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Title: EFFECTS OF PETROLEUM MULCH ON SOIL WATER CONTENT AND SOIL TEMPERATURE

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Petroleum mulch applied on the soil surface over a row of planted seeds promotes a more rapid and a more uniform germination of seeds, enhances elongation of seedlings and in some cases increases the yield of the crop. The beneficial effects of petroleum mulch have usually been attributed to increased soil temperatures below the mulch. Some reports have pointed out that evaporation of soil water is reduced as a result of the mulch application.

An experimental arrangement was designed so that changes in soil temperature and soil water content of mulched and unmulched soil, subjected to the same radiation load could be measured under controlled conditions. Soil at a pre-determined water content was packed into boxes with inside dimensions of 4.0 x 40.0 x 48.0 cm. A ten cm wide band of mulch was applied to one side of the slab leaving 30 cm of bare soil. The soil was subjected to a temperature cycle by

turning on infra-red heat lamps at 8:00 A. M., increasing the energy output at hourly intervals with a variable transformer until 2:00 P. M. and then decreasing the energy output until the lights were turned off at 8:00 P. M. Soil temperatures were measured at two-hour intervals with calibrated thermistors inserted into the soil slab. Soil water content changes at selected points were measured at regular intervals with a collimated gamma-beam, movable in a vertical as well as a horizontal direction. The heat flux into the soil was measured with heat flux discs.

It was observed that an application of petroleum mulch, changes the temperature and water regime of a soil. The mulch covered soil was about 5°C warmer than the bare soil at the time the soil temperatures attained their maximum value. At all other times the temperature difference between mulched and bare soil was smaller. The bare soil rapidly lost water in the upper four centimeters. The mulch covered soil lost water in the upper cm of soil but gained water at depths below this zone. This gain in water was observed in the zone where seedlings are normally placed, indicating that the beneficial effect of petroleum mulch on germination and seedling growth must be attributed to improved soil water conditions as well as to improved soil temperature conditions.

Effects of Petroleum Mulch on Soil Water Content and Soil Temperature

by

Ahang Kowsar

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INTRODUCTION

The use of mulches in agriculture is a common practice. Farmers have been using straw mulch, a mulch of plant debris, corn stalks, saw dust, or paper to reduce evaporation or to keep the soil from becoming too warm or too cold. The main purpose of most of such management practices is to influence favorably, germination, emergence and early plant growth. Although provision of optimum environmental conditions for plant growth in the field is nearly impossible, one may conpromise and choose those factors which for a given set of conditions provide the best results. Petroleum mulch helps to a degree, to establish favorable conditions for germination, emergence and early growth of plants.

The use of petroleum mulch is a rather new development in agriculture and is in the experimental stage. When sprayed onto the soil over planted seeds, in a band usually five to six inches wide, the mulch forms a thin skin of petroleum resins over the soil particles. It has been observed in many instances that seeds covered in this manner germinate several days earlier, and develop more rapidly than seeds not covered. The seeds germinate also at a more uniform rate when thusly covered.

A review of the literature reporting the results of studies designed to evaluate the agronomic benefits of petroleum mulch applications, indicates that different opinions exist concerning the manner in which the physical environment of a soil is changed when the mulch is applied. Experiments were designed to elucidate the mode of action of petroleum mulches. Instruments were developed with which small changes in temperature and water content of a soil slab could be measured. The soil slab was designed to represent a vertical cross section of an actual soil profile and mulch was applied so that the field geometry was simulated. The experiments were conducted in an air conditioned laboratory. After several preliminary trials an experimental procedure was arrived at. Soil was packed into containers at a predetermined water content. A band of mulch was applied to the surface of the soil. The soil was then subjected to a daily temperature cycle with an amplitude representative of a moderately warm day in the Willamette Valley. Changes in soil water content and soil temperature were measured at regular intervals.

The purpose of these measurements was to establish whether the effect of an application of petroleum mulch on seed germination and early plant growth should be attributed to changes in the soil water content, to changes in soil temperature or to an interaction of these two variables.

REVIEW OF LITERATURE

The use of petroleum mulches sprayed onto the soil immediately following the seeding of row crops has found increased application in recent years. The mulches consists of water soluble petroleum resins which are sprayed onto the soil in a band about six to ten inches wide over the seeds. Observations of more rapid and more uniform germination have been reported in many instances. Often the more vigorous early seedling growth resulting from a mulch application is reflected in increased yields at harvest time. The improved growth is most often attributed to an increase in soil temperature resulting from the application of mulch, even though improved soil water conditions are also mentioned. Soil water content and soil temperature are possibly the most important physical parameters to be considered in the evaluation of seed germination and subsequent seedling growth.

Soil Water Availability and Germination

Sedgley (1963) examined the relationship between soil water potential and germination. Using seeds of Medicago tribuloides Desr. he demonstrated a decrease in the rate of germination as the soil water suction increased. Improved germination at the low soil water suctions was attributed to a large contact area between the seed surface and the water films in the soil pores. Owen (1952) made similar observations.

Mederski and Wilson (1960) attributed the impairment of plant growth by lack of water to a decrease in uptake. At low water contents the continuity of the moisutre films is broken and the ion transfer from soil to root is impeded. As the thickness of the moisture film decreases the solvent properties of soil water decrease and at the same time the density of the cation swarm surrounding the soil particles decreases.

Peters (1957) maintained that the uptake of water by corn roots is a function of the specific soil water content as well as the soil water potential. Root elongation and its moisture uptake decrease as the water content per unit tension decreases. He speculated further that the transfer of solids from the endosperm is a function of moisture content and moisture tension.

Soil Temperature and Germination

Willis, Larson and Kirkham (1957) demonstrated that an increase in soil temperature accelerates the rate of emergence and rate of growth, and prompts earliness in corn. They further observed that corn growth rates approximate Van't Hoff's Law with a Q_{10} value ranging from 2. 0 to 2. 8 for the temperature range of 15 to 27°C. Allmaras, Burrows and Larson (1964) studied the effects of soil temperature on growth of corn in the northern U. S. and concluded that a few degrees temperature change can cause a large change in the early growth of the plant. They established 81.3°F (27.4°C) as the optimum soil temperature for the early growth of corn. They further concluded that the rate of growth was a linear function of the soil temperature at a depth of four inches. Cannon (1917) studied the rate of germination of corn during the summer and autumn. He determined that most seeds germinated after four days during the summer, but only after 14 days in the autumn. This difference was attributed to differences in soil temperature. The importance of favorable soil temperatures was further emphasized by his observation that Opuntia versicolor, a native of Southern Arizona shows strong vegetative growth at low air temperatures as long as the roots are kept at a high enough temperature. An adverse effect on the growth rate of corn seedlings by low soil temperatures was also reported by Larson, Burrows and Willis (1960). Bonner and Galston (1952) established 34°C as the optimum temperature for the germination of corn seed. They attributed the high rates of growth at high temperatures to an increased rate of chemical reactions.

Knoll, Lathwell, and Brady (1964) believe that low root zone temperatures retard the growth of corn seedlings because of impaired uptake of phosphorus. At low temperatures the phosphorus uptake is reduced which leads to anthocyanin synthesis and purpling of corn. Even high phosphorus levels cannot counteract this harmful effect.

Letey *et al.* (1961) report that the rate of oxygen supply is increased with an increase in soil temperature. The solubility of oxygen decreases 1.6% per $^{\circ}$C, and the diffusion rate of O_2 through water increases 3-4% per $^{\circ}$C. They suggest that as a result of improved oxygen supply, sunflowers take up more potassium, phosphorus and calcium, and that cotton accumulates more calcium and phosphorus.

Mederski and Jones (1963) state that an increase in root temperature increases ion absorption, diffusion rate, reaction velocity, solubility, synthesis and translocation which culminates in an increased rate of plant growth.

Petroleum Mulch and Germination

Petroleum mulch through its effect on soil water content and soil temperature stimulates germination, and early plant growth and in some instances results in higher yields of plants.

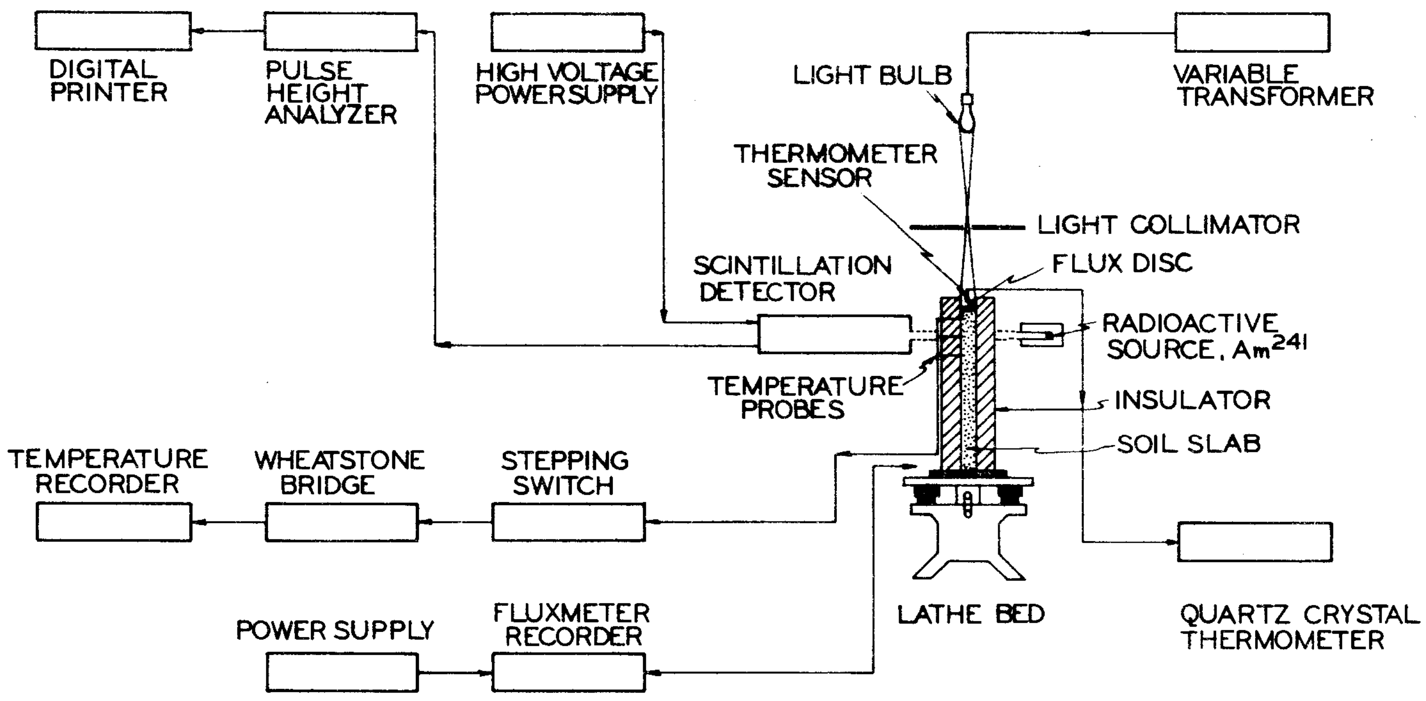
Some researchers attribute the beneficial effect of the petroleum mulch exclusively on the increase in soil temperature. Hale, Stockton and Dickens (1965) report an increase in cotton seedling emergence, plant height and weight, yield and earliness. They maintain that the mulch had no effect on soil moisture distribution, but increased the maximum soil temperature. Takatori, Lippert, and Whiting (1963) measured a temperature difference of up to 18°F at a depth of six inches between mulched and bare soil. They applied the mulch in bands ranging in width from 3 to 24 inches, with the six-inch wide band giving the best results. A research report by Armour Agricultural Chemical Co. (1964) states that an increase in soil temperature ranging from 10 to 20°F was obtained in the soil at the depth of the seed by applying petroleum mulch. No quantitative information on soil water content was presented. Zahara, Davis, and Fry (1965) report that the soil temperature at a depth of 3.5 inches was higher by 10°F under a four-inch wide band of petroleum mulch. A higher rate of emergence of seedlings was observed, but there was no significant increase in the yield of cantaloupes. Johnson, Hedden, and Wilson (1966) report that petroleum mulch increased the soil temperature by 2°F at the two-inch depth. Mulching also increased germination, earliness, and the total yield of cucumbers by 25 percent. Norton and Bratz (1966) have noted earlier maturity, larger fruit size, and some increase in yield with the application of petroleum mulch on cucumber, sweet corn, and pole beans. Pole beans and sweet corn matured about five days earlier when mulch was applied. The soil temperature was increased by 2°F under a six-inch wide band of mulch and 7°F under a 12-inch wide band. Barnes (1960) observed an increase of 25% in germination of cotton seeds by application of petroleum mulch. He also points out that those plants which emerged through the mulch were more vigorous than those emerging from bare soil. Petroleum mulch also increased plant growth, hastened maturity and increased yield of cantaloupes (Darby, Scudder and Whitner, 1962).

Some research reports do mention the effect of a petroleum mulch application on changes in soil water content. Esso researchers (1962) attribute the earlier growth of crops and increased yields to the reduction of evaporation caused by the sealing of the soil surface by the mulch, the increase in soil temperature and a reduction of the leaching of minerals from the root zone. They measured an increase of 300 percent in the rate of germination of carrot seed. Hachett and Bloodworth (1963) did not notice any change in soil temperature under the mulch at the two-inch depth but noticed a higher moisture content in the 0-3 inch soil layer. Two days after application of the mulch the soil water content was one to two percent higher under the mulch than under the bare soil. Four days after application the water content was two to four percent higher under the mulch and after ten days the mulched and the bare soil had about equal amounts of moisture. Seedling emergence was accelerated two to three days, and a yield increase of 118, 123, and 230 percent over the check was obtained when 60, 125, and 170 gallons of petroleum mulch per acre were applied. Sale (1966) reports that petroleum mulch increased the earliness and uniformity of emergence in some vegetable crops and attributes these phenomena to an increase in soil water content and soil temperature. Wilson and Hedden (1965) report petroleum mulch resulted in a 3°F increase in soil temperature at a depth of two inches and 1.5% increase in water content in the top three inches of soil. The mulch increased emergence and maturity of cucumbers, tomatoes, and snap beans. Fletcher (1964) also mentions improved soil water conditions as one of the beneficial effects of a mulch application. He further notes that a lack of soil crust formation when mulch is applied is important in certain instances. When the effects of a petroleum mulch application on soil water content were measured, the changes were not always apparent. Cochran *et al*. (1964) found that a band of mulch caused an increase in the temperature of the soil but could not detect changes in soil water content. A higher rate of emergence of cotton seedlings in mulched plots was noticed when the planting was early in the season; however the mulch did not show any effect on the maturity of the plants at harvest time.

MATERIALS AND METHODS

An experimental arrangement was designed to measure changes in water content resulting from diurnal temperature cycles imposed on a slab of soil and to observe possible changes in water movement which might be brought about by an application of petroleum mulch on the surface of the soil.

A schematic diagram of the experimental arrangement used is shown in Figure 1. The soil slab was 4. 0 cm thick, 40. 0 cm wide, and 48. 0 cm high. Changes in soil water content were measured with a gamma beam attenuation system. Water content changes were measured at regular intervals at several points in the slab. This was accomplished by moving the collimated beam in the vertical direction and the soil slab itself in the horizontal direction. Changes in soil temperature were obtained with infra red heat lamps. The heat flux was regulated with a powerstat. The lightbeam was collimated to avoid heating the components of the gamma beam apparatus. Soil temperatures were measured at regular intervals with thermistors inserted into the soil slab. The heat flux at the surface of the soil was measured with a heat flux measuring system. The experiments were conducted in an air conditioned laboratory.



EQUIPMENT LAYOUT FOR PETROLEUM MULCH EXPERIMENT

Figure 1. Schematic diagram of the experimental arrangement used for the petroleum mulch experiment.

The Soil Slabs

Construction of the Containers

Figure 2 shows a typical situation of an application of petroleum mulch to a row crop. Line a and line b represent lines of symmetry and therefore constitute the boundary conditions of the problem to be studied. The width of the slab was selected to represent the distance L between lines a and b. For L a distance of 40 cm was chosen. This corresponds closely to the spacing of certain row crops in the field. To represent narrower spacings it would be possible to insert spacers in the box. The depth of the slab was chosen to be 48 cm. In a pilot experiment it was observed that for the amplitudes used, the temperature remained nearly constant at a depth of 30 cm. By selecting the depth near 50 cm it could be assumed that a soil column of infinite depth was being studied. The width of the soil slab was selected to be 4. 00 cm. This represents the optimum thickness of a soil slab when changes in water content are measured with a gamma beam where the source of gamma radiation is Americium 241.

The soil was contained in boxes made of 1/4 inch plywood. Pieces of plywood were cut to the appropriate sizes and water proofed by applying two coats of epoxy paint. The pieces were glued together with the water proofed side on the inside. Epoxy paint was then applied to the joints on the inside to make the boxes completely water proof. To strengthen the boxes and avoid deflection of the sides, braces were made of 1/2 inch L-iron as shown in Figure 3. The top of the brace was 12 cm below the top of the box. To eliminate heat loss through the sides of the boxes during the experiments, styrofoam insulation was used. Sheets, five cm thick, were glued to all four sides. Finally a styrofoam cover was made for each box. A completed assembly is shown in Figure 3.

Packing the Containers

For the successful completion of the experiment it was essential to prepare soil slabs with a uniform soil water content. It appeared difficult to obtain uniform distribution of water by wetting up the soil and it was impossible to place pre-wetted soil in the containers and obtain a uniform density. It was hypothesized that if ice could be mixed thoroughly with the soil in a pre-determined quantity, the thawing would result in a uniform distribution of water. This method was tested and found to give a uniform water distribution and soil density.

The soil used was Chehalis silty clay loam, with 6. 5, 65. 6, and 27. 9% sand, silt, and clay respectively. The soil water release curve for the soil used is shown in Figure 4. The amounts of water to be added to obtain a given soil water content were based on this graph. All soil used was passed through a two mm sieve.

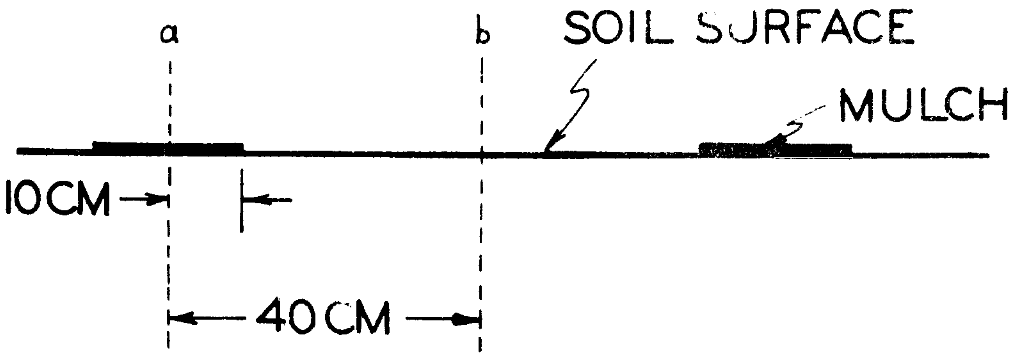


Figure 2. Schematic diagram of bands of petroleum mulch applied to row crops in the field.

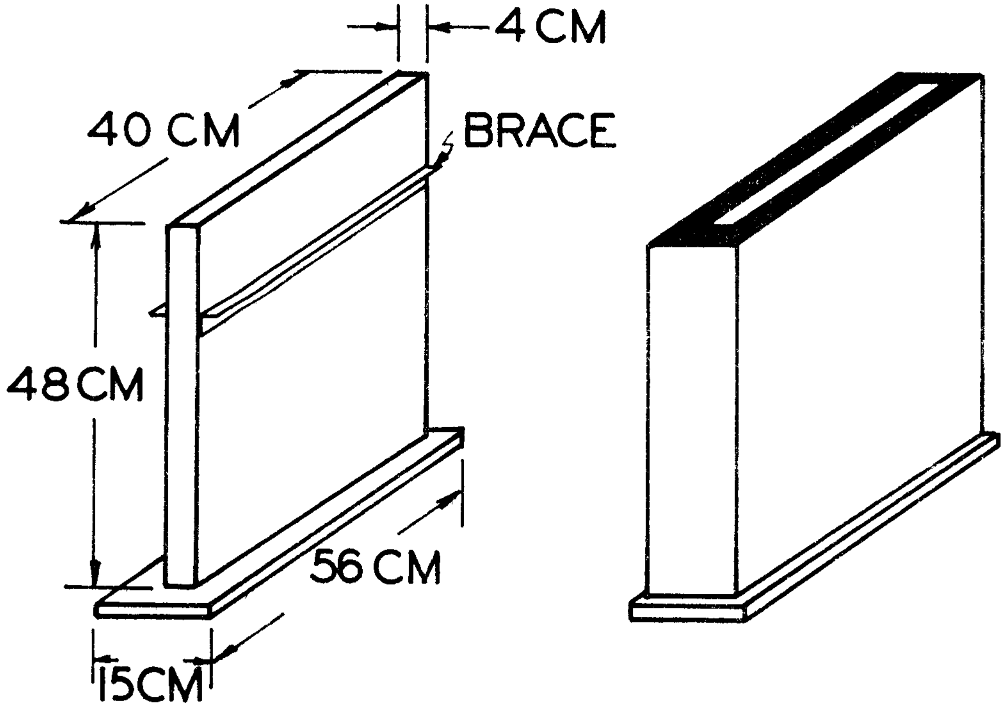


Figure 3. Schematic diagram of the soil container without insulation (left), and with insulation (right), used for the petroleum mulch experiments.

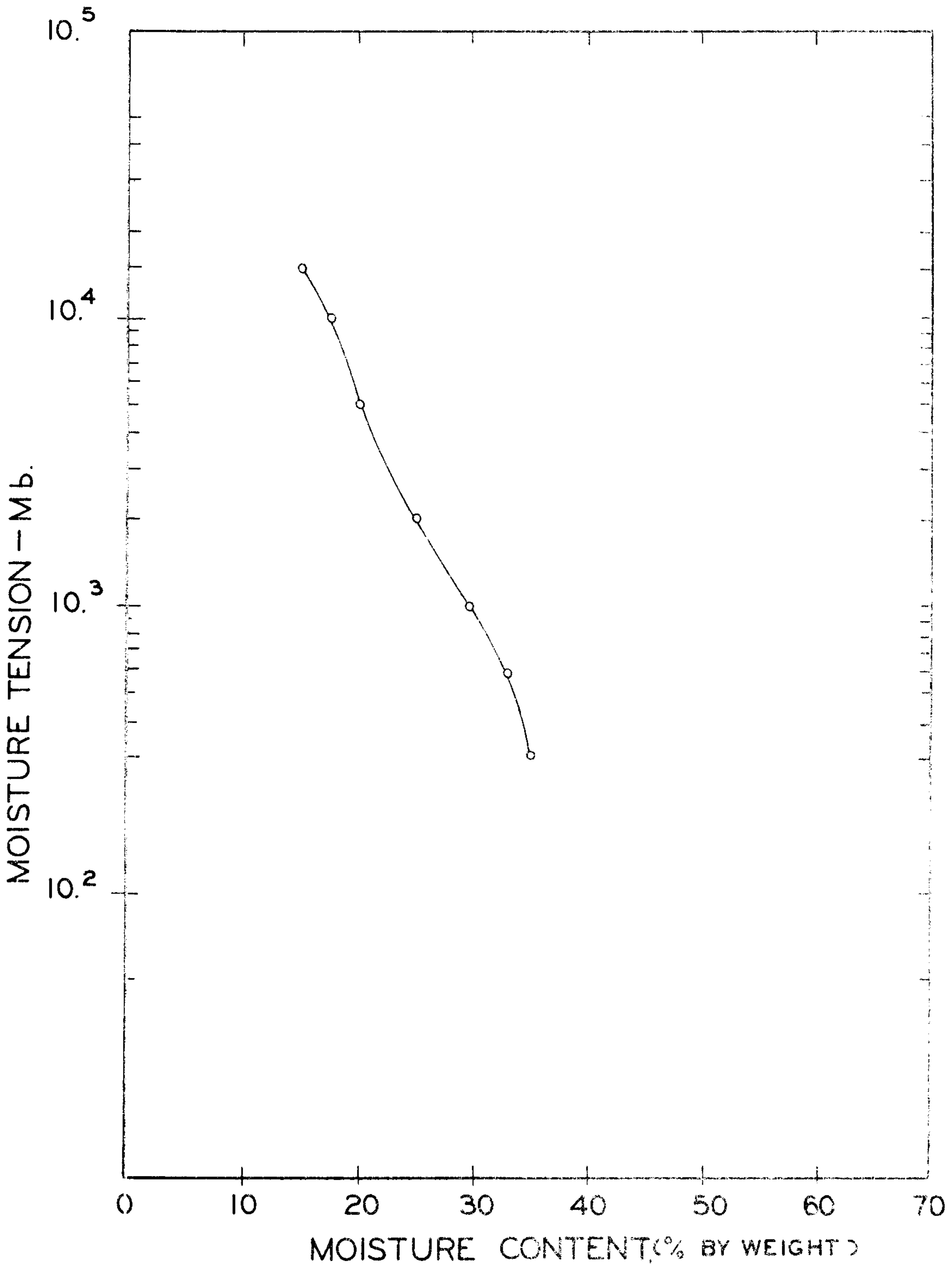


Figure 4. Soil water suction curve for Chehalis soil.

Mixing of soil and ice and packing of the boxes was done in a cold room maintained at 28°F. A pre-determined amount of flaked ice was weighed and added to each lot of soil. The quantity of soil was chosen to be sufficient to fill a box and the quantity of ice was chosen to obtain a certain water content of the soil upon mixing. In order to obtain the correct quantity of ice to be added, the water content of the air-dry soil was determined before hand. Since most of the ice particles were larger than two mm, the mixture of soil and ice was passed through a two mm sieve. The large particles of ice covered with soil were put into plastic bags, covered with cloth towels and hammered with a light mallet. This procedure was continued until the entire mixture passed through the sieve. The mixture was then stirred well to decrease any chance of accumulation of ice at one point. The mixture was poured into the boxes through a funnel built for this purpose. The height of the stem was 48 cm. The bottom of the box was tapped on the floor three times after every fourth scoop of the mixture added. The mixture of ice and soil had a somewhat higher volume than the initial volume of the soil. Some of the soil left over was used for a gravimetric water content determination. The packed boxes were covered with the lids and moved to the air conditioned laboratory for storage until the beginning of the experiment.

Heat Conductivity of the Soil

For the analysis of the problem of heat and water transfer in soil, knowledge of the thermal conductivity of the soil as a function of its water content is essential. The thermal conductivity of the soil at different water contents was determined with a thermal conductivity probe. The principle of operation of this method is that the temperature rise of a probe imbedded in the soil and heated at a constant rate depends on the rate at which the heat is conducted away by the soil, hence on its thermal conductivity. The soil was contained in beakers large enough to represent an infinite medium for this measurement. Details of the method are given by Cochran, Boersma, and Youngberg (1967).

In earlier experiments with Chehalis soil it was found that air-dry Chehalis soil contains about 16 percent water. In order to obtain soil at lower water contents, eight drying cans were filled with air-dry soil and put in an oven at 105°C. The first can was removed after 15 minutes, the second after one-half hour, the third after one hour, the fourth after two hours, the fifth after eight hours, the sixth after 16 hours and the seventh and eighth after 24 hours. The actual water contents attained were subsequently determined. Containers (250 ml beakers) were then filled with soil. The beakers numbered one through eight were filled with 250 grams of the oven dried soil.

Container number nine was filled with air-dry soil, containers 10 through 20 were filled with air-dry soil with water added. The first sample of soil was spread thinly on a plastic sheet and 3. 5 ml of water was applied using a syringe with a small hypodermic needle. As the water was applied, it was mixed with the soil to obtain a uniform distribution. The soil was then packed into the container through a plastic funnel in such a way that all parts of the container had equal thickness of soil. The container was hit flatly against the table top three times, the first time after the container was approximately one-third full, the second time after the container was approximately two-thirds full, and the third time after the container was full. The container was then covered immediately with a plastic sheet which was secured with a rubber band to prevent loss of moisture by evaporation. The second sample of soil was then spread thinly on a plastic sheet and 5. 0 ml. of water was added. This sample was packed into a container using the method described above. All the remaining samples of soil had water added, using the same process. Each successive soil sample had 1. 5 ml more water added than the previous sample. Finally the containers were shaken with an electric vibrator, and thereupon put into a constant temperature cabinet and kept for a week.

