Soil and Air Temperature Changes Induced by Subsurface Line Heat Sources

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PREFACE

Multiple use of waste heat from power plants may become an important consideration in their development and siting. The heat in the cooling water must be considered a resource to be managed for effective use. Soil warming was suggested as one of several possible productive uses for the heated discharges. The sub-surface application of heat to soil by circulating the warm water through a network of buried pipes was proposed. In geographical regions where soil temperature limits plant growth such a system might be operated profitably. It was further suggested that the piping system also might be used to supply water to an overhead irrigation system or as a sub-surface irrigation system with thermal gradients enhancing water distribution. Authors of this report, based on results obtained during 1969 through 1972, are K. A. Rykbost, graduate research assistant in soil science, and L. Boersma, professor of soil science (project leader).

The Pacific Power and Light Company of Portland, Oregon, and the Office of Water Resources Research, U.S.D.I. provided funding for a research project to evaluate the effect of warming soils above their natural temperatures on crop growth. The research program was conducted cooperatively by the Oregon State University departments of Soil Science, Horticulture, and Agronomic Crop Science. Research was carried out at the Hyslop Field Laboratory.

CONTENTS

SOIL AND AIR TEMPERATURE CHANGES INDUCED BY SUBSURFACE LINE HEAT SOURCES

1. INTRODUCTION

In regions where soil temperatures limit plant growth, artificial soil warming may be an economically feasible practice. This hypothesis was evaluated in a soil warming experiment near Corvallis, Oregon. These experiments were prompted by the observation that multiple use of waste heat discharge in the condenser cooling water of thermal power plants may well become an important consideration in the development and siting of these plants. The thermal discharge might be used to achieve increased soil temperatures by circulating warm water through a subsurface pipe network. The effect of increased soil temperatures on crop growth was described in a separate report (Rykbost et al., 1974). This report describes energy balances and water regimes of soils heated above natural temperatures.

1.1 Energy Dissipation by Underground Line Heat Sources

The rate of energy dissipation from a line source at some depth in the soil depends on several parameters. Kendrick and Havens (1973) presented the following equation for steady state conditions:

$$Q = \frac{2\pi k \Delta T}{\ln \frac{(2d-r)}{r} + \sum_{n=1}^{N} \ln \frac{(n\ell)^2 + (d-r)^2}{(n\ell)^2 + r^2}} \qquad (1)$$

where Q is the rate of heat loss per unit length of pipe (cal/cm min), r is the pipe diameter (cm), ℓ is the spacing (cm), d is the depth (cm), k is the thermal conductivity of the soil (cal/cm min C), and N is the number of parallel pipes on either side of the center pipe. Kendrick and Havens (1973) also evaluated an arrangement where the direction of flow was the same in neighboring pipes and an arrangement where the flow was opposite in adjacent pipes.

1.2 Thermal Conductivity and Soil Water Content

The thermal conductivity of soil increases with increasing water content. De Vries (1966) presented measured as well as computed values of thermal conductivity for sandy, clayey, and peat soils over a wide range of water contents. Values for a sand and a clay are reproduced in Figure 1. It emphasizes the strong dependence of thermal conductivity on water content. Soil water is continually depleted and replenished during crop production. Thermal conductivities may vary as much as three-fold during short periods of time as a result. The importance of thermal conductivity on the energy balance is shown by equation 1. The rate of energy dissipation is proportional to the thermal conductivity. Rates of energy loss may be expected to vary considerably during the growing season.

Smith and Byers (1938) evaluated the influence of soil texture on thermal conductivity. They showed that for dry soil, coarse texture resulted in the highest thermal conductivity because of less pore space and better particle contact. A linear relationship was observed between increasing pore space and decreasing thermal conductivity. Similar observations were made by Nakshabandi and Kohnke (1965).

