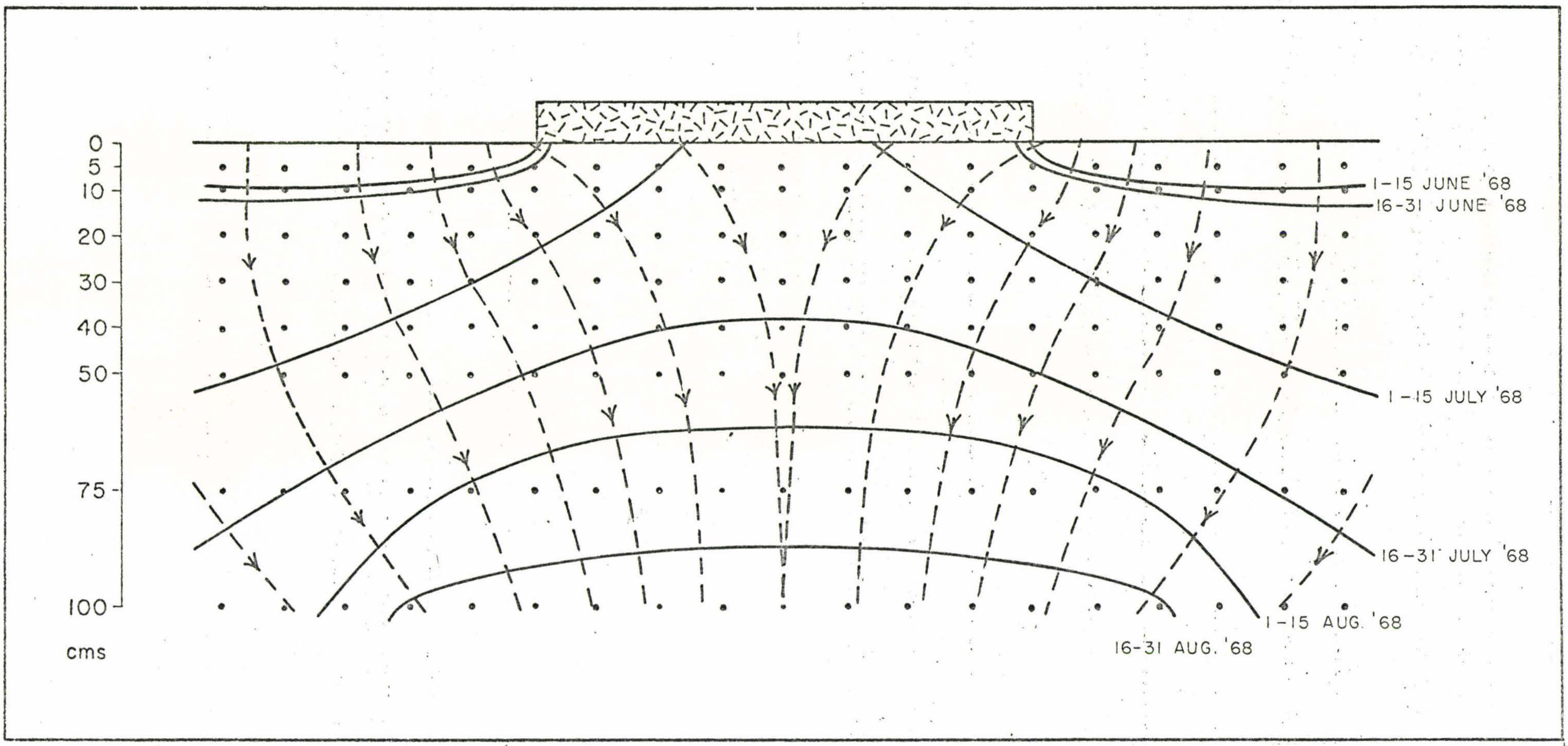
Horizontal scale: 1:24

the warming of the soil beneath it, and the inward flow of heat from the warmer surface layers which lay beyond the perimeter of the mulch is well demonstrated by the 22° geotherm in Figure 32.

At depths below about 20 cm., the sub-mulch zone of cooler soil extended laterally to points lying more than 150 cm. beyond the mulch perimeter. Moreover, below about 20 cm. the areal extent of the cooled soil increased with depth. This is confirmed by a consideration of the downward progression of the 20°C geotherm through the soil during these three summer months. Mean values of the temperatures read daily at 1400 hours during the first and last halves of each of these months were calculated, and successive positions of the 20°C geotherm are shown in Figure 34. The distance between successive lines on this Figure represents the net downward movement of the 20° geotherm between one 15-day period and the next. Thus, when one such line lay close to its predecessor or successor, the rate of heat-flow was minimal, whereas a wider separation was indicative of a more rapid flow. Thus, the soil lying at a depth of 10 cm. beyond the perimeter of the mulch warmed extremely slowly during the latter half of June. On the other hand, the soil lying at depths of 10-50 cm. and 150 cm. beyond the mulch perimeter warmed very rapidly during the first half of July. It was not until the latter

Figure 34

THE POSITIONS OF THE 20°C GEOTHERM, JUNE TO AUGUST 1968



Horizontal scale: 1:24

half of that month that the topmost 40 cm. of soil beneath the mulch centre experienced a rapid influx of heat.

An indication of the direction of heat-flow is given by broken lines drawn perpendicular to the geotherms in Figure 34.[1] These show that in the near-surface layers of soil which lay outside the mulched area, the downward heat flow was nearly vertical. However, with increasing depth and increasing proximity to the mulch-covered zone, the direction of heat flow acquired an increasing horizontal component. At depths in excess of 50 cm. beneath the centre of the mulches surface, the flow of heat was almost vertical, but at these greater depths its horizontal component increased with distance from the mulch.

The temperature changes from one month to the next which occurred beneath the centre of the mulch and at a point lying 150 cm. outside its perimeter are presented in Table 12.

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1. It was hoped that the directions of heat-flow could have been more precisely determined by the use of heat-flow discs, but a sufficient number of these could not be made available.

TABLE 12

MONTHLY CHANGES OF TEMPERATURE (°C) MAY-AUGUST, 1968

Depth	May-June		June-July		July-August	
(cm.)	Centre	150 cm.Out	Centre	150 cm.Out	Centre	150 cm.Out
5	6.0	4.4	4.0	4.2	1.3	0.8
10	5.8	4.5	3.6	4.4	1.8	-1.2
20	5.8	4.3	3.4	4.0	1.6	-0.8
30	5.6	4.4	3.6	4.0	2.0	-0.8
40	6.1	4.0	3.6	4.1	1.9	-0.5
50	5.9	3.9	4.0	4.4	1.5	-0.2
75	6.1	3.4	3.9	4.6	1.5	-1.0
100	5.5	4.1	3.2	4.2	2.3	-2.0

During the period May-June, the soil at each of the eight depths beneath the centre of the mulch experienced a rise in temperature which exceeded that at each of the corresponding depths in the profile located 150 cm. beyond the mulch's perimeter, notwithstanding the fact that June temperatures in the latter profile exceeded those in the former.[1]

1. See Figure 32 on p.125.

The greater rises in temperature beneath the centre of the mulch must have resulted from a considerable inward flux of heat by day, the loss of which was impeded by the mulch during the succeeding night.

However, during the period June-July the soil at each depth in the uncovered profile was warmed more than that at the corresponding depth beneath the centre of the mulch. The differences were not great, but they resulted in a slight increase in the magnitude of the temperature differences as between the mulched and unmulched areas.[1] July was a particularly dry and sunny month, and this fact also increased these temperature differences.

During the period July-August, the temperatures increased at all depths beneath the mulch centre. However, apart from a slight increase in temperature at a depth of 5 cm. all other levels in the profile which lay 150 cm. outside the perimeter of the mulch experienced a drop in temperature because the radiation balance was now negative. This situation resulted from the same set of processes as has already been reported for the period May-June. The direction of the heat flux into the sub-mulch area brought in

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1. Compare Figures 31 and 32 on pages 124 and 125 respectively.

heat by day, the loss of which, by night, was impeded by the mulch. Thus, although the sub-mulch temperatures in August (Figure 33, p.126) were the highest recorded throughout the year, the differences between these and the corresponding values in the profile which lay 150 cm. beyond the perimeter of the mulch were not as great as they had been during July.[1]

(b) September and October, 1968.

The monthly mean temperatures recorded at 1400 hours daily during September and October 1968 are presented in Figures 35 and 37 respectively. Figure 35 shows that a zone of cooler soil was still present beneath the mulch in September, but at all depths this was now a much weaker feature than had been the case during the preceeding months. The maximum difference between the temperatures at corresponding depths beneath the centre of the mulch and the profile lying 150 cm. outside its perimeter was recorded at a depth of 5 cm. and this was only 1.1°C.

Mean values of the temperatures read daily at 1400 hours during the last half of August and the first and last halves of September were calculated, and successive positions

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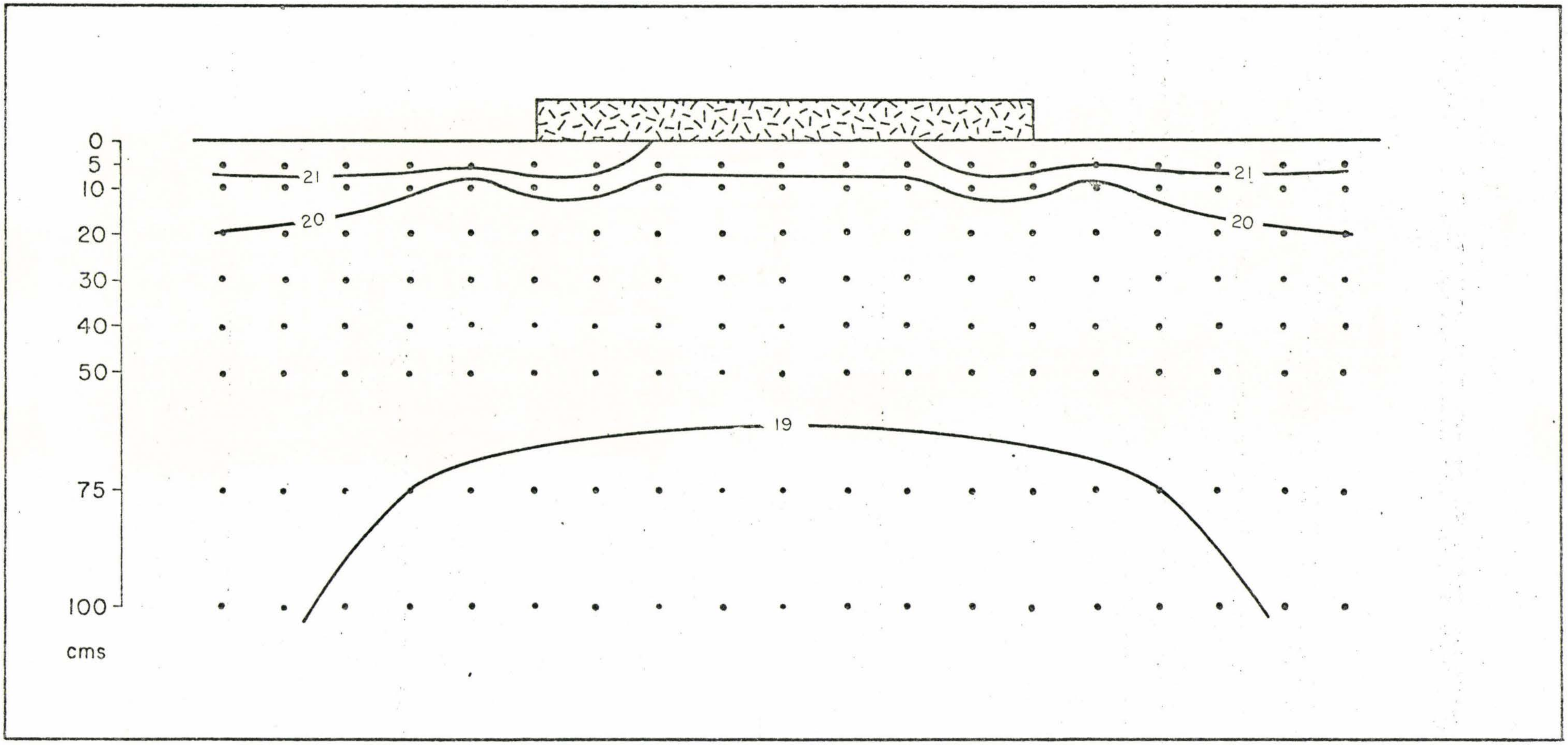
1. See Figure 33, p.126.

Figure 35

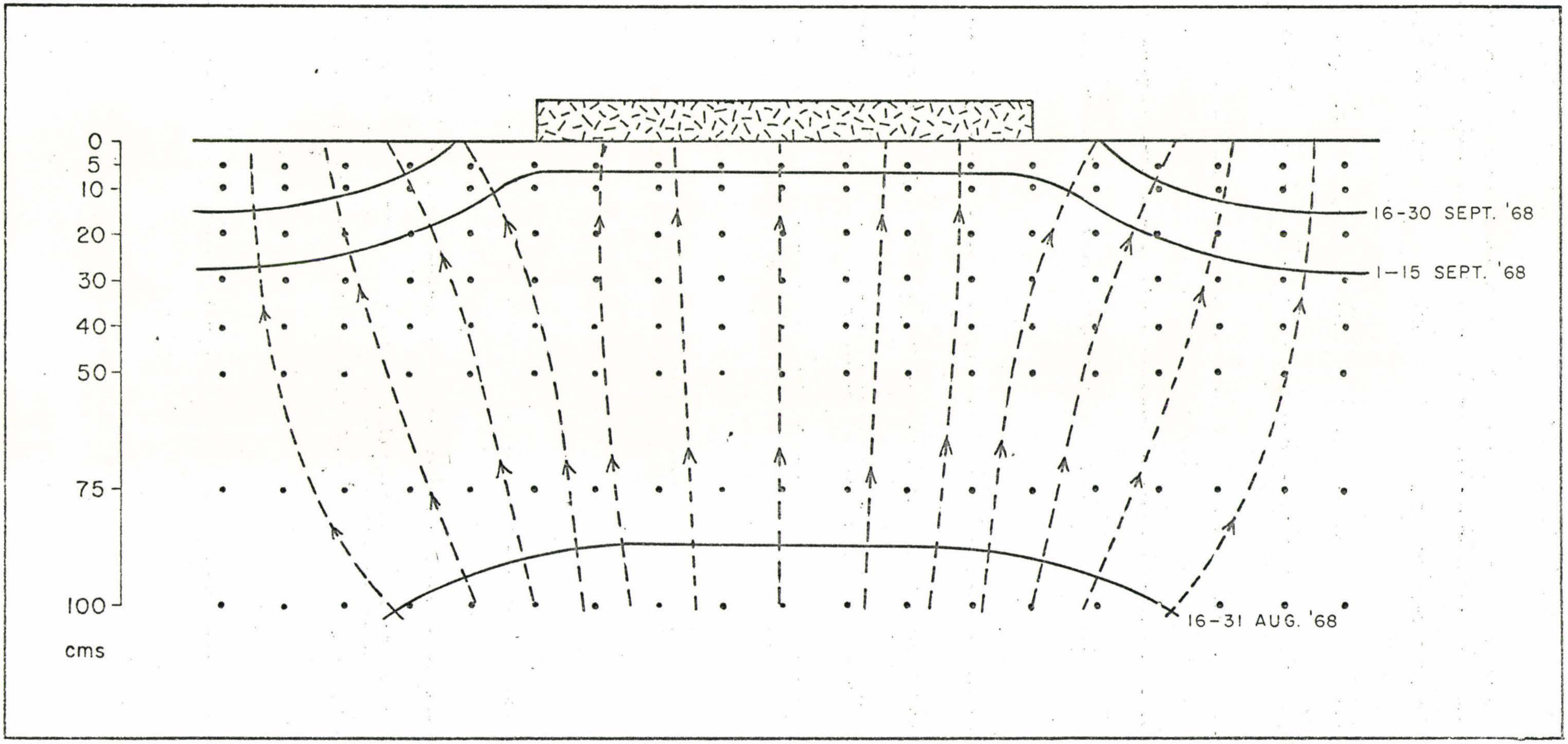
MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH SEPTEMBER, 1968



Horizontal scale: 1:24

Figure 36

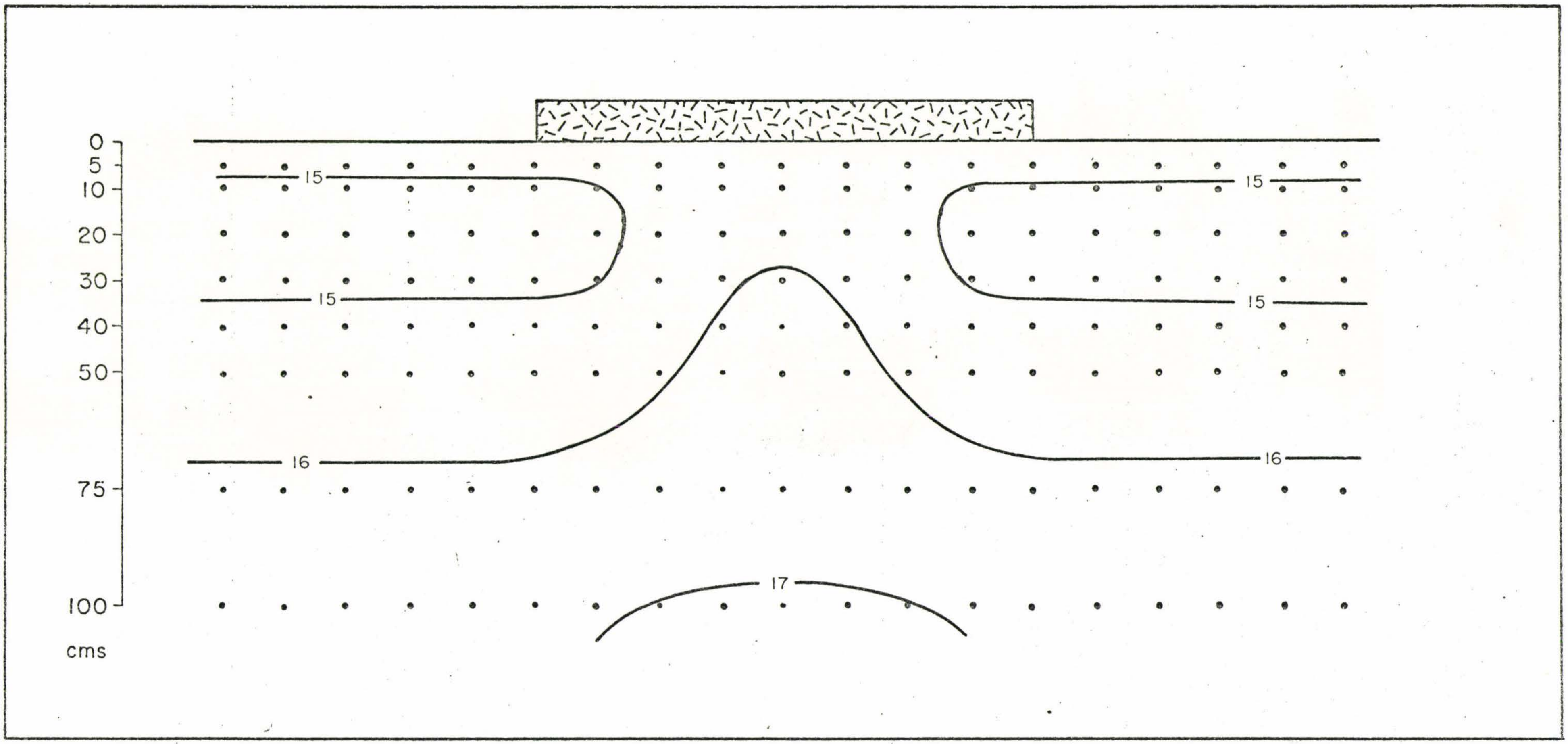
THE POSITIONS OF THE 20°C GEOTHERM IN AUGUST AND SEPTEMBER, 1968



Horizontal scale: 1:24

Figure 37

MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH OCTOBER, 1968



Horizontal scale: 1:24

of the 20°C geotherm are shown in Figure 36. The distance between successive lines on this Figure represents the net upward movement of the 20°C geotherm between one 15-day period and the next. Thus the rate of cooling between 16-31 August and the first half of September was much greater than that between the first and last halves of the latter month. As approximate indicators of the direction of heat flow, broken lines were drawn at right angles to the 20°C geotherms in Figure 36. These show that throughout the six-week period from mid-August to the end of September, most of the heat lost from beneath the mulch moved vertically upwards towards the surface. However, beyond the perimeter of the mulch the direction of heat-flow acquired, in addition, a horizontal component directed outwards.