The temperature rise of the thermistor at the center of the probe was recorded with a Heath recorder. The recorder was adjusted to read 1°C for the full span (0-100) of the chart, so that 0.01°C could be read accurately and a third significant figure could be estimated. The experimental arrangement is shown in Figure 5. The probe was inserted into each container through the plastic cover so that the whole length of the probe and part of its handle was in the soil. The power switch was turned on and heat applied to the probe. The rise in temperature of the probe was recorded. The recorder registered the rise in temperature of the probe in each container for eight minutes, resulting in a graph as shown in Figure 6. The dissipation part of the curve was plotted on semi-logarithmic paper using the logarithmic scale for the time variable. The thermal conductivity, λ, was then calculated with the equation

$$\lambda = 0.000686 \frac{\log t_2/t_1}{T_2 - T_1} \text{cal sec}^{-1}\ {}^{\circ}\text{C}^{-1} \tag{1}$$

where t is time in seconds and T the temperature of the probe in °C.

Upon completion of the measurements, soil samples were taken for a gravimetric water content determination.

Temperature Measurements

Soil temperatures were measured with thermistors. These were inserted into the soil through holes in the side of the box. The

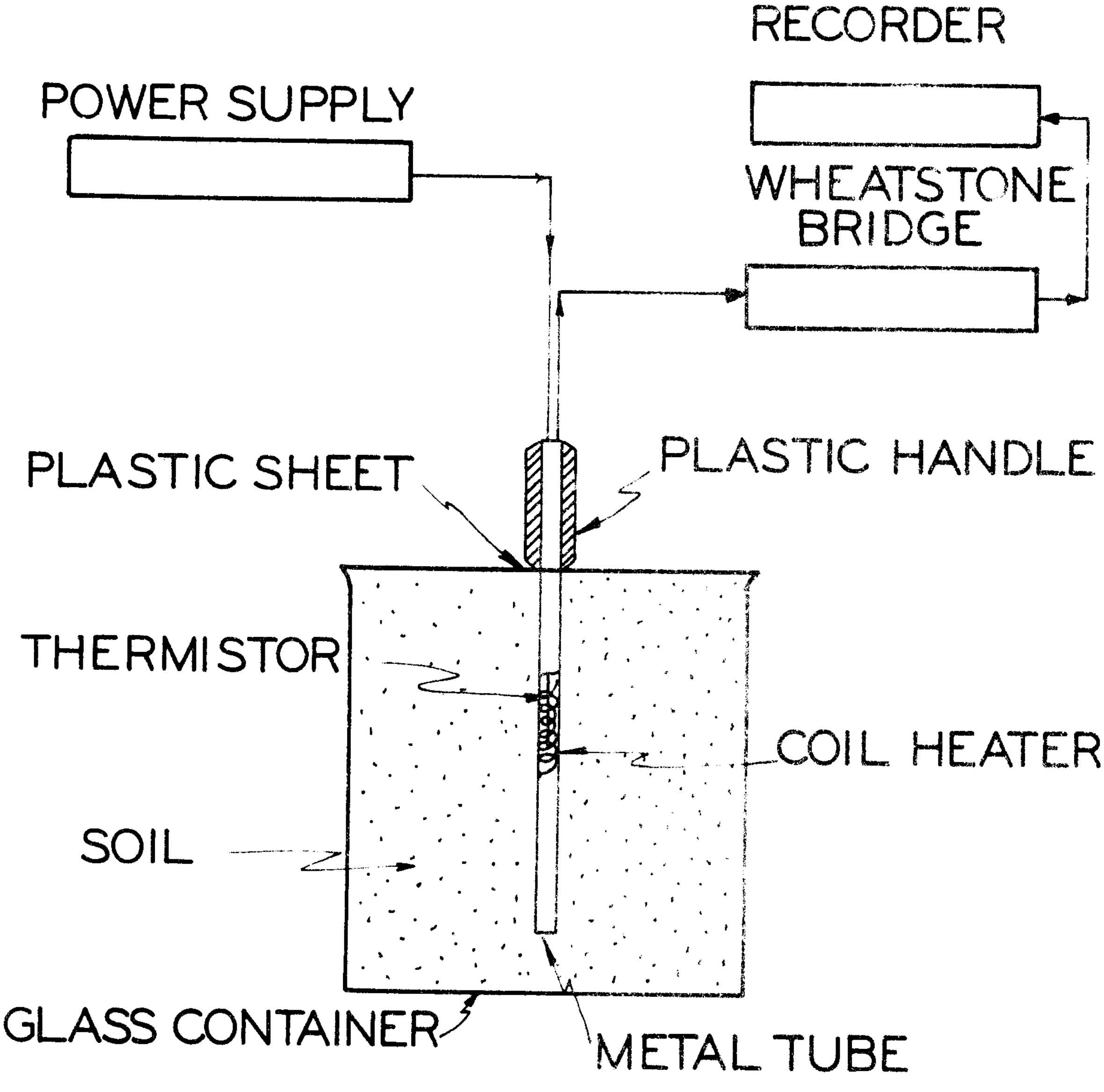


Figure 5. Schematic diagram of the experimental arrangement used to measure the heat conductivity of the soil.

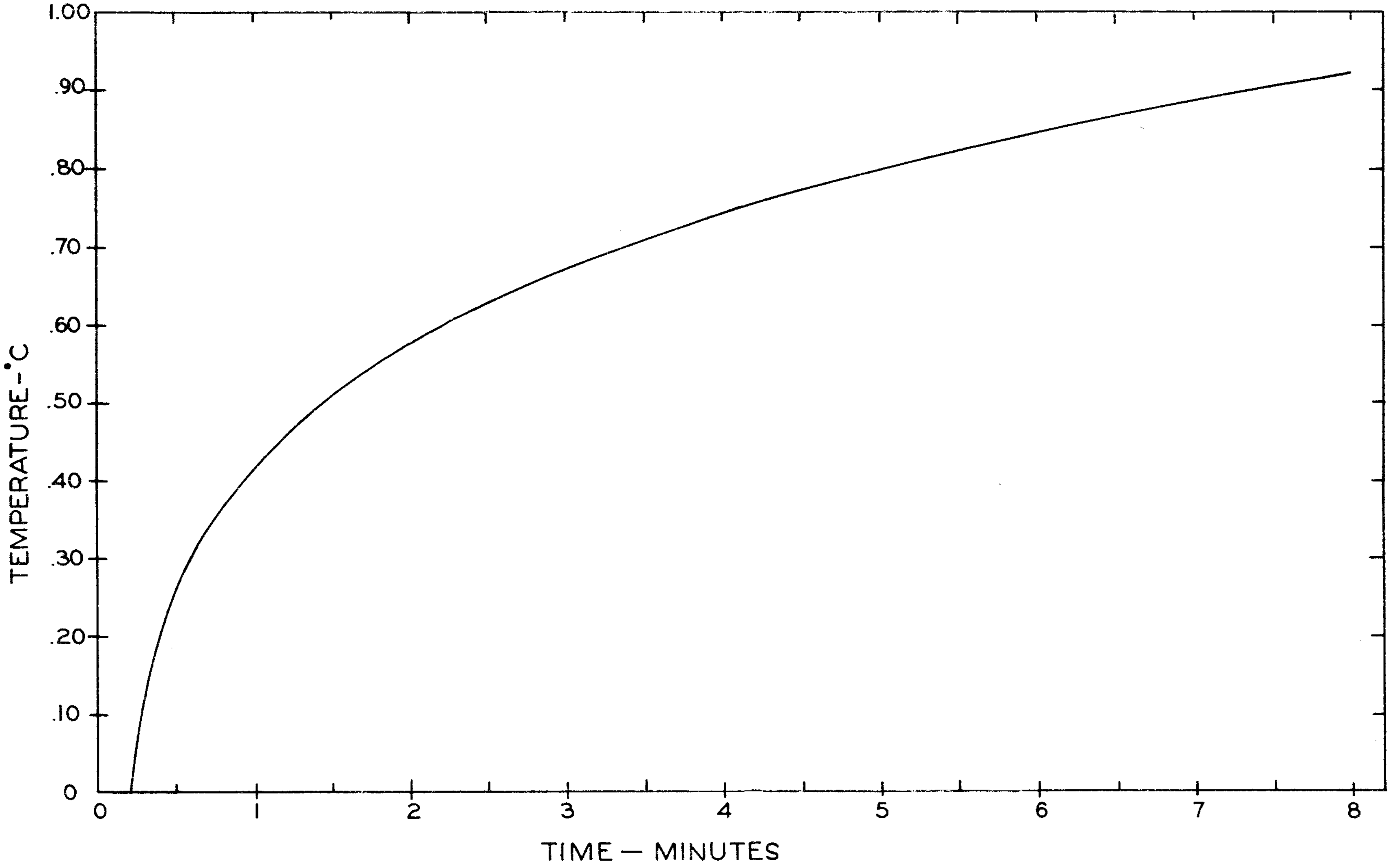


Figure 6. Temperature rise of the heat conductivity probe as a function of time.

placement of the thermistors is shown in Figure 7. The units were placed at depths of 1, 3, 6, 10, 17, 37, and 42 cm below the soil surface. They were placed in six vertical columns, three of which were below the area over which the petroleum mulch was to be applied and three were below the bare soil. The leads of the thermistors in each column were tied together with lacing cord. The thermistors penetrated two cm into the soil and were inserted at the time an experiment was initiated. Fenwall GB 41P8 glass probe thermistors were used. These need to be calibrated individually. For this calibration a Hewlett Packard 2801 A quartz thermometer was used as a reference. Thermistor resistance values at several temperatures were obtained and plotted as shown in Figure 8.

Soil temperatures were recorded with a single channel strip chart recorder. The individual thermistors were switched in sequence into a Wheatstone bridge measuring circuit using a timer and rotary stepping switch. The bridge voltage output was recorded as a series of steps, each one representing a thermistor.

Figure 9 shows a sample of the temperature recorder chart. Numbers 1 through 40 represent individual thermistor outputs. Each number identifies the position at which the temperature measurement was made. The chart readings were calibrated for the particular Wheatstone bridge circuit in terms of resistance, with a decade resistance box. The calibration curve showing the chart reading versus

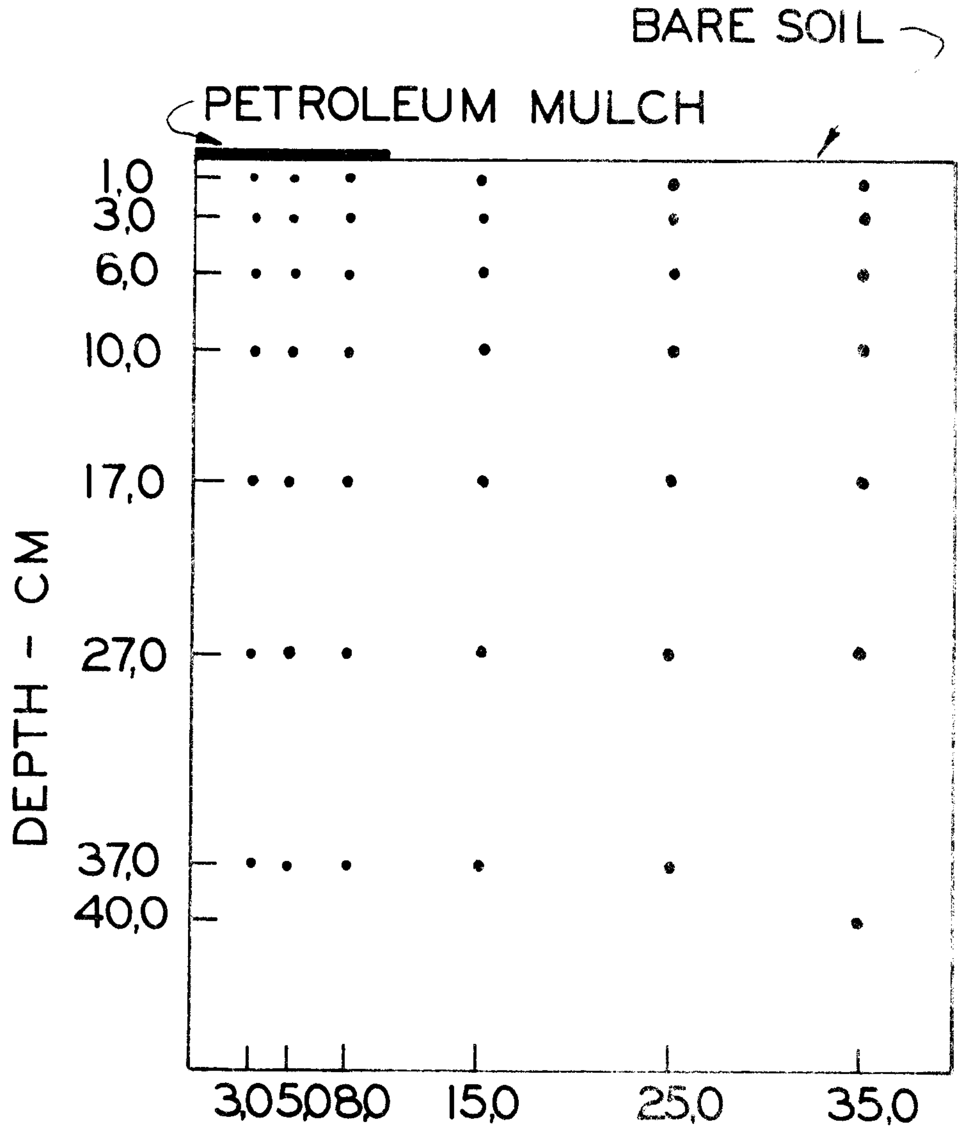


Figure 7. Positions at which soil temperature measurements were made.

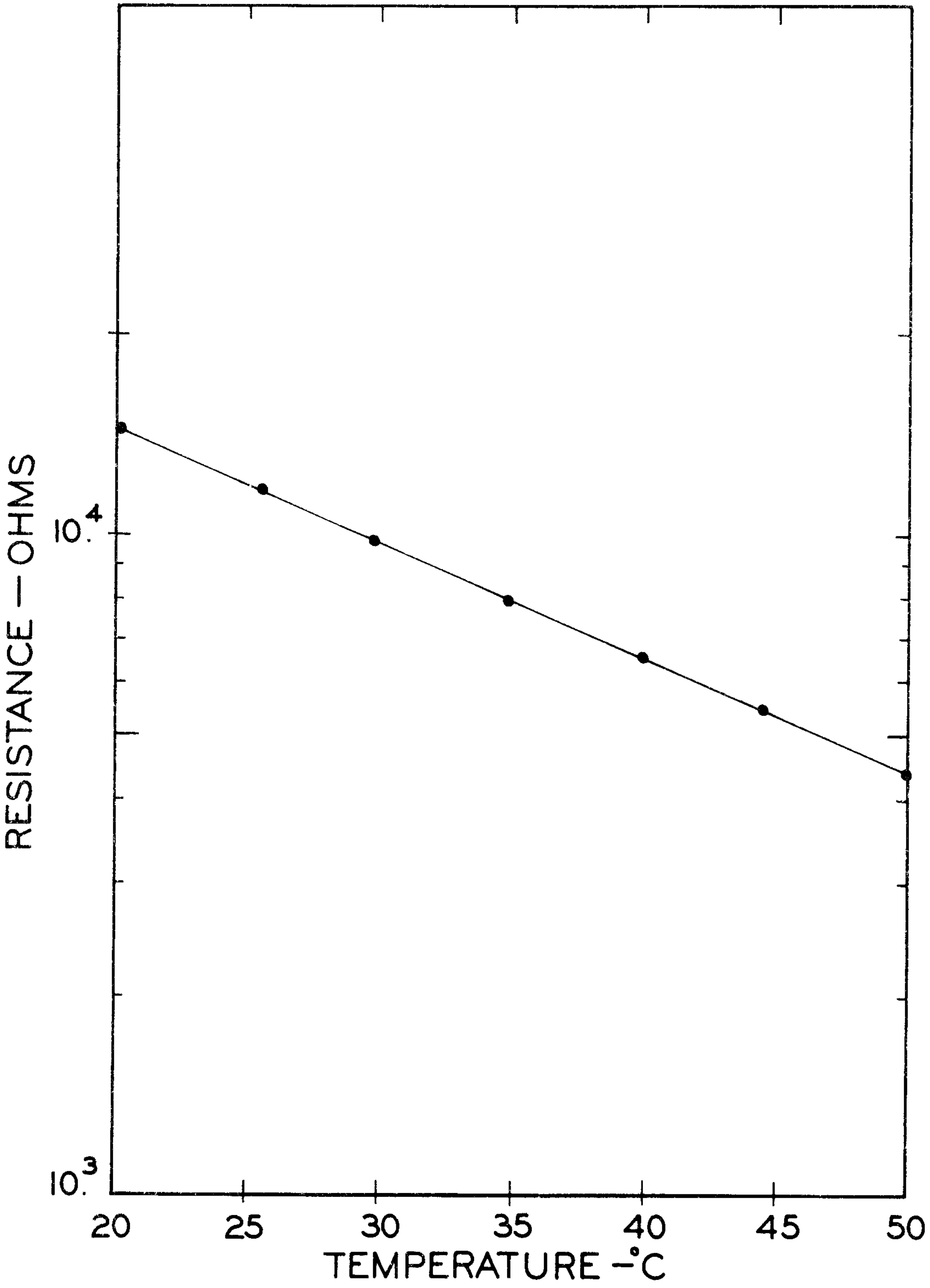


Figure 8. Thermistor resistance as a function of temperature.

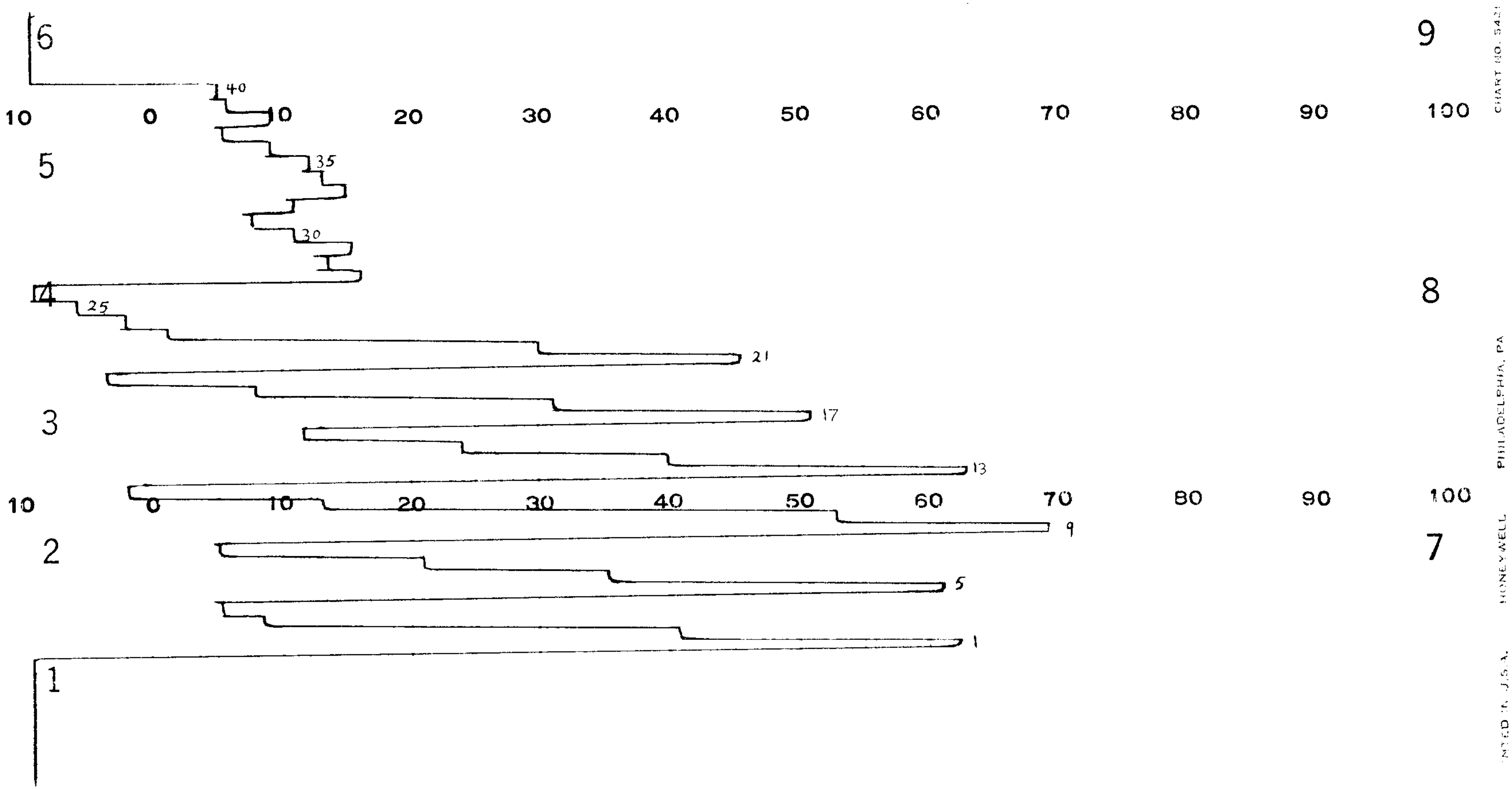


Figure 9. Sample of a temperature recording, each benchmark representing a thermistor.

resistance is shown in Figure 10. For each thermistor a table was prepared showing the temperature corresponding to a given chart reading. Part of the table for thermistor No. 3 is shown in Table 1. For example: a chart reading of 8.4 corresponds to a temperature of 31.35°C.

Table 1. Sample of tables prepared for each thermistor to convert chart reading to temperature.

Chart reading	Temperature, °C				
	.0	.2	.4	.6	.8
1.0	29.50	29.56	29.62	29.68	29.74
2.0	29.80	29.85	29.90	29.95	30.00
3.0	30.05	30.19	30.15	30.20	30.25
4.0	30.30	30.35	30.40	30.45	30.50
5.0	30.55	30.60	30.65	30.70	30.75
6.0	30.80	30.84	30.88	30.92	30.96
7.0	31.00	31.05	31.10	31.15	31.20
8.0	31.25	31.30	31.35	31.40	31.45
9.0	31.50	31.55	31.60	31.65	31.70
10.0	31.75	31.80	31.85	31.90	31.95
11.0	32.00	32.05	32.10	32.15	32.20
12.0	32.25	32.30	32.35	32.40	32.45
13.0	32.50	32.55	32.60	32.65	32.70
14.0	32.75	32.80	32.84	32.88	32.92
15.0	32.96	33.00	33.06	33.12	33.18
16.0	33.24	33.30	33.36	33.42	33.48
17.0	33.54	33.60	33.65	33.70	33.75
18.0	33.80	33.85	33.90	33.95	34.00
19.0	34.06	34.12	34.18	34.24	34.30
20.0	34.35	34.40	34.45	34.50	34.55

Thermistors having nearly identical calibration curves were pooled and only one table was prepared. The precision of the temperature measurements using this procedure was 0.1°C.

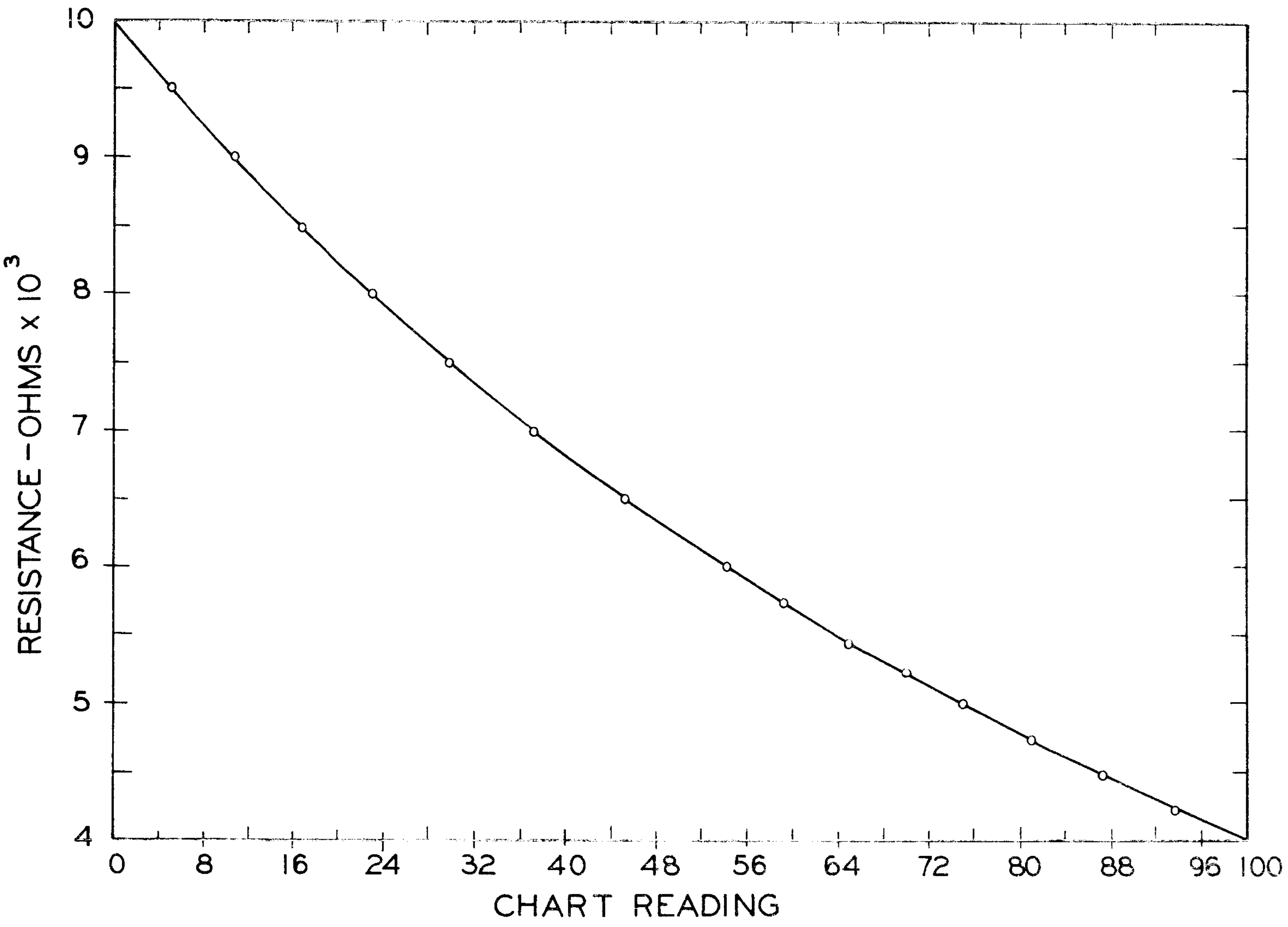


Figure 10. Recorder calibration curve, showing the relation between chart reading and resistance.

The thermistors were numbered one through 50 with number one having the lowest resistance and number 50 having the highest resistance at a given temperature. Five thermistors with the lowest resistance and five thermistors with the highest resistance were discarded and only 40 thermistors were used in the experiments. The thermistors have bare leads protruding from the glass probe which contains the thermistor head. One lead was insulated with small diameter insulating tubing. A larger diameter tubing was then used to cover both leads and part of the glass casing. The latter insulator was glued to the glass to secure it in place. Each thermistor was connected to the switch panel with two wires, each one meter long. The thermistors were connected to these wires with Amphenol "Wire Form" connectors, allowing quick assembly and disassembly. The Amphenol connectors were insulated by covering them with a piece of Vinyl tubing soaked in methyl-ethyl-ketone. The soaking causes the tubing to expand. Upon drying the tubing shrinks over the connector making a tight fit.

Each thermistor was identified by a numbered strip wrapped around the insulation. Since the thermistor near the surface of the soil would be exposed to the most extreme temperatures, those with the widest range were selected for this position.

Heat Flux Measurements

To measure and record the soil heat flux, a Model 310 Soil Heat Flux Recording System manufactured by C. W. Thornthwaite and Associates, Centerton, N. J. was used. The sensing unit is a small round disc, about the size of a quarter of a dollar. One unit was placed at a depth of two cm below the soil surface under the bare soil and a second one was placed at a depth of two cm below the mulch covered soil. One meter length of lead wire connected each sensor to a recorder, calibrated to read heatflux directly in calories per square centimeter per minute (langley's per minute).

Output of both sensors was recorded on the same unit by connecting them at alternate times. The time at which a change from one sensor to the other was made was noted on the chart paper.