1.3 Temperature Gradients

Estimation of expected rates of energy dissipation with equation 1 requires values for temperature gradients. These are determined by the temperature difference between heat source and soil surface. Choosing appropriate values for either is difficult. The heat source temperature is the temperature of the condenser cooling water. It may be expected to remain fairly constant over a period of several weeks, but can fluctuate widely during the year. Cooling waters withdrawn from small streams or shallow ponds may exhibit some diurnal temperature fluctuations, but this would probably be the exception rather than the rule. Changes in level of power generation might also result in minor changes in cooling water temperatures. Seasonal fluctuations may be of the order of 25 C, however (Kolfat, 1969).

Soil surface temperatures have a wide range on a daily as well as seasonal basis (Van Wijk and De Vries, 1966). Daily fluctuations at the soil surface may be greater than seasonal changes in the heat source temperature. A reference point at some depth below the surface where daily changes are fairly small may be a better index for establishing a temperature gradient for analysis of the subsurface heating systems.

Soil surface temperatures fluctuate in response to air temperature changes. Air temperature data is readily available for nearly all locations in the United States. It may be possible to develop a basis for predicting energy dissipation rates using heat source and air temperatures for the establishment of temperature gradients. If a valid prediction of energy dissipation rates can be made from air temperature data, it would be simple to develop estimates for any locality without a