In Figure 34 it was shown that throughout the months of June, July and August, the vertical and horizontal components of heat-flow through the soil were directed inwards towards the sub-mulch zone. It is therefore clear that the end of August marked the change-over from inward to outward fluxes of heat within the sub-mulch zone and its surroundings, in both the vertical and horizontal directions.

The changes in mean temperature from one month to the next which occurred beneath the centre of the mulch and at a point lying 150 cm. outside its perimeter are presented in Table 13. During the period August-September, heat losses from each depth in the profile lying 150 cm. beyond the mulch perimeter exceeded those from the corresponding depths beneath the centre of the mulch. The same applied to the period September-October, but the heat losses from each depth in both profiles were now greater than they had been during the preceeding period.

TABLE 13

MONTHLY CHANGES OF TEMPERATURE (°C)

AUGUST-OCTOBER, 1968

Depth	August-September		September-October	
(cm.)	Centre	150 cm.Out	Centre	150 cm.Out
5	-2.2	-4.2	-4.7	-5.9
10	-2.2	-3.6	-4.2	-5.3
20	-1.8	-2.5	-3.5	-5.2
30	-1.7	-2.2	-3.7	-4.8
40	-1.4	-1.9	-3.0	-4.8
50	-1.1	-1.7	-2.9	-4.5
75	-0.6	-1.6	-2.3	-3.4
100	-0.1	-1.5	-1.9	-2.9

The more rapid cooling at each depth in the profile which lay 150 cm. beyond the perimeter of the mulch now resulted in the development of a cone of somewhat warmer soil beneath the mulch, which is clearly indicated by the geotherms in Figure 37. This was the first appearance of this feature, which thus established the fact that October was the month during which the mulch began to exert its winter protective influence. The differences in temperature between corresponding depths in the two profiles during October increased from 0.1°C at 5 cm. to 1.2°C at 100 cm. The much smaller warming influence of the mulch near to the surface resulted from the fact that, beyond its perimeter, daytime heating of the soil was still recorded down to a depth of 10 cm., and this balanced the trapping of upward-flowing heat from the sub-mulch zone at night.

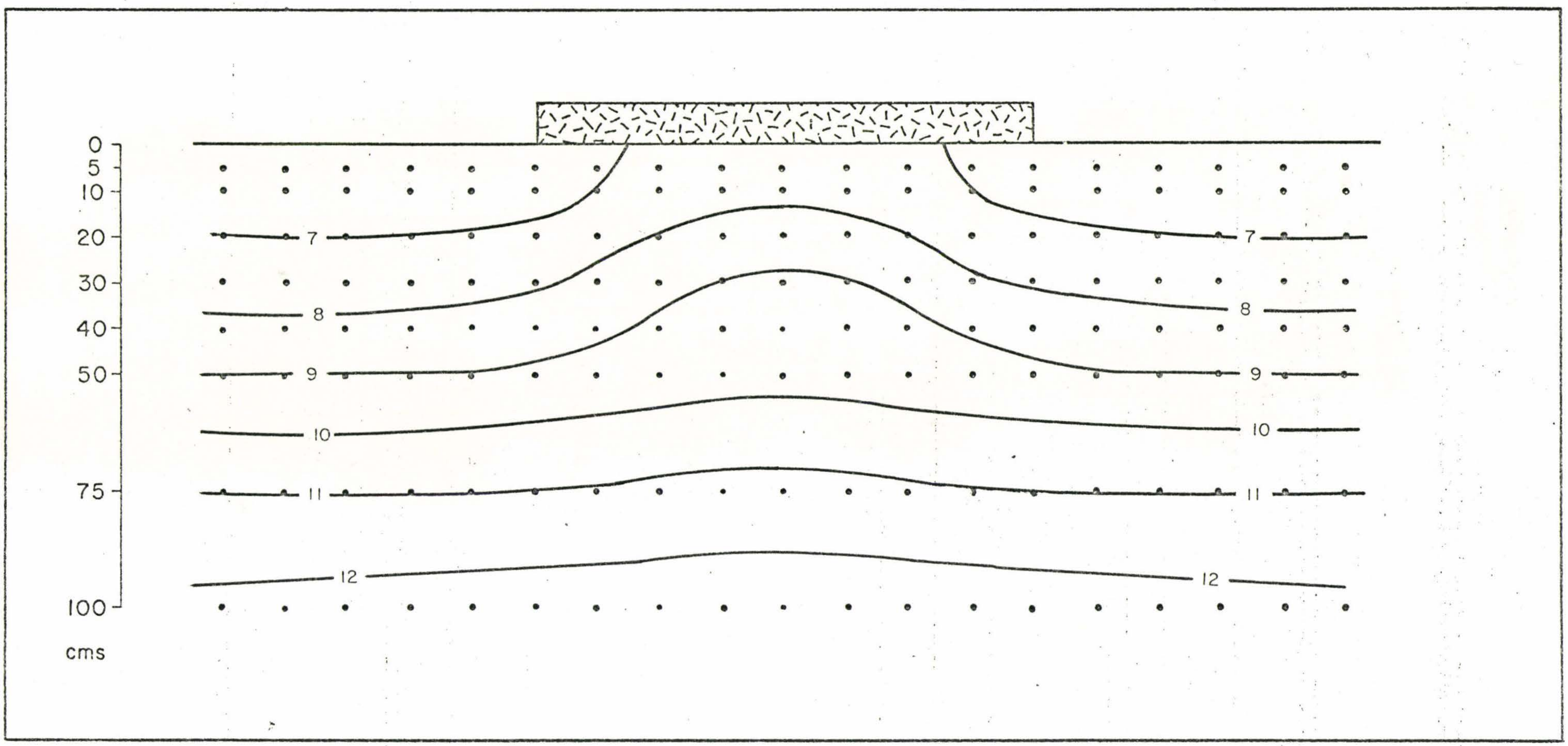
(c) November 1968 to February 1969.

The monthly mean temperatures recorded at 1400 hours daily in November and December 1968 and in January 1969 are shown in Figures 38, 39, 40 and 41 respectively.

The changes in mean temperature from one month to the next which occurred beneath the centre of the mulch and at a point lying 150 cm. outside its perimeter are presented in Table 14. The cooling which took place between

Figure 38

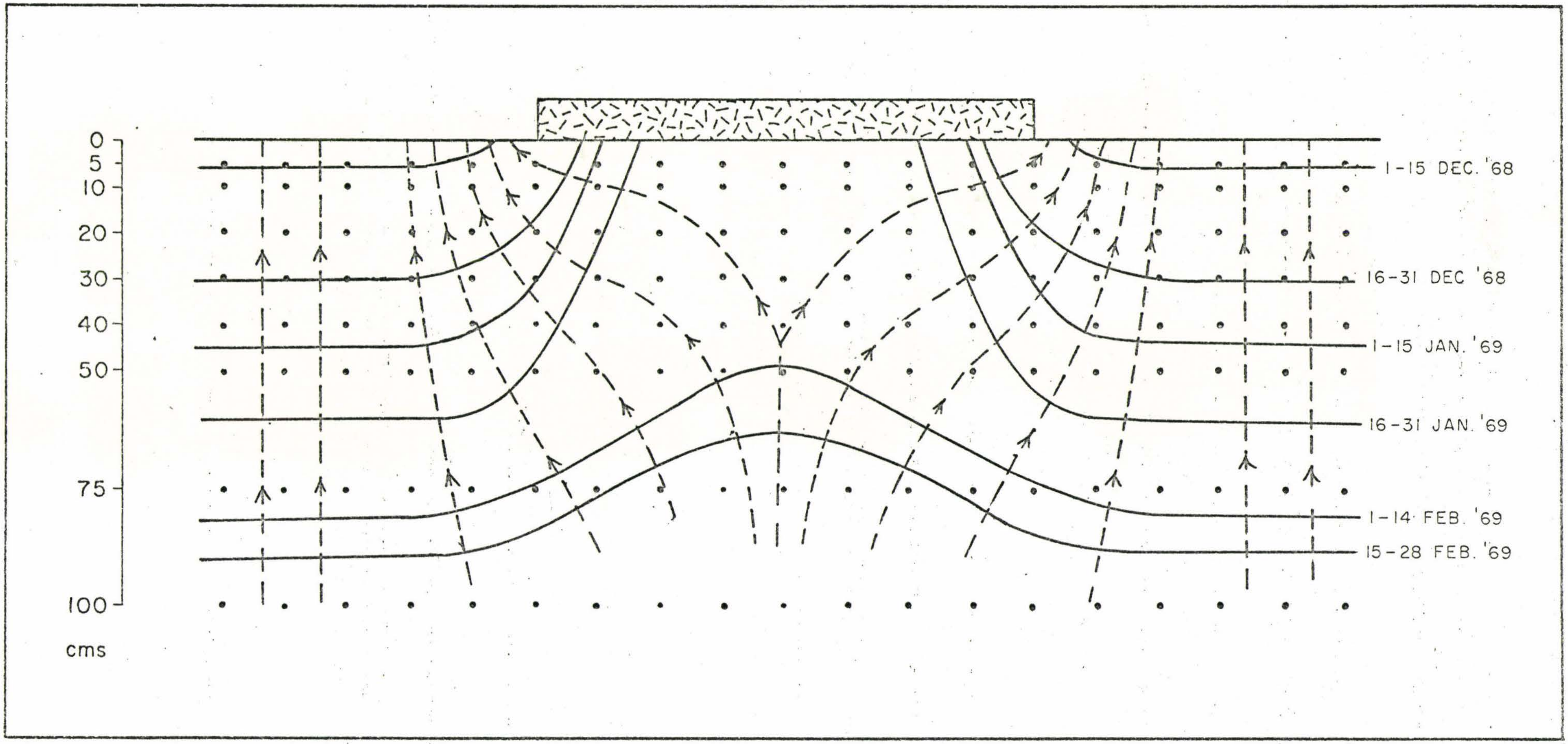
MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH NOVEMBER, 1968



Horizontal scale: 1:24

Figure 39

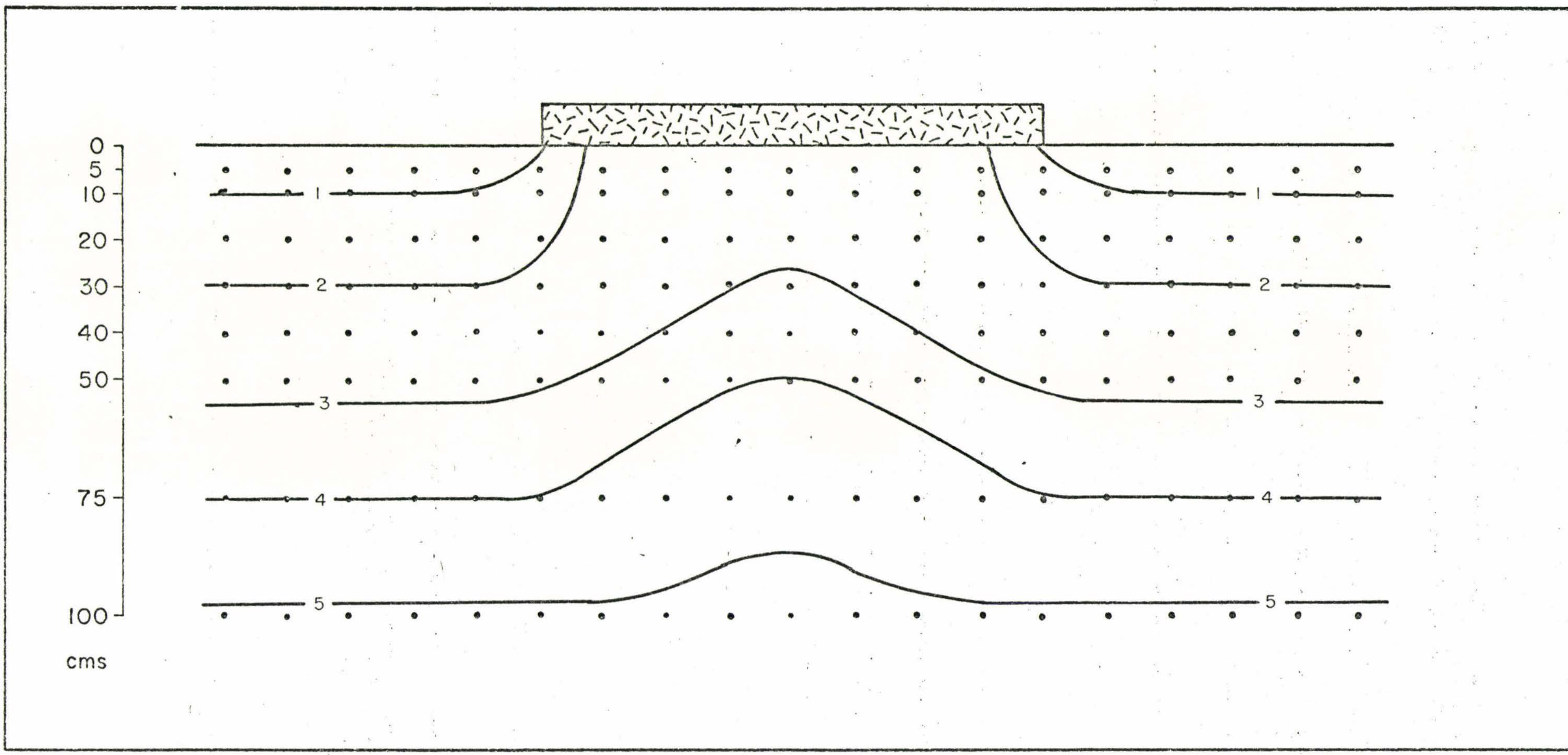
THE POSITIONS OF THE 1°C GEOTHERM IN DECEMBER 1968 AND JANUARY AND FEBRUARY 1969



Horizontal scale: 1:24 .