Water Content Measurements

Theory

Changes in water content were monitored with a gamma beam system. This method is based on Beer's Law

$$I = I_0 e^{-\mu \rho x} \tag{2}$$

which states that the attenuation of transmitted radiation intensity I, is an inverse logarithmic function of the mass absorption coefficient μ, the density ρ, and the thickness x of the material the radiation passes through. In this experiment where the gamma beam was transmitted through the soil and water, the container wall and the insulating material, Beer's Law becomes

$$I = I_0 e^{-(\mu_w \theta + \mu_s \rho_s)x - \mu_c \rho_c x_c - \mu_i \rho_i x_i} \qquad (3)$$

where:

I = transmitted radiation intensity

I_0 = radiation with no interference

e = base of natural logarithm

μ_w = mass absorption coefficient of water (cm^2/gm)

μ_s = mass absorption coefficient of dry soil (cm^2/gm)

μ_c = mass absorption coefficient of the container material (cm^2/gm)

μ_i = mass absorption coefficient of the styrofoam (cm^2/gm)

θ = moisture content (gm/cm^3)

ρ_s = soil bulk density (gm/cm^3)

ρ_i = insulator bulk density (gm/cm^3)

x = sample thickness (cm)

x_c = thickness of the container (cm)

x_i = thickness of the insulating material (cm)

In this equation the variables are θ and I. For a given measurement of I, the value of θ can easily be calculated provided that the values of the other parameters, which remain constant, are known. Since the objective of the experiment was to measure changes in water content rather than absolute values of water content, no effort was made to measure the values of all the parameters in Equation 2. The change in water content $\Delta\theta = \theta_2 - \theta_1$ can be obtained as follows:

$$I_1 = I_0 e^{-(\mu_s \rho_s + \mu_w \theta_1)x - \mu_c \rho_c x_c} \qquad (4)$$

$$I_2 = I_0 e^{-(\mu_s \rho_s + \mu_w \theta_2)x - \mu_c \rho_c x_c} \qquad (5)$$

where I_1, is the count rate obtained for a water content θ_1, and I_2 is the count rate obtained for a water content θ_2.

$$I_2/I_1 = \frac{I_0 e^{-(\mu_s \rho_s + \mu_w \theta_2)x - \mu_c \rho_c x_c}}{I_0 e^{-(\mu_s \rho_s + \mu_w \theta_1)x - \mu_c \rho_c x_c}} \qquad (6)$$

$$= e^{-\mu_s \rho_s x - \mu_w \theta_2 x - \mu_c \rho_c x_c + \mu_s \rho_s x + \mu_w \theta_1 \mu x + \mu_c \rho_c x_c}$$

$$= e^{-\mu_w \theta_2 x + \mu_w \theta_1 w}$$

$$= e^{-(\theta_2 - \theta_1)\mu_w x}$$

$$\ln \frac{I_2}{I_1} = - \mu_w x(\theta_2 - \theta_1) \tag{7}$$

$$-(\theta_2 - \theta_1) = |\Delta\theta| = \frac{1}{\mu_w x} \ln \frac{I_2}{I_1} \tag{8}$$

The value of μ_w for Americium 241 was determined to be 0. 1947 cm^2/gm and $x = 4$ cm for all boxes, yielding the equation

$$\Delta\theta = 1.351 \ln I_2/I_1 \quad cm^3 cm^{-3} \tag{9}$$

To facilitate the recording of measurements and calculation of results, a table was prepared containing all the necessary information. Such a table is shown as Table 2. Changes in soil water content were calculated with Equation 9. All measurements were related to the initial reading I_0. The change in water content $\Delta\theta$, is shown as a percent change.

Equipment

The gamma attenuation equipment used consisted of a source of low energy gamma radiation, a scintillation detector, a single channel gamma spectrometer, and a printer.

The source of low energy gamma radiation employed was Am 241 (229 mc). This isotope has a near monoenergetic gamma output with approximately 60% of its radiation having an energy of 0. 061 Mev.

Table 2. Sample of data sheet used to record the measured radiation intensities. The calculation of $\Delta\theta$, the change in soil water content, is also shown.

Soil: Chehalis
Initial water content: 28%
$I_o = 36111$
$1/I_o = 2.769 \times 10^{-5}$

Starting date: 9-11-67
Position: mulched
Depth: 1 cm
$1/\mu_w x = 1.351$

Date	Time	I_θ	$\frac{I_\theta}{I_0}$	$\ln \frac{I_\theta}{I_0}$	$\Delta\theta$
					%
9-11-67	8:00	36111			
	10:00	36259	1.0041	-.0041	- .554
	14:00	34359	.9515	+.0497	+ 6.714
	20:00	33698	.9332	+.0691	+ 9.335
	22:00	37669	1.0431	-.0423	- 5.715
9-12-67	8:00	35599	.9858	+.0143	+ 1.932
	10:00	33473	.9269	+.0759	+10.254
	14:00	33936	.9398	+.0621	+ 8.390
	20:00	34807	.9639	+.0368	+ 4.972
	22:00	35147	.9733	+.0271	+ 3.661
9-13-67	8:00	33921	.9394	+.0625	+ 8.444
	10:00	34187	.9467	+.0548	+ 7.403
	14:00	35229	.9773	+.0230	+ 3.107
	20:00	35038	.9703	+.0301	+ 4.066
	22:00	35090	.9717	+.0287	+ 3.877
9-14-67	8:00	34460	.9543	+.0457	+ 6.174
	10:00	36189	1.0023	-.0023	- .311
	14:00	35237	.9758	+.0245	+ 3.310
	20:00	36087	.9993	+.0070	+ .946
	22:00	35321	.9781	+.0221	+ 2.986
9-15-67	8:00	35823	.9920	+.0080	+ 1.081

With the low energy output, a minimum of shielding is required. The optimum sample thickness is four to five centimeters.

The gamma rays were monitored with a scintillation detector, (Model HP 10602A), consisting of a sodium iodide, thallium activated crystal three inches in diameter and two inches thick, a photomultiplier tube and a pre-amplifier. A Hewlett-Packard single channel gamma spectrometer was employed for counting the radiation detected by the scintillation tube. This spectrometer consisted of a high voltage power supply (Model HP 5551A) for the scintillation tube and a scaler, timer and pulse height analyzer (Model HP 5201L). The output from the scaler was digitized and routed directly to a Hewlett-Packard Model HP 562AR printer. A scintillation count for any preset time was printed. A digital to analog converter (Model HP 580A) was included which allowed a strip chart recording with a Heathkit (Model EUW-20A) recorder when desired. The pulse height analyzer was set to detect transmitted gamma radiation of 0. 061 ± 0. 015 Mev.

The arrangement of the source holder, shields and braces to hold the detector is shown in Figure 11. A tapered collimating slit 1. 0 by 0. 10 cm was provided on both the source holder and detector side. The slits were aligned with a mercury vapor light beam. The source holder and braces to hold the detector were mounted on a platform, moveable along two parallel shafts on split bearings. The split bearings were needed to pass the supports of the shafts. The

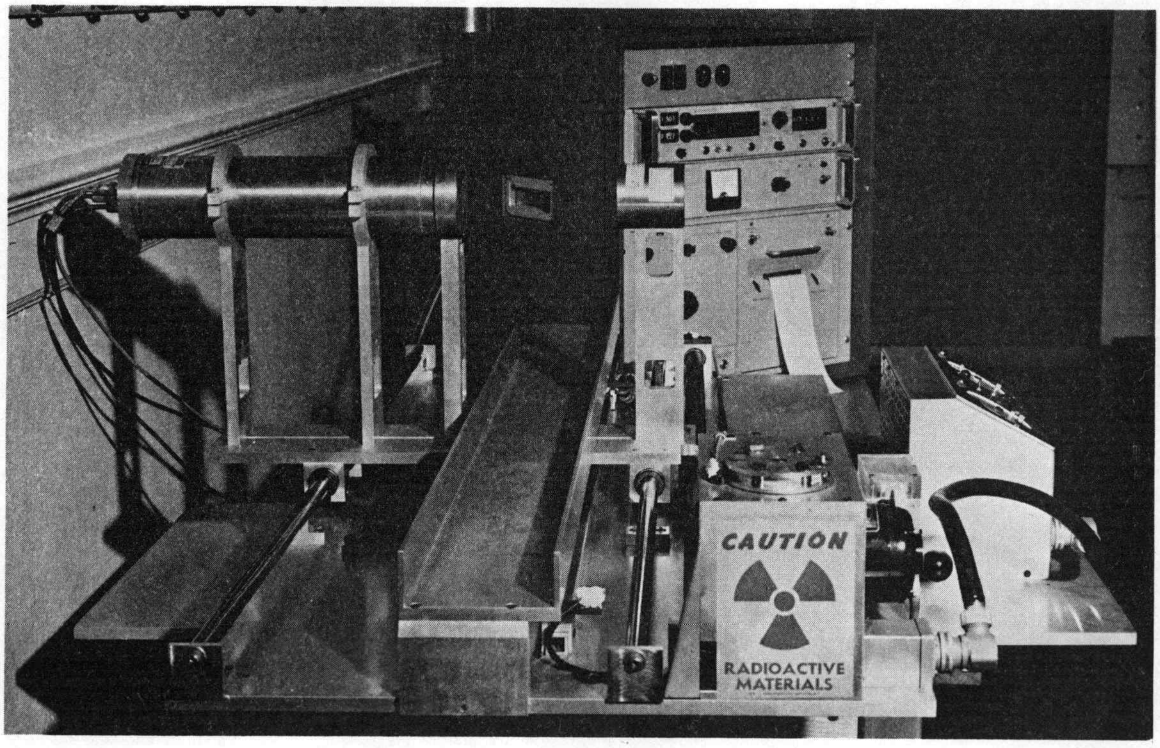


Figure 11. Photograph of the gamma attenuation equipment used to monitor the soil water content changes.

platform was moved along the shaft with a bolt, passing through a split nut connected to the platform. The shaft was driven with a geared down reversible motor. The control for this tracking system is visible in Figure 11. The entire assembly was mounted on a platform which can be tilted and put in a vertical position. In this experiment the assembly was used in the vertical position. For identification of positions a position marker was attached to the platform on which the source was mounted.

Gamma attenuation readings were taken at pre-determined points at regular intervals. The position of these points are noted in Figure 12. To move the gamma beam in a vertical direction to reach a certain point the screw drive was used. To move from point to point in the horizontal direction the soil container was placed on a lathe bed. A three-foot metal lathe bed, shown in Figure 13 was used to support the soil container as it was moved back and forth through the collimated gamma ray beam. Two guides were mounted on the lathe tracks and a steel plate was bolted to the ways forming a platform to support the soil container. A bolt was threaded through a nut underneath one of the guides allowing the soil container to be easily moved and positioned in the gamma ray beam. The position of the lathe bed was indicated by a position marker. The platform on the lathe bed was positioned at the desired location by cranking a handle connected to the threaded bolt.

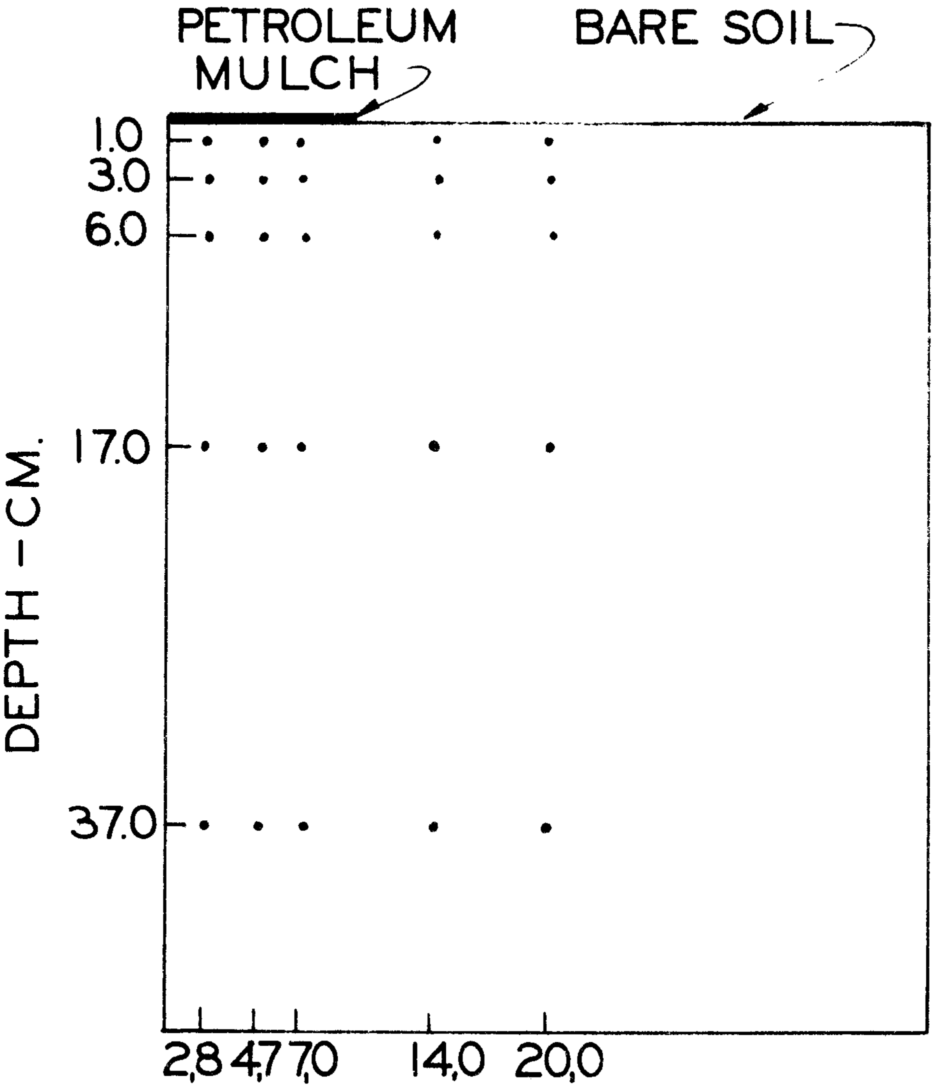


Figure 12. Positions at which water content measurements were made.

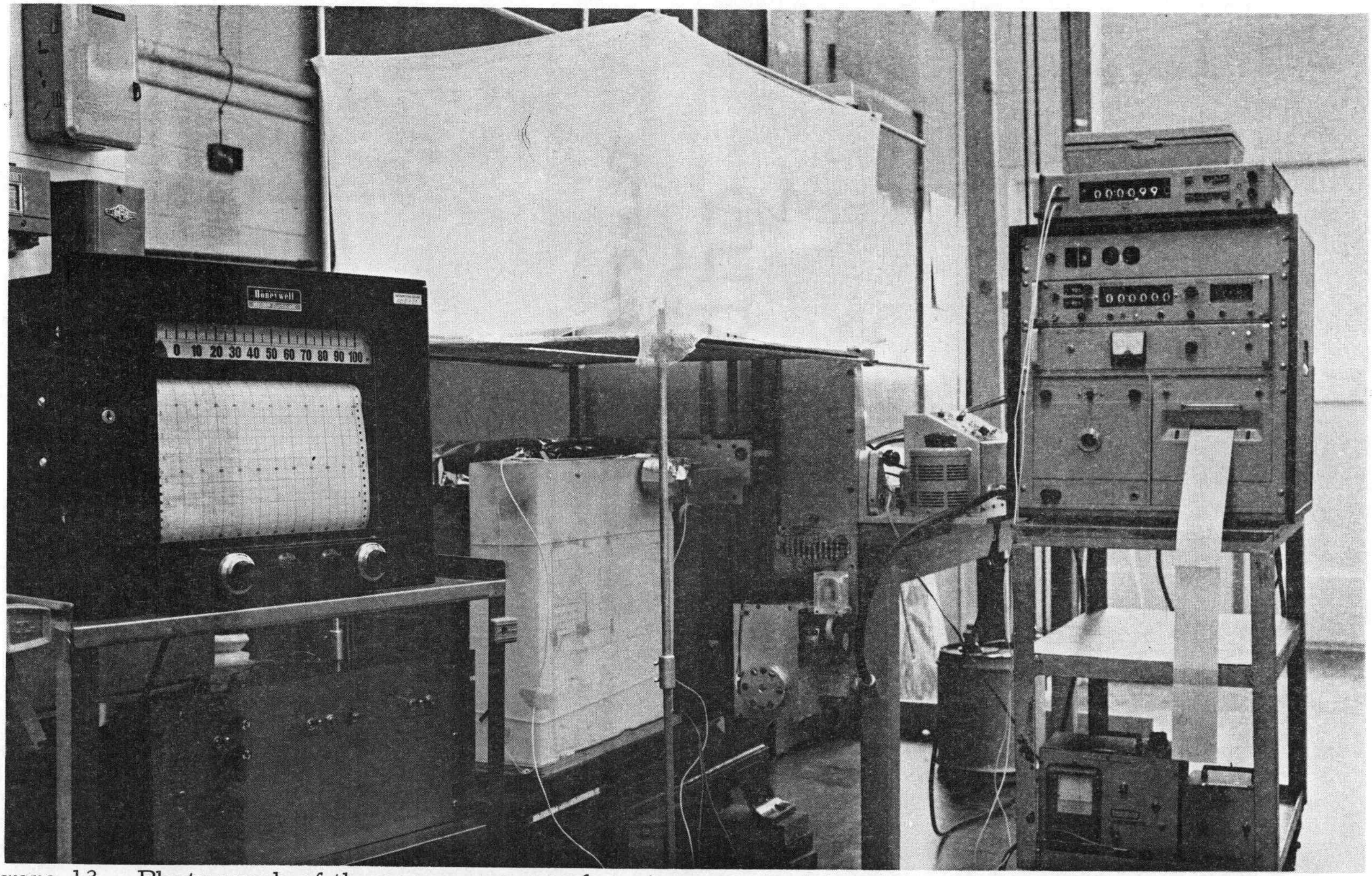


Figure 13. Photograph of the arrangement of equipment used for the petroleum mulch study.

Heating of the Soil

To heat the soil three, 250 watt, infra-red lamps were mounted on a board, which was suspended above the soil containers at a distance of 56 cm. A collimating device consisting of a sheet of 1/4 inch plywood with a slit cut-out, was inserted between the soil and the lamps. The purpose of the collimating device was to eliminate direct illumination of the components of the gamma attenuation system. The slit was positioned in such a manner that direct illumination of areas outside the soil surface was kept to a minimum. The upper side of the plywood was covered with aluminum foil to keep the wood from heating up so that transfer of heat to the areas below by means of long wave radiation would be prevented. Examination of the light intensity along the soil surface indicated that the energy distribution was not uniform. It was also noted that the light intensity was too high to obtain the desired soil surface temperature amplitude. To cut down the light intensity the slit was covered with a very coarse weave cloth. To obtain a uniform distribution of radiant energy more than one layer of cloth was used at certain places. These places were selected by trial and error.

A diurnal cycle simulating the daily course of the sun was obtained by changing the light intensity with a variable transformer at hourly intervals starting at 8:00 A. M. The light intensity was increased each hour on the hour until 2:00 P. M. Starting at 3:00 P.M. the light intensity was decreased every hour on the hour until 8:00 P. M. at which time the lights were turned off. The scheme which was followed is shown in Table 3.

Table 3. Schedule of light intensities maintained over the soil surface.

Time	Light Intensity	Lamp Voltage
	ft. candles	Volts
8:00 A. M.	100	74
9:00 A. M	200	85
10:00 A. M.	300	96
11:00 A. M.	400	105
12:00 A. M.	500	110
1:00 P. M.	600	116
2:00 P. M.	600	116
3:00 P. M.	500	110
4:00 P. M.	400	105
5:00 P. M.	300	96
6:00 P. M.	200	85
7:00 P. M.	100	74

To make sure that all parts of the soil surface received the same amount of energy at all times, a point was marked on the lathe bed and the lathe was positioned at that point at the end of each water content measurement.

Application of Petroleum Mulch

After imbedding a heat flux disc in the soil at a depth of two cm at the place where the mulch was to be applied, an area of 4 x 10 cm at one end of the box was covered with a thin layer of petroleum mulch. The mulch was applied 24 hours before the start of the experiment. The mulch was stirred well before the application to ascertain a uniform distribution of solids in the liquid matrix. The box cover was replaced after putting on the mulch.

The mulched soil attained a rather shiny, smooth surface with a brownish black color. The liquid mulch is brown, but as it dries up it changes to a brownish black color.

Experimental Procedure

An experiment was initiated by taking a soil box from the storeroom and putting it on the lathe bed. A heat flux disc then was burried at the depth of two cm in the bare soil and was connected to the heat flux recorder. Thermistors were then inserted through the holes into the soil. The initial readings of soil temperature, soil water content and heat flux were recorded. The lights then were turned on and the experiment was started. Temperature measurements were taken at two hour intervals. Soil water content measurements were made at 8:00, 10:00, 14:00, 20:00, and 22:00 hours. Light intensities were changed according to the schedule shown in Table 3.

RESULTS

The results of the three types of measurement, temperature, heat flux, and soil water content, are presented for two experiments, A and B. Experiment A was conducted for four days and experiment B for three days. The only difference in experimental variables was the initial water content. The soil of experiment A had an initial water content of 28% and the soil of experiment B had an initial water content of 26%.

Temperature Measurements

Experiment A

The temperature T, was measured at two hour intervals using the automatic switching arrangement of the temperature recorder. The initial temperature was measured at the start of the experiment. The temperature as a function of the time of the day is shown in Figures 14, 15, 16, 17, and 18 for the depths of one, three, six, ten, and 17 cm, respectively.

Examination of Figure 14, indicates that the temperature at a depth of one cm below the mulch was always higher than the temperature at the same depth below the bare soil. The difference in the temperature, ΔT, of the two points decreased from the first to the fourth day. For example, the maximum difference which occurred at

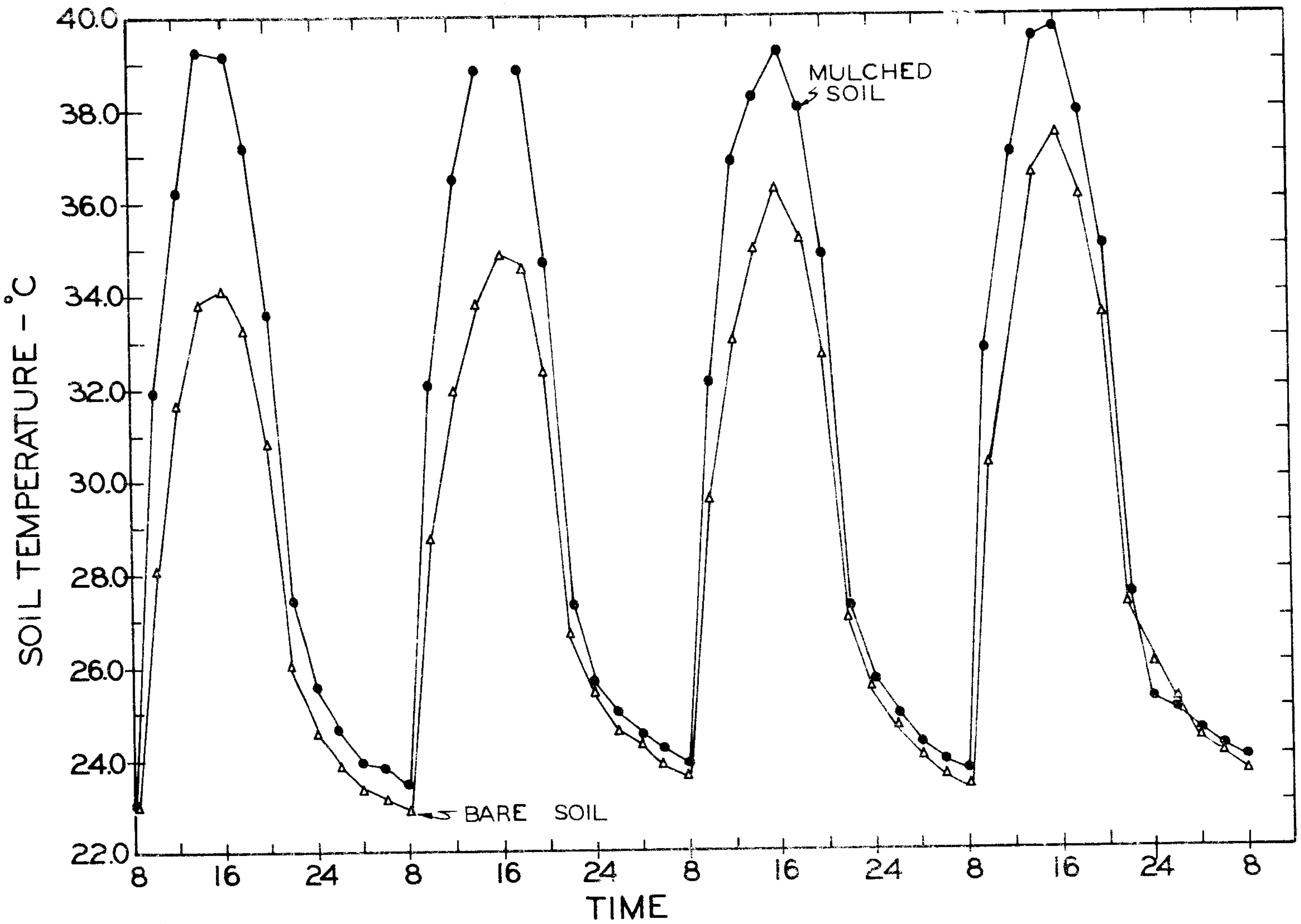


Figure 14. Soil temperatures under the mulch covered and bare soil surface at a depth of one cm plotted as a function of time. Experiment A.

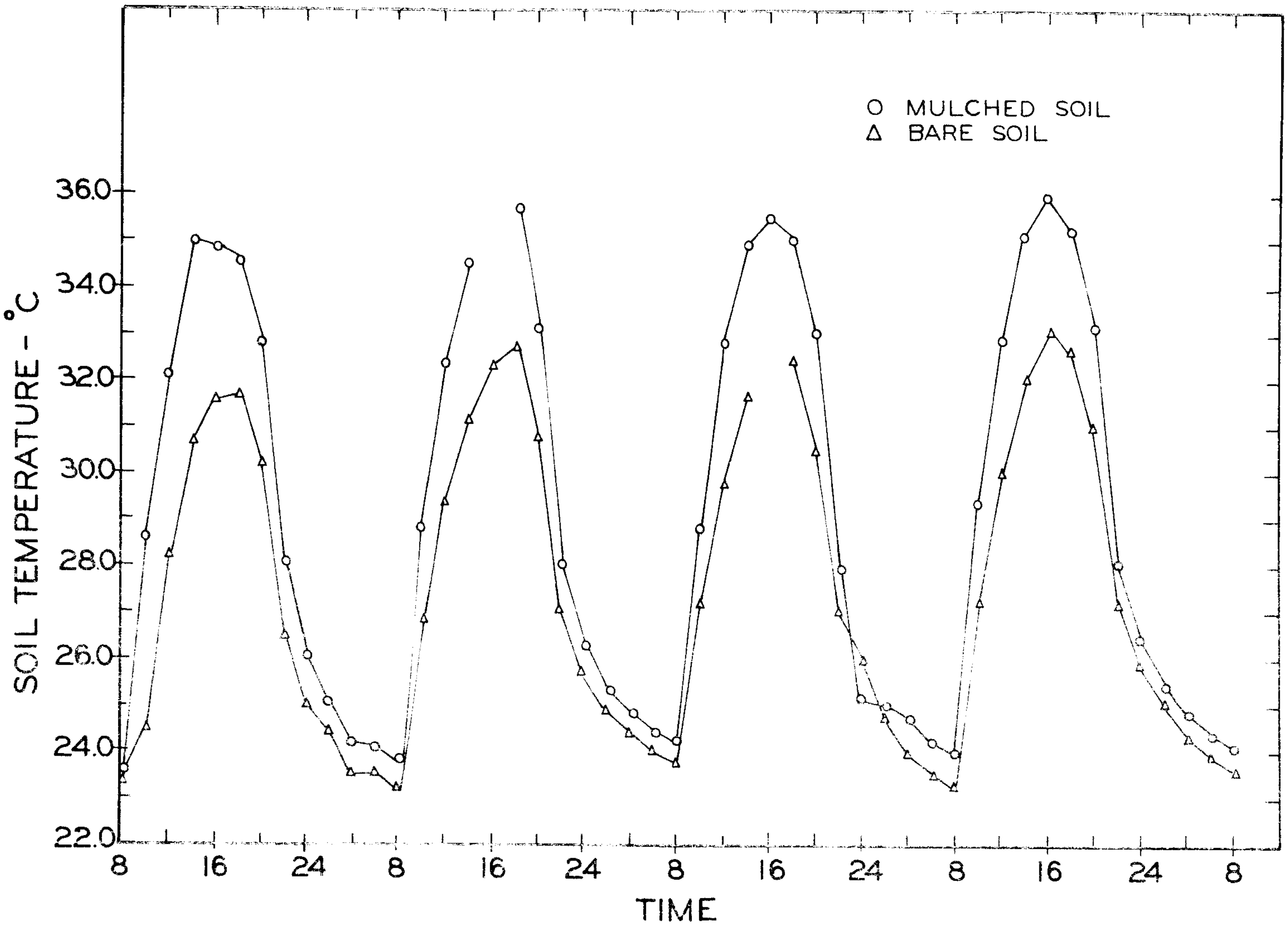


Figure 15. Soil temperatures under the mulch covered and bare soil surfact at a depth of three cm plotted as a function of time. Experiment A.