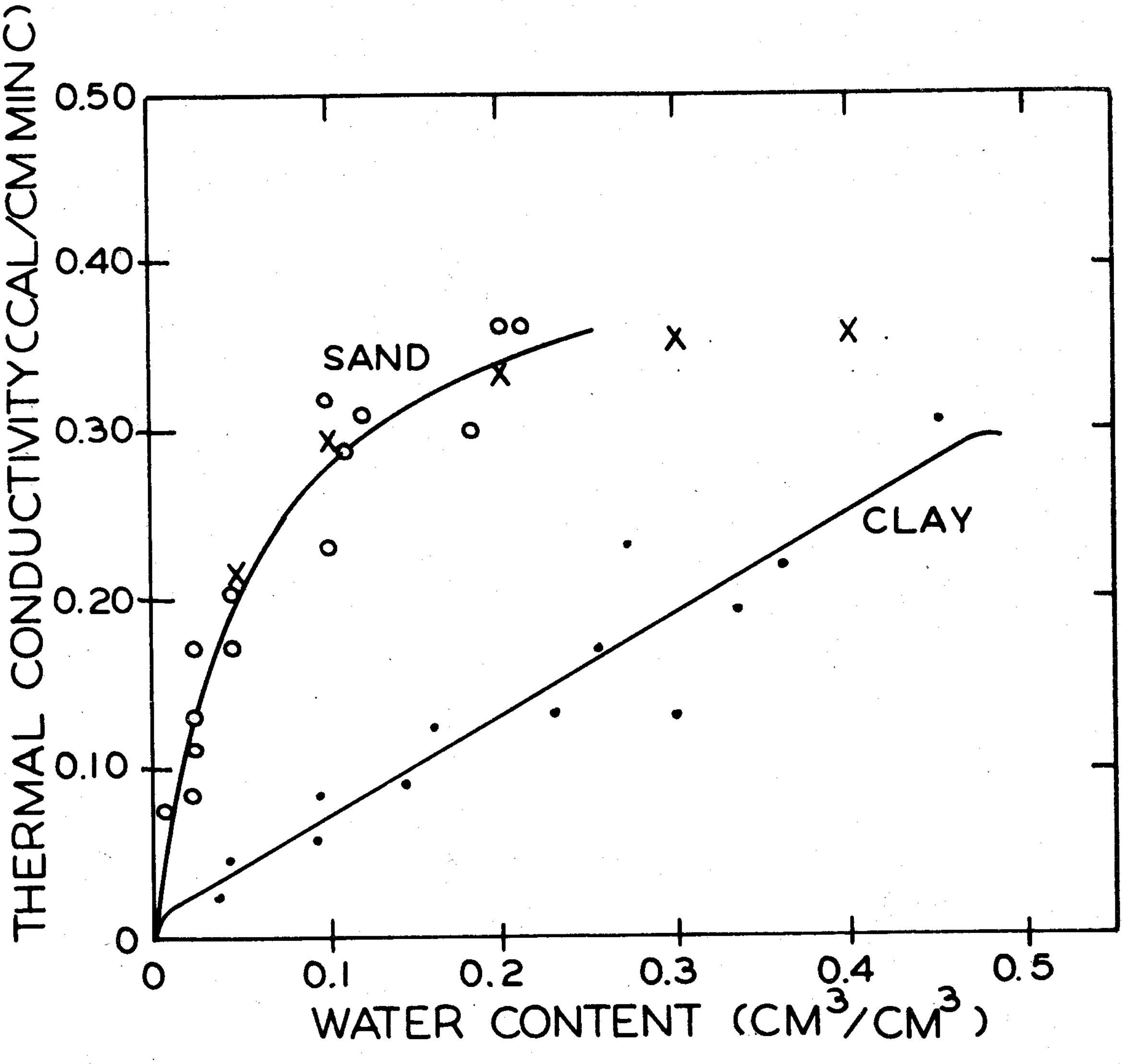

Figure 1. The thermal conductivity of a sandy soil and a loam soil. The data points are measured values, solid lines represent theoretical values.

knowledge of soil temperatures. This could be very important as soil temperature data are not readily available in many regions.

1.4 Effect of Design Parameters on Heat Loss Rates

Effects of pipe network design on energy dissipation are illustrated by solving equation 1 for several sets of conditions. Assuming for all cases: N = 6 (13 total pipes), $\Delta T = 20$ C, and k = .20 cal/cm min C, solutions were obtained for four different designs. The solution to equation 1 is independent of N for values of N greater than 6.

CASE I: $\ell = 180$ cm; d = 90 cm; r = 5 cm

then: Q = 5.4 cal/cm min; R = 3.0×10^{-2} cal/cm^2 min.

CASE II: $\ell = 120$ cm; d = 90 cm; r = 5 cm

then: Q = 4.8 cal/cm min; R = 4.0×10^{-2} cal/cm^2 min.

CASE III: $\ell = 120$ cm; d = 60 cm; r = 5 cm

then: Q = 5.8 cal/cm min; R = 4.9×10^{-2} cal/cm^2 min.

CASE IV: $\ell = 180$ cm; d = 90 cm; r = .5 cm

then: Q = 3.6 cal/cm min; R = 2.0×10^{-2} cal/cm^2 min.

The values of R are dissipation rates per unit area served by a unit length of pipe. Inspection of R values illustrates the effect of depth, spacing, and pipe diameter on dissipation rates. Increasing the pipe density by 33 percent (CASE I to CASE II) increases the dissipation rate by 35 percent. Reducing the depth by one-third (CASE II to CASE III) increases the dissipation rate by 22 percent. Decreasing the pipe diameter from 5 cm to .5 cm (CASE I to CASE IV) reduces the dissipation rate by 32 percent.

Kendrick and Havens (1973) evaluated effects of spacing, depth, and pipe diameter and reported similar results. Their analysis of flow direction indicated that dissipation rates would be slightly higher for conditions where flow in the neighboring pipes is in the same direction. They calculated the area required to dissipate the heat rejected by a 1,000-megawatt generating station to be 4,000 to 15,000 hectares, depending on design factors and soil thermal conductivities.

Comparison of experimentally determined energy dissipation rates with those predicted by theoretical models was an objective of the study. It was anticipated that in the event the models were inadequate a relation could be established between energy dissipation rates and a readily available climatic parameter such as air temperature.