Figure 40

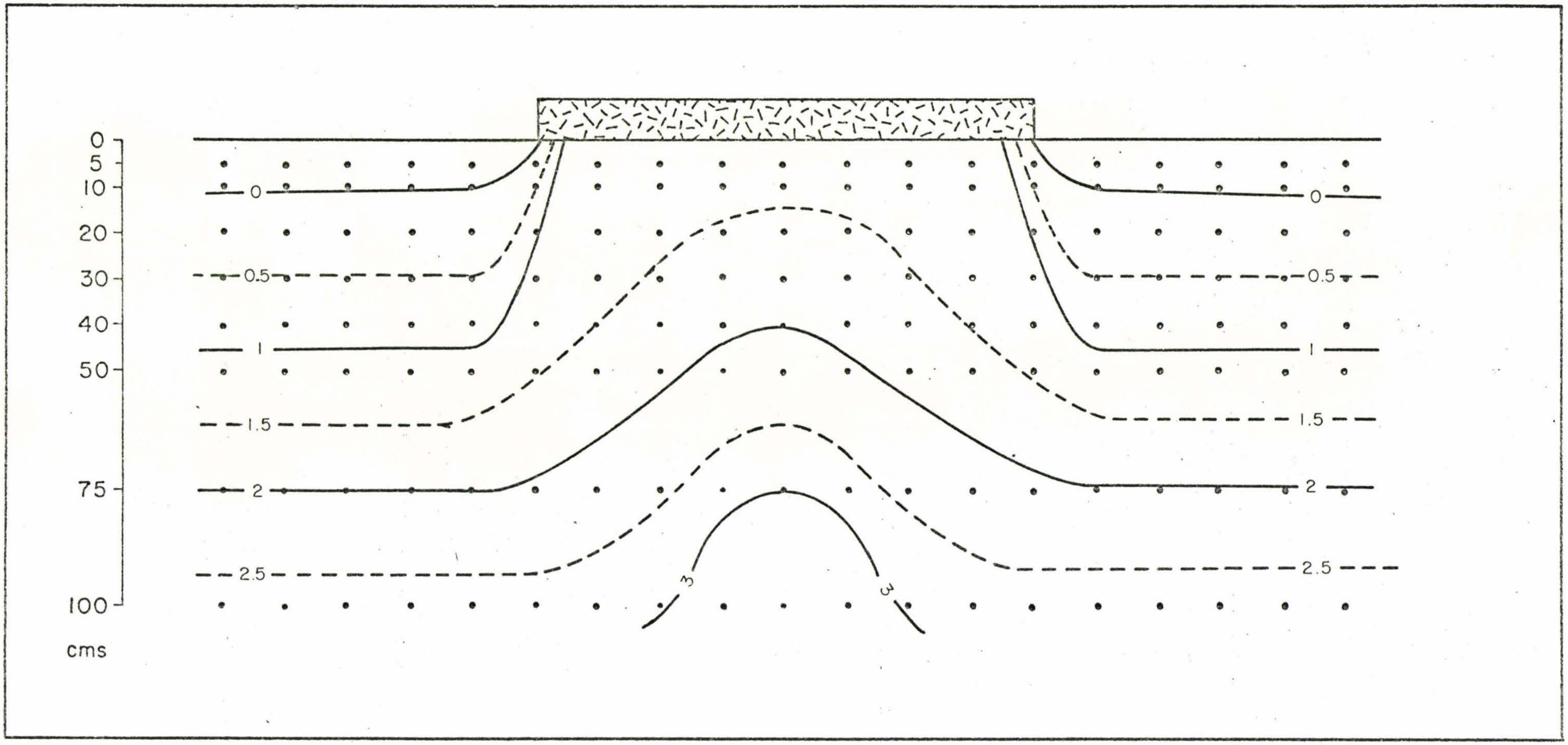
MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH DECEMBER, 1968



Horizontal scale: 1:24

Figure 41

MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH JANUARY, 1969



Horizontal scale: 1:24

TABLE 14

MONTHLY CHANGES OF TEMPERATURE (°C), OCTOBER 1968-

-FEBRUARY 1969.

Depth	October-November		November-December	
(cm.)	Centre	150 cm. Out	Centre	150 cm. Out
5	-8.1	-9.1	-5.2	-5.6
10	-7.8	-8.6	-5.3	-5.4
20	-7.6	-7.9	-5.4	-5.5
30	-7.0	-7.5	-6.1	-5.6
40	-6.9	-7.1	-6.0	-6.2
50	-6.9	-6.6	-5.7	-6.1
75	-4.9	-4.7	-7.1	-7.4
100	-4.3	-4.2	-7.4	-7.5

Depth	December-January		January-February	
(cm.)	Centre	150 cm. Out	Centre	150 cm. Out
5	-1.0	-0.8	-1.1	-0.1
10	-1.1	-0.9	-1.2	-0.1
20	-1.2	-1.2	-1.3	-0.2
30	-1.3	-1.4	-1.3	-0.2
40	-1.5	-1.4	-1.2	-0.6
50	-1.7	-1.4	-1.3	-0.6
75	-1.8	-2.0	-1.3	-0.5
100	-2.1	-2.4	-1.2	-0.6

October and November, 1968, both beneath the centre of the mulch and throughout the profile which lay 150 cm. outside its perimeter, was much greater at all depths than had been the case during the preceeding monthly interval.[1] In response to the negative radiation balance, cooling during the period October-November was most marked in the near-surface layers,[2] as a result of which the geotherms during November[3] were much closer together than had been the case during the preceeding month.[4]

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1. See the figures for September-October given in Table 13 on p.
2. See Table 14 on p.143
3. See Figure 38 on p.139
4. See Figure 37 on p.135

The figures for October-November, which are given in Table 14, show that the protective influence of the mulch was only 1.0°C at a depth of 5 cm., and it became insignificant at depths below 30 cm. Hence the warmer zone beneath the mulch only increased in intensity by very small amounts during the period October-November, 1968, and these increases were confined to the near-surface layers.[1]

Mean values of the temperature read daily at 1400 hours during the first and last halves of each of the months December 1968 - February 1969 inclusive were calculated, and successive positions of the 1°C geotherm are shown in Figure 39. As approximate indicators of the direction of heat-flow, broken lines were then drawn at right angles to these successive positions. The broken lines indicate that throughout the winter season there was an outward flow of heat from the sub-mulch zone, and the distances between successive positions of the 1°C geotherm indicate that the rate of heat loss from the topmost 50 cm. of soil in this zone was a maximum during the first half of February.

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1. Compare Figures 37 and 38. (pp. 135 and 139.).

The only near-surface layers of surrounding soil which benefitted from this outflow of heat from the sub-mulch zone were those which lay within 60 cm. of the mulch perimeter, and that figure was reduced to 30 cm. for soil lying at depths below 75 cm.[1] On the other hand, it has already been shown that at all depths below about 20 cm. the cooling influence of the mulch during the summer months extended laterally to points lying more than 150 cm. beyond its perimeter.[2]

The change in the position of the 1°C geotherm as between 1-15 December and 16-31 December, as shown in Figure 39, indicates that the topmost 30 cm. of soil lying beyond the perimeter of the mulch cooled rapidly during that month. However, this cooling was very largely confined to the first twenty-one days, for the 40.6 cm. of snow which fell between 22nd and 28th amounted to 72 percent above the normal monthly total. This overall snow-cover trapped much of the upflowing heat, for whilst the flow towards the surface from the greater depths continued, the losses from the near-surface layers were reduced. Thus, a comparison of monthly mean temperatures for November and December, as shown in Table 14,

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1. See Figure 46.

2. See Figure 35.

reveals that the greatest heat losses in this period occurred in the deepest parts of the profiles. As a result of this, the vertical temperature gradients in December (Fig. 40) were less steep than had been the case during the preceeding month (Figure 38). It is also seen from the November-December figures given in Table 14, that the overall snow-cover considerably reduced the protective influence of the mulch, and the rate of heat loss from the sub-mulch zone was now not significantly less than that from its surrounding soil.

Following the unusually heavy snowfall between 22nd and 28th December, 1968, a normal total of 33.8 cm. fell during the succeeding month. The persistence of a snow cover throughout January, 1969, caused the decline in monthly mean temperatures between December and January, both beneath the centre of the mulch and throughout the profile which lay 150 cm. outside its perimeter, to be much less than had been the case during the preceeding monthly interval.[1] The snow cover further weakened the protective influence of the mulch. Over the period December-January, the decline in monthly mean temperatures at each depth beneath the centre of the mulch was not significantly different

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1. See Table 13.

from the corresponding figure in the profile which lay 150 cm. outside the mulch perimeter. As had been the case during the preceeding monthly interval, the greatest heat losses during the period December-January were recorded in the the deepest parts of these two profiles. Consequently, the vertical temperature gradients in January, 1969 (Figure 41), were less steep than had been the case during the preceeding month.[1]

Measurements of electrical resistance made at a point lying 150 cm. outside the perimeter of the mulch and at a depth of 10 cm. clearly established that, in this soil, water turned into ice at a temperature of 0°C. This was the mean January temperature at a depth of 10 cm. for those four points of measurement which lay more than 30 cm. outside the mulch perimeter, and it can therefore be reasonably concluded that the soil at lesser depths was frozen.[3] This frozen layer of soil increased in thickness very slowly, for it is seen from Figure 42 that the depth of the 0° geotherm in February was no greater than 20 cm. Its slow downward

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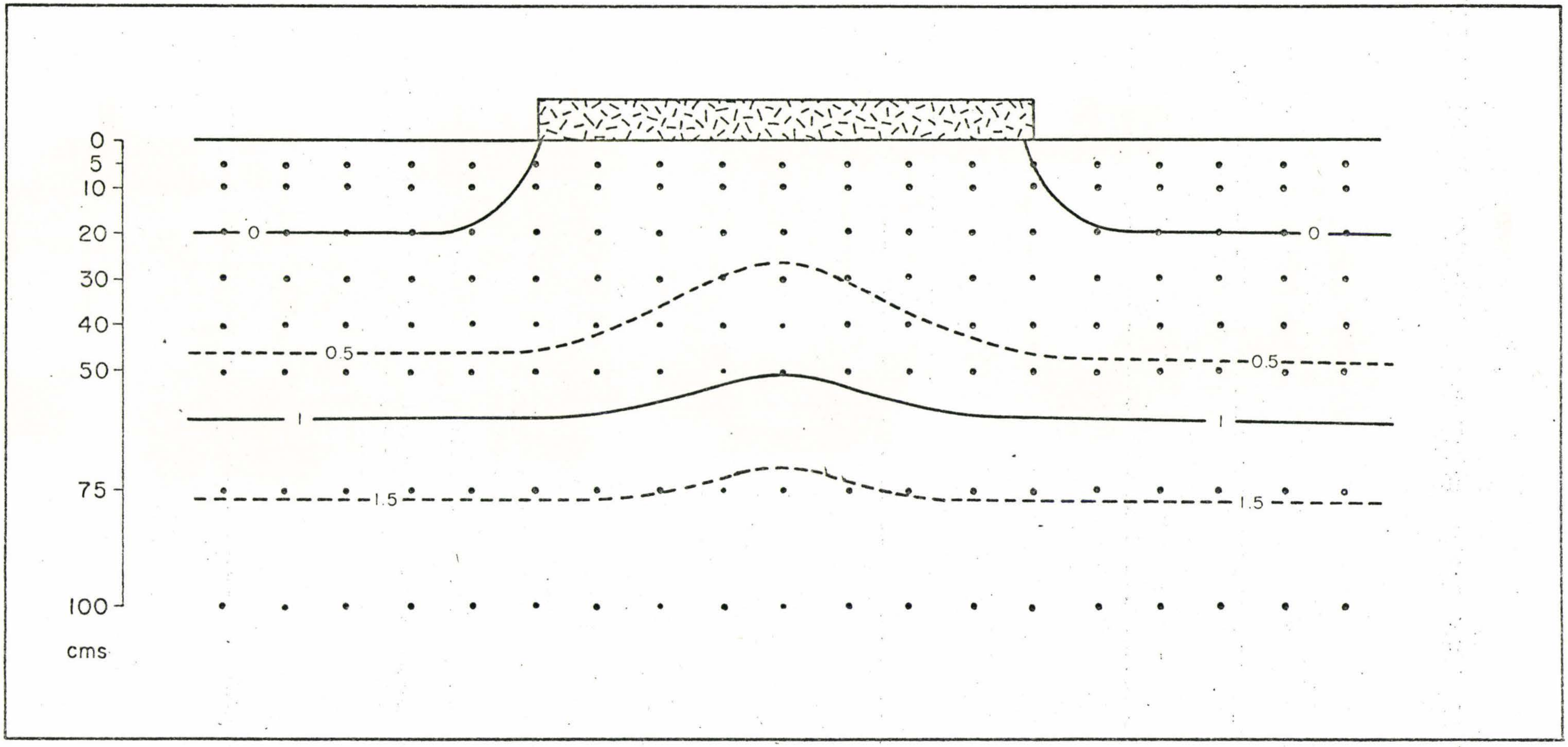
1. Figure 40.

2. See Figure 41.

3. To avoid any disturbance of the snow-cover, the frozen state of the near-surface layers of soil was confirmed by daily probing with a metal rod of small diameter.

Figure 42

MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH FEBRUARY, 1969



Horizontal scale: 1:24

movement was due to the fact that the freezing of soil water was accompanied by the release of latent heat of fusion. Notwithstanding, the fact that the thermal diffusivity of the overlying soil was high due to its frozen state,[1] the greater facility with which this released heat might have escaped upward was countered by the overlying snow-cover. Consequently, much of the latent heat of fusion served to retard the rate of cooling in the unmulched soil.This accounts for the fact that the changes in monthly mean temperatures from January to February within the frozen near-surface layers of the profile located 150 cm. beyond the mulch perimeter were insignificant, and they were not more than 0.6°C at greater depths.[2] No temperature as low as 0°C was, at any time, recorded anywhere beneath the mulch, and hence no latent heat of fusion was released to retard the cooling process. Consequently, it is seen from Table 13 that at depths of 5 and 10 cm. beneath the centre of the mulch, the decline in monthly mean temperatures between January and February was ten times greater than at the corresponding depths in the outermost profile. At depths of 20 and 30 cm. the decline beneath the

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1. The thermal diffusivity of ice is 0.011-0.015 $cm.^2$ sec^{-1}, whereas the value for still water is only 0.0013-0.0015. (Geiger, R., 1965).

2. See Table 13.

mulch centre was six times greater, and it was twice as much at the four depths between 40 and 100 cm. inclusive. As a result of this greater loss of heat, the intensity of the warmer zone beneath the mulch declined sharply, and in February [1] it was a much less prominent feature than had been the case during the preceeding month.[2] In fact, the temperature differences between the central and outermost profiles were now no greater than 0.3°C at any depth. Nevertheless, the temperature of the soil beneath the mulch never fell to the freezing point, and this fact would be one of great significance in the protection of the upper root-systems of many fruit trees.

(d) March, 1969.

The distribution of monthly mean temperatures in March is shown in Figure 43, and a comparison of this with Figure 42 indicates that no significant changes took place during the February-March interval. This is also evidenced by the very small changes in the monthly mean temperatures for these two months as shown in Table 15. It was with no surprise that such small changes were recorded, for the first phase of the investigation had clearly established that March

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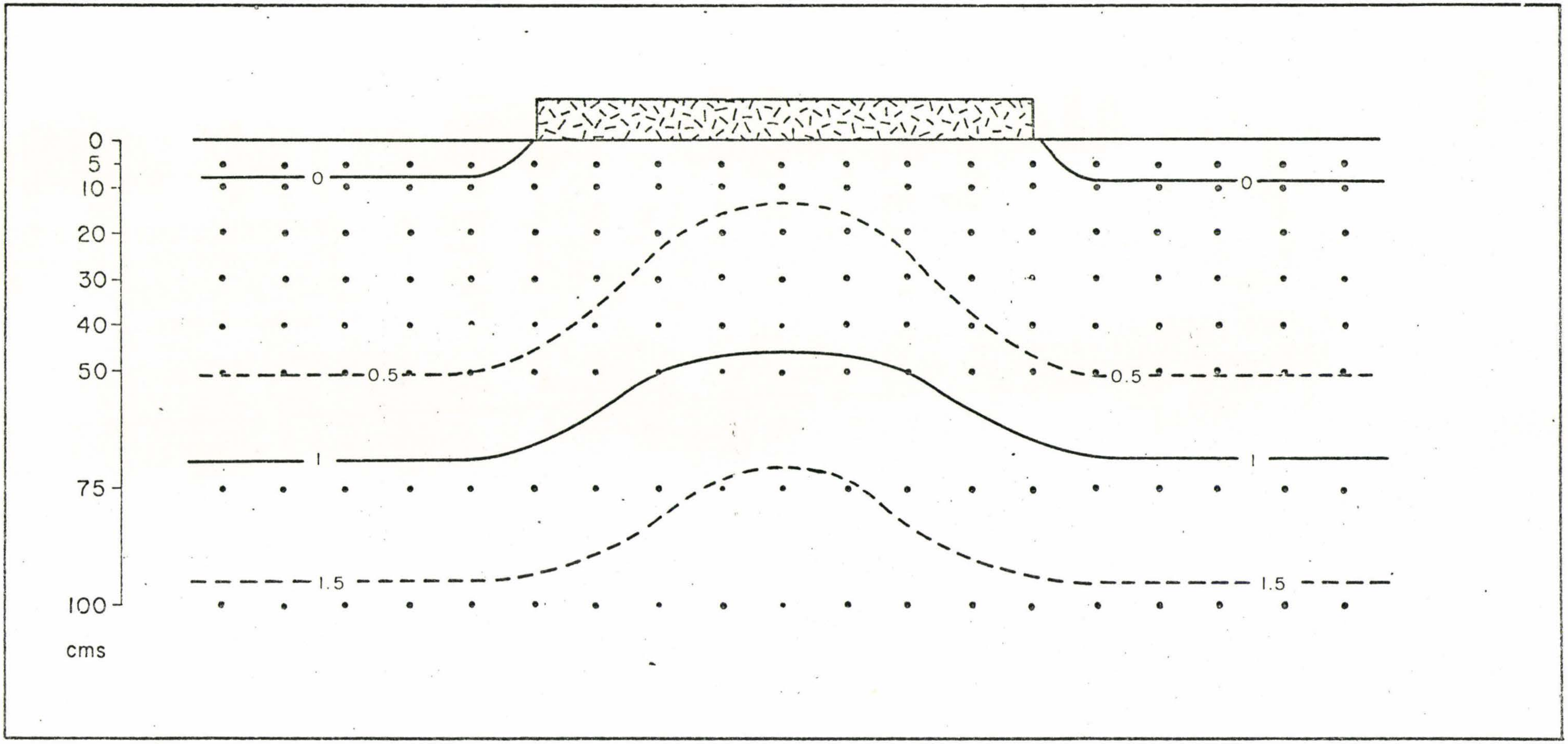
1. See Figure 42.

2. See Figure 43.

Figure 43

MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH MARCH, 1969



Horizontal scale: 1:24

was the "change-over" month, in which the warming influence of the mulch in winter gradually gave way to its cooling influence in summer.

The frozen layer of soil lying outside the perimeter of the mulch decreased in thickness during March, and resistance measurements showed the 150 cm. outside the perimeter of the mulch the soil at a depth of 10 cm. thawed between 18th and 21st.

TABLE 15

MONTHLY CHANGES OF TEMPERATURE(°C) FEBRUARY - APRIL 1969.