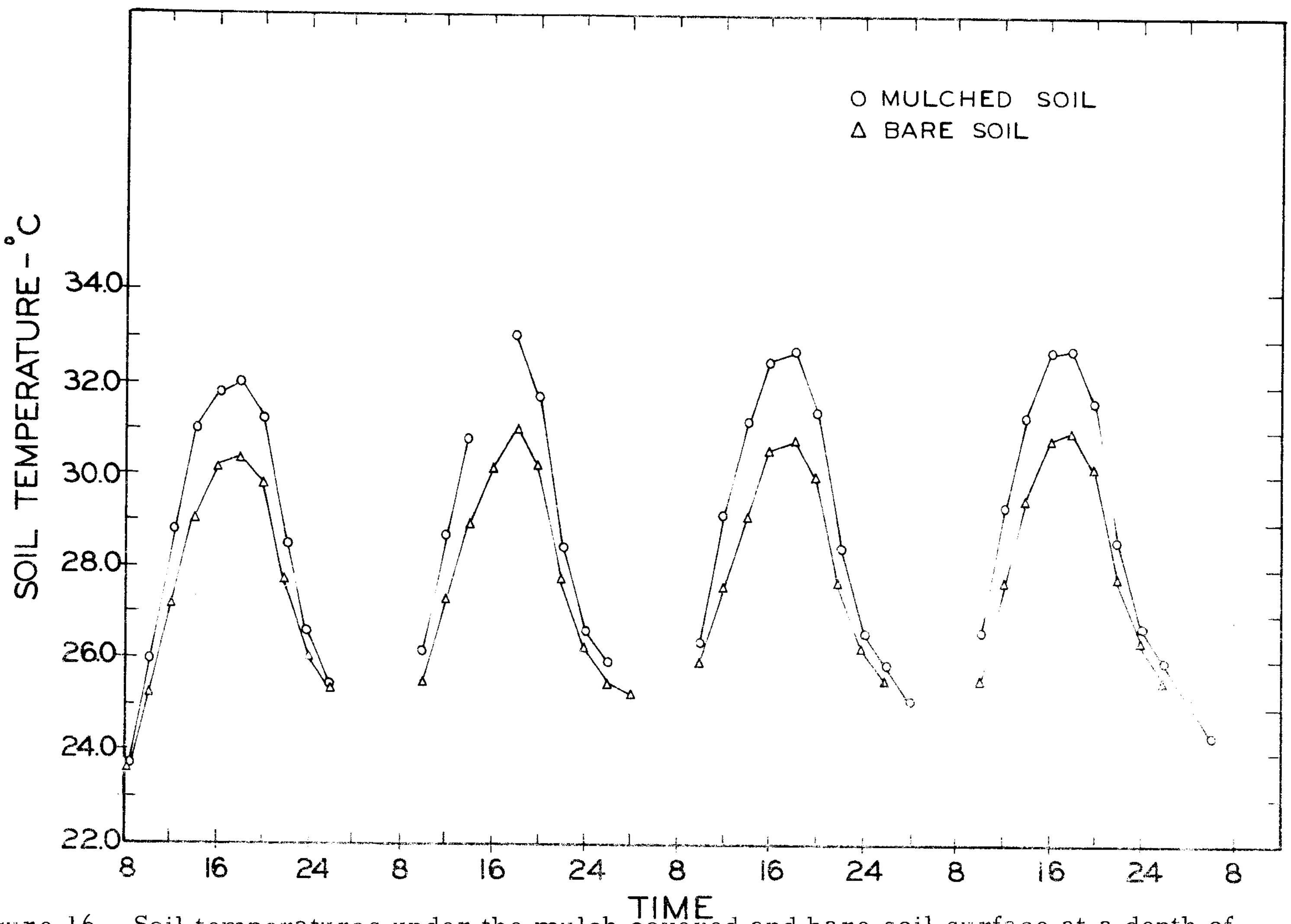


Figure 16. Soil temperatures under the mulch covered and bare soil surface at a depth of six cm plotted as a function of time. Experiment A.

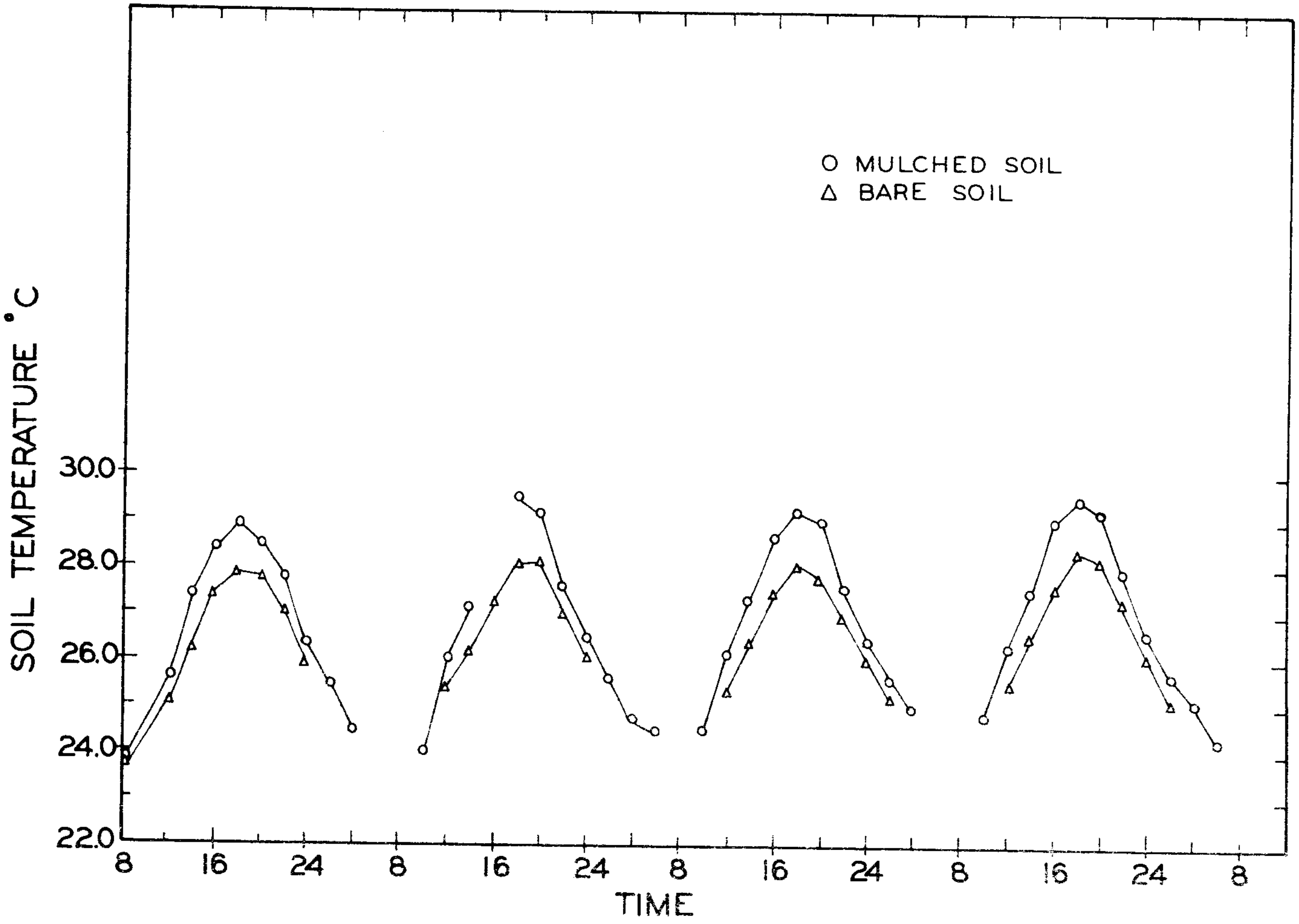


Figure 17. Soil temperatures under the mulch covered and bare soil surface at a depth of ten cm plotted as a function of time. Experiment A.

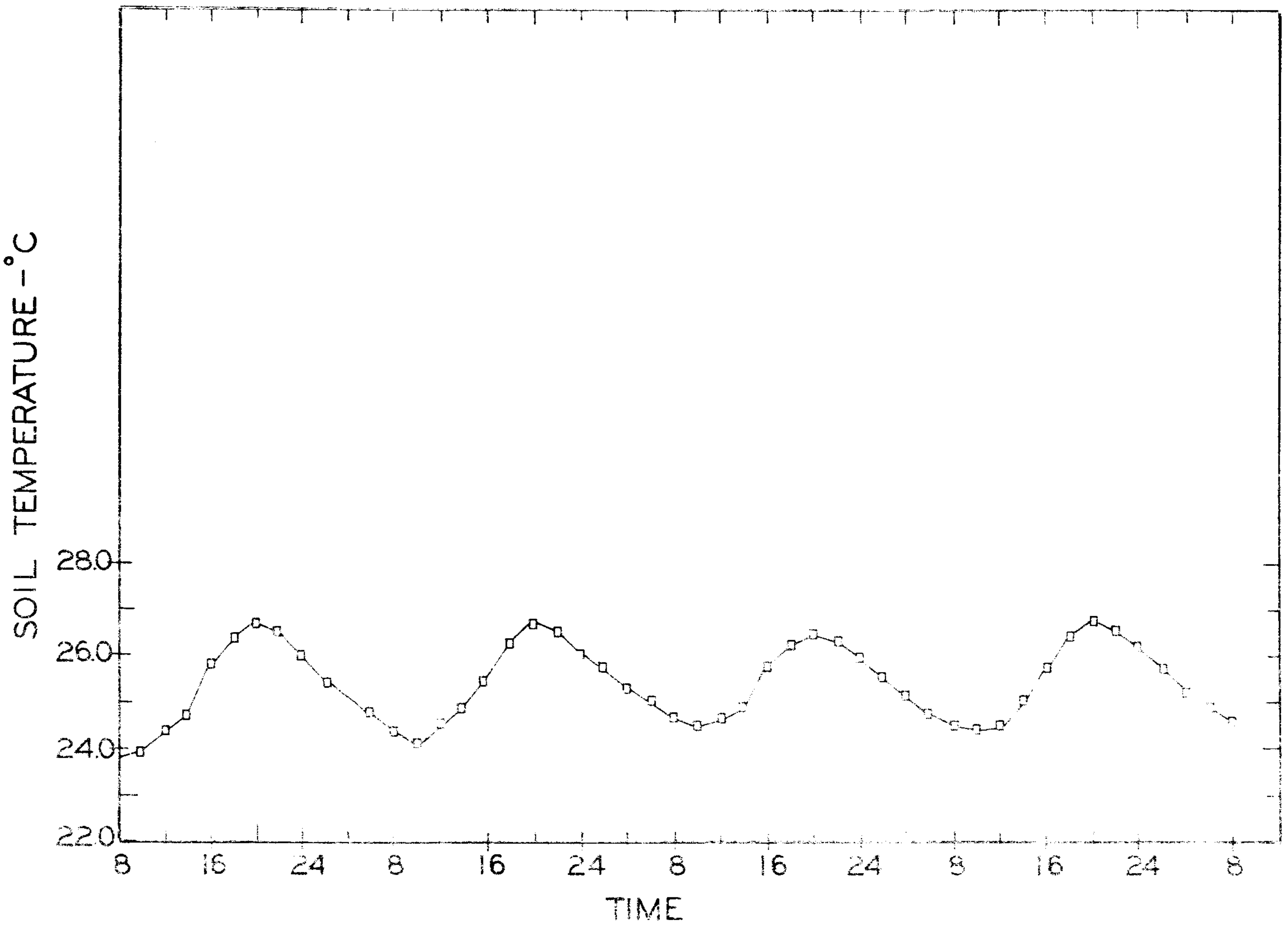


Figure 18. Soil temperatures under the mulch covered and bare soil surface at a depth of 17 cm plotted as a function of time. Experiment A.

16:00 hours was 4.91, 4.08, 2.94, and 2.28°C for the first, second, third, and fourth day, respectively. The maximum temperature under the mulch remained nearly constant, and ranged from 39.16 to 39.76°C, during the course of the experiment. The maximum temperature under the bare soil increased almost linearly from 34.25°C on the first day to 37.48°C on the fourth day. The difference in temperature, ΔT, decreased while the lights were turned off. The rate of drop in temperature under the mulch was greater than the rate of drop in temperature under the bare soil at the early hours of the night, but the rates equalized about midnight, or 02:00 hours, and during the rest of the night ΔT stayed almost constant. The temperature difference at the lowest temperature which occurred at 8:00 A.M. decreased from 0.5 to 0.1°C during the four nights of the experiment.

At a depth of three cm the situation was somewhat different. Under the mulch as well as under the bare soil a gradual increase in temperature from the first to the fourth day was observed. The maximum temperature under the mulch increased 1.0°C and under the bare soil 1.3°C. The temperature was always higher under the mulch than under the bare soil. The maximum difference was about 3.0°C and occurred at 14:00 hours.

The temperature changes at the six cm depth followed the same trend as was noted for the three cm depth. The maxima occurred at

18:00 hours and the ΔT at those points was 1.60 to 2.0°C. Because of limitations of the recorder calibration, temperatures lower than 25°C could not be recorded leaving a gap in the data during the night. But Figure 16 indicates that the temperatures are almost equal from 02:00 until sometime at the beginning of the day.

The temperature changes at the 10 cm depth, shown in Figure 17 followed the same trend as those noted at depths of three and six cm with the maxima occurring at 18:00 hours and the ΔT being around 1.0°C at that point.

The temperature changes at a depth of 17 cm approximate sine curves with the maxima occurring at 20:00 hours and minima occurring at 10:00 hours. At this depth the temperature difference, ΔT between bare and mulched soil was no longer noted.

Experiment B

This experiment was conducted for three days. The temperature was measured at two hour intervals beginning at the start of the experiment. The temperature as a function of time is shown in Figures 19, 20, 21, 22, and 23 for the depths of one, three, six, ten, and 17 cm respectively. Figure 19 shows that there was a decrease in the maximum temperatures of the soil at the one cm depth under the mulch from the first to the third day, of about 0.36°C. On the other hand, the maxima under the bare soil increased 1.63°C from

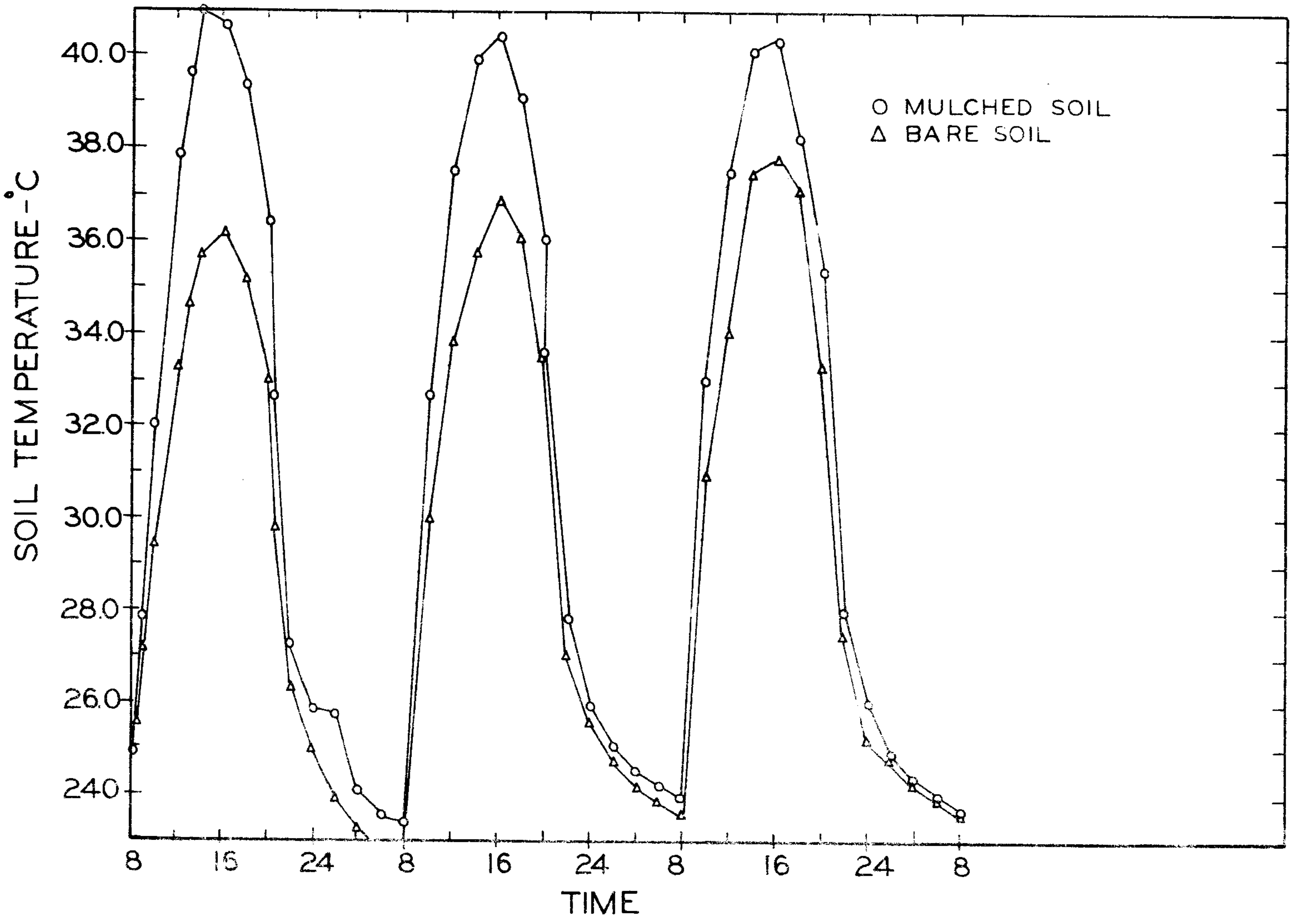


Figure 19. Soil temperatures under the mulch covered and bare soil surface at a depth of one cm plotted as a function of time. Experiment B.

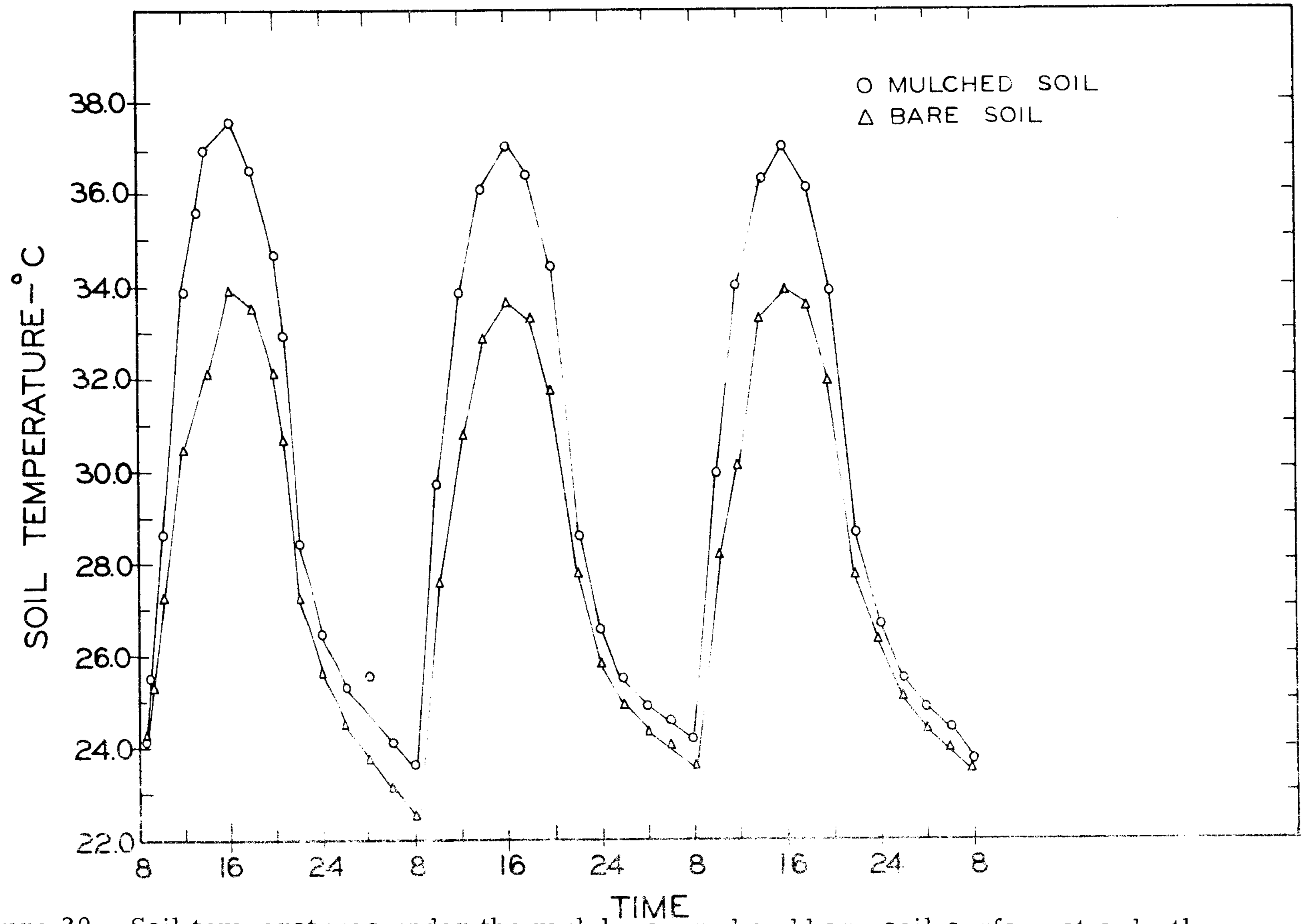


Figure 20. Soil temperatures under the mulch covered and bare soil surface at a depth of three cm plotted as a function of time. Experiment B.

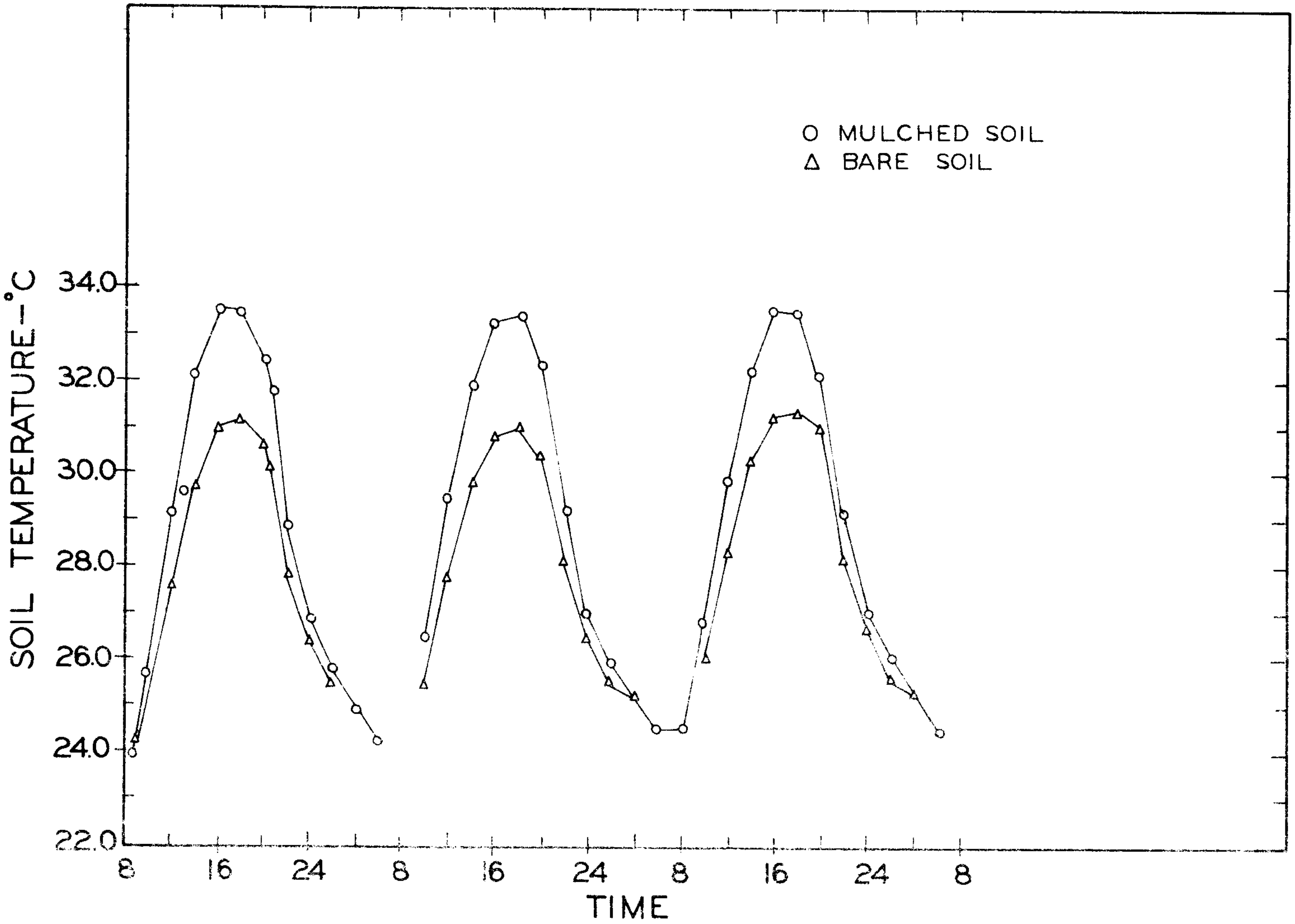


Figure 21. Soil temperatures under the mulch covered and bare soil surface at a depth of six cm plotted as a function of time. Experiment B.