2. EXPERIMENTAL PROCEDURES

2.1 Site Description

The soil heating experiment was at the Hyslop Crop Science Field Laboratory, 10 kilometers northeast of Corvallis, Oregon. The site is on the main floor of the Willamette Valley, a few kilometers east of the Coast Range foothills. The elevation is approximately 70 meters above sea level at a latitude of 44° 38' north and longitude 123° 12' west. Total annual rainfall is 100 cm with 70 percent occurring from November through March and 5 percent occurring during the three summer months. Mean annual temperature is about 17 C with daily minima below -15 C and daily maxima above 38 C being quite rare (Bates and Clahoun, 1971).

The experimental site is on a nearly level terrace. Soil within the one-hectare research plot is classified in the Woodburn Series, an Aqualtic Argixeroll in the new Soil Conservation Service classification scheme.

2.2 Soil Warming System

Warm water was not available at the site. It was therefore decided to simulate the underground system of pipes with warm water flowing through them with a network of buried electrical heating cables.

2.2.1 Layout and Hookup

The Hyslop Farm area is supplied with 20.8 kilovolt (KV), three phase "y", 60 megahertz power from the regional distribution network of the Pacific Power and Light Company. The heat sources were supplied from a transformer fed 12,000 volts from one phase to the primary neutral. The transformer had one secondary winding providing 480 volts center tapped to ground with a capacity of 250 kilovolt-amperes. The voltage was distributed by a triplex aluminum secondary cable to each metering site.

Six individually controlled electric heating cables were installed in April, 1969. The field plot layout is illustrated in Figure 2. A simplified schematic wiring diagram is presented in Figure 3.

A variety of heating cables was used, each specified to maintain a constant dissipation rate per unit area. All cables, except one, were single-conductor units, consisting of one resistance heating wire completely surrounded by a highly compressed magnesium oxide insulation, contained in an outer sheath of seamless copper tubing. In the greenhouse a dual conductor cable was used, consisting of two resistance