Depth (cm.)	February-March		March-April		April-May	
	Centre	150 cm. Out	Centre	150 cm. Out	Centre	150 cm.Ou
5	0.1	0.4	3.4	8.1	7.2	9.4
10	0.2	0.2	3.3	7.6	7.1	8.5
20	0.2	0.4	3.1	6.7	6.7	8.0
30	0.1	0.1	2.9	6.2	6.6	7.8
40	0.1	0.0	2.4	5.7	6.2	8.0
50	0.1	-0.1	2.3	4.8	5.8	8.1
75	0.1	-0.2	1.6	3.3	4.9	7.8
100	0.2	-0.2	1.2	2.3	3.6	6.6

This was mainly in response to a succession of days during which a total of 1.22 cm. of rain fell, removing all traces of snow from the surface and supplying the necessary latent heat of fusion to enable the soil to thaw more rapidly than would otherwise have been the case.

(e) April and May, 1969.

In April the net radiation balance became positive, and two effects of this change were quickly established:

(i) Beyond the perimeter of the mulch the near-surface layers of soil became the warmest,[1] whereas in the preceeding month they had been the coldest.[2]

(ii) The mulch impeded the entry of much of the incoming radiation into the underlying soil. It is seen from Table 15 that beneath the centre of the mulch the increase in the monthly mean temperature between March and April was, at each depth, less than a half of the corresponding figure in the profile which lay 150 cm. outside the mulch perimeter. Thus Figure 44 shows that the cone of cooler soil, which was to remain a characteristic feature of the sub-mulch zone throughout the succeeding summer months, began to develop in April.

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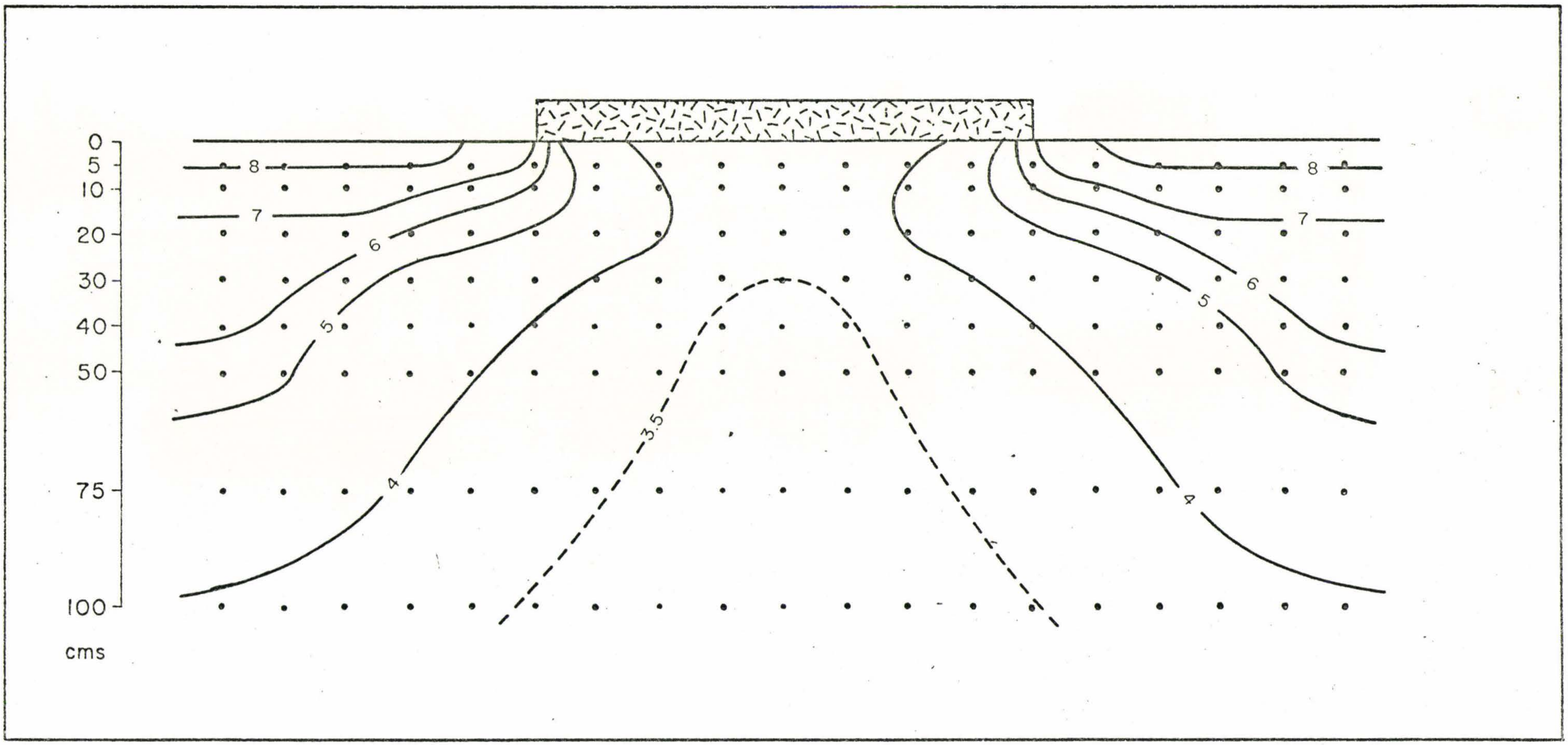
1. See Figure 46.

2. See Figure 43.

Figure 44

MONTHLY MEAN VALUES OF TEMPERATURES RECORDED DAILY AT 1400 HOURS THROUGH APRIL, 1969



Horizontal scale: 1:24

During the interval between April and May, the increases in the monthly mean soil temperatures beneath the centre of the mulch were again significantly less than those at corresponding depths in the profile which lay 150 cm. outside the mulch perimeter.[1] It is thus seen from Figure 45 that, in May, the cone of cooler soil beneath the mulch became a much more prominent feature.

In Figures 44 and 45, the configuration of the geotherms clearly indicates that heat was flowing from the warmer soils surrounding the mulch into the cooler zone beneath it. During April [2], this inward flow was mainly confined to the topmost 20 cm. of soil, for the temperature gradients at greater depths were weak. However, in May[3], the inward flow of heat affected the soil at all depths, as is evidenced by the much closer spacing of the geotherms around the cone of cooler soil at depths below 40 cm. Thus the mulch now exerted a cooling influence on all the soils which lay beyond its perimeter, through distances which increased from about 90 cm. in the upper 20 cm. to more than 150 cm. at greater depths.

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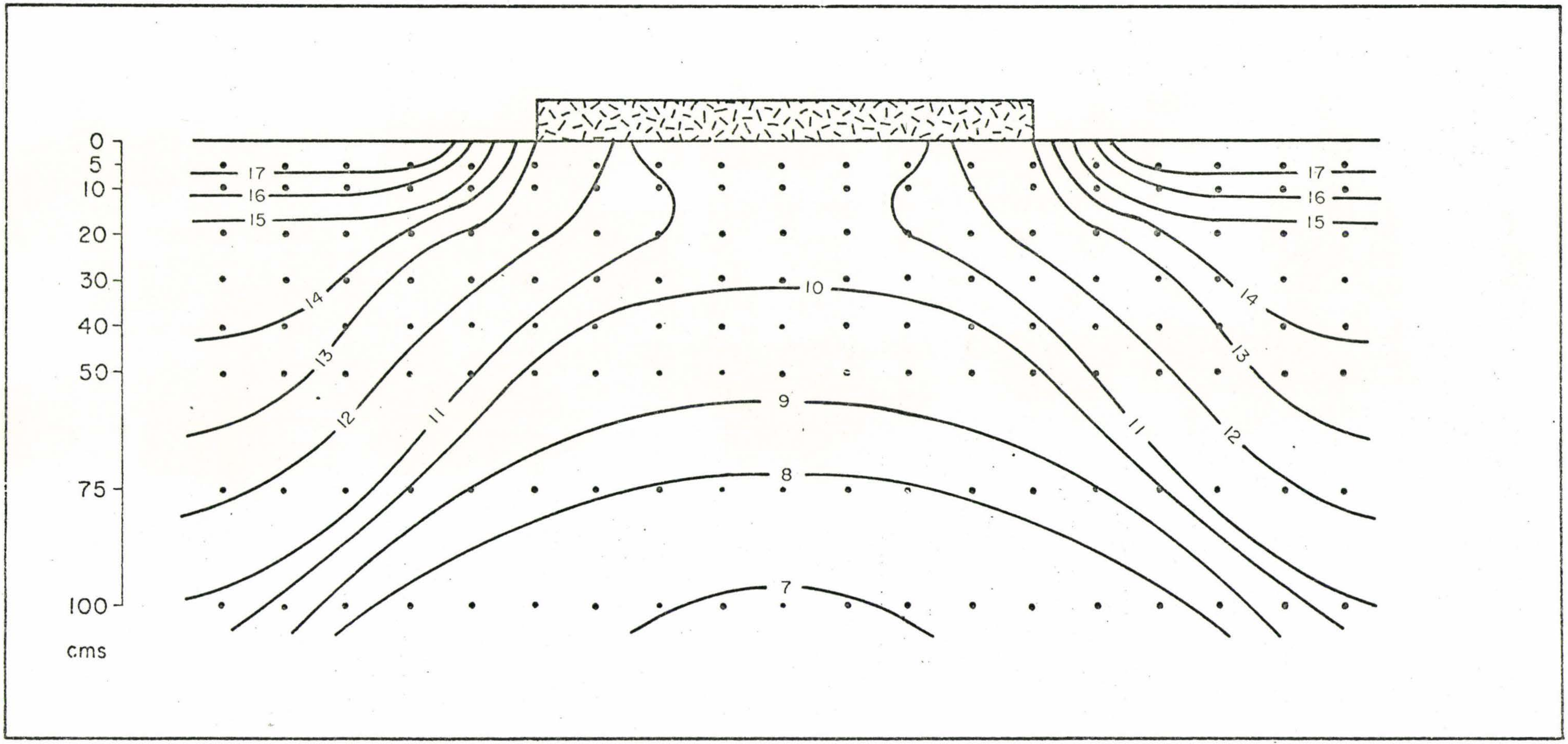
1. See Table 15.
2. Figure 44.
3. Figure 45.

Figure 45

MONTHLY MEAN VALUES OF TEMPERATURES (°C) RECORDED DAILY AT 1400 HOURS THROUGH MAY, 1969



Horizontal scale: 1:24

4. <u>Comments on the effectiveness of electrical resistance measurements as indicators of soil freezing and thawing.</u>

It cannot be assumed that soil at some particular depth will freeze when its temperature falls to 0°C. On many occasions freezing will not take place until the temperature has fallen to some lower value, which seems to depend upon the amount of water in the soil and certainly upon the concentration of dissolved minerals within it.

The technique which was devised for determining whether or not the soil was frozen [1] proved to be very successful. Six pairs of electrodes were used, and these were placed at depths of 10 and 20 cm. in three locations; beneath the centre of the mulch, beneath its perimeter and beneath a point lying 150 cm. outside its perimeter.

Notwithstanding the fact that temperatures beneath the mulch in winter were only 1.5 - 2.0°C higher than those of the surrounding soils, the measurements of electrical resistance clearly established that the soil beneath the mulch centre and that beneath its perimeter did not freeze at any time. This represents a benefit conferred by a mulch in winter which may be of considerable significance to the root

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1. pp. 51, 52.

systems of many fruit trees.

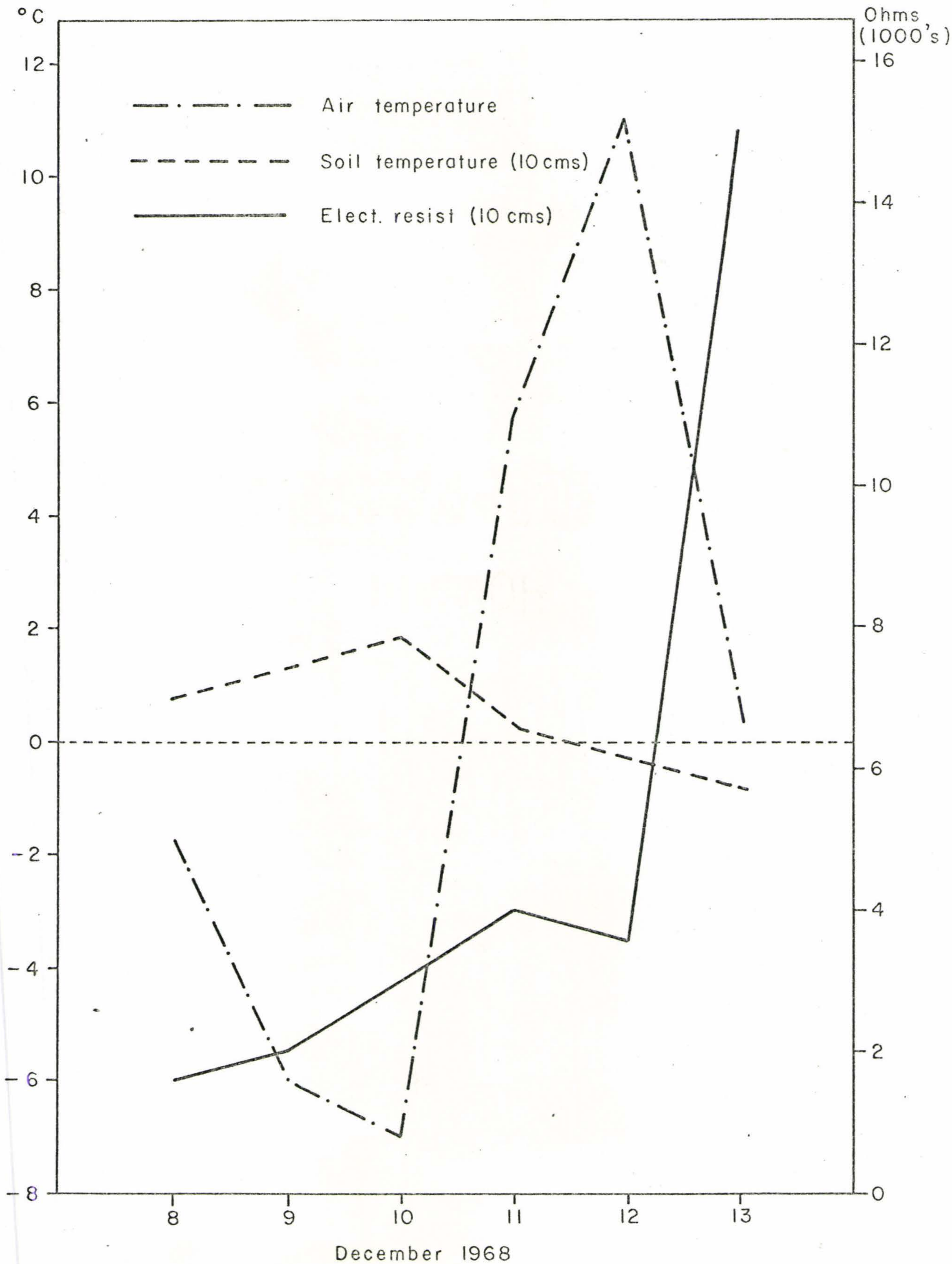
One and one half meters outside the perimeter of the mulch the soil at a depth of 10 cm. froze between December 12 and 13, and the changes in temperature and electrical resistance which preceeded and accompanied this event are represented in Figure 46. The air temperature at 1400 hours, as measured by an Assmann psychrometer held at a height of 120 cm., fell from -1.8°C on December 8 to -6.0°C and -7.0° on the two succeeding days. By digging with a hand-trowel at several points lying 150 cm. outside the perimeter of the mulch, it was established that the surface layer of frozen soil increased in thickness from about 2 cm. on December 8 to 6 cm. on December 10. Some of the released latent heat of fusion must have passed downwards into the soil, thus causing a steady rise of temperature at the 10 cm. level. Here the electrical resistance of the soil also increased, probably due to drying consequent upon the upward migration of water in the form of vapour to the underside of the frozen surface.[1]

The air temperature at 1400 hours increased from -7.0°C on December 10 to 5.8°C and 11.0°C on December 11

1. The saturation vapour pressures over ice at 0°C and -1°C are only 6.1 mb and 5.6 mb respectively, whereas the values over water at 1°C and 2°C are 6.6 mb and 7.1 mb. (Smithsonian Meteorological Tables, 1949).

Figure 46

TEMPERATURES AND ELECTRICAL RESISTANCE
1400 HOURS DEC. 8-13, 1968



The air temperature at 1400 hours increased from -7.0°C on December 10 to 5.8°C and 11.0°C on December 11 and 12 respectively. This led to the thawing of the near-surface soil, and some of the latent heat of fusion involved in this process would seem to have been drawn from underlying layers. Thus the soil temperature at a depth of 10 cm. decreased from 1.8°C at 1400 hours on December 10 to 0.2°C and -0.3°C on December 11 and 12 respectively. Meanwhile, the electrical resistance at this same depth increased from 1400 ohms on December 11 to 3600 ohms on the following day, probably due to percolation of water from the thawing surface layer. This decrease, which was accompanied by a decline in soil temperature from 0.2°C to -0.3°C, clearly testified to the fact that the soil remained in an unfrozen state at the lower of these values.

The air temperature at 1400 hours declined from 11.0°C on December 12 to 0.3°C on the following day. Nevertheless, the thawing of the near-surface layers of soil continued, and it would seem that further supplies of energy in the form of latent heat were drawn from the underlying layers. Thus, the temperature at a depth of 10 cm. declined from -0.3°C at 1400 hours on December 12 to -0.8°C at the same time on the following day. This decline was accompanied by a very sharp increase in electrical resistance from 3600 ohms to 15,000 ohms. It is thus certain that the soil lying 150 cm. outside the perimeter of the mulch and at a depth of 10 cm. froze sometime between 1400 hours on December 12 and the same time on the succeeding day, and at a temperature which lay somewhere between -0.3°C and -0.8°C.

If this aspect of the study had been considered to be of greater importance, both the time and the temperature at which freezing occurred could have been much more precisely determined from hourly observations. However, all that was required to aid the attempts to account for certain short-period changes of soil temperature was indisputable evidence as to whether or not the soil at depths of 10 and 20 cm. had frozen or thawed since the previous day's observations. In this connection, the measurements of electrical resistance which were made in the period December 1968 through April 1969 proved to be invaluable.