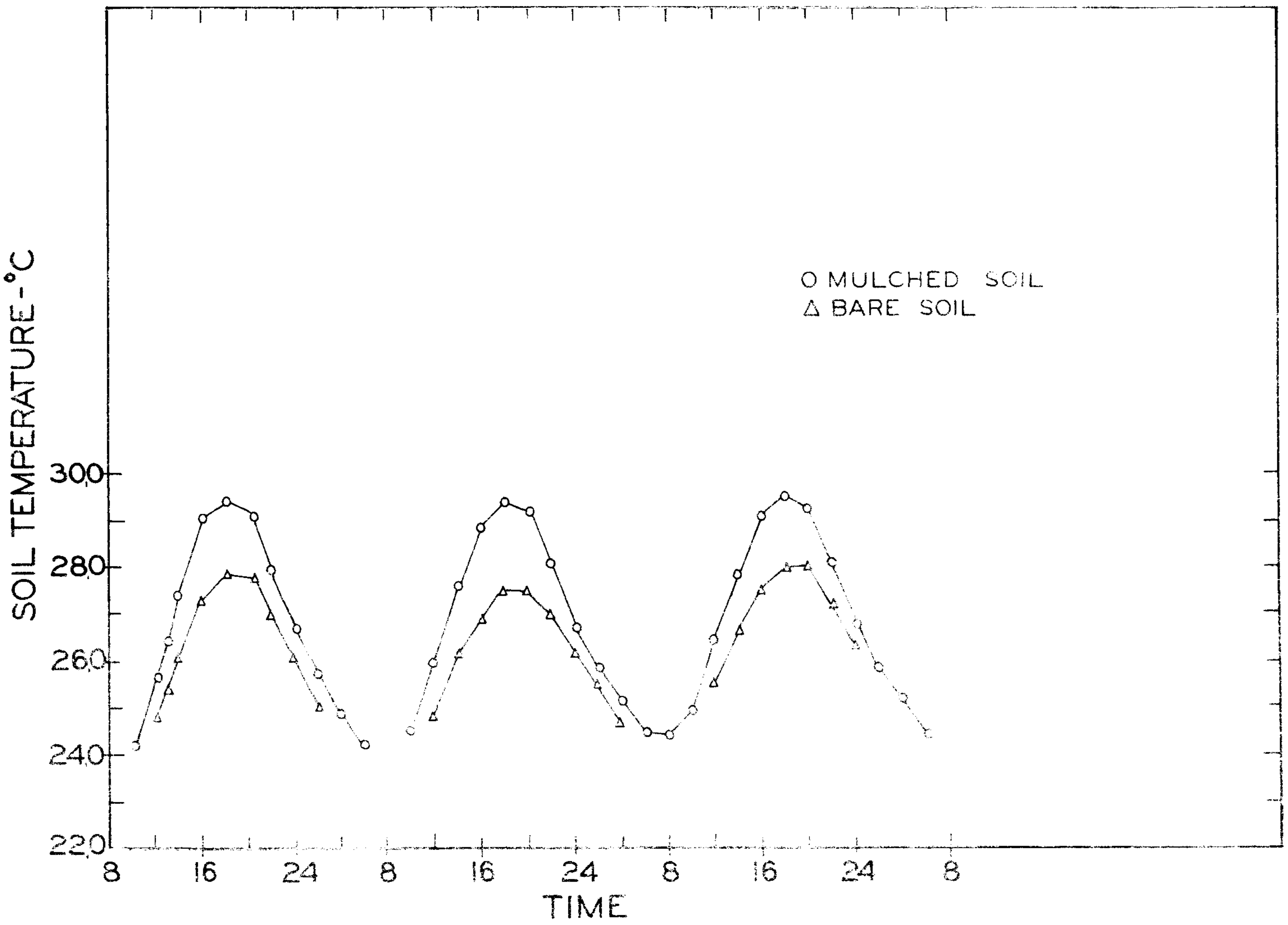


Figure 22. Soil temperatures under the mulch covered and bare soil surface at a depth of ten cm plotted as a function of time. Experiment B.

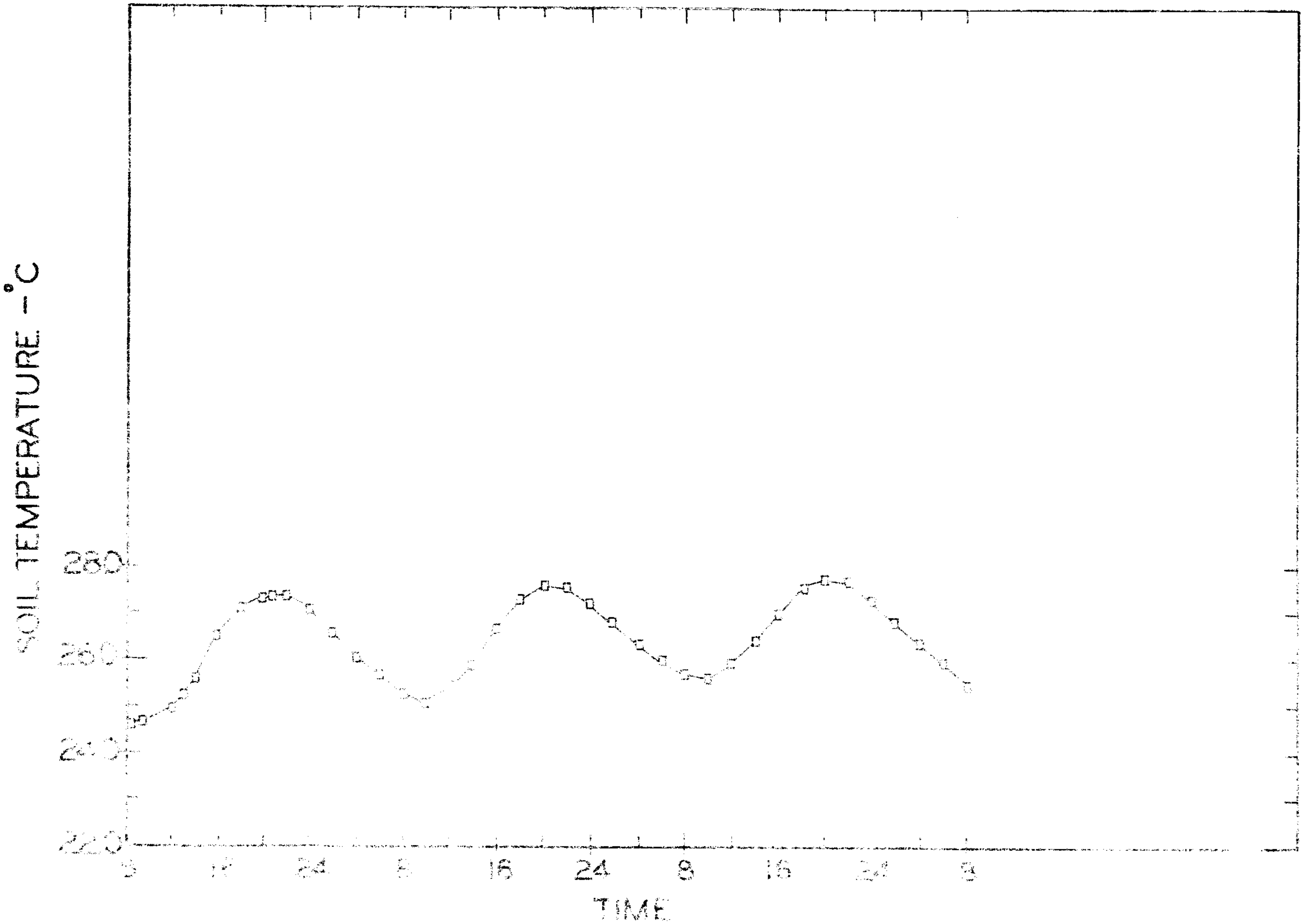


Figure 23. Soil temperatures under the mulch covered and bare soil surface at a depth of 17 cm plotted as a function of time. Experiment B.

the first to the third day. The maximum temperature difference between the mulched and the bare soil, at a depth of one cm, which occurred at 16:00 hours was 4.47, 3.55, and 2.48°C from the first to the third day. The decrease was about 1.0°C per day. The temperature difference at the lowest temperatures decreased from the first to the third day. The difference, ΔT, between the mulched and the bare soil was .85, .35, and .10°C during the three nights.

The temperature under the mulch at each hour of the day was lower and at each hour of the night was higher than the corresponding point in the preceeding day or night. For the bare soil the temperature was always higher than the corresponding point in the preceeding cycle.

The temperature at a depth of three cm under the mulch was always higher than the temperature under the bare soil at the same depth. The difference in maxima which occurred at 16:00 hours decreased from 3.64°C on the first day to 3.10°C on the third day. The maximum for the bare soil was the same on the first day and the third day, but the maximum for the mulched soil decreased .54°C. The temperature differences between mulched and bare soil observed during the night decreased as the experiment progressed.

The temperature changes at the six cm depth followed the same trend as was noted for the three cm depth. The temperature difference between mulched and bare soil at the highest temperature decreased slightly during the three days. The maxima occurred at 18:00 hours and ΔT was 2.25, 2.40, and 2.05°C for the first, second, and the third day respectively. The temperature at all locations were nearly equal at 04:00 hours.

The temperatures at the ten cm depth followed the same trend as those noted at the six cm depth, but the difference in temperatures was less. At the maxima, which occurred at 18:00 hours, the ΔT's were 1.50, 1.78, and 1.51°C for the first, second and third day, respectively. Since temperatures lower than 25°C could not be recorded, some data between 02:00 and 10:00 hours are missing. It seems, however, reasonable to assume that the temperature below the bare and the mulched soil at ten cm depth were equal at about 04:00 hours.

The temperature changes at the 17 cm depth followed a near sinosoidal curve. The maxima occurred at 20:00 hours and the minima at 10:00 hours. At this depth a temperature difference, ΔT, between bare and mulched soil was not noted.

Heat Flux Measurements

Results of the heat flux measurements are shown in Figures 24 and 25. The flux is considered positive when the heat movement is into the soil and negative when the movement is out of the soil.

When considering the results of the heat flux measurements it must be kept in mind that the heat flux discs only record the heat

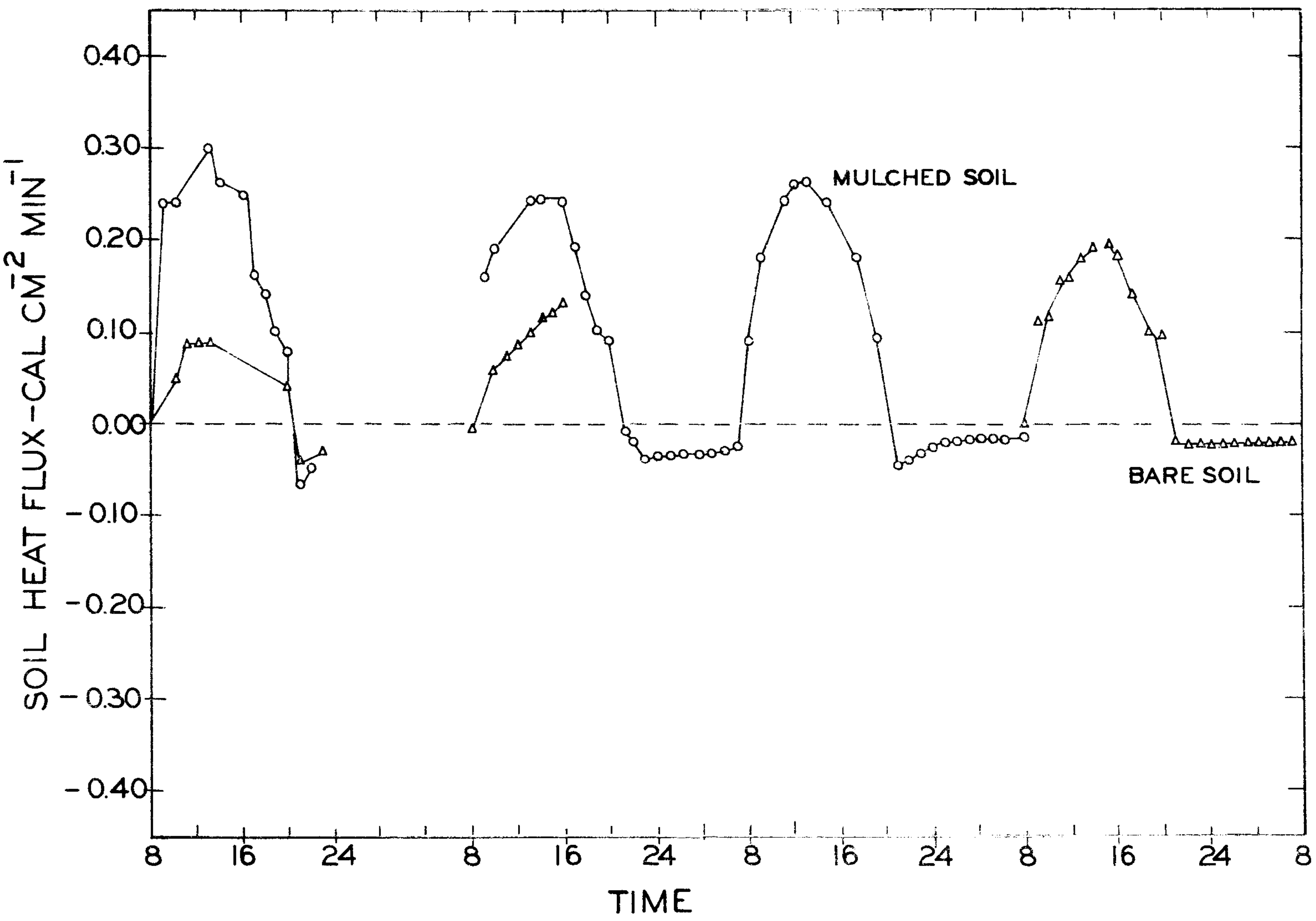


Figure 24. Heat flux measured at a depth of 2.0 cm below the mulch covered and bare soil surface. Experiment A.

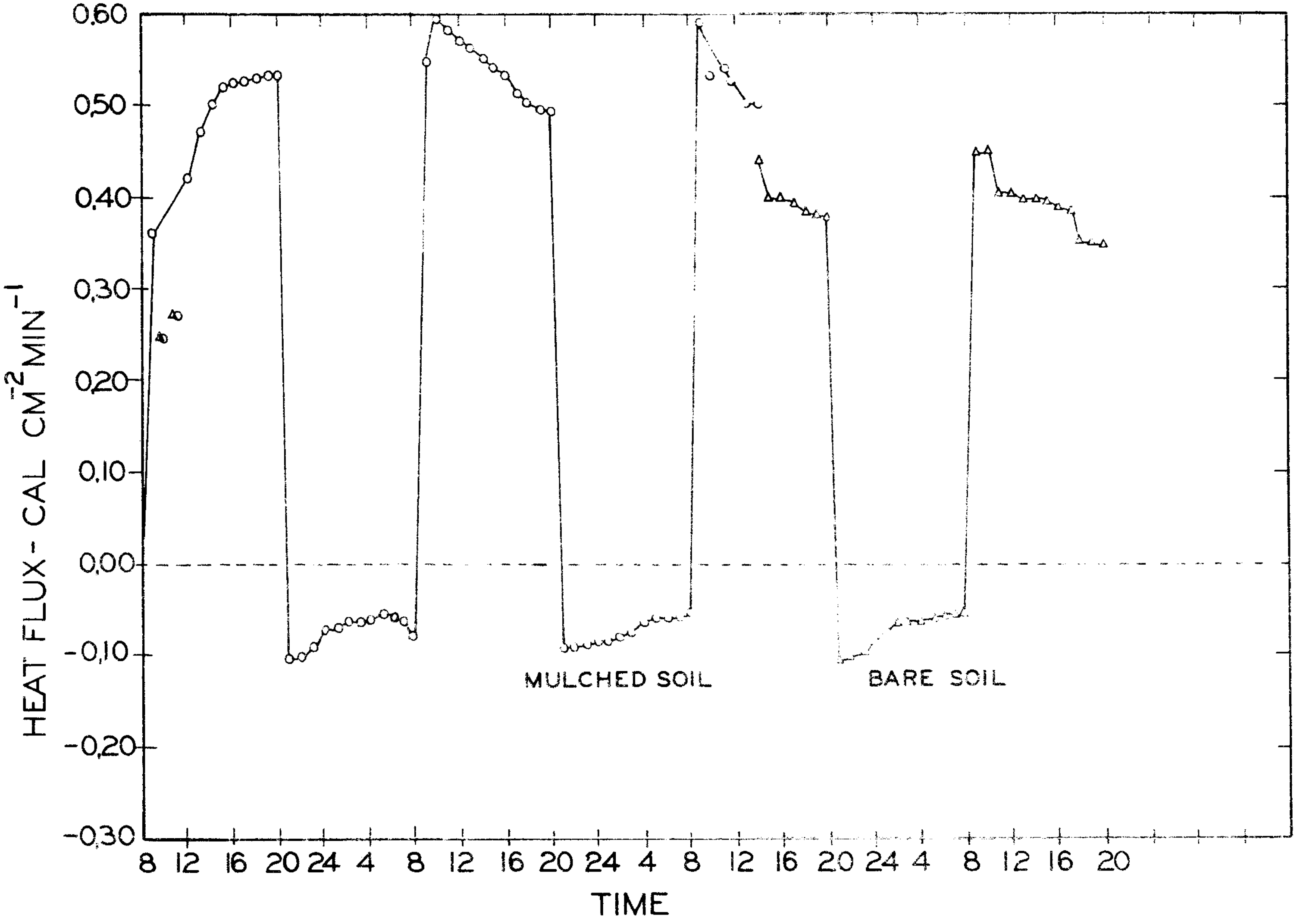


Figure 25. Heat flux measured at a depth of 2.0 cm below the mulch covered and bare soil surface. Experiment B.

transfer by conduction. In moist soils much of the heat is transferred in the form of water vapor. The water vapor can flow around the disc and heat transferred in this manner is not recorded. The recorded heat flux into the soil was always greater under the mulch than under the bare soil, during the day. The recorded heat flux out of the soil was always greater from the mulched soil than from the bare soil. During the course of the experiment the recorded heat flux into the soil increased for the bare soil and decreased for the mulched soil. Figure 25 indicates that the maximum heat flux into the bare soil which occurred at 13:00 hours increased from 0. 09 cal cm^{-2} min^{-1} on the first day to 0. 19 cal cm^{-2} min^{-1} on the fourth day. This is an increase of nearly 100%. The maximum heat flux into the mulched soil decreased from 0. 30 cal cm^{-2} min^{-1} on the first day to 0. 25 cal cm^{-2} min^{-1} on the third day. This is a decrease of about 13%.

The maximum heat flux from the soil occurred at 21:00 hours and decreased for the mulch as well as for the bare soil. For the mulched soil the heat loss rate decreased from . 07 cal cm^{-2} min^{-1} to 0. 05 cal cm^{-2} min^{-1} from the first to the third night. For the bare soil the heat loss rate decreased from 0. 04 cal cm^{-2} min^{-1} to 0. 02 cal cm^{-2} min^{-1} from the first to the fourth night.

After the lights were turned off, the heat flux dropped to a minimum value, then increased gradually to a new level and stayed constant for the rest of the night. The constant level started around

01:00 hours for the mulched soil. Continuous night data for the bare soil are available only for the fourth night at which time the heat flux remained nearly constant for the entire period.

Water Content Measurements

Experiment A

Water content measurements were made at 08:00, 10:00, 14:00, 20:00, and 22:00 hours each day for the duration of the experiment. Results of these measurements are shown in Figures 26, 27, 28, 29, and 30. Each Figure shows the percent change in water content at the indicated depth under the mulch and under the bare soil. The percent change in soil water content was calculated with Equation 9. The depths at which water content measurements were made were 1. 0, 2. 0, 4. 0, 17. 0, and 37. 0 cm below the surface of the soil.

At a depth of 1. 0 cm the water content under the mulch increased. Only three out of the 20 measurements showed a decrease in water content below the initial level. A consistent trend in the change in water content with changes in soil temperature was not apparent. On the first and the fourth day the water content increased with an increase in the temperature of the soil, but on the second and the third days the water content decreased with a rise in the temperature of the soil. During the night hours of the first, second and third

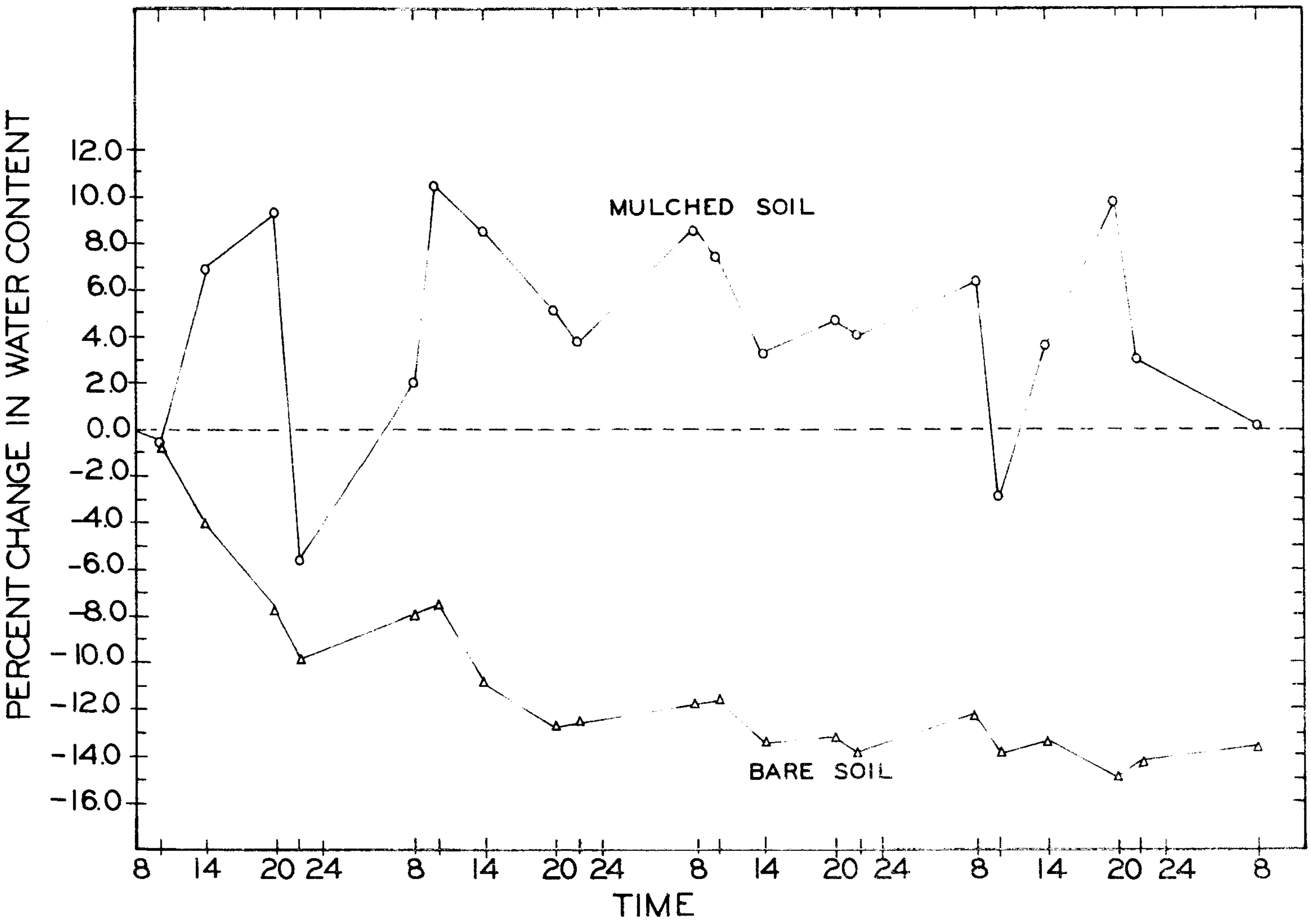


Figure 26. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of one cm. Experiment A.

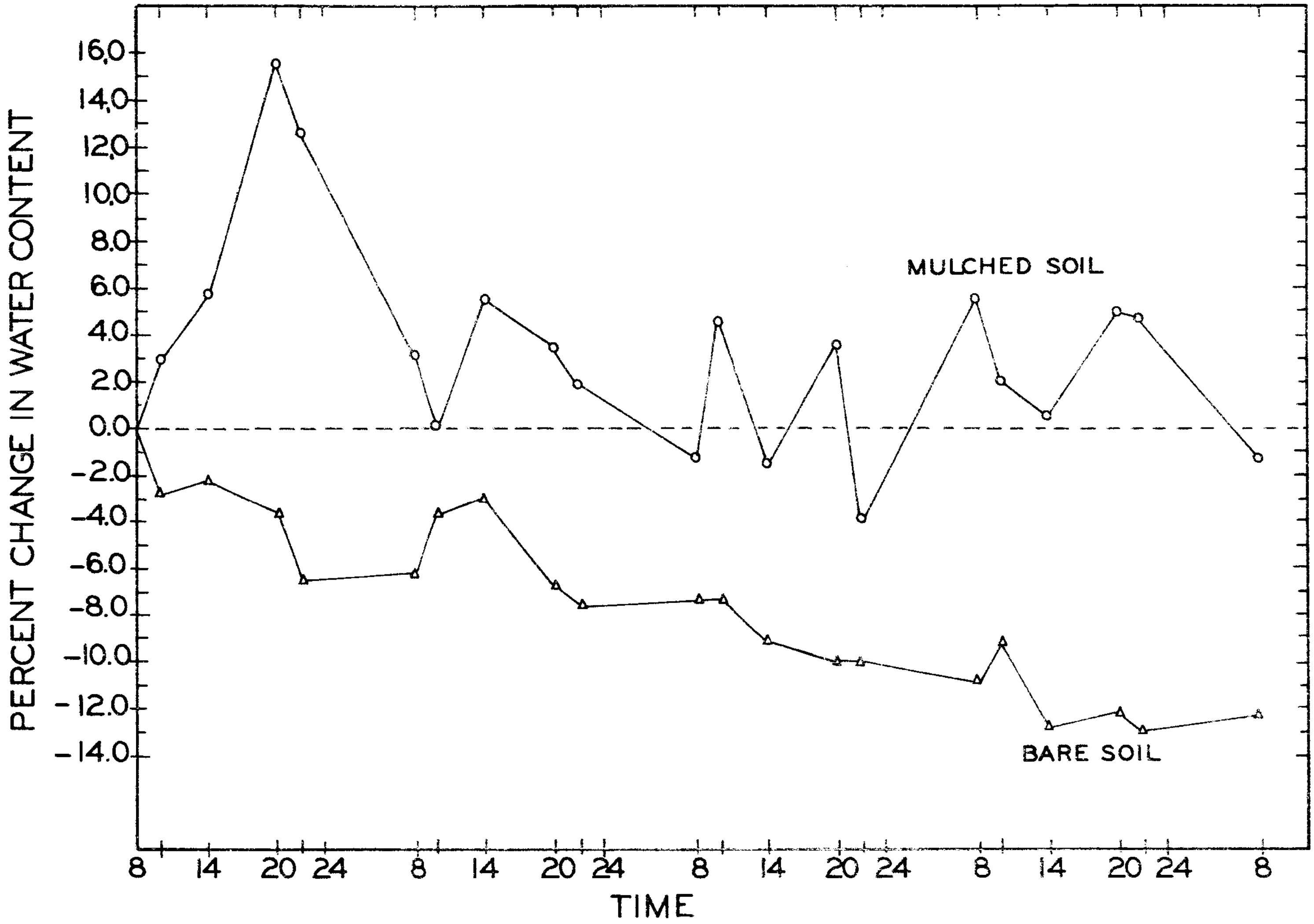


Figure 27. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of two cm. Experiment A.

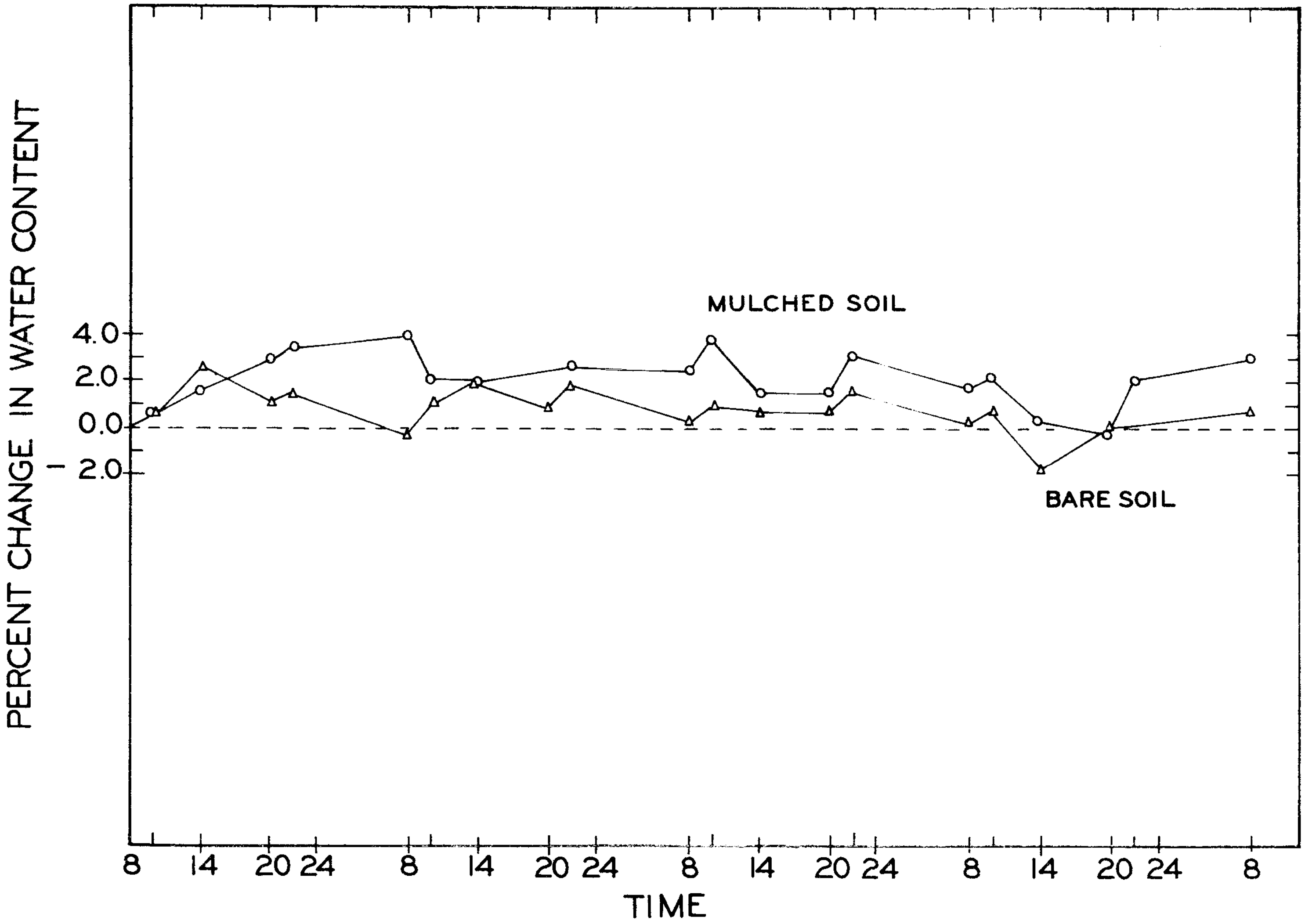


Figure 28. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of four cm. Experiment A.