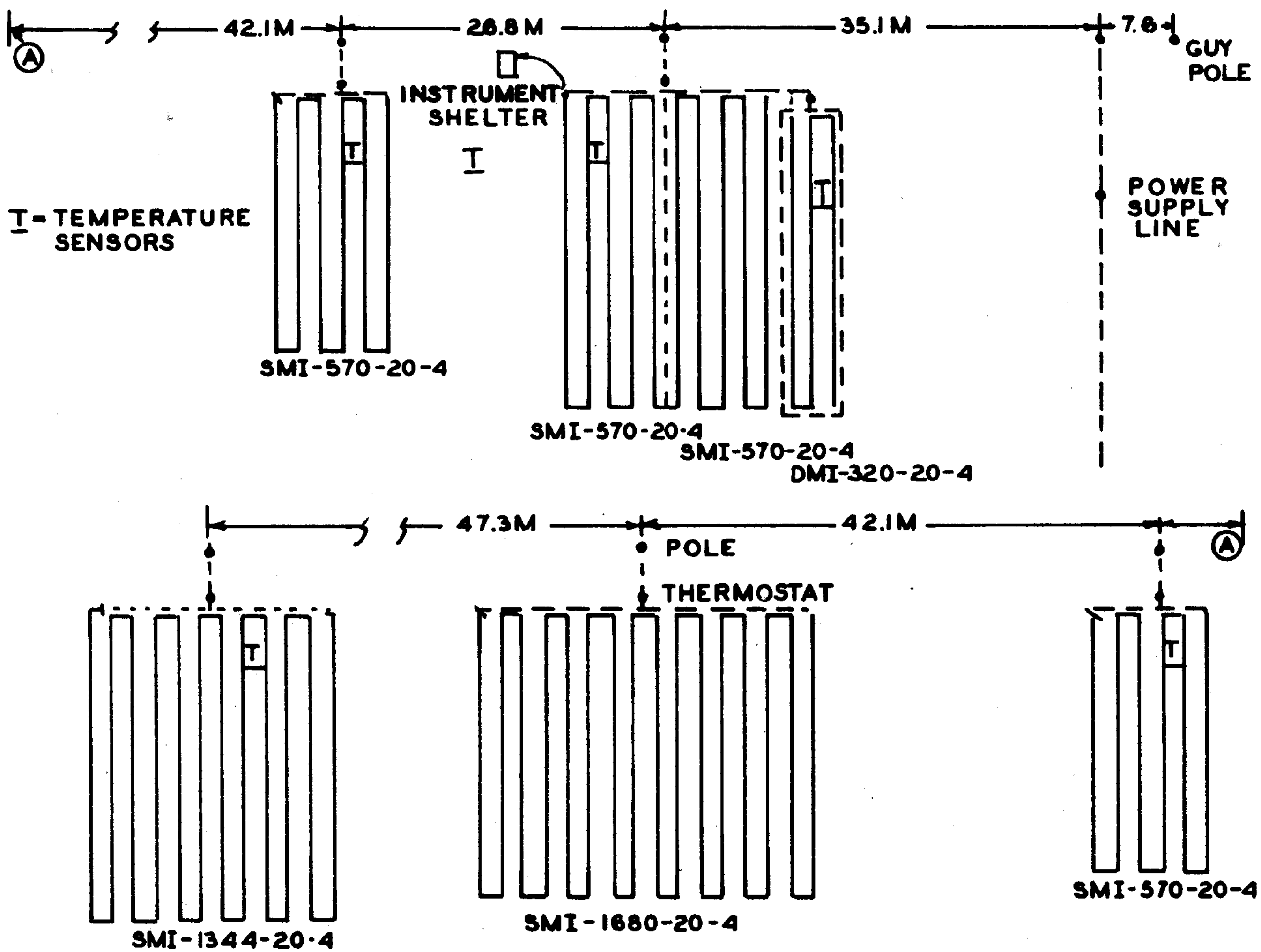

Figure 2. Layout of plots used in the soil warming experiment.