Many other measurements of freezing point temperatures and the associated values of electrical resistance were made both in the laboratory and in the field, and these covered a wide range of soil types. It was found that when a soil freezes at a temperature lower than -0.5°C, the accompanying increase in electrical resistance is always very pronounced.[1] However, when freezing takes place at or only just below 0°C, the in-

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1. See Figure 47.

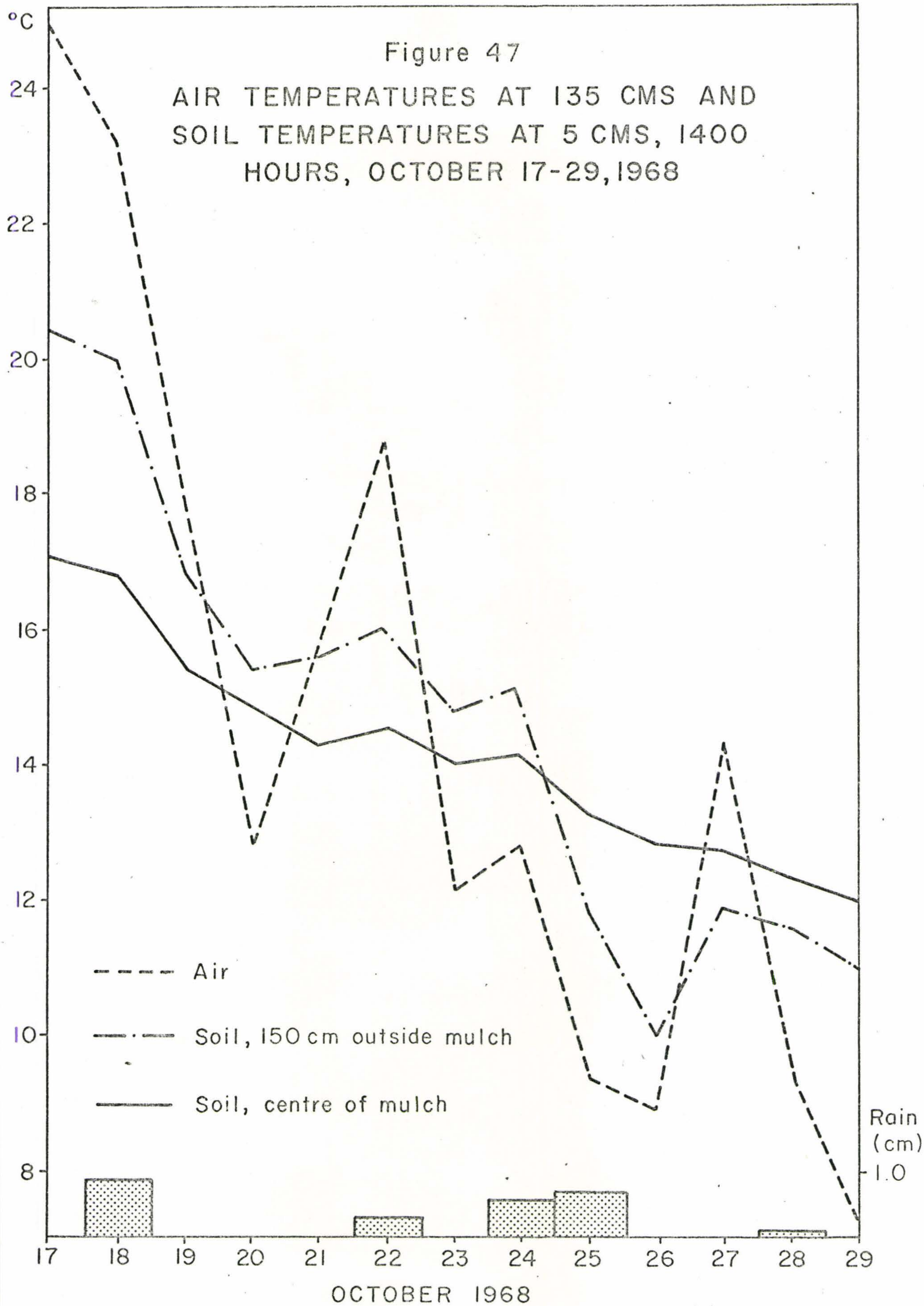
crease in electrical resistance is less sudden though still sufficiently pronounced to give a clear indication of the fact that freezing is in progress. In this case, the release of latent heat of fusion retards the freezing process and might even result in a freeze-thaw oscillation of short periodicity at the lower boundary of the slowly freezing layer. That the freezing process is relatively slow and possibly interrupted is clearly indicated by the lesser rate of increase in successive values of electrical resistance. On the other hand, when soil freezes at a temperature below -0.5°C, the process is a much more rapid one. The released latent heat of fusion introduces no significant retardation, nor is it sufficient to produce any freeze-thaw oscillation. Under these conditions, the very rapid increase in electrical resistance within the soil is such as to indicate with certainty that freezing has occurred.

All the measurements which were made clearly indicated that, irrespective of soil-type, depth, moisture content and the temperature at which freezing had occurred, thawing did not take place until the soil temperature reached 0°C. This was accompanied by a decline in electrical resistance at a rate somewhat less than that of the increase which was associated with freezing at temperatures very close to zero. It is well known that the thawing of the underside of a frozen layer of soil is a slow process, since this cannot take place until the requisite quantities of latent heat of fusion have been absorbed. Thus, although it was impossible to determine a precise time at which thawing occurred, it was easy to specify the times at which this process began and ended.

5. <u>Daily fluctuations of temperature in the topmost layers of a mulched soil during the fall.</u>

During the fall, maximum air temperatures in the Hamilton area frequently show marked changes from day to day as a result of short-period invasions by air masses of widely differing characteristics. It is well known that the corresponding day to day changes of temperature in the near-surface layers of an unprotected soil are less, but no quantitative information was available concerning such further reductions as would obviously be induced by a straw mulch.

Throughout the period October 17-29, 1968, air temperatures measured at 1400 hours daily with an Assmann psychrometer held at a height of 135 cm. are represented in Figure 47, as also are the corresponding soil temperatures measured at a depth of 5 cm. beneath the centre of the mulch and beneath a point lying 150 cm. outside its perimeter. Rainfall measurements are also shown. In response to the very variable macroclimatic conditions, the air temperatures at 1400 hours


°C
24
22
20
18
16
14
12
10
8
Figure 47
AIR TEMPERATURES AT 135 CMS AND
SOIL TEMPERATURES AT 5 CMS, 1400
HOURS, OCTOBER 17-29, 1968
Air
Soil, 150 cm outside mulch
Soil, centre of mulch
Rain
(cm)
1.0
17
18
19
20
21
22
23
24
25
26
27
28
29
OCTOBER 1968

fluctuated widely over short periods, and the range of values over the thirteen days was 17.4°C. One and a half meters outside the perimeter of the mulch, and at a depth of 5 cm., the corresponding figure was 10.2°C. Here the temperature of the soil changed in sympathy with that of the overlying air, and although the changes were less abrupt there was no delay in the response. The mulch exerted a strong protective influence against the rapid changes in air temperature, and this is evidenced by the fact that at a depth of 5 cm. beneath its centre the range in the values of temperature measured at 1400 hours over the thirteen-day period was no more than 4.9°C. This figure is only 48 percent of that recorded at the same depth 150 cm. beyond the mulch perimeter and only 28 percent of that in the overlying air.

It is seen from the figures in Table 16 below that the effect of the mulch in reducing the range in the values of soil temperature measured at 1400 hours throughout this thirteen day period was by no means confined to the 5 cm. level. In fact, at each depth beneath the mulch the range in the values was only about 50 percent of the corresponding figure in the unprotected profile.

This protection afforded by the mulch against large and rapid changes of temperature would be of great benefit to root systems and particularly to those of young fruit trees planted, as is usual, in the fall.

Whilst temperatures at a depth of 5 cm. in the unprotected soil always changed in sympathy with air temperatures, those at a depth of 5 cm. beneath the centre of the mulch showed a tendency to decline steadily in accordance with the seasonal trend.[1] For example, air temperatures and those at a depth of 5 cm. in the unprotected soil increased between October 20 and 21, whereas a continued decline was recorded beneath the centre of the mulch. This opposed trend of sub-mulch temperature was also in evidence between October 26 and 27, when air temperatures and those at a depth of 5 cm. in the unprotected soil rose even more steeply. However, on those days when rain fell, percolation through the mulch subjected its underlying soil to a reduced measure of such increases of temperature as were recorded in the air above. Examples of this occurred during the 24-hour periods October 21-22 and 23-24.

It has previously been shown that a mulch begins to exert its winter warming influence during the month of October, and Figure 47 provides a clear demonstration of this

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1. See Figure 47.

TABLE 16

RANGE IN THE VALUES OF SOIL TEMPERATURE MEASURED AT 1400 HOURS, OCTOBER 17-29, 1968.

Depth (cm.)	Beneath centre of mulch	150 cm. outside mulch
5	4.9°C	10.2°C
10	4.2	8.3
20	3.6	6.9
50	2.0	4.1
75	1.6	3.1
100	1.2	2.4

fact. Up to October 24, the soil temperatures at a depth of 5 cm. beneath the centre of the mulch were at all times cooler than those at the same depth in the unprotected profile and this has been referred to as the summer effect. However, after October 24, the sub-mulch temperatures were the higher, and daily readings established that they remained so until the next change-over in the spring of 1969. Thus in 1968, the mulch began to exert its winter warming influence on the underlying soils during the 24-hour pèriod October 24-25.

6. Daily temperature waves.

In addition to halving the day-to-day changes of soil temperature as measured at 1400 hours, the mulch induced a very marked reduction in the amplitude of the daily temperature wave at each depth. This confirms Dancer's observations, 1964. This can be demonstrated by considering measurements of soil temperature made at two-hourly intervals on April 25-26, 1969, when daylight hours were sunny, and June 13-14, 1969, when cloudy skies gave some light rainfall. The measurements made at nine locations during these two periods are represented in Figures 48 and 49 respectively, and the amplitudes of the daily temperature waves were as shown in Table 17 below.

Figures 48 and 49, together with the data presented in Table 17, clearly demonstrate that the mulch reduced the amplitudes of the daily temperature waves, and that this effect was most marked at a depth of 5 cm. It was more prominent during the sunny April period before soil temperatures beneath the mulch centre had begun to rise, and less so during the June period when the sky was cloudy and by which time the temperature of the sub-mulch soil had increased consequent upon an influx of heat from its warmer surroundings.

Apart from the marked reduction in the amplitudes of the daily waves induced by the mulch, the most prominent feature of the April period was the fact that at depths of

Figure 48

SOIL TEMPERATURES APRIL 25–26, 1969

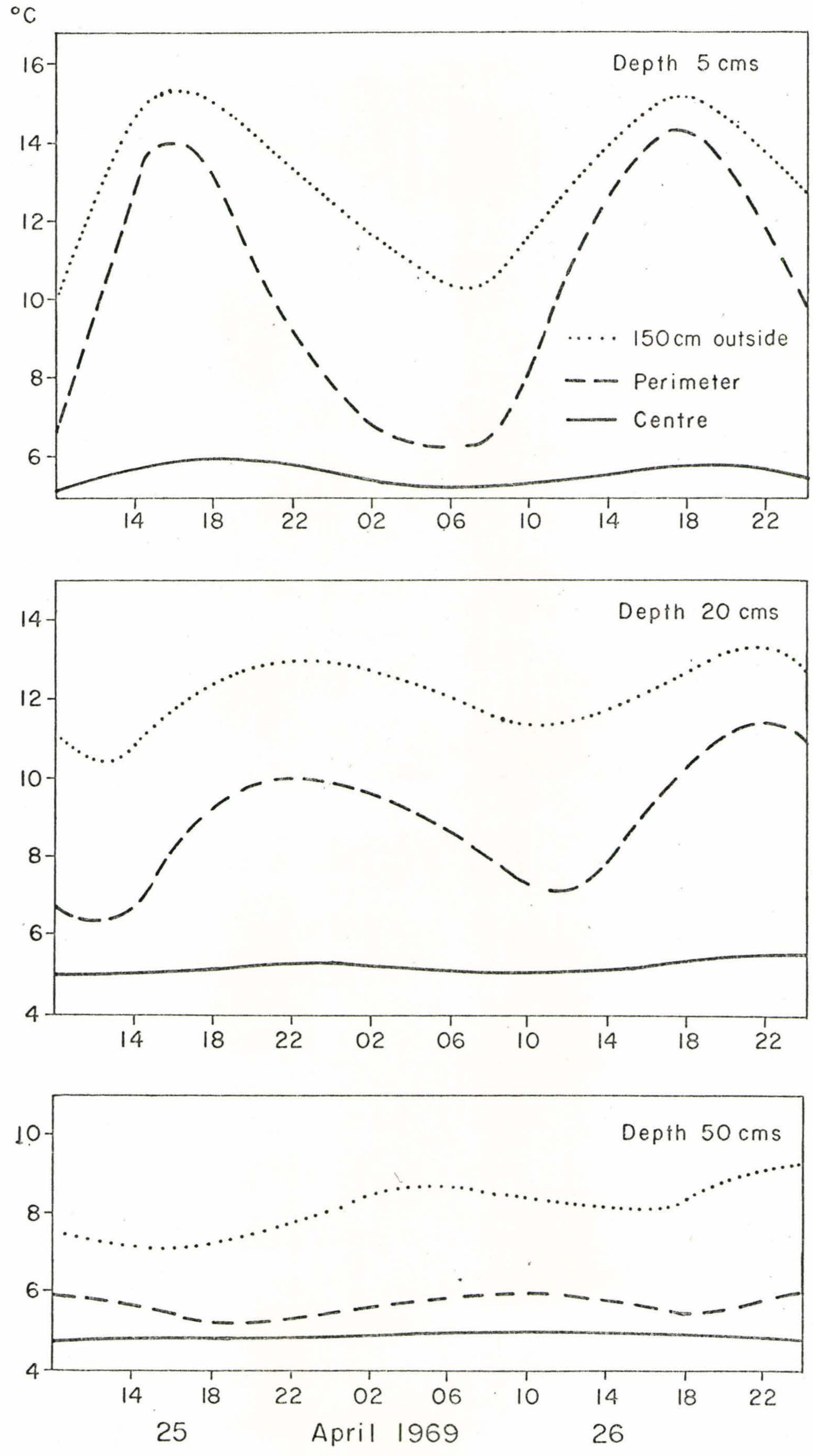
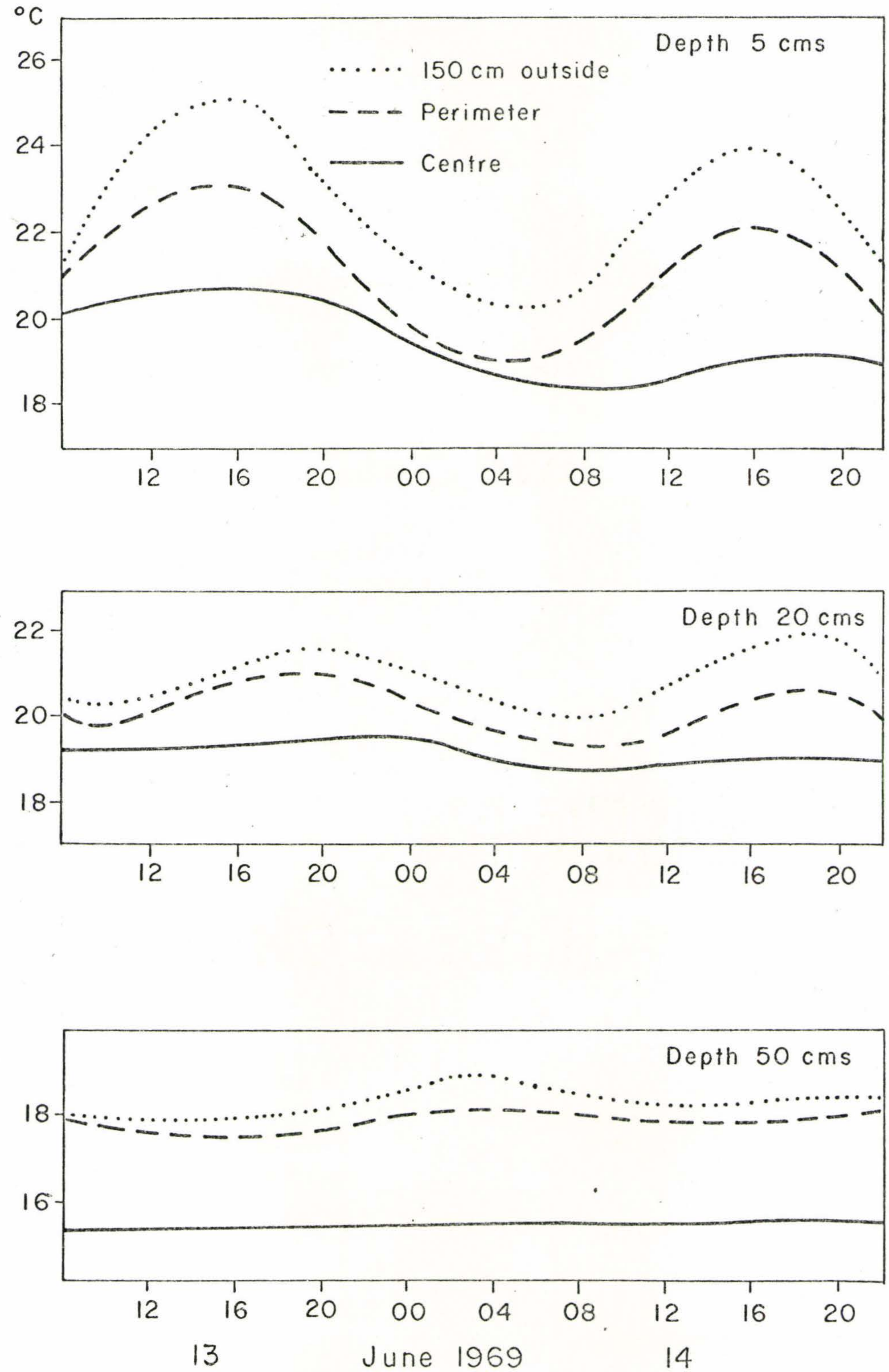


Figure 49

SOIL TEMPERATURES JUNE 13-14, 1969



5 and 10 cm. the amplitudes beneath the mulch perimeter were much greater than those beneath a point lying 150 cm. outside it.[1]

TABLE 17

AMPLITUDES OF DAILY TEMPERATURE WAVES

Location	April 25-26, 1969			June 13-14, 1969		
	Depth (cm.)			Depth (cm.)		
	5	20	50	5	20	50
150 cm. outside mulch	4.9°C	3.1°C	2.2°C	5.0°C	1.9°C	1.2°C
At mulch perimeter	8.1	5.0	0.8	4.0	1.6	0.6
Centre of mulch	0.6	0.4	0.2	2.2	0.7	0.2

This resulted from a strong inward flux of heat from the rapidly warming soil lying beyond the perimeter of the mulch to the unwarmed soil beneath it. Thus the maximum temperature at a depth of 5 cm. beneath the mulch perimeter was only 0.9°C less than that 150 cm. outside it. At night, the soil beneath the mulch perimeter lost heat not only to the surface, but also to the cooler zone beneath the mulch. Hence the minimum temperature at a depth of 5 cm. beneath the mulch perimeter was lower than that 150 cm. outside it by as much as 4.1°C, and it was this fact that was mainly responsible for the greater

1. See Figure 48 and Table 17 above.

amplitude of the daily wave at the former location. The same inward heat flux accounts for the fact that the amplitude at a depth of 20 cm. was still markedly greater beneath the mulch perimeter than at a point lying 150 cm. outside it. On the other hand, the amplitudes at the 50 cm. level, as shown in Table 17 above, indicate that there was no such influx of heat at this depth.