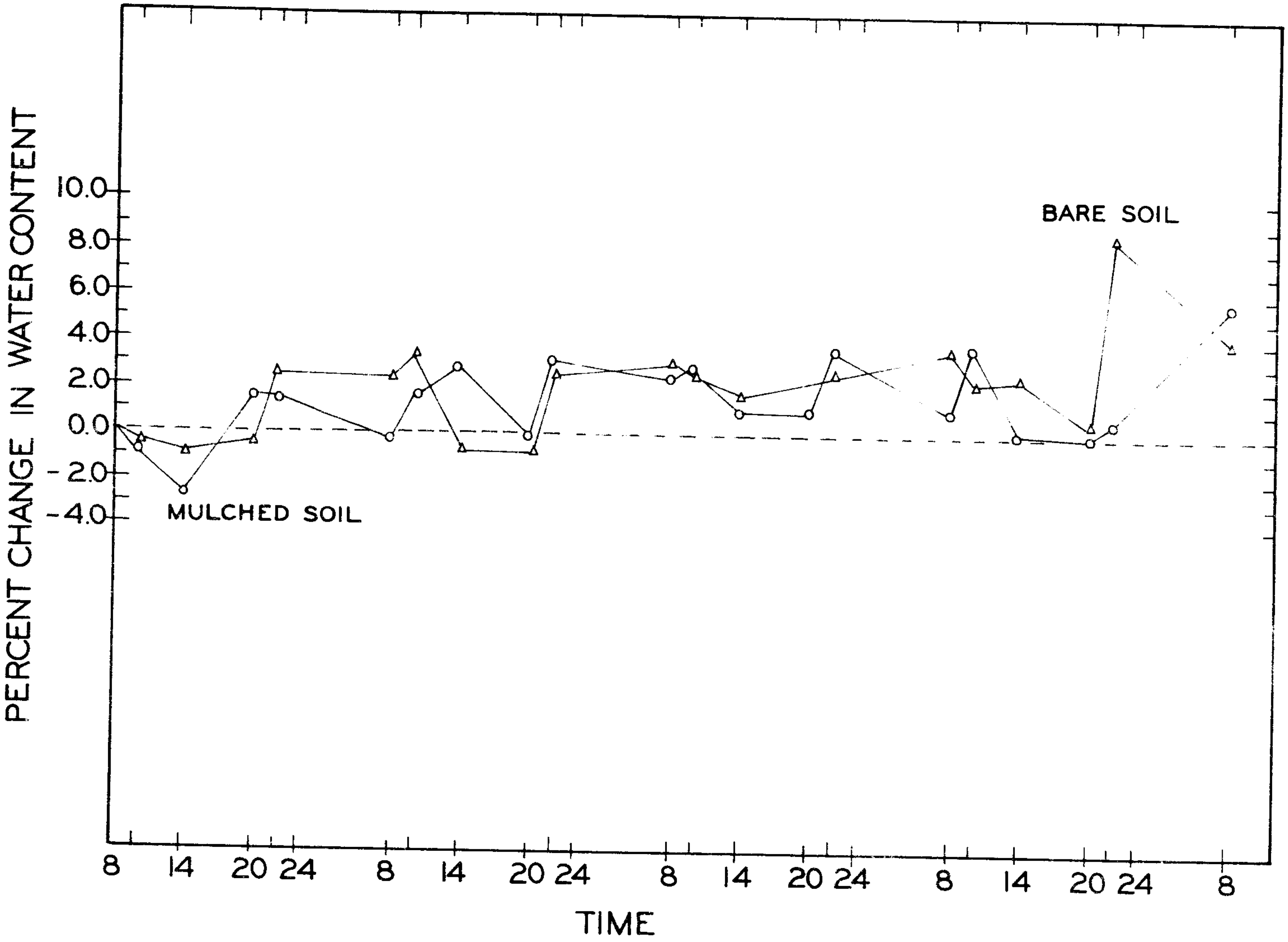


Figure 29. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of 17 cm. Experiment A.

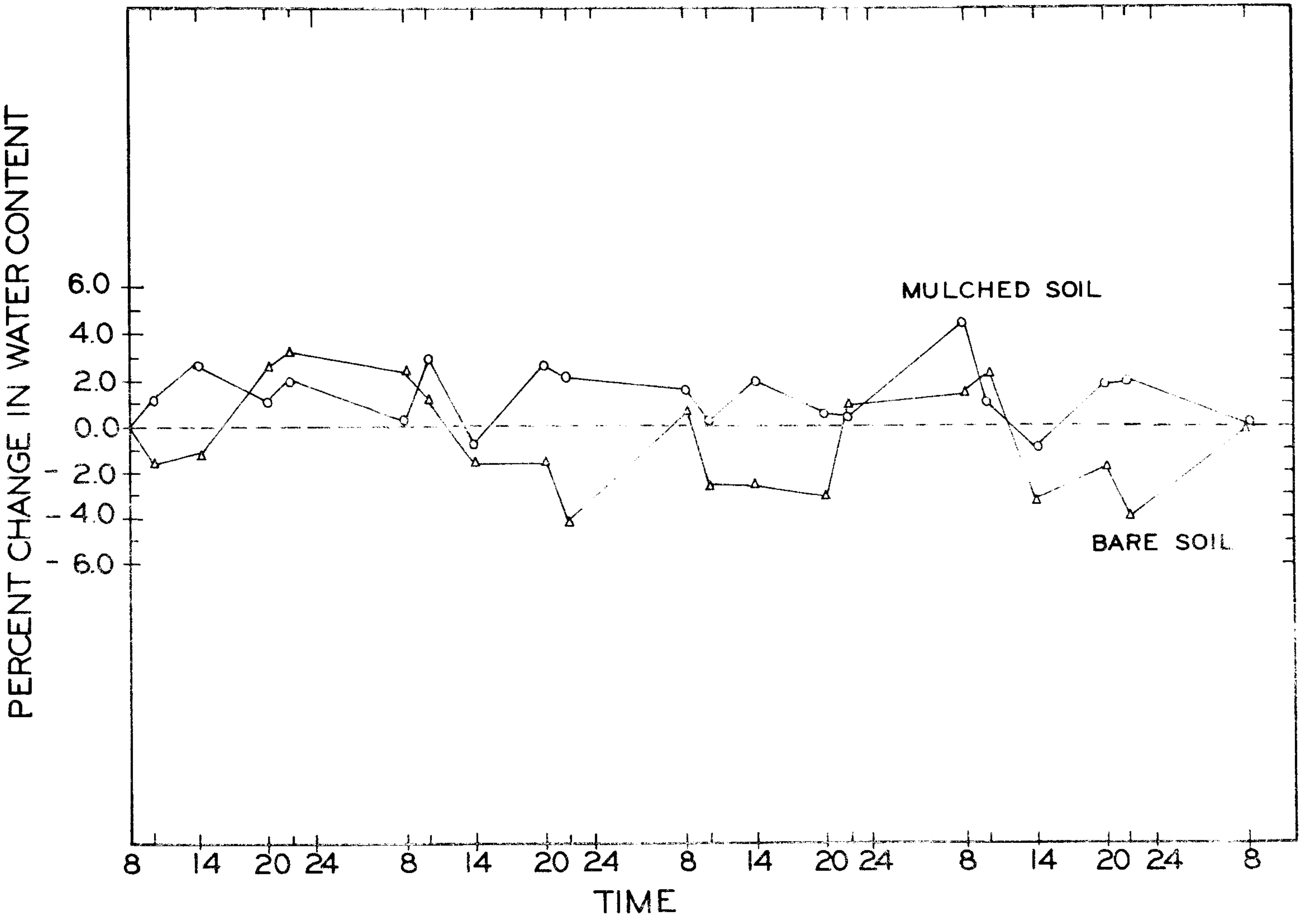


Figure 30. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of 37 cm. Experiment A.

day, there was an increase in water content from 22:00 hours to 08:00 hours. During the fourth night the water content decreased.

At a depth of 1.0 cm below the bare soil the water content decreased during the course of the experiment. The greatest drop in water content occurred during the first day when the soil lost ten percent water. During the night hours there was a slight gain. The minima for the period were 9.9, 12.8, 13.8, and 14.4 percent for the first, second, third and the fourth day respectively.

At the 2.0 cm depth under the mulch an increase in water content was noted most of the time. Only four out of 20 measurements showed a decrease in water content below the initial level. The largest increase was not measured at the same time each day. The greatest gain was measured at 20:00 hours twice, and once at 14:00 and 10:00 hours. The maximum increases were: 15.6, 5.5, 5.6, and 4.8 percent for the first, second, third, and fourth day respectively. The minima for the same period were 0.1, 1.5, 4.1, and 1.4 percent.

At a depth of 2.0 cm under the bare soil, there was a loss of water. Although there was a slight increase in water content at the early hours of the day, each cycle had a lower water content than had been noted at the same time of the preceding cycle. The minima were 6.1, 7.6, 10.8, and 12.8 percent for the first, second, third, and fourth cycle respectively.

At a depth of 4.0 cm there was an increase in water content both under the mulch and under the bare soil, but the increase was nearly always higher under the mulch. The maxima under the mulch occurred at the end of the night for the first three days, but the minima under the bare soil occurred at the same time. The minima under the mulch occurred around 14:00 hours on the second and the third day while the maxima under the bare soil on the first and second day occurred at 14:00 hours.

At a depth of 17.0 cm the measurements seem to indicate a small gain in water content. At a depth of 37.0 cm the changes in water content measured are not consistent and one would conclude that there was no change at that level. Figures 26 through 30 showed the changes in soil water content as a function of time below the mulched and the bare soil. In those figures, each curve followed the changes which occurred at a given location during the course of the experiment. In Figures 31 through 34 the changes in soil water content as a function of depth can be followed. The gain in water is considered positive and the loss of water is considered negative.

Experiment B

Water content measurements were made at 08:00, 10:00, 14:00, 20:00, and 22:00 hours each day for the duration of the experiment. Results of these measurements are shown in Figures 35, 36, 37, 38, and 39. The depths at which water content measurements were made

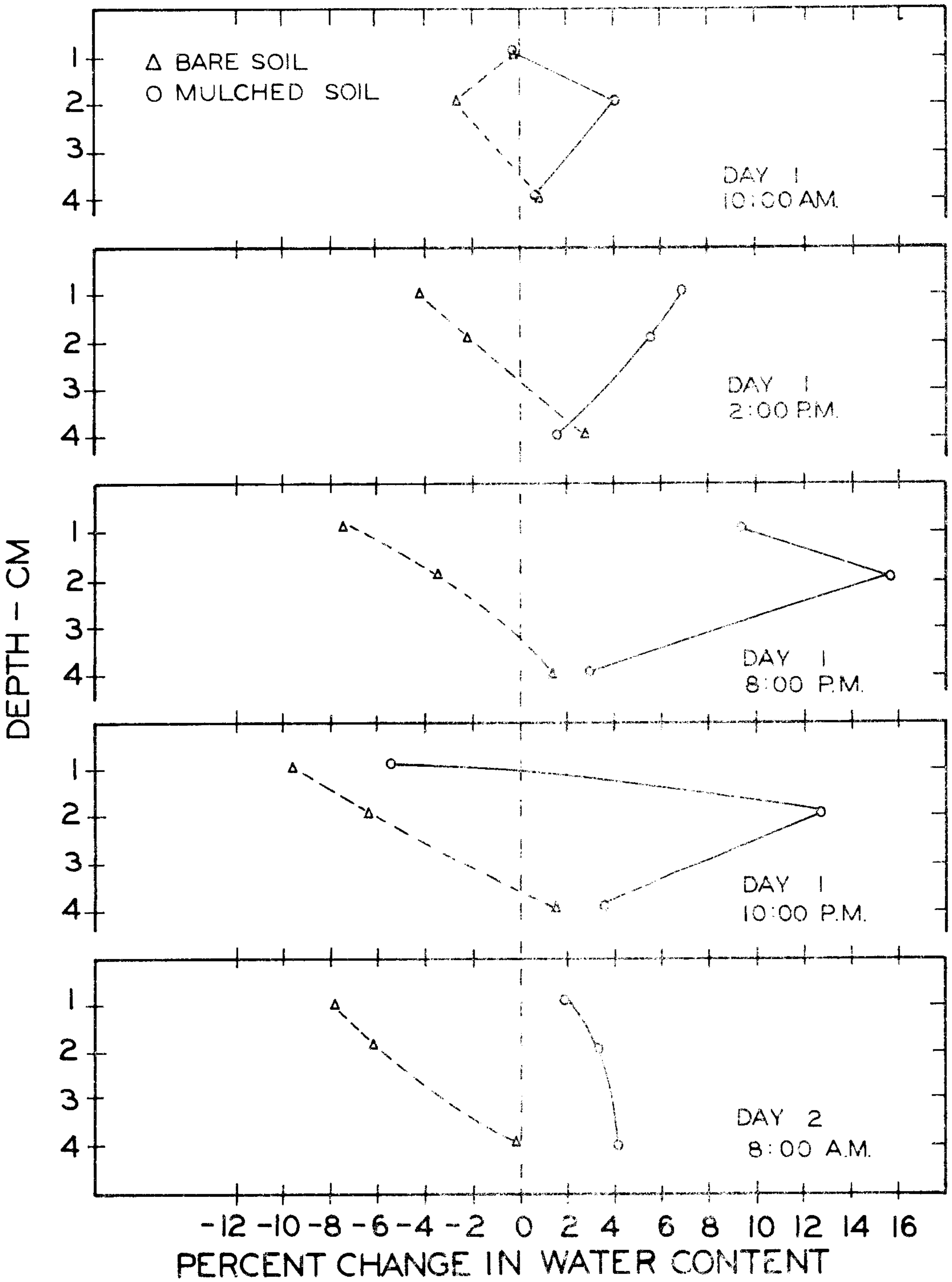


Figure 31. Percent change in soil water content plotted as a function of the depth below the mulch covered and bare soil. Day 1. Experiment A.

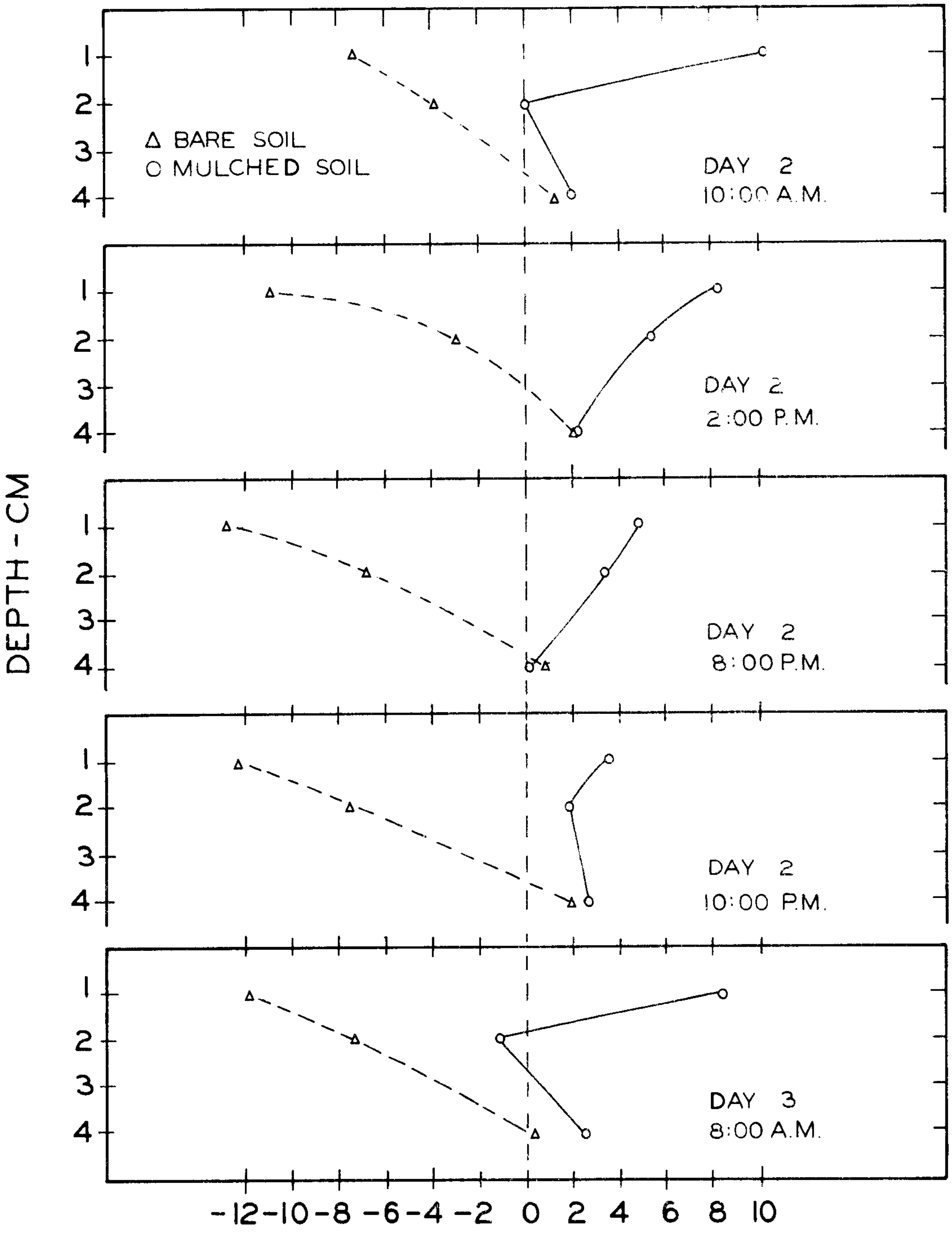


Figure 32. Percent change in soil water content plotted as a function of the depth below the mulch covered and bare soil. Day 2. Experiment A.

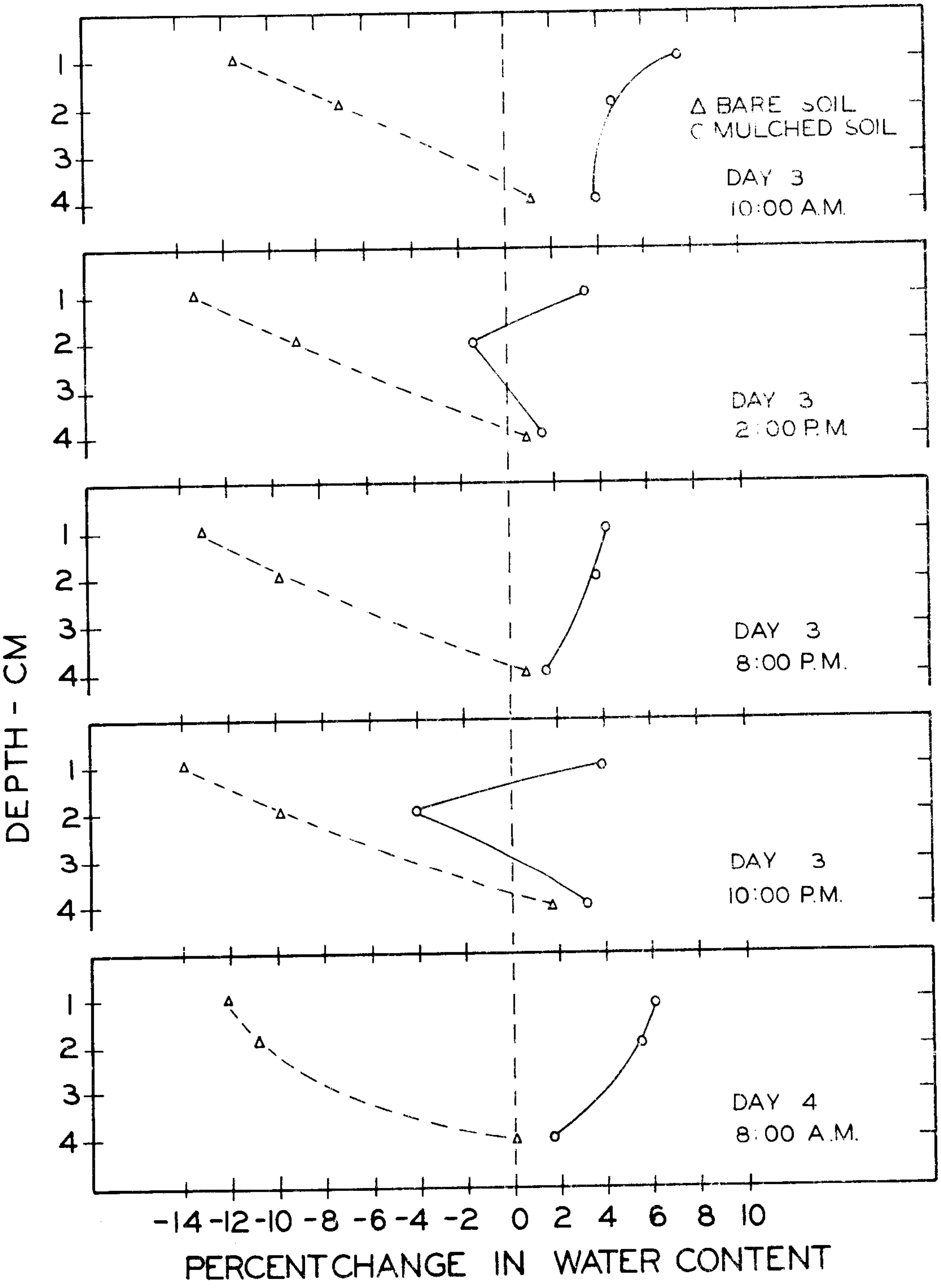


Figure 33. Percent change in soil water content plotted as a function of the depth below the mulch covered and bare soil. Day 3. Experiment A.

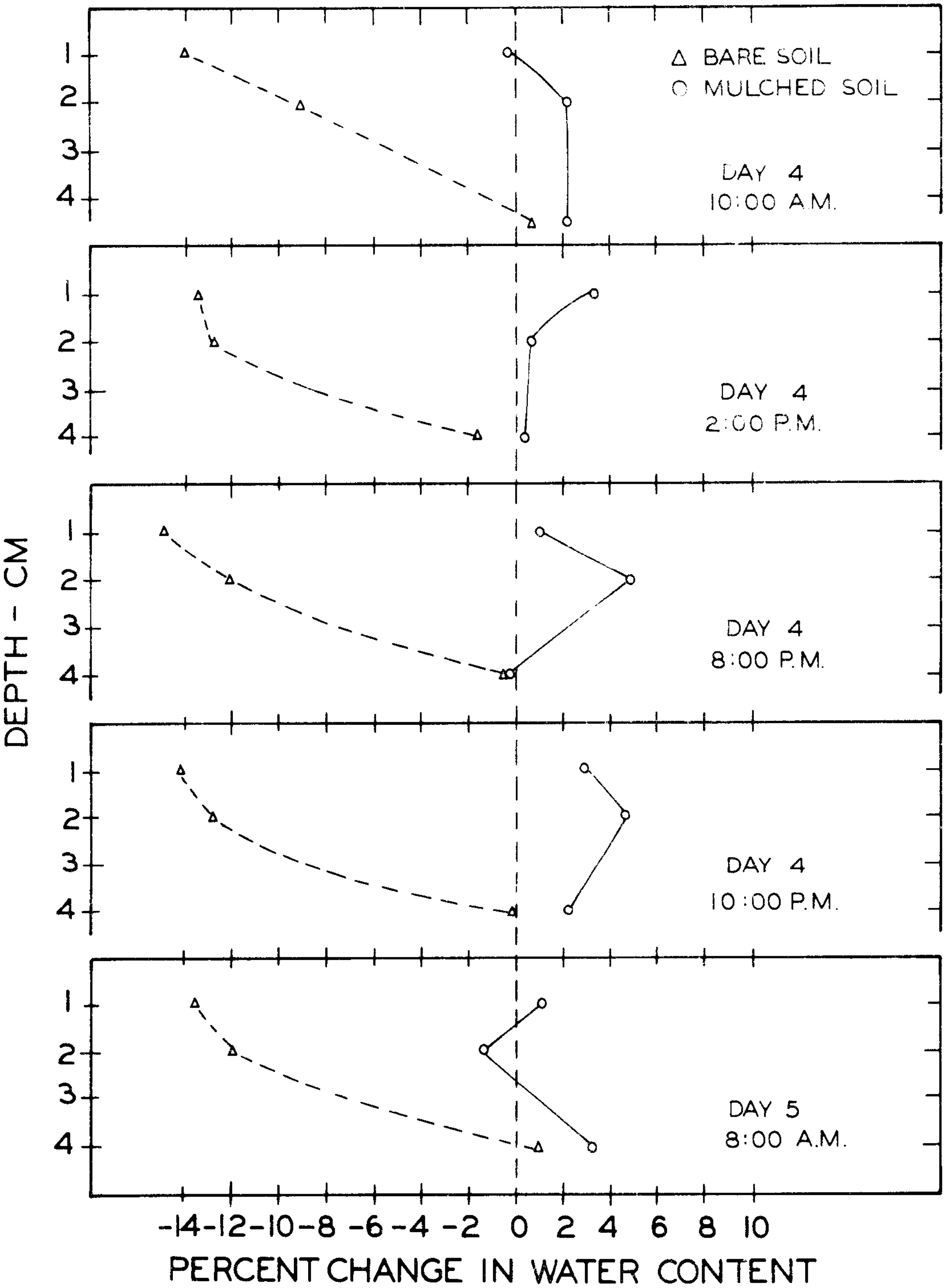


Figure 34. Percent change in soil water content plotted as a function of the depth below the mulch covered and bare soil. Day 4. Experiment A.