Figure 49 and the data given in Table 17 relating to the period June 13-14 show that, at least under the cloudy conditions which then prevailed, the influx of heat was not sufficiently marked to produce an amplitude beneath the mulch perimeter greater than that at the point lying 150 cm. beyond it. This was due to the fact that the gradient of temperature across the mulch perimeter at depths of 5 and 20 cm. was now much less steep both by day and by night, as is evidenced by the data given in Table 18 below.

During the winter months it was found that the amplitude of the daily temperature wave at all depths and in all positions was always very small and most often imperceptible.

TABLE 18

DIFFERENCES IN MAXIMUM AND MINIMUM TEMPERATURES BETWEEN THE PROFILES LYING BENEATH THE MULCH CENTRE AND 150 cm. OUTSIDE ITS PERIMETER

Depth (cm.)	April 25-26, 1969		June 13-14, 1969	
	Difference in maxima	Difference in minima	Difference in maxima	Difference in minima
5	9.3°C	5.0°C	4.5°C	1.7°C
20	7.8°C	5.1°C	2.4°C	1.2°C

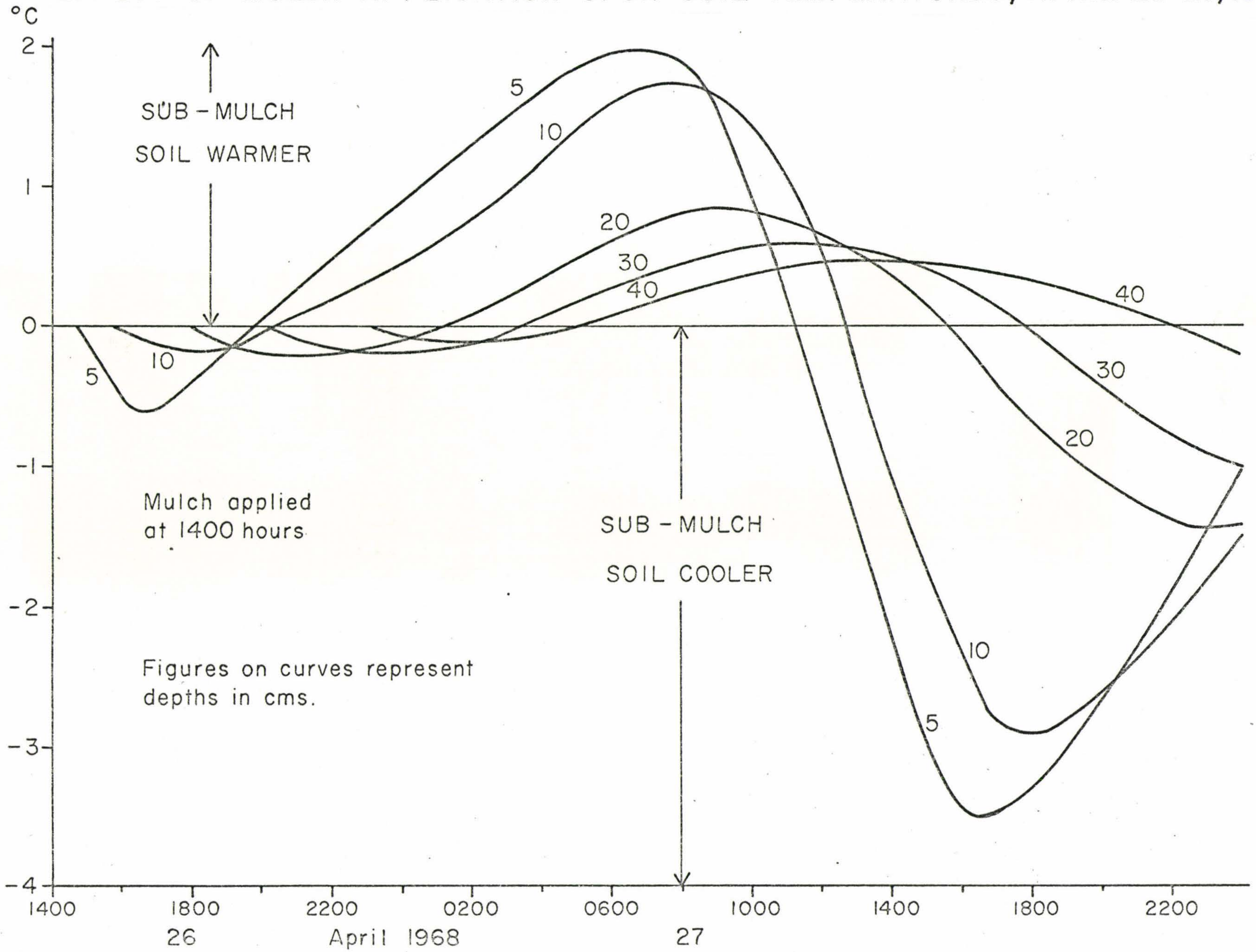
7. The rate of penetration of the effects produced by a mulch.

There are considerable differences of opinion among users as to the time required for the effects of a mulch upon soil temperature to penetrate to some specified depth. In an attempt to resolve this uncertainty, plots were instrumented precisely as shown in Figure 9 with the object of applying two mulches on different dates in the early portion of the growing season and a third in the late fall. Before each mulch was applied, observations were undertaken over periods of several days to examine the degree of horizontal homogeneity of temperature throughout all profiles. On the very uniform soil of the McMaster campus no problems were encountered in this respect. In particular, the means of the readings from the three outermost rods in the line of ten agreed precisely with the corresponding means from the three innermost rods, and it was therefore decided that mean temperatures derived from these two groups of rods should be used in assessing the rate of penetration of the effect of a mulch.

The first mulch used for this purpose was placed in position at 1400 hours on April 26, 1968, and Figure 50 shows the extent to which the sub-mulch temperatures in the topmost 40 cm. of soil were higher or lower than those lying beyond the mulch perimeter throughout the succeeding 34 hours. Consequent upon the exclusion of incoming radiation by the straw, the temperature at a depth of 5 cm. beneath the mulch began to fall below that of the surrounding soil in less than an hour, and temperatures at depths of 10, 20, 30 and 40 cm. responded similarly after the lapse of 2, 4, 6 and 9 hours respectively. During the succeeding night the mulch impeded the upward loss of heat, as a result of which soil temperatures beneath it were higher than those in the unprotected profiles. By 1600 hours on the following day, the near-surface layers of the sub-mulch soil were the cooler by at least 3.5°C, and it is seen from Figure 50 that this trend affected the deeper layers at later times and to a diminishing extent.

Figure 50

EFFECT OF MULCH APPLICATION UPON SOIL TEMPERATURES, APRIL 26-27, 1968

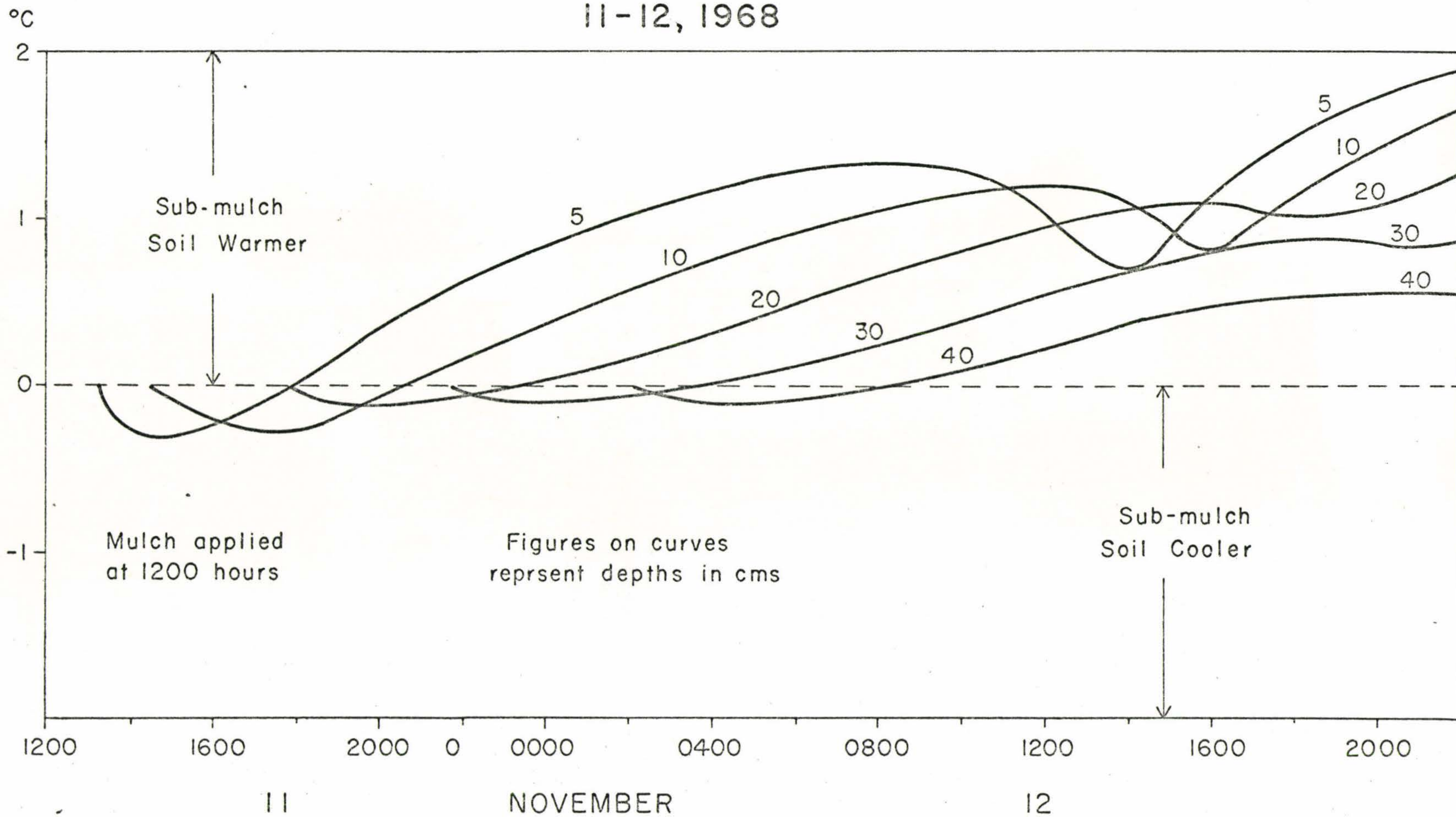


The second mulch was applied on the morning of May 24, and it will shortly be shown that the lapses of time before this began to produce an effect at the various depths were only slightly less than those which had been determined in the case of the mulch applied on April 26. Moreover, the pattern of temperature differences as between the mulched and unprotected profiles over the succeeding 34 hours was virtually identical to that which has already been presented in Figure 50.

The third mulch in this series was applied at 1200 hours on November 11, 1968, and Figure 51 shows the extent to which the sub-mulch temperatures in the topmost 40 cm. of soil differed from those lying beyond the mulch perimeter throughout the succeeding 34 hours. Consequent upon the exclusion of incoming radiation by the straw, the temperature at a depth of 5 cm. beneath the mulch began to fall below that of the surrounding soil in just over an hour, and temperatures at depths of 10, 20, 30 and 40 cm. responded similarly after the lapse of about 2.5, 6, 10 and 14 hours respectively. During the succeeding night the sub-mulch soil was the warmer, and it remained so throughout the following day since the net radiation balance was now negative. In the afternoon hours of that day the warming influence of the mulch at depths of 5 and 10 cm. declined for a few hours as the

Figure 51

EFFECT OF MULCH APPLICATION UPON SOIL TEMPERATURES, NOVEMBER 11-12, 1968



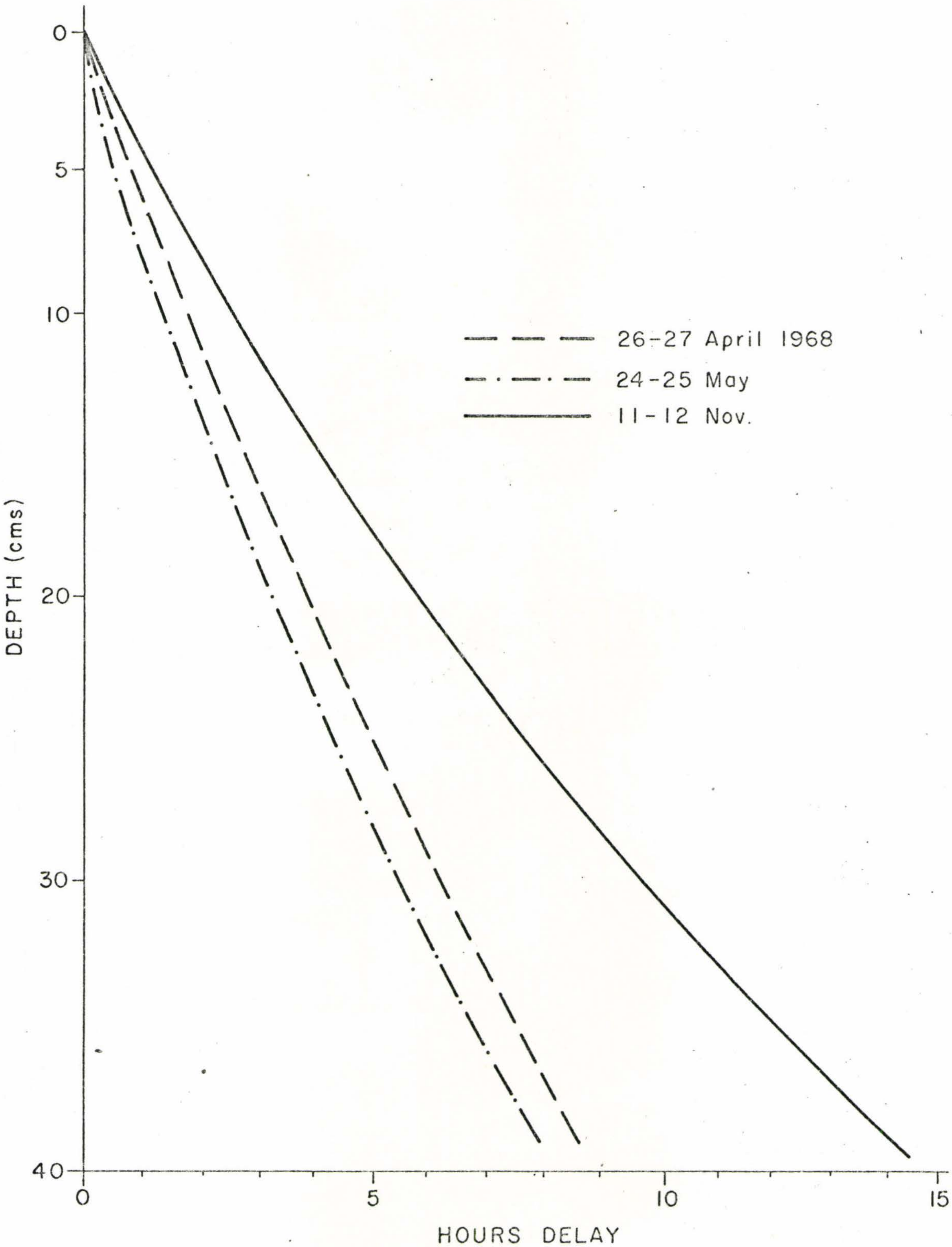
temperature of the near-surface soils which lay beyond its perimeter responded to a short period of positive radiation balance.

The intervals between the times at which the three mulches were applied and those when their effects were first observed at each depth are shown in Figure 52. The curves for April 26-27 and May 24-25 lie close together, and it is evident that in the early part of the growing season the time taken for the effect of a newly applied mulch to penetrate through the topmost 40 cm. of soil is not significantly affected by the lapse of a month. In the case of the mulch which was applied during the second week of November, the corresponding time was considerably greater, and this suggests that the conservation by the mulch of the heat that was now flowing upward in the soil was less effective than had been its exclusion of incoming radiation in earlier months.[1] It is seen from Figure 51 that when a mulch was applied in November, its underlying soil at a depth of 5 cm. was not the warmer by more than 1.9°C after the lapse of 34 hours. On the other hand, Figure 50 shows that when a mulch was applied in late April its underlying soil at the 5 cm. level was the cooler by as much as 3.5°C after the lapse of only 26 hours.