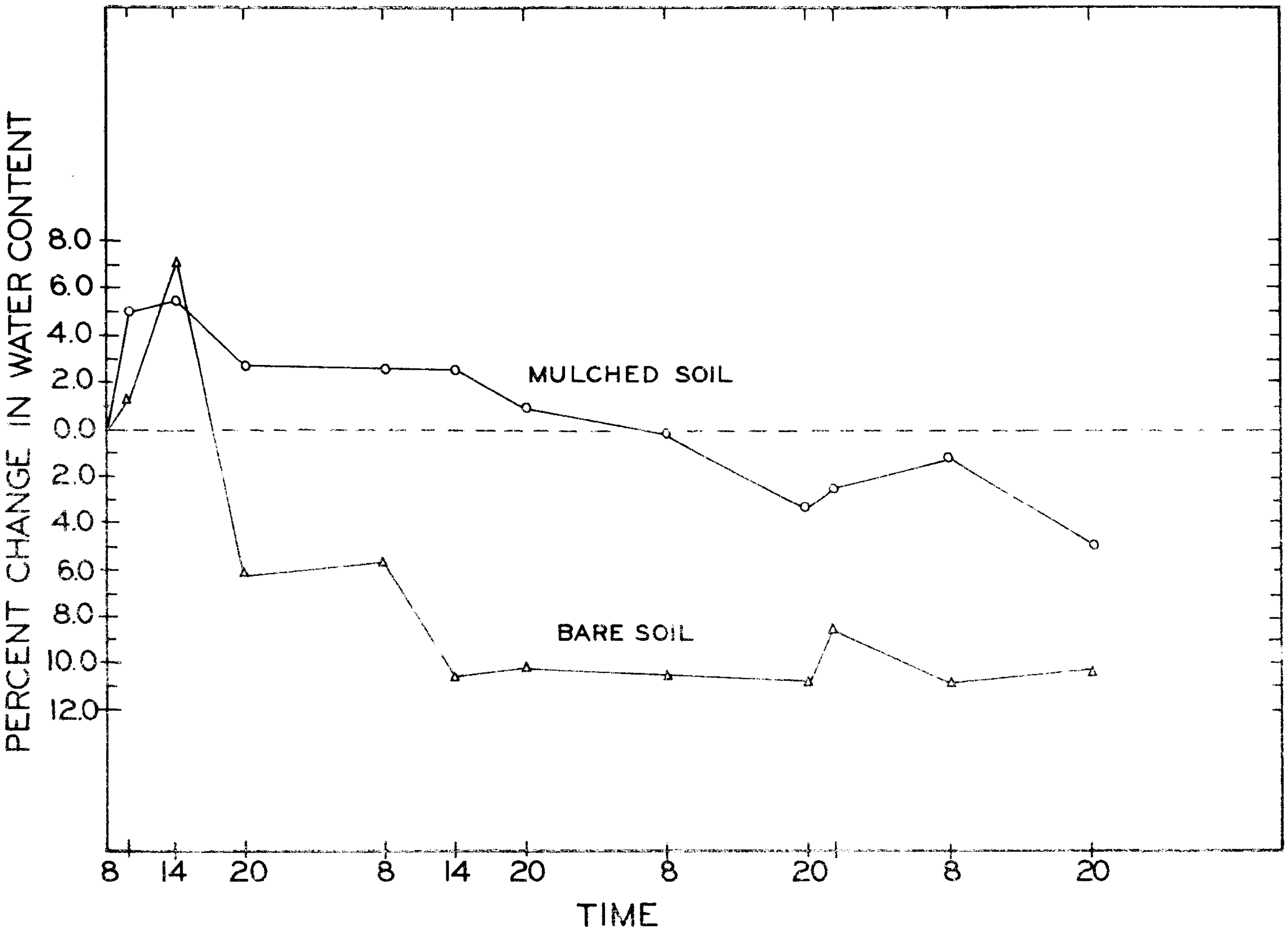


Figure 35. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of 1.5 cm. Experiment B.

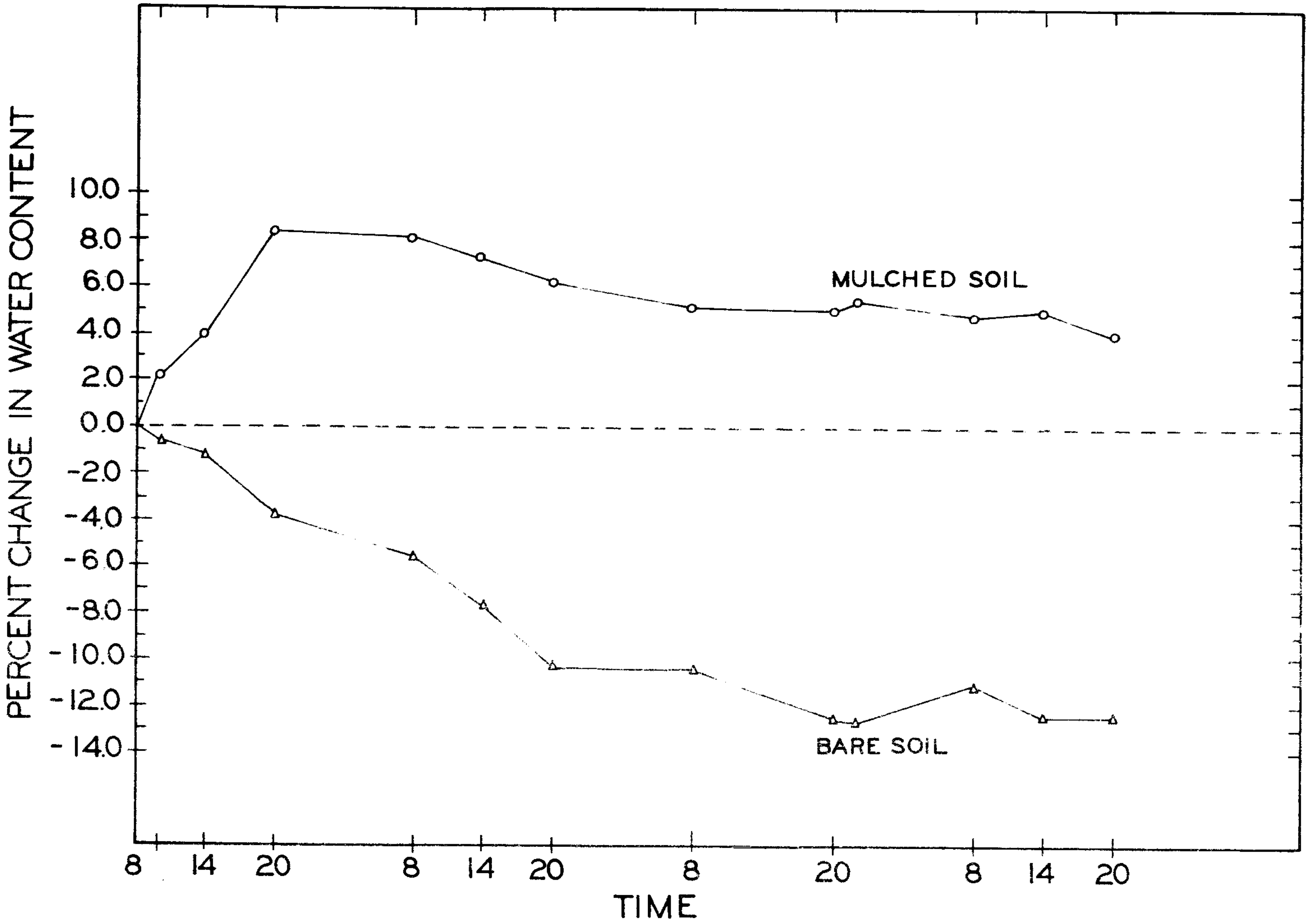


Figure 36. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of 2.5 cm. Experiment B.

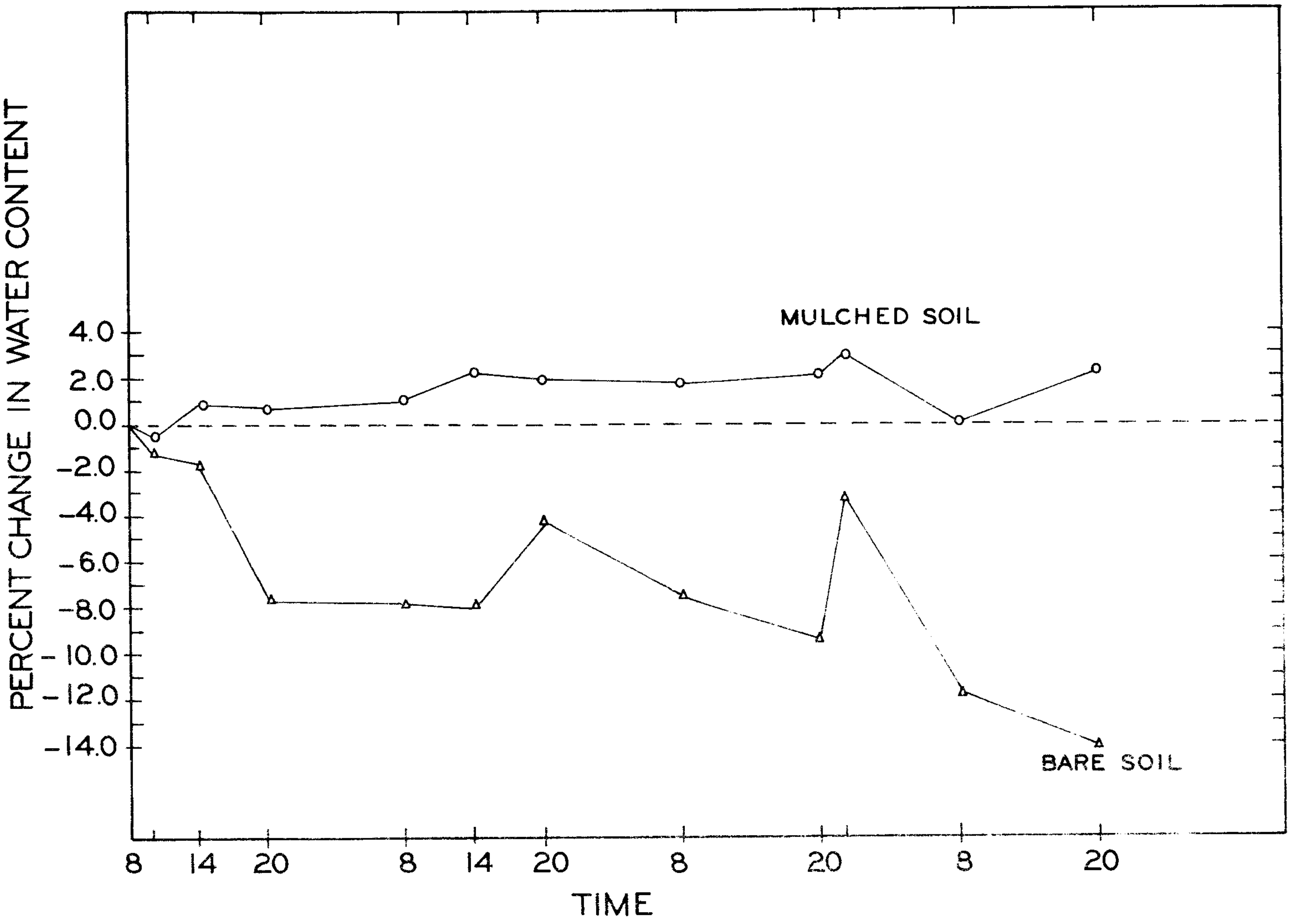


Figure 37. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of 4.5 cm. Experiment B.

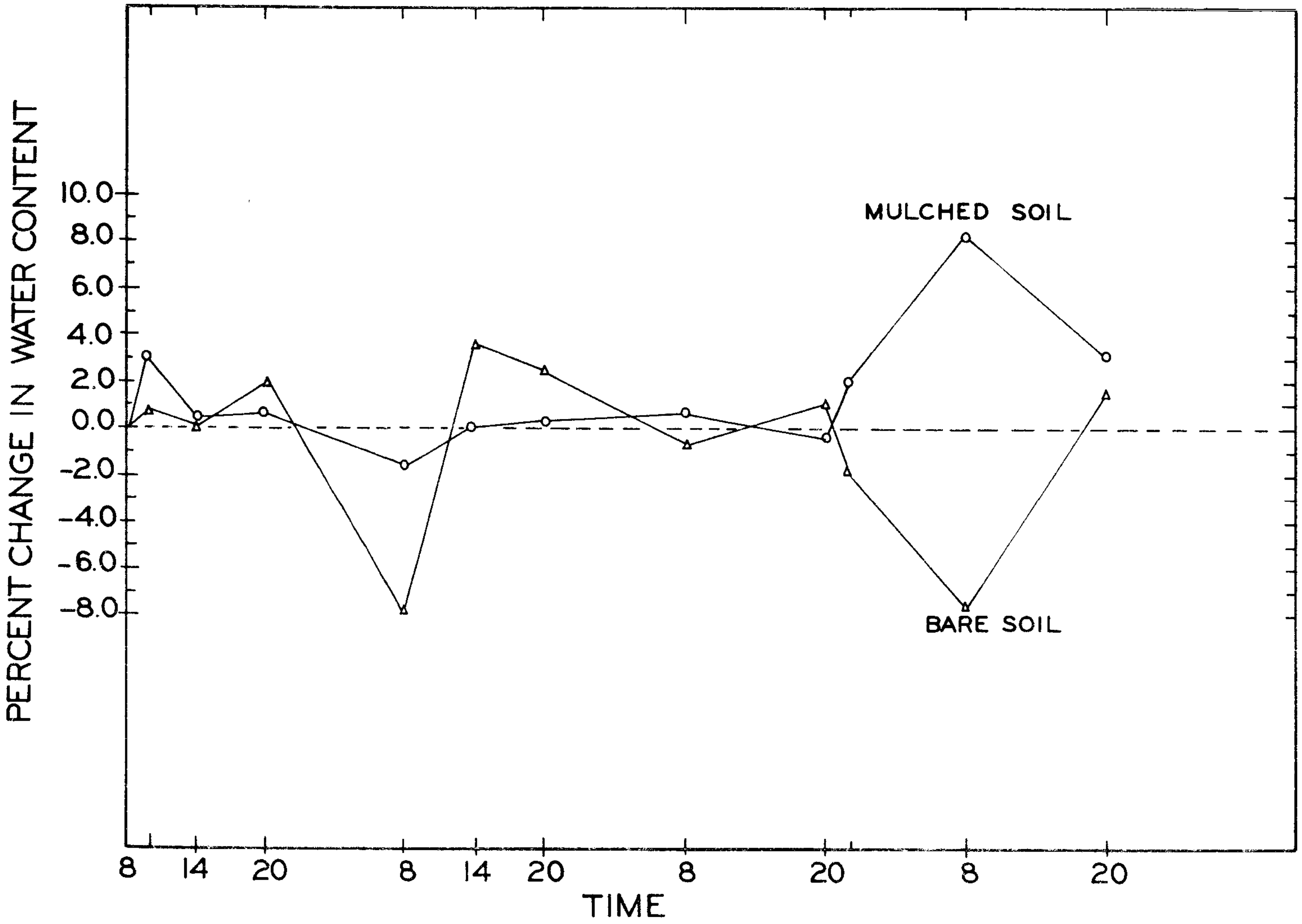


Figure 38. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of 17.5 cm. Experiment B.

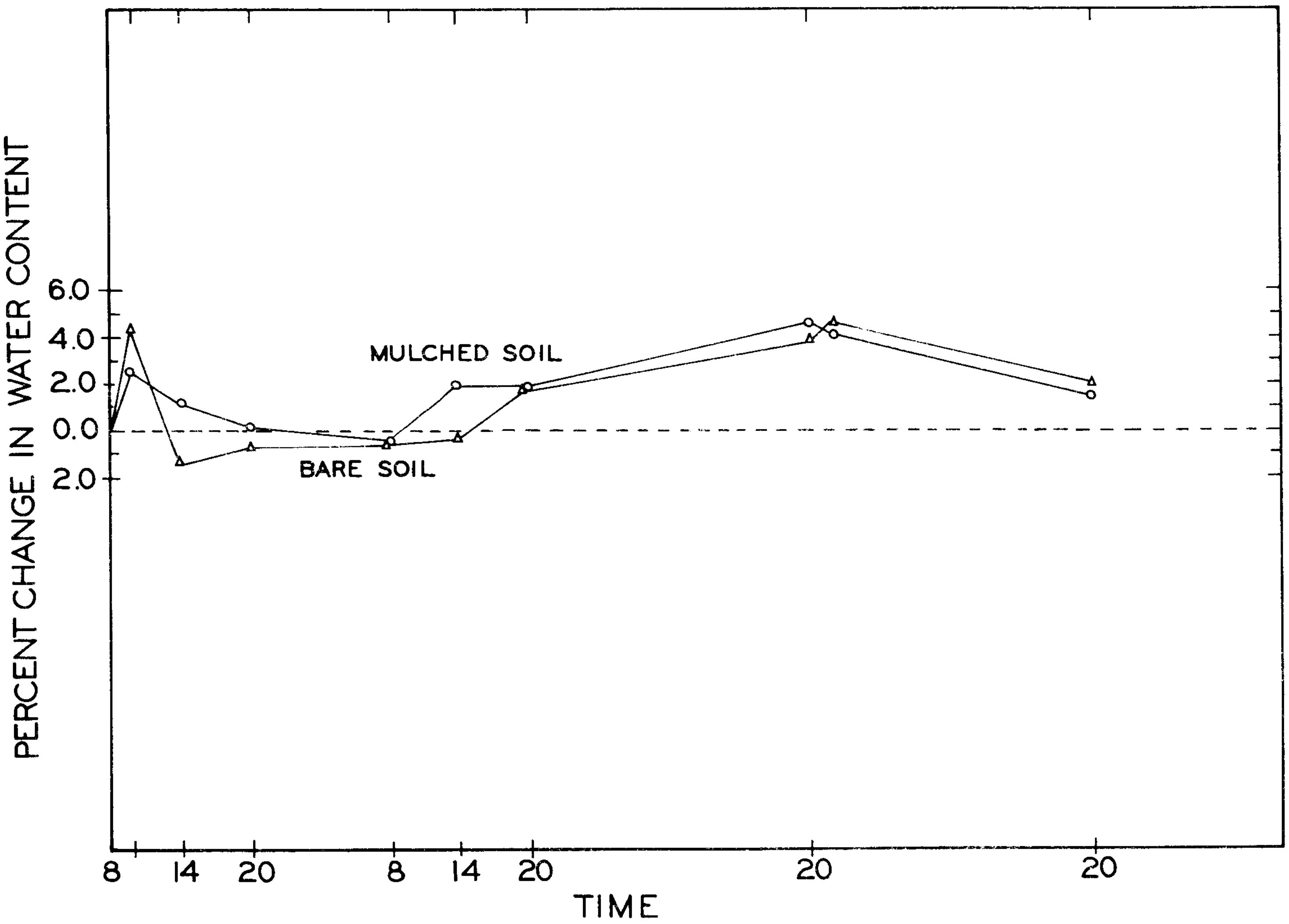


Figure 39. Percent change in soil water content as a function of time under the mulch covered and the bare soil surface at a depth of 37.5 cm. Experiment B.

were 1.5, 2.5, 4.5, 17.5, and 37.5 cm below the surface of the soil.

At a depth of 1.5 cm the water content under the mulch increased during the first day and then started to decrease slowly. The highest gain in water content was measured at 14:00 hours on the first day. At 20:00 hours on the first day, the increase was 2.8 percent and remained constant until 14:00 hours on the second day. On the third day the water content decreased and reached a low of 3.1 percent. At 20:00 hours on the third day, the end of the experiment, the water loss was 4.8 percent. The decrease in water content occurred at night during the first two cycles. In the third cycle the water content decreased during the day and increased during the night, as can be observed in Figure 35.

At a depth of 1.5 cm under the bare soil the water content decreased after an initial increase on the first day to 7.2 percent at 14:00 hours. At 14:00 hours on the second day, the change in soil water content reached a low of 10.4 percent and stayed almost constant for the remainder of the experiment.

At a depth of 2.5 cm, the water content under the mulch increased 8.3 percent at 20:00 hours the first day, remained constant during the night and started to decrease at a slow rate until the end of the experiment when it had decreased to 4.1 percent. The water content under the bare surface at the same level decreased from the start of the experiment. The decrease was 12.6 percent at 22:00

hours on the third night. The water content remained constant thereafter until the end of the experiment.

At a depth of 4. 5 cm under the mulch there was a slight increase in the water content. At the same depth under the bare surface the water content was consistently decreasing. At a depth of 17. 5 cm no consistent trend in the change in water content under the mulched surface as well as under the bare surface could be detected. At a depth of 37. 5 cm there was a slight increase in the water content under the mulched as well as under the bare soil.

Figures 35 through 39 showed the changes in soil water content as a function of time below the mulched and the bare soil. In those Figures, each curve followed the changes which occurred at a given location during the course of the experiement. In Figures 40, 41, and 42 the changes in soil water content as a function of depth can be followed. The gain in water is considered positive and the loss of water is considered negative.

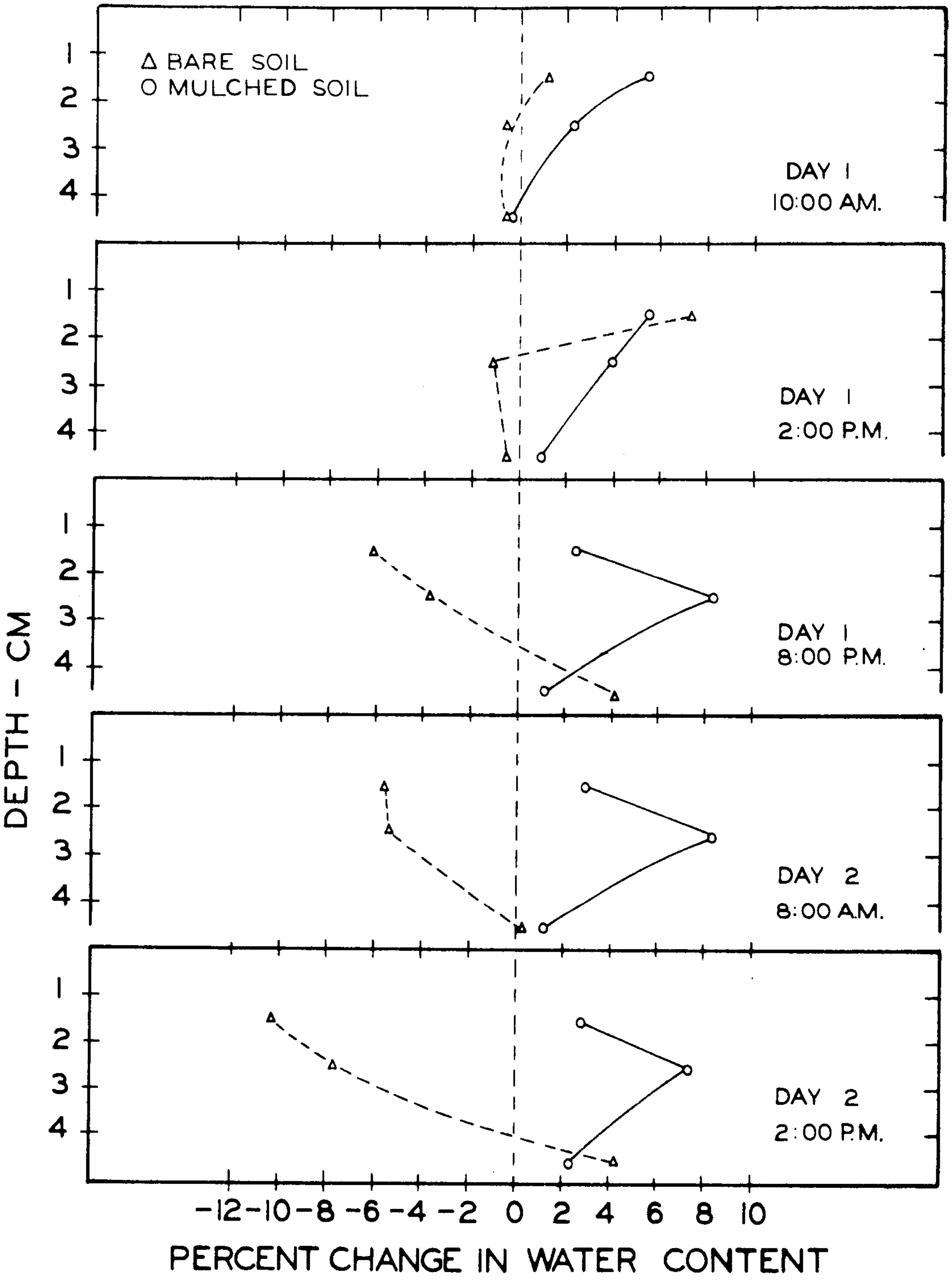


Figure 40. Percent change in soil water content plotted as a function of the depth below the mulch covered and bare soil. Day 1. Experiment B.

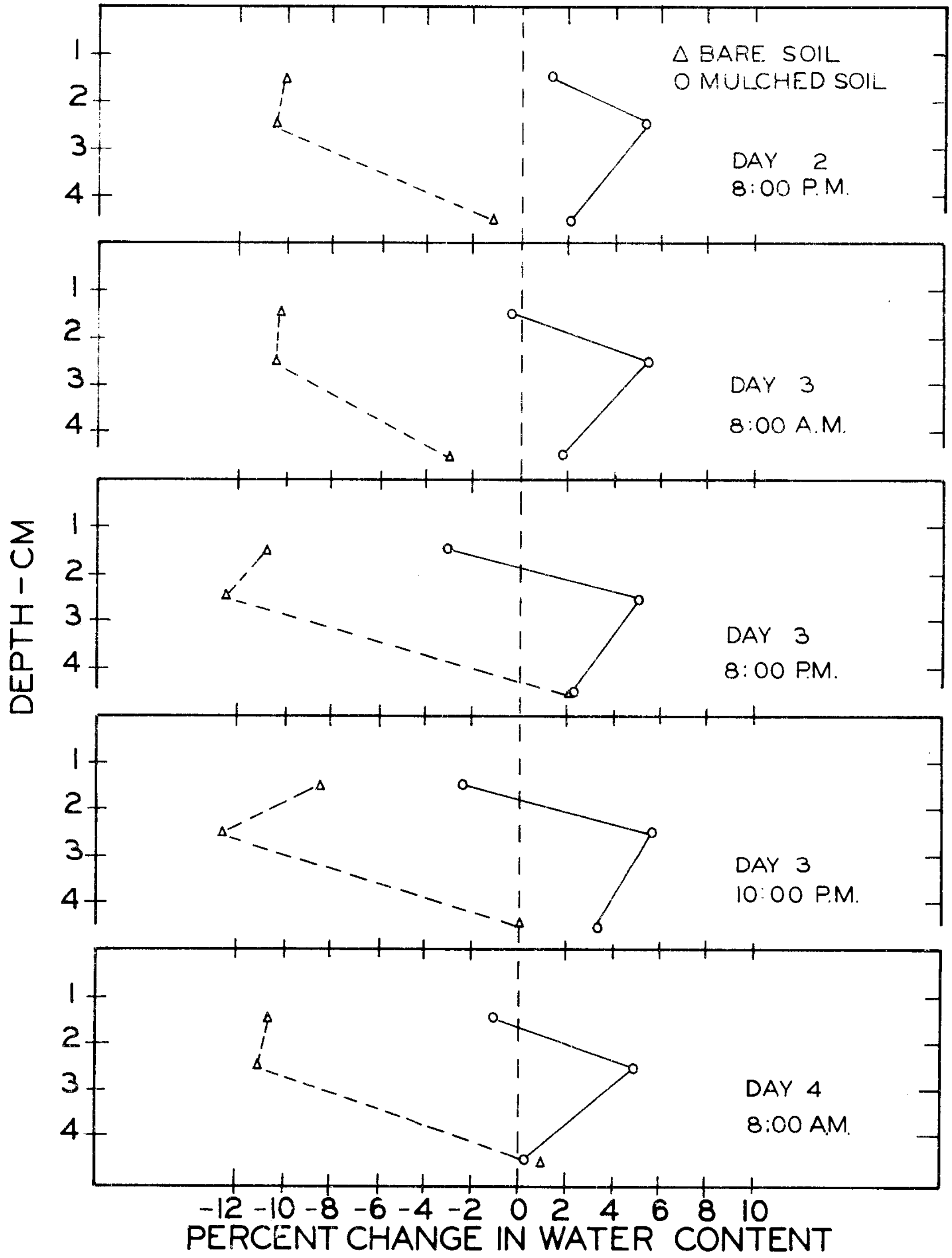


Figure 41. Percent change in soil water content plotted as a function of the depth below the mulch covered and bare soil. Day 2. Experiment B.

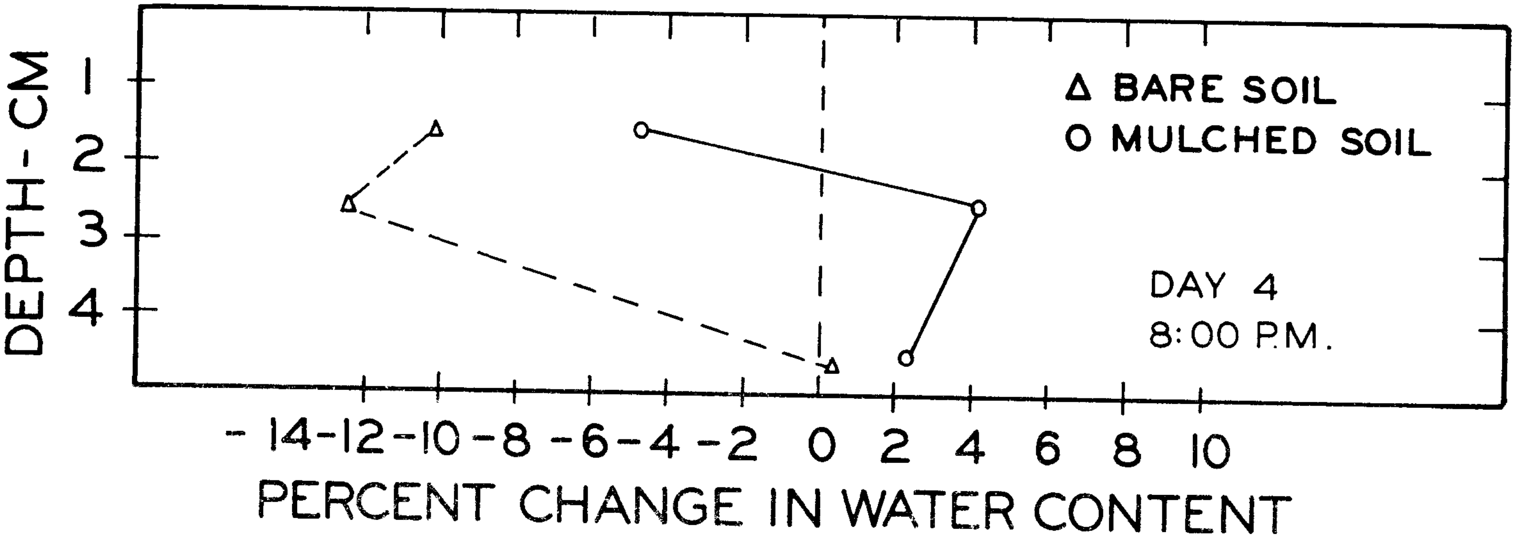


Figure 42. Percent change in soil water content plotted as a function of the depth below the mulch covered and bare soil. Day 3. Experiment B.