1. This is why the warming effect of a mulch in winter, when the temperature gradient in the soil is comparatively gentle, is much less marked than its cooling effect in summer when that gradient is much steeper.

Figure 52

DELAY IN PENETRATION OF THE EFFECT OF THE MULCH



In the case of the mulch which was applied on November 11, the average rate of penetration of its effect through the topmost 40 cm. of soil was 2.1 cm. hr^{-1}, whereas the corresponding figures for the mulches which were applied on April 26 and May 24 were 4.6 cm. hr^{-1} and 5.0 cm. hr^{-1} respectively.[1]

8. <u>A comparison between newly applied and well established mulches for winter protection</u>.

There are considerable differences of opinion among fruit growers as to whether or not the time lapse since the application of a mulch has any effect upon its protective influence in winter. For this reason, the winter temperatures recorded beneath the more compacted mulch which had been in position since May 24, 1968, were compared with those beneath the one of higher air content which had been laid-out on November 11, 1968. In mid-December of that year, the soil temperatures beneath the more recently applied mulch were the higher by amounts up to 1.8°C. By mid-January, 1969, when both mulches were uniformly covered with snow, these positive differences had fallen to a maximum of 0.8°C, and they became zero in February by which time the newer mulch, under

1. Data derived from Figure 52.

the weight of snow, had become as compacted as the older. However, it seems very probable that during a winter in which snowfall totals in December and January are low, the amount of additional protection afforded by a mulch which had been applied as late as mid-November might well prove to be of vital importance to young fruit trees. Alternatively, if an older mulch was fluffed-up in the fall to increase its air content, its protective influence in December and January would be significantly improved.

9. The seasonal effects of a mulch upon soil moisture values.

The sub-surface sensor of the neutron probe proved to be very satisfactory for the measurement of soil moisture at depths of 30, 45 and 60 cm. Readings obtained at corresponding positions along the two radii shown in Figure 9 never differed by more than 2 percent by volume, and differences of this magnitude were very rarely recorded. On the great majority of occasions there was no difference between the two readings obtained from corresponding positions.

The surface sensor of the neutron probe could not be used in this study. Its use on the sub-mulch soil would have necessitated the very frequent removal and replacement of several large patches of straw, which would have destroyed the attempts made to achieve homogeneity within the mulching material when it was laid, and the uniformity of its effects upon the underlying temperatures and moisture values. Use of the surface sensor beyond the perimeter of the mulch would have necessitated the removal of rectangular patches of sod, and readings so obtained would not have been representative of the grass-covered surroundings. Thus measurements of moisture in the topmost 10 cm. of soil within the sub-mulch zone and its surroundings were obtained by the gravimetric method, but these were made less frequently than the sub-surface measurements to minimise disturbance of the mulching material.

As was expected, the mulch had little effect upon the moisture content of its underlying soil during the winter months, and this is exemplified by the values of soil moisture, expressed as a percentage of volume, given in Table 19.

After the soil, saturated by the spring thaw, had dried somewhat, the mulch slowly began to conserve the supplies of soil moisture beneath it, but this effect was quickly obliterated by subsequent rain. This is well demonstrated by a consideration of some of the soil moisture values measured in April, 1969. The total of 9.24 cm. of rain which fell in that month did not amount to more than 117 percent

TABLE 19

SOIL MOISTURE (PERCENT BY VOLUME) AT DEPTH OF 30 CM.

Date	Distance from centre of mulch (cm.)								
	15	45	75	105	135	165	195	225	255
Nov. 12, 1968	34	33	33	33	33	33	32	32	32
Dec. 6, 1968	35	34	33	33	33	33	33	33	32
	Mulched zone								

of the normal figure, but 6.45 cm. of that total fell in the period April 15-23. By April 14, just before the rainy period commenced, the readings of soil moisture at a depth of 30 cm. beneath the central portion of the mulch, expressed as a percentage of volume, exceeded those at the outermost points of measurement by 4. However, the data presented in Table 20 show that this difference had been halved at the end of the rainy period. This was due to the fact that the rainfall increased the soil moisture content at a depth of 30 cm. beyond the perimeter of the mulch. At that depth beneath the mulch, and at the 60 cm. level in all profiles, the moisture content of the soil was not increased by the rainfall since it had already been at or very close to field capacity.

As was expected, the effects of the mulch on soil moisture values were found to be most marked during the summer months when it so effectively reduced soil temperatues, and this was especially the case after a particularly dry spell. July 1968 was a dry month in which the rainfall of 1.55 cm. was only 27 percent of the normal total, and most of this fell on July 5.

TABLE 20

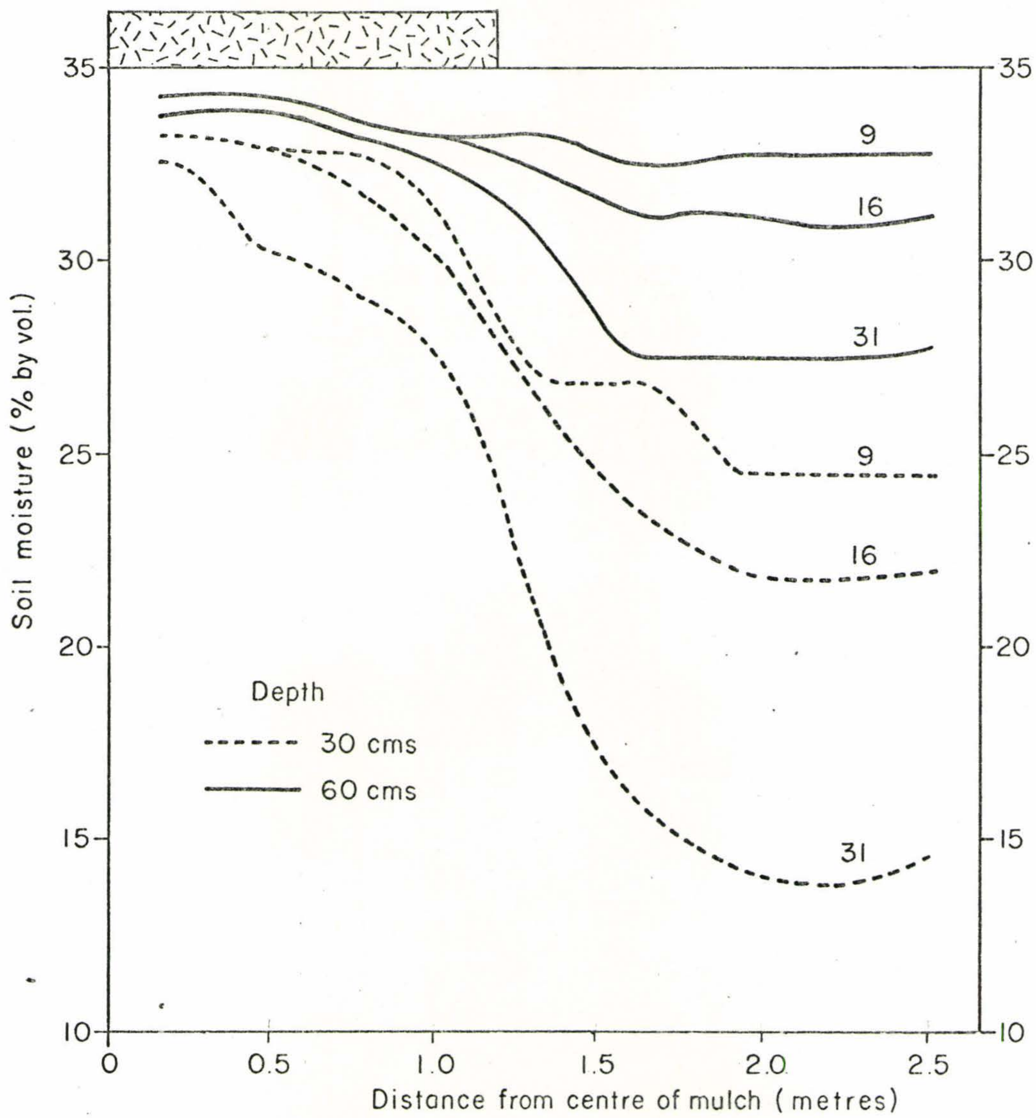
SOIL MOISTURE (PERCENT BY VOLUME) IN APRIL, 1969.

Date	Depth (cm.)	Distance from centre of mulch (cm.)								
		15	45	75	105	135	165	195	225	255
April 14, 1969.	30	34	34	34	33	32	31	31	30	30
	60	36	35	35	35	35	35	35	34	33
April 24, 1969.	30	34	34	34	33	33	33	33	32	32
	60	35	35	35	35	35	35	35	34	33
		Mulched zone								

Figure 53 shows the distribution of soil moisture values at depths of 30 cm. and 60 cm. on three dates during that month; 9th, 16th and 31st. Near the centre of the mulch the values at each depth, expressed as a percentage of volume, did not

Figure 53

SOIL MOISTURE (% BY VOLUME) JULY 9-31, 1968



change by as much as 1 throughout this dry period, whereas 105 cm. beyond the mulch perimeter they declined by 10 and 5 at depths of 30 cm. and 60 cm. respectively. By the end of the month, the gradient of soil moisture across the mulch perimeter was particularly steep at the 30 cm. level, and it seems certain that under these conditions soil moisture would move outward from beneath the mulch to the much drier soil lying beyond its perimeter.

This dry month was followed by a wet August and September, during which there was a marked decline in the excess of soil moisture values beneath the mulch as compared with those in the surrounding area. It is seen from the data given in Table 21, that on September 6, following a 24-hour period in which 4.01 cm. of rain fell, the outward gradient of soil moisture values was gentle. By September 30 it had increased at the 30 cm. level since, in spite of the fact that an additional 4.17 cm. of rain fell during the interim period, many days had been conducive to evaporation from the uncovered soil.

During the following year, the months of August and September represented another very dry period during which rainfall amounted to no more than 15 percent of the normal combined totals. Measurements of soil moisture made on September 25 and presented in Table 22 further demonstrate

TABLE 21

SOIL MOISTURE (PERCENT BY VOLUME) IN SEPTEMBER, 1968.

Date	Depth (cm.)	Distance from centre of mulch (cm.)								
		15	45	75	105	135	165	195	225	255
Sept. 6, 1968	30	35	34	32	32	32	31	31	30	30
	60	34	34	34	33	32	30	30	29	27
Sept. 30, 1968	30	34	33	33	31	29	28	27	26	25
	60	35	35	34	33	33	32	31	30	30
		Mulched zone								

TABLE 22

SOIL MOISTURE MEASUREMENTS ON SEPTEMBER 25, 1969.

Depth (cm.)	Distance from centre of mulch (cm.)								
	15	45	75	105	135	165	195	225	255
0 - 10 *	25	24	23	19	7	6	6	5	5
30 +	30	28	27	22	18	14	12	12	12
60	31	31	31	28	22	20	19	18	18
	Mulched zone								

* percent by weight
\+ percent by volume

the effectiveness of the mulch in conserving soil moisture during such a very dry period.

Within the topmost 10 cm. of soil, the moisture values, obtained by the gravimetric method and expressed as a percentage of weight, fell from 25 near the centre of the mulch to 5 at each of the two outermost points of measurement, and the drop from 19 to 7 across the perimeter of the mulch was particularly abrupt. The outward decline at depths of 30 and 60 cm., expressed as a percentage of volume, was also well marked, and there can be no doubt that a mulch produces very significant increases in the availability of moisture in its underlying soils during dry summer periods. Such increases are especially marked in the near-surface layers of soil, and would encourage root development in this zone which is usually the richest in nutrients.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

1. Introduction

Circular patches of straw of various diameters are commonly placed around fruit trees in the Niagara Peninsula, but no detailed information is available concerning the effects of such mulches on the microclimate of the underlying soil. Consequently, the users have no knowledge as to whether or not the diameter of such a mulch is of any real significance, and they hold widely differing opinions concerning the magnitudes of its heat-retaining effects in winter and its cooling and moisture-retaining effects in summer.

The detailed investigations which have been reported in previous chapters were therefore undertaken with two objectives in mind:

(a) To determine the influence of mulch-diameter upon temperatures within the underlying soil.

(b) To acquire detailed information concerning the effect of a circular mulch of diameter 240 cm. on soil temperatures and moisture-values, both beneath it and beyond its periphery, in all seasons of the year.

2. The effects of a mulch upon sub-surface temperatures

(a) In winter.

It was established that, in each of the two winters covered by the observations, straw mulches began to exert a warming influence on their underlying soils in mid-October. When the mulches and their surroundings were uniformly covered with 20-30 cm. of snow, it was anticipated that the straw would not produce any additional protective effect. However, this was not the case. Under such conditions, sub-zero temperatures were recorded in an un-mulched control plot down to a depth of about 20 cm., but beneath a mulch of diameter 60 cm. they were restricted to the topmost 5 cm. of soil. By contrast, beneath the centres of mulches of diameter 120 cm. and 240 cm. the temperatures of the near-surface soil layers were +0.5°C and +2.0°C respectively. As a result of the additional protective influence of the mulches, cones of comparatively warm soil reached upward towards the surface. This feature was most strongly developed beneath the 240 cm. mulch, and in this case the outward flow of heat from the warmer zone pushed the zero-degree geotherm outward to a distance of about 30 cm. from the mulch perimeter.

Under a snowcover of 20-30 cm., a comparison of temperatures beneath the mulches with those in the control plot established that, in the case of the 60 cm. mulch, it was only in the topmost 5 cm. of its underlying soil that the temperature gain amounted to 0.5°C. This figure was typical of the great majority of winter days and was never exceeded. It is thus evident that a mulch of such small diameter affords no worthwhile protection against low soil temperatures during the winter season.

Beneath the centre of the 120 cm. mulch, temperatures at depths down to about 15 cm. exceeded the corresponding values in the control plot by more than 1°C, and this mulch induced a temperature gain of more than 0.5°C. through a soil thickness greater than 50 cm. In addition, a slight protective influence spread laterally for at least 30 cm. beyond the perimeter of the mulch, and this also affected all soil layers to a depth in excess of 50 cm.

Beneath the centre of the 240 cm. mulch the temperature gains amounted to 2.5°C, 1.5°C and 0.5°C at depths of 5, 50 and 100 cm. respectively. Moreover, this largest mulch extended its protective influence beyond its perimeter through distances which increased from 60 cm. in the near-surface layers to a larger figure at a depth of 50 cm.

It is thus evident that even when heat losses from a soil are impeded by a snow cover as deep as 20-30 cm., a circular mulch whose diameter is at least 120 cm. provides additional protection. Moreover, when the diameter of the mulch is increased from 120 to 240 cm., this additional protection at any specified depth is nearly trebled, and there is a significant increase in the spreading of the protective effect beyond the perimeter of the mulch, more particularly at depths of between 20 and 50 cm. which define the zone of maximum root activity for peach trees.

From all the daily readings which were taken in the month of February, when air temperatures in the Niagara Peninsula reach their lowest values, an attempt was made to investigate the relationship between the diameter of a mulch and the extent to which its underlying soils are warmer than those at correponding depths in an unmulched control plot. It was found that the warming effect of a mulch increased rapidly with diameter up to 240 cm.[1] Thereafter, the increase seemed to be much less, and it is probable that no significant increase in the magnitude of the warmer zone which develops beneath the centre of a circular mulch in February would result from any increase in its diameter beyond 480 cm. Moreover, since the amount of mulching material required to cover a circular patch of diameter 480 cm. is four times the amount required to lay the same thickness

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1. See Figure 19.

on a patch of diameter 240 cm., the extra costs of material and labour would be large and the additional gain in the magnitude of the warmer zone very small.

It would thus seem that for the winter protection of individual fruit trees, circular mulches of diameter 240 cm. are to be strongly recommended. Mulches of diameter 120 cm. provide their underlying soil with much less protection against low winter temperatures, and those of diameter 60 cm. are virtually useless in this connection. Even those temperature increases induces by 240 cm. mulch might seem, on first consideration, to be of only minor significance. However, it is a very important fact that they were at all times sufficient to prevent freezing of the soil beneath the mulch. By contrast, the unprotected soil which lay beyond the mulch perimeter was frozen to depths in excess of 30 cm. for long periods during each of the two winters. Moreover, measurements of electrical resistance showed that this freezing was sometimes rapid, and such an occurrence would cause coagulation of the cell sap within roots, frequently resulting in the death of a fruit tree. When cooling rates are much slower, as was the case beneath 240 cm. mulch, the sugar within the sap of a root system becomes concentrated. This not only lowers the freezing-point, but also reduces the amount of damage that might result if sub-mulch freezing should happen to occur in a particularly severe winter (Kramer 1949).

A 240 cm. mulch also provides an underlying root system with complete protection against such mechanical injury as is frequently caused by the heaving of soil during the freezing process. Fine roots are often broken off by such soil heaving, and the severity of the damage is frequently sufficient to result in the death of a fruit tree.

There is some considerable difference of opinion among fruit growers in the Niagara Peninsula as to whether or not the time-lapse since the application of a mulch has any effect upon its protective influence in winter. In an attempt to resolve this difference, two 240 cm. mulches were laid out, one in mid-May of 1968 and another in mid-November. By mid-December, the soil temperatures beneath the more recently applied mulch were the higher by amounts up to 1.8°C. By mid-January these positive differences had fallen to 0.8°C, and they became zero in February, by which time the newer mulch had become as compacted as the older. However, it seems very probable that during a winter in which snowfall totals in December and January are low, the amount of additional protection afforded by a mulch which was applied as late as mid-November might well prove to be of vital importance. Alternatively, if an older mulch was fluffed-up in the fall to increase the air content, its protective influence in December and January would be significantly improved.

(b) Spring.

As was to be expected, it was found that a 240 cm. mulch markedly reduces the diurnal range of soil temperature beneath it. This effect was particularly evident in the spring, and it represents the most important benefit conferred by a mulch upon root systems during these months when the temperatures of unprotected soils are changing rapidly. The reduction in the diurnal range of temperature in the near-surface layers of soil beneath a 240 cm. mulch in spring is exemplified by hourly observations made throughout the period March 14-15, 1966. Beneath the centre of the mulch and a point lying 30 cm. inside its perimeter, the diurnal range of temperature at a depth of 2.5 cm. was only 1.3°C, whereas the corresponding figures for points lying 30 and 60 cm. outside the perimeter and beneath the centre of the control plot were 7.0°C, 8.7°C and 9.4°C respectively.

A 240 cm. mulch begins to exert a cooling influence on its underlying soils in mid-April, and in a peach orchard the cooler sub-mulch temperatures in spring have the very beneficial effect of helping to retard blossoming until the danger of late frosts is over.

(c) Summer

During the summer months, when an unprotected soil is exposed to a strong downward flux of heat from its surface, the extent to which a mulch impedes the warming of its underlying soil increases with its diameter. This results from the fact that the inward flow of heat from the warmer soils lying beyond the mulch perimeter becomes less effective as its diameter increases. Thus a cone of comparatively cool soil extends upward into the sub-mulch layers, and this feature was found to be most pronounced beneath a mulch of diameter 240 cm.

The near-surface layers of soil beneath the centre of the 60 cm. mulch were cooler than those in the control plot by 9°C, and the corresponding figures for the 120 cm. and 240 cm. mulches were 10°C and 12°C respectively. Consequent upon the inward flow of heat generated by these temperature differences, the near-surface layers of soil which lay 30 cm. beyond the perimeter of the 60 cm. mulch were cooler than their counterparts in the control plot by 5°C, and the corresponding values for the 120 cm. and 240 cm. mulches were 6°C and 7°C respectively. Even at a distance of 60 cm. beyond the perimeter of the 240 cm. mulch the near-surface layers of soil were still cooler than those of the control plot by as much as 5°C, and on the hottest days this largest mulch extended its cooling influence to points lying 150 cm. outside its perimeter. This marked cooling of the near surface layers of soil is very beneficial, for in the absence of a mulch the excessively high temperatures prevent root development in thos topmost layers which are almost invariably the richest in nutrients, (Proebsting, 1943).

The cooling effect of a 240 cm. mulch on its underlying soils in summer declines from 12°C at a depth of 5 cm. to 2.5°C at a depth of 100 cm. At all depths below 20 cm. this cooling effect stretches outward to a distance of more than 150 cm. beyond the mulch perimeter. This is in marked contrast to the warming effect in winter, which is only about one-fifth the magnitude and which does not extend for more than 60 cm. beyond the mulch perimeter. Thus, when a fruit grower elects to use mulches to protect the roots of his trees against low winter temperatures, it is very important that he should acquire information concerning the distribution of the root systems. A more approximate figure would suffice when mulches are to be used to protect root systems against high temperatures in summer.

(d) Fall

As in the spring months, a 240 cm. mulch markedly reduces the diurnal range of soil temperature beneath it during the fall. In addition, it provides a very significant measure of protection against those considerable and very sudden changes of air temperature which are a feature of the fall months.[1] Temperatures in the near-surface layers of an unprotected soil rise and fall quite sharply in response to changes in air temperature. However, the near-surface layers of soil beneath a 240 cm. mulch experience a slow and almost uninterrupted decline of temperature, and this is of considerable benefit to root systems in their slow approach to dormancy.

The cooling effect of a mulch upon its underlying soil declines throughout the early fall, and in mid-October it is replaced by the warming effect which is characteristic of the ensuing winter.

(e) Time required for the effects of a mulch to penetrate into its underlying soil.

There are considerable differences of opinion among fruit growers in the Niagara Peninsula concerning the time required for the effects of a mulch to penetrate into

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1. See Figure 47.

its underlying soil. The detailed investigations which were undertaken in an attempt to resolve these differences clearly established that, in the spring months, it takes only 8-9 hours for the cooling effect of a mulch by day and its warming effect at night to penetrate through that topmost 40 cm. of soil in which the upper portions of a peach tree's root systems are located. Even in the late fall, when the vertical gradient of temperature in the soil is much less, only 14 hours are required for the warming effect of the mulch, both by day and by night, to reach that same depth. Both of these delay-intervals are considerably less than the "two-or-three- days" to "two-or-three weeks" previously assumed by the fruit growers.

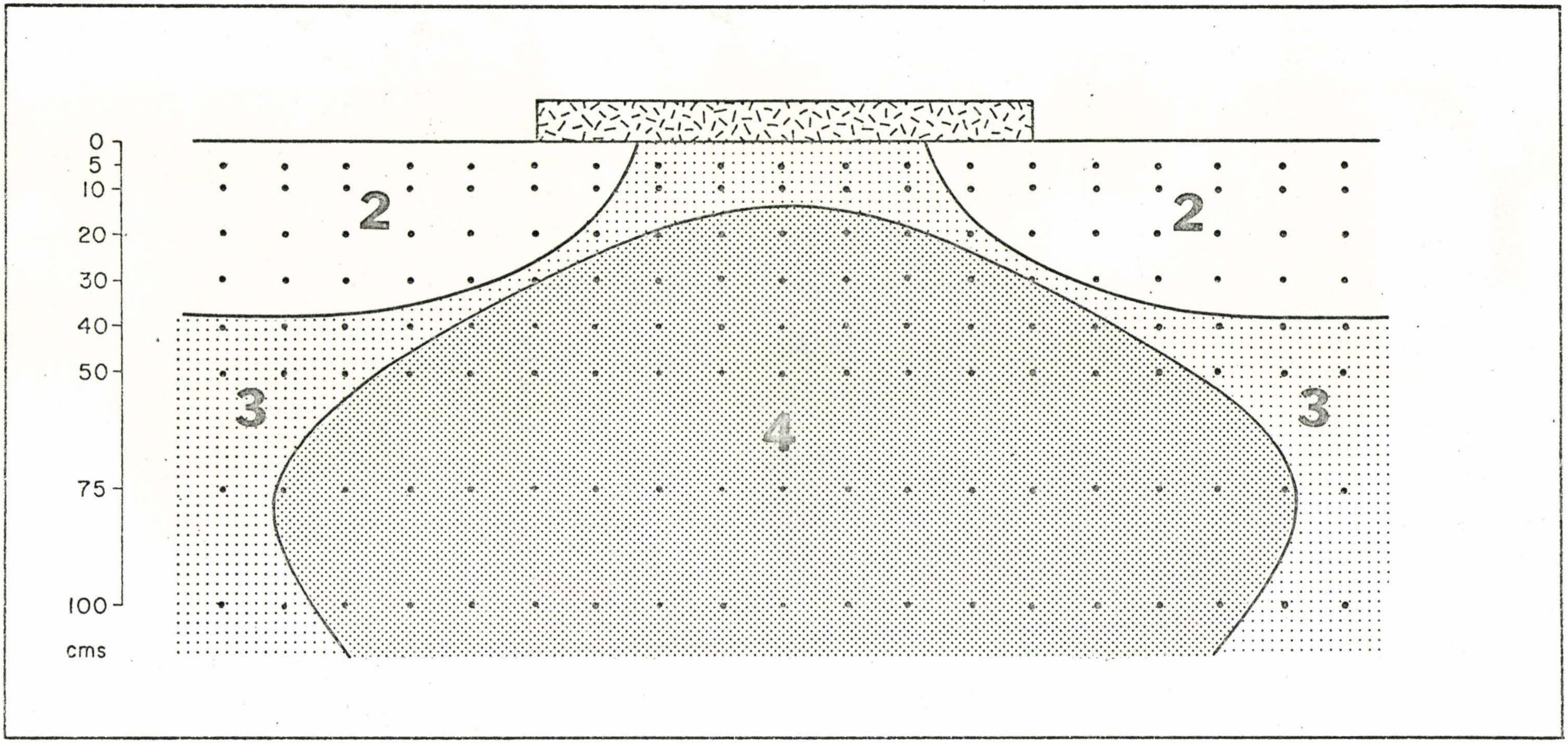
(f) Optimum soil temperatures for the roots of peach trees.

Optimum soil temperatures for the growth of peach and apple trees lie within the range 15-20°C (Proebsting 1943), and a summary of the beneficial effects of 240 cm. mulch upon temperatures within its underlying soil can conveniently be presented by a consideration of the number of months during which the temperature at each sensing point lay within this range.

It is seen from Figure 54 that the surface portions of the root system of a peach or apple tree lying at depths

Figure 54

NUMBER OF MONTHS IN EACH OF THE YEARS 1968 AND 1969 DURING WHICH OPTIMUM SOIL TEMPERATURES FOR THE GROWTH OF PEACH TREES WERE RECORDED AT EACH SENSING POSITION



Horizontal scale: 1:24

of 15-35 cm. beneath a 240 cm. mulch would experience optimum soil temperatures for 4 months, whereas the corresponding figure beyond the perimeter of the mulch would be only 2 months. At greater depths, the mulch would increase the period of optimum soil temperatures for the major portion's of a tree's root system from 3 months to 4, and at a depth of 75 cm. this effect would be spread outwards to a distance of 120 cm. beyond the mulch perimeter. These very significant benefits result from the reduction of soil temperatures effected by the mulch in summer, both beneath it and up to 150 cm. beyond its perimeter. This was particularly marked in July, when temperatures in the uncovered soil exceeded the upper limit of the optimum range for peach and apple trees down to a depth of 80 cm. There can be little doubt that this increase in the length of the period over which optimum soil temperatures are recorded is mainly responsible for the favourable effect of a mulch upon the rehabilitation of peach trees of low vigor (Proebsting Jr. 1958), and for the greatly increased yield from healthy trees which a mulch is known to induce (Archibald, 1960).

3. <u>The effect of a mulch upon moisture values in its underlying soil.</u>

As was expected, the effects of a 240 cm. mulch on soil moisture values were most marked during the summer months, and especially after a particularly dry spell. July 1968 was one such dry month, in which the rainfall was only 27 percent of the normal total. Near the centre of the mulch the values of soil moisture at depths of 30 and 60 cm., expressed as a percentage of volume, remained close to 32 and 34 respectively throughout this dry period, whereas 105 cm. beyond the mulch perimeter they declined from 24 to 14 at a depth of 30 cm. and from 32 to 27 at a depth of 60 cm. By the end of the month, the gradient of soil moisture across the mulch perimeter was particularly steep at the 30 cm. level, and it seems certain that under these conditions soil moisture would move outward from beneath the mulch to the much drier soil lying beyond its perimeter.

During the following year, the months of August and September represented another very dry period during which rainfall amounted to no more than 15 percent of the normal total. Measurements taken on September 25 further demonstrated the effectiveness of the mulch in conserving soil moisture during such a very dry period. Within the topmost 10 cm. of soil, the moisture values, obtained by the gravimetric method and expressed as a percentage of weight, fell from 25 near the centre of the mulch to 5 at a distance

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1. See Figure 54.

of 120 cm. outside it, and the drop from 19 to 7 across the perimeter of the mulch was particularly abrupt. The outward decline at depths of 30 and 60 cm., expressed as a percentage of volume, was also well marked.[1]

There can therefore be no doubt that a mulch produces very significant increases in the availability of soil moisture during dry summer periods. Such increases are especially marked in the near-surface soil layers, and these would encourage root development in this zone which is normally richest in nutrients.

Various authors have shown that in the growing of peaches, cherries, plums and apples, inadequate supplies of soil moisture during the season of development invariably lead to small-sized fruits of poor quality. (Kimball 1933, Feldstein and Childers 1957). This study clearly established that a 240 cm.mulch represents a method whereby soil moisture values can be maintained at a very satisfactory level without the expense of irrigation.

4. Recommendations to fruit growers in southern Ontario.

There can be no doubt that when straw is to be used to form circular mulches around fruit trees, the most favour-

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1. See Table 22

able diameter is 240 cm. A halving of this figure would result in a very considerable loss of protection, and it would seem that a doubling of it would not add significantly to the benefits conferred.

A 240 cm. mulch reduces summer temperatures beneath it by amounts which decrease from 12°C in the near-surface layers of soil to 2.5°C at a depth of 100 cm. These reductions have the following very important consequences:

(a) They increase the length of the period of optimum soil temperatures for the upper portions of a fruit tree's root system from2 months to 4 months, and for its major portions from 3 months to 4 months.

(b) They lead to such a remarkable conservation of soil moisture in periods of particularly dry weather that only in very prolonged periods of severe drought would any irrigation be necessary.

The reduction of soil temperatures in summer extends outward to about 150 cm. beyond the perimeter of the mulch, but the much higher values of soil moisture in a dry period are closely confined to the sub-mulch zone.

In winter, a 240 cm. mulch increases soil temperatures beneath it by amounts which decrease from 2.5°C near the surface to 0.5°C at a depth of 100 cm. These values might seem to be small, but in southern Ontario winters of normal severity they are at all times sufficient to prevent freezing of the soil beneath the mulch. The finer roots of a fruit tree are therefore protected against mechanical damage which would result from soil heaving which frequently accompanies freezing. Furthermore, whilst the cooling rates in an unprotected soil are often very rapid, those beneath the mulch are slow, thus permitting the sugar within the sap of a root system to become concentrated. This not only lowers the freezing point, but also reduces the amount of damage to a root system that might result if sub-mulch freezing occurred in a particularly severe winter.

The effect of a 240 cm. mulch in raising soil temperatures during the winter does not extend outwards to a distance of more than 60 cm. beyond its perimeter. Thus, if those finer parts of a fruit tree's root system are to be adequately protected,it is essential that reasonably accurate information be obtained concerning their lateral spread. It is by no means adequate to assume that this will be equal to the lateral spread of the tree's branches, (Vuorinen, 1958).

If a mulch is applied as late as mid-November, the protection which it provides to its underlying soil in winter exceeds that provided by a spring mulch by 1.8°C in December and 0.8°C in January. These additional increments of soil temperature may well be of vital importance when snowfall totals in those two months are below normal. Alternatively, the winter protection afforded by an older mulch would be significantly increased if the mulching material was fluffed-up in the fall to increase its air content.

During the spring months, a 240 cm. mulch markedly reduces the diurnal range of temperature in its underlying soil. It also retards the warming of the soil, and this helps to delay blossoming until the danger of late frost is over.

In the fall, a 240 cm. mulch shields its underlying soil against those large fluctuations of temperature which characterise this season, and this confers considerable benefits upon root systems by ensuring a slow and uninterrupted approach to dormancy.

6. Suggestions for further work

Investigations into the effects of circular mulches upon fruit trees have been almost exclusively confined to their effects upon either tree growth or yield, and only the most cursory attention has been paid to their effects upon the climates of their underlying soils. Nevertheless, the effect of a mulch upon both tree growth and yield is a function of the extent to which it modifies the climate of the soil, and this will depend upon soil type, the diameter and thickness of the mulch, the nature of the mulching material and the slope of the orchard surface.

It would therefore seem that carefully co-ordinated studies should be undertaken simultaneously, and should involve experts in the growth, health and yield of fruit trees[1] as well as microclimatologists.[2] The active co-operation of the fruit growers would also be essential to allow for the replication of data from different soils and exposures. Such co-ordinated studies by those who share an interest in the production of heavier crops of better quality fruit might well be of considerable economic significance, and particularly in the Niagara Peninsula where many of the best peach and apple orchards have recently been lost in various development schemes.

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1. Detailed information is required concerning the lateral spread of root systems, and the extent to which this can be reliably estimated from the type and age of a tree and its visible characteristics.

2. The microclimatologists would be well advised to focus their attention upon the simultaneous acquisition of sub-mulch temperatures and moisture values from soils of different type and sites of different slope.

APPENDIX

SOIL PROFILE DESCRIPTIONS

1. The site of the Phase 1 investigations to the north of Cootes Paradise.

A pit was dug very close to the experimental site, and the following is a brief description of the soil profile:

Layer	Depth (cm.)	Description
1	0-5	Dark brown [7.5 YR 4/2 (dry)] silty clay loam, with a fine crumb structure and many roots but with no distinct boundary.
2	5-10	Dark brown [7.5 YR 4/2 (dry)] silty clay loam, with some mottling. Fissured, with an angular blocky structure, but with no distinct boundary.
3	10-50+	Reddish brown [5 YR 4/3 (dry)] silty clay, the clay fraction increasing with depth. Mottled, with a prismatic structure and interrupted by bands of very hard grey shale of varying depth.

Slope: slightly southward.

Vegetation: short grass.

Drainage: poor.

Parent Material: lacustrine sediments over Queenston Shale.

Note: The writer gratefully acknowledges the help given to her by Mr. J. Cruickshank in the preparation of this soil description. He was at that time a temporary Associate Professor of Geography at McMaster University.

2. The site of the Phase 2 investigations on the campus of McMaster University.

A pit was dug very close to the experimental site, and the following is a brief description of the soil profile:

Horizon	Depth (cm.)	Description.
A1	0-2	Dark brown (10YR 4/3) humic loam. A fine crumb structure with many fine roots. Moist and stonefree, merging into
A 21	2-10	Dark yellowish-brown (10YR 4/4) loamy sand. Medium crumb structure but with a tendency to fine granular and fine blocky variations. Abundant fine roots, undulating boundary.
A 22	10-22	Brown (10 YR 5/3) sandy loam. Moist, with some worm casts and many fine roots along major cracks. Crumb and fine granular structure, distinct undulating boundary.
B A	22-35	Strong brown (7.5 YR 4/6) silty loam. Coarse granular to fine sub-angular blocky structure. Many fine roots penetrating into blocky peds of uniform colour. Abundant earthworm feaces along major root channels, distinct undulating boundary.
Bt	35-80	Reddish-brown (5 YR 5/4) silty loam. Medium blocky structure, with ped surfaces showing a weak development of clay skins. A few small Mn or Fe-Mn concentrations forming a distinct layer at 60-67 cm. A very marked reduction in the number of fine roots below 60 cm., accompanied by an equally marked development of major root channels which are black lined and filled with earthworm casts. A sharp boundary.

Horizon	Depth (cm.)	Description
II C1	80-100	Moist dark-brown (7.5 YR 4/4) sand. Loose, friable.
III C2	100+	Dark red (2.5 YR 3/6) weathered shale, with some yellowish-brown earthy pockets. Traces of black mottling and of clay skins.

Drainage of profile: very slightly impeded.

Note: The writer gratefully acknowledges the assistance of Dr. B.T. Bunting in the preparation of this soil description.

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