DISCUSSION

The Effect of Petroleum Mulch on Soil Water Content

The Conservation of Water Below the Mulch

Of the several physical changes brought about by the application of the mulch in the soil environment, the creation of a barrier to water vapor movement must be considered the most essential. The degree to which such a barrier limits the rate of water loss by evaporation can be evaluated by considering Figure 43. This diagram represents water vapor flowlines and was obtained by a relaxation technique assuming that for steady state conditions the flowlines are represented by a solution of the Laplace equation (Luthin and Gaskell, 1950). The solution represented by the diagram, assumes a steady rate of vapor loss from a zone four cm below the surface of the soil. Although the diagram only represents an approximation of the real conditions it does indicate that the rate of loss of water vapor from the soil below the mulch is at a much slower rate than the rate of loss from the soil below the uncovered surface. The water loss per unit surface area below the mulch is less than 25% of the rate of loss per unit surface below the bare soil. For the experimental conditions this reduction in water loss would even be greater.

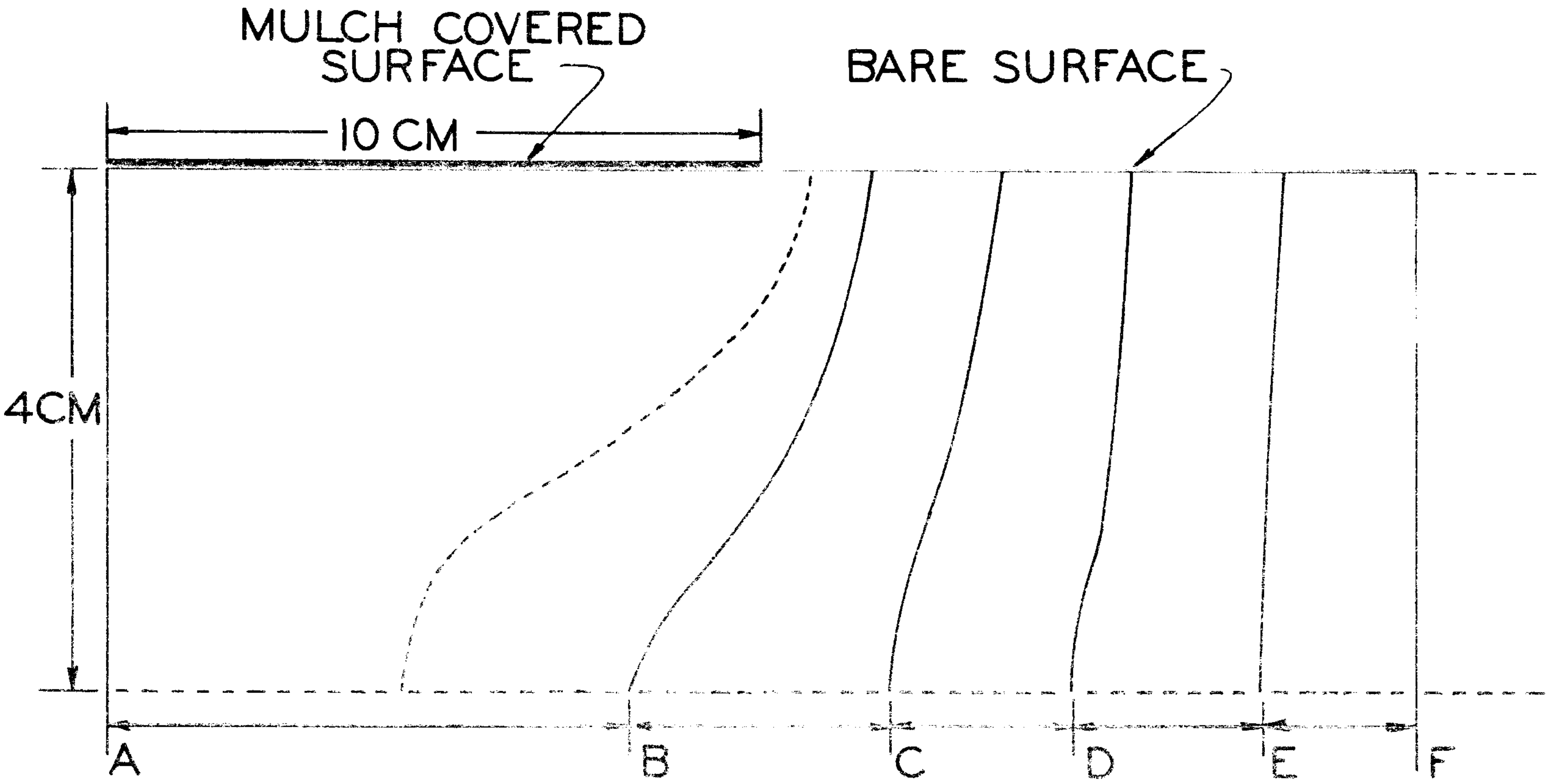


Figure 43. Theoretical water vapor flow lines obtained by the relaxation method.

The Increase in Water Content Below the Mulch

The application of a barrier to vapor diffusion does not explain the increase in water content observed in the soil below the mulch. The order of magnitude of the increase in soil water content measured was about five percent, or 0.05 cm^3 cm^{-3}.

The water vapor concentration of air at saturation increases as the temperature increases. It seems logical to reason that the water evaporated below the mulch remained there in vapor form, while the liquid water was replaced by a suction gradient toward the location where the evaporation occurred. Table 4 demonstrates that this reasoning can not explain the changes in water content. An increase in temperature from 25°C to 40°C increases the water vapor density 0.0281×10^{-3} gm/cm^3. The order of magnitude of this change is smaller than the observed change by a factor of 2×10^3.

Table 4. Water vapor concentrations of saturated air at indicated temperatures. (Handbook of Physics and Chemistry)

Temperature °C	Density of water vapor
°C	10^{-5} gm/cm^3
20	1.73
25	2.30
30	3.04
35	3.96
40	5.11

Mechanism of Water Transport

Changes in soil water content can be induced by thermal gradients and/or suction gradients. The flow of water in soils as a result of thermal gradients is generally considered to take place from warm to cold, and occurs in the liquid as well as in the vapor phase. Cary (1966) gives four possible reasons for the water to flow in the liquid phase from warm to cool under a temperature gradient:

1. The surface tension of water against air increases as the temperature drops, giving rise to a surface tension gradient.
2. Soil water suction increases as the temperature drops giving rise to a suction gradient.
3. Transfer results from a suction generated by kinetic energy changes associated with the hydrogen bond distribution which develops under a thermal gradient.
4. Flow results from thermally induced osmotic gradients.

The thermally induced liquid phase flow of moisture through soil from warm to cool is described by the equation:

$$J_{\ell} = - \frac{KQ}{gT} \frac{dT}{dz} \qquad (10)$$

where:

J_ℓ = thermally induced liquid phase flow (mm/hr)

K = capillary conductivity (mm/hr)

Q = liquid phase heat transport (ergs/gm)

g = acceleration of gravity (cm/sec^2)

T = temperature (^{o}K)

dT/dz = temperature gradient (^{o}K/cm)

Flow in the vapor phase is thought to be primarily a molecular diffusion process. When the vapor pressure gradient in the soil is determined by the temperature only, and not by osmotic or water content changes, the vapor transport is described by the relation:

$$J_v = - \beta \frac{DPH}{R^2T^3} \frac{dT}{dz} \tag{11}$$

where:

J_v = thermally induced vapor phase flow (mm hr^{-1})

β = geometry factor

P = vapor pressure of water (cal cm^{-3})

D = diffusion coefficient of water vapor in air (cm^2 sec^{-1})

H = heat of vaporization of water (cal mole^{-1})

R = gas constant (cal ^{o}K^{-1}, mole^{-1})

T = temperature (^{o}K)

dT/dz = temperature gradient (^{o}K cm^{-1})

Equations 10 and 11 can be used to estimate the order of magnitude of water transport by assuming reasonable values for the parameters in the equations. Values of thermally induced liquid phase flow, J_ℓ, and vapor phase flow, J_v, were calculated at depths of 0.50, 1.0, 3.0 and 6.0 cm at two hour intervals on the first day of experiment A.

The values of the parameters used were:

$\beta = 1.25$ (Cary, 1965)

$Q = 4.9 \times 10^{-2}$ cal gm^{-1} (Cary, 1965)

$K = 2.0 \times 10^{-4}$ mm hr^{-1} (estimated)

$g = 980$ cm sec^{-2}

$R = 1.9872$ cal mol^{-1} $^oK^{-1}$

$D = 0.239$ cm^2 sec^{-1} (Weast, 1964)

$P = 3.165 \times 10^{-5} \times p$ cal cm^{-3}

p = mm Hg

dT/dz = experimental data (Experiment A)

T = experimental data (Experiment A)

p = experimental data (Experiment A)

The vapor pressure, P, is given in terms of mm Hg in standard handbooks, but in Equation (11) it is given in terms of cal cm^{-3}. The conversion is made as follows:

$$
\begin{aligned}
P &= p \text{ mm Hg} \\
&= 0.1 \text{ p cm Hg} \\
&= 0.1 \times 13.52 \times 980 \text{ p dynes cm}^{-2} \\
&= 0.1 \times 13.52 \times 980 \text{ p ergs cm}^{-3} \\
&= \frac{0.1 \times 13.52 \times 980}{4.2 \times 10^{7}} \text{ p cal cm}^{-3} \\
&= 3.165 \times 10^{-5} \text{ p cal cm}^{-3}
\end{aligned}
$$

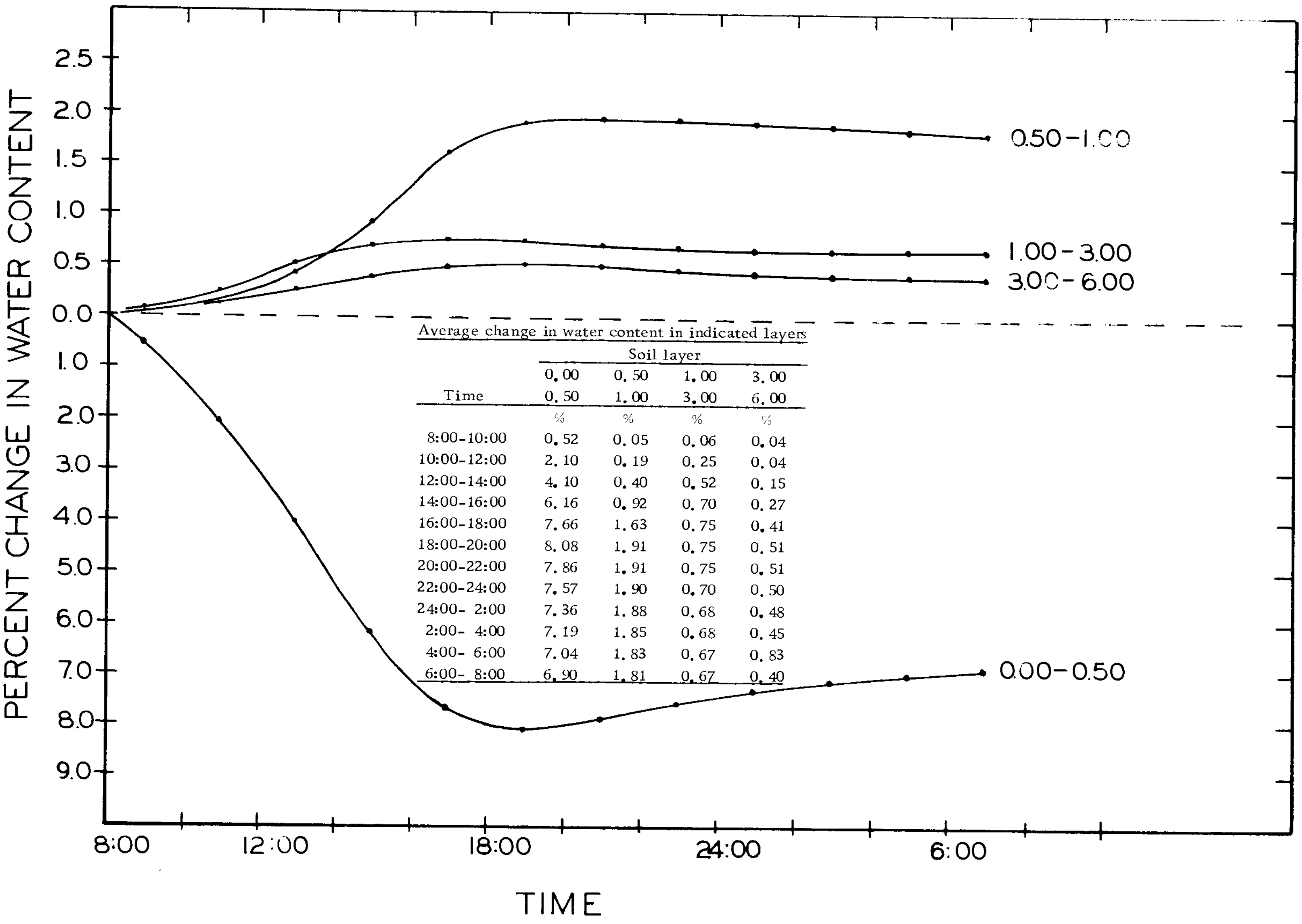
To obtain J_v in mm hr^{-1} the product of Equation (11) must be multiplied by 8.85×10^{5}, when the values of the parameters shown are used. Results of the calculations are shown in Table 5. The amount of water lost from or stored in a certain layer during a given period of time was calculated using the data shown in Table 5. Results of these calculations are shown in Figure 44. The gain or loss of water was expressed as a percent of the soil volume.

The results indicate that there was a loss of water in the layer 0.00-0.50 cm and a gain of water in all layers below a depth of 0.50 cm. The largest gain of water was in the layer 0.50-1.00 cm. The magnitude of the gain of water calculated is in good agreement with the experimental results. This can be ascertained by comparing Figure 44 with Figures 26, 27 and 28. The results further show that during the cooling cycle there was little net movement of water. The layer 0.00-0.50 cm lost about 8.0 percent water during the heating

Table 5. Values of J_ℓ and J_v calculated at indicated depths at two hour intervals, during the first day of experiment A.

Time	0.50 cm			1.00 cm		
	J_ℓ	J_v	$J_\ell+J_v$	J_ℓ	J_v	$J_\ell+J_v$
	10^{-4} mm hr^{-1}			10^{-4} mm hr^{-1}		
8:00	0	0	0	0	0	0
10:00	24	368	392	23	344	367
12:00	34	634	668	33	587	620
14:00	38	838	876	38	781	819
16:00	30	635	665	28	437	465
18:00	19	370	389	18	207	225
20:00	- 7	101	108	6	97	103
22:00	- 7	-75	-82	-6	-73	-79
24:00	- 6	-57	-63	-5	-53	-58
2:00	- 4	-42	-46	-4	-36	-40
4:00	- 4	-34	-38	-3	-29	-32
6:00	- 4	-34	-38	-3	-29	-32
8:00	- 3	-27	-30	-2	-27	-29

	3.00 cm			6.00 cm		
	J_ℓ	J_v	$J_\ell+J_v$	J_ℓ	J_v	$J_\ell+J_v$
	10^{-4} mm hr^{-1}			10^{-4} mm hr^{-1}		
8:00	0	0	0	0	0	0
10:00	18	225	243	9	99	108
12:00	23	342	365	14	173	187
14:00	25	419	444	17	238	255
16:00	20	345	365	10	145	155
18:00	14	228	242	10	140	150
20:00	6	97	103	9	128	137
22:00	- 3	-33	-36	0	0	0
24:00	- 3	-31	-34	0	0	0
2:00	- 3	-30	-33	0	0	0
4:00	- 2	-25	-27	0	0	0
6:00	- 2	-25	-27	0	0	0
8:00	- 2	-21	-23	-3	-14	-17



Average change in water content in indicated layers

	Soil layer			
Time	0.00 0.50	0.50 1.00	1.00 3.00	3.00 6.00
	%	%	%	%
8:00-10:00	0.52	0.05	0.06	0.04
10:00-12:00	2.10	0.19	0.25	0.04
12:00-14:00	4.10	0.40	0.52	0.15
14:00-16:00	6.16	0.92	0.70	0.27
16:00-18:00	7.66	1.63	0.75	0.41
18:00-20:00	8.08	1.91	0.75	0.51
20:00-22:00	7.86	1.91	0.75	0.51
22:00-24:00	7.57	1.90	0.70	0.50
24:00- 2:00	7.36	1.88	0.68	0.48
2:00- 4:00	7.19	1.85	0.68	0.45
4:00- 6:00	7.04	1.83	0.67	0.83
6:00- 8:00	6.90	1.81	0.67	0.40

Figure 44. Changes in soil water content calculated on the basis of Equations 10 and 11.

cycle and regained less than 1. 0 percent during the cooling cycle. The experimental results indicated that after the first day, the distribution of the soil water remained more or less constant. This is attributed to the occurrence of water movement under suction gradients. As a result of the loss of water in the upper soil layer and the accumulation of water in the layers immediately below it, large suction gradients were developed. Some values of soil water suction are shown in Table 6. It is assumed that water, moved downward under the influence of temperature gradients on the second day of the experiment, was returned under the influence of suction gradients.

Changes in Water Content Verified by the Temperature Measurements

The changes in soil water content which occurred during the course of the experiment and were measured with the γ-attenuation equipment are verified by the temperature measurements. The daily maximum temperature measured in the bare soil increased. whereas the daily maximum temperature of the mulched soil remained constant. This suggests that the water content of the mulched soil remained constant after the initial increase, and the water content of the bare soil gradually decreased.

The heat flux into the bare soil shown in Figure 24 increased continually during the course of the experiment. The maximum measured flux was 0. 09 cal cm^{-2} min^{-1} on the first day and increased to 0.195 cal cm^{-2} min during the last day. This is the result of the advance of a drying front into the soil, (Gardner and Hanks, 1966). During the initial phases of the experiment heat was being used for evaporation of water above the zone of the heat flux discs. As the upper layers of the soil dried out, less heat was being used for evaporation in this zone but transferred downward by conduction to be used for evaporation at lower depths. During the cooling cycle the heat was transferred upward in the form of water vapor. The heat flux discs used to obtain a measurement of the rate of heat transfer into the soil only recorded heat flow by conduction. Heat flow in the form of water vapor was not measured. As a result the recorded number of calories transferred upward during the cooling cycle was much smaller than the recorded number of calories transferred downward. The heat flux into the mulched soil did not change much during the course of the experiment. The difference in downward flux and upward flux recorded below the mulch is probably a result of heat transferred by liquid water movement around the heat flux disc.

The Effect of Petroleum Mulch on Heat Flux and Soil Temperature

Results of the soil temperature measurements are shown in Figures 14 through 23. In both experiments the surface layer temperature below the mulch was about $4^{o}C$ higher than the surface layer temperature below the bare soil. This temperature difference became less on later days.

The higher temperatures of the soil below the mulch are the result of a greater heat input. Results of heat flux measurements are shown in Figures 24 and 25. The greater heat flux below the mulch is a result of the color of the mulch itself and the higher thermal conductivity of the soil below the mulch. The color of the mulch was much darker than that of the adjacent bare surface, making it a better absorber for radiation. The degree to which the heat absorbtion of the soil was enhanced by the color of the mulch is difficult to evaluate from the experimental data.

The difference in thermal conductivity of the soil below the mulch and the bare soil was also important in bringing about the noted temperature differences. The thermal conductivity of the soil used in the experiments, as a function of the water content is shown in Figure 45.

The amplitude of the soil temperature is inversely proportioned to $(\lambda C)^{1/2}$. For the bare soil the heat conductivity, λ, as well as the heat capacity, C, decreased. The resulting increase in amplitude is shown in Figures 14 and 19. The soil temperature amplitude of the mulch covered soil did not change much.

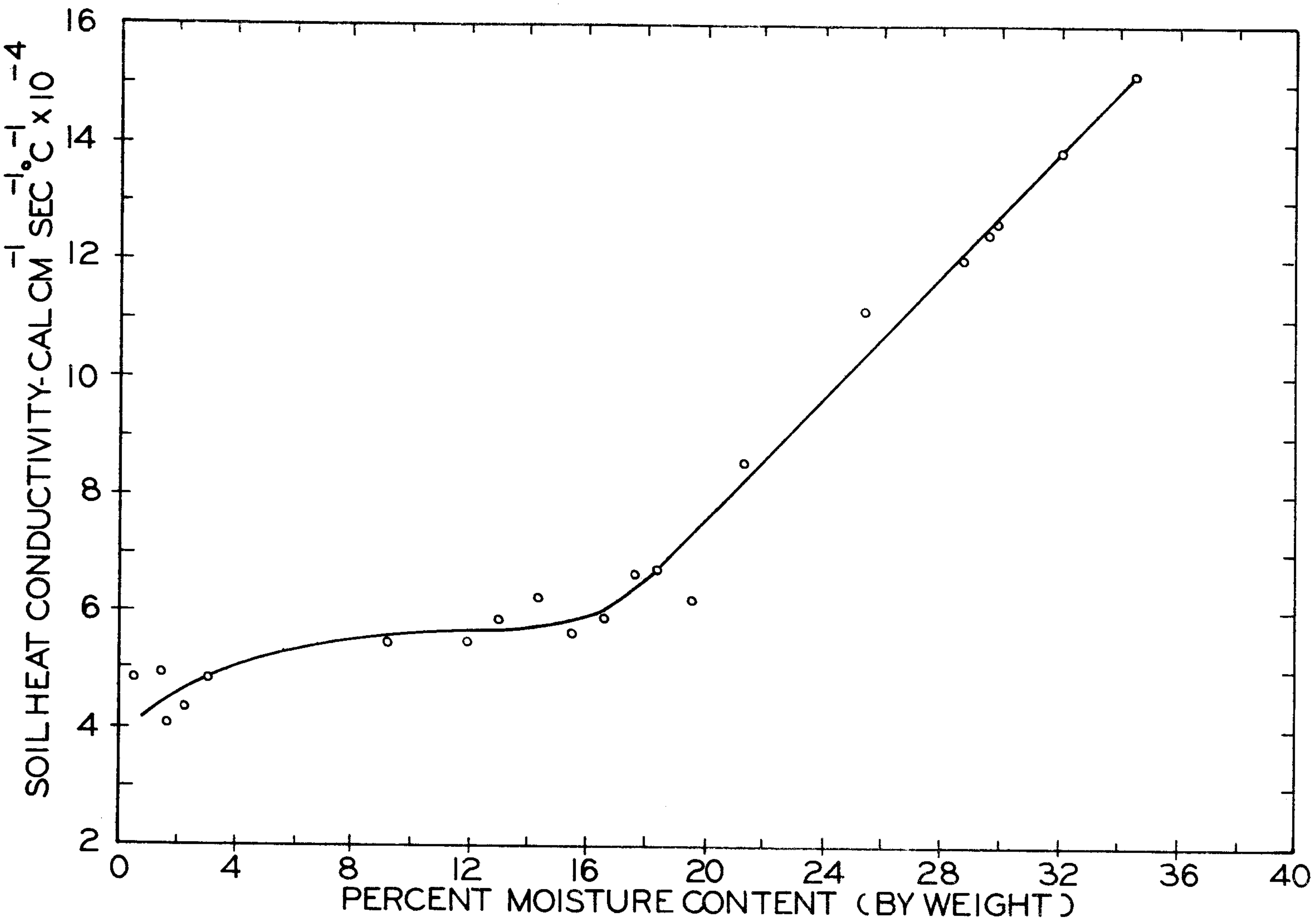


Figure 45. The thermal conductivity of Chehalis soil as a function of soil water content.

The Effect of Petroleum Mulch on Physical Conditions for Plant Growth

It has been demonstrated that an application of petroleum mulch causes a slight increase in soil temperatures and a considerable change in the soil water conditions. As a result of the mulch application the soil atmosphere below the mulch and very near the surface is very humid and loss of the water vapor to the atmosphere is prevented. The application of the mulch is likely to result in an increase in the water content of the soil.

The changes in soil water content can be very important for the germinating conditions of seeds. Even slight changes in soil water content bring about appreciable changes in soil water suction. This is demonstrated by the data of Table 6, obtained from experiment B.

Table 6. Soil water content and soil water suction below mulched and bare soil at different times during the experiment, at a depth of 1.5 cm, experiment B.

		Water content		Water content	
Day	Time	Mulch	No mulch	Mulch	No mulch
	hr	%	%	bars	bars
1	8:00	28.0	28.0	1.29	1.29
1	18:00	30.4	22.0	0.90	3.40
2	10:00	30.6	17.8	0.87	10.00

The importance of differences in soil water suction with respect to germination and seedling growth has been discussed by several authors. Sedgley (1963) reported that *Medicago tribuloides* Desr.

shows a distinct reaction to moisture tension in the germination process. After 24 hours, 80% ± 8% of seeds germinated at one cm tension while no seed germinated at 200 cm tension. Sedgley attributed this phenomenon to the area of contact between water and seed. At higher moisture tension there is less contact between the seed surface and the water.

Meyer (1963) considered the availability of water (solvent) in a liquid or gaseous form essential for the process of imbibition which causes the solution of colloidal particles, swelling of seed and the subsequent breaking of the seed coat. Owen (1952) in an intensive study of wheat germination at water potentials in the range of -205 to -322, showed that the percent of germination at lower suctions is much higher than at higher suctions.

While the bare soil lost moisture rapidly during the first day and gradually for the rest of the experiment, the mulched soil gained water rapidly on the first day and the water content remained almost constant for the remainder of the experiment. Petroleum mulch helps to bring about better conditions for germination by improving the soil water conditions. Early seedling growth is also enhanced. The root system of the seedling has to spend less energy to absorb water due to lower water potentials, stimulating the growth of a more virorous seedling.

The importance of increased soil temperatures should not be overlooked. Proper temperature is an important factor for all biological processes. Meyer _et al._ (1963) believe that the temperature sensitivity of seeds during the germination process differs from species to species and conclude that germination could not be characterized by a simple temperature coefficient. They give a range of 32-35°C as optimum temperature for corn germination. Crocker and Barton (1953) believe that the temperature has an effect on the rate of water absorption by the seeds. They quote and experiment by Davis and Porter (1936) in which the rate of absorption of moisture by corn kernels at 5, 10, 20, and 30°C was studied. After 24 hours the kernels at 30°C had absorbed 25.70 to 34.53 percent water and germinated 10 to 15% while the seeds at 20°C had absorbed 17.79 to 24.99 percent moisture with no germination.

SUMMARY AND CONCLUSION

An experimental set up was designed to study the effects of petroleum mulch on the soil water content and the soil temperature. It was observed that the soil water content at the seed level increased during the first day of an application of the mulch and remained almost constant or decreased gradually towards the end of the experiment. This increase in water content relative to the bare soil is attributed to the sealing effect of petroleum mulch, and the translocation of water under temperature gradients. The temperature of the soil under the mulch was always higher than under the bare soil. This higher temperature is attributed to the black-body effect of petroleum mulch and its higher heat conductivity.

The higher temperatures and improved soil water conditions mediate more rapid germination and more vigorous seedling growth.

The results of this study can only serve to indicate how an application of petroleum mulch stimulates germination and seedling growth. Additional experiments are necessary to identify the conditions under which maximum benefits can be expected from a mulch application more clearly. These experiments should consider such parameters as initial soil water distribution, initial soil temperature, surface temperature amplitudes and amount of mulch applied.

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