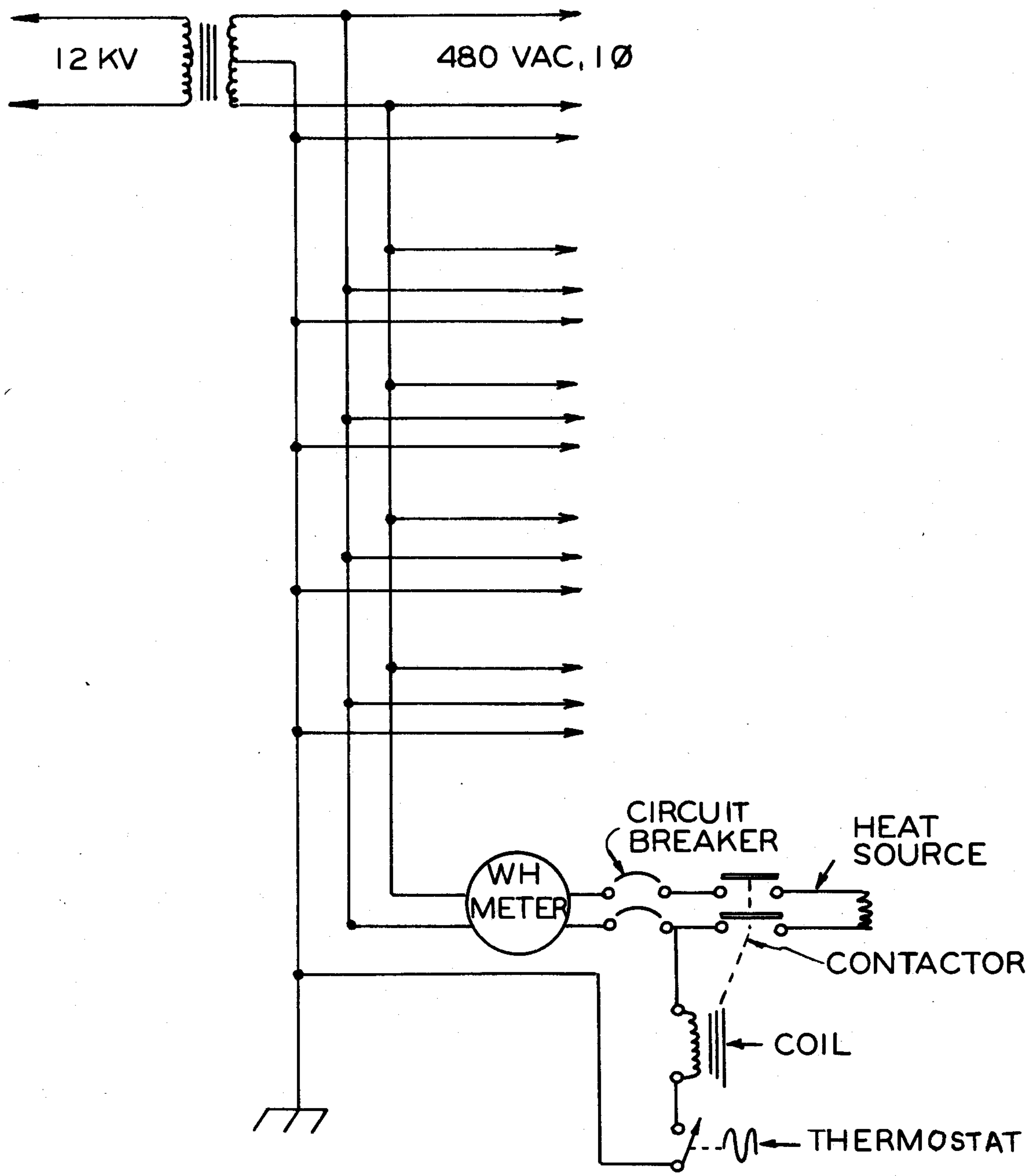

Figure 3. A simplified schematic wiring diagram of the heat sources and their components to the secondary power source.

heating wires running parallel in a single sheath, both terminating at one end. All cables were manufactured by the Climate Control Division of the Singer Company, Auburn, New York. Each cable was designed for 480-volt excitation and a dissipation rate of 65.5 watts per linear meter (watts/meter). Cable specifications are presented in Table 1.

Table 1. Heating source specifications.

Catalog number	Heated length	Watts	Current	Sheath diameter	Heater gauge	Heater comp.
	m	watts	amp	cm		
SMI-574-20-4	175	11,480	23.8	.55	16	alloy
SMI-1344-20-4	410	26,880	63.3	.52	18	copper
SMI-1680-20-4	512	33,600	70.0	.55	16	copper
DMI-320-20-4	98	6,400	13.3	.78	18	alloy
DME-405-20-4	123	8,060	16.8	.78	18	alloy

Connections were made to contractor switches with cold-wire extensions brazed on at cold-hot, waterproof junctions, factory installed. Each heated plot was provided with a pole-mounted watthour meter and switching equipment fed from the secondary cable. Each circuit was metered by a 480-volt, two-stator, polyphase watthour meter and protected by an appropriate capacity two-pole circuit breaker.

It was noted that the heating cables using a copper resistance wire have an average dissipation rate somewhat lower than the manufacturer's rating. This presumably is a function of the positive temperature coefficient of resistance of the copper. As the cable becomes warmer, total resistance increases and current consumption drops to about 49 watts/meter.

Initially all cables were installed at a depth of 92 centimeters (cm) with 183 cm lateral spacing between adjacent loops. In August, 1970, the cable on the GRASS plot was disconnected. A new cable was installed at a depth of 51 cm with a lateral spacing of 122 cm between loops. In November, 1970, the GREENHOUSE cable was replaced with a new cable buried 55 cm deep with a 122 cm lateral spacing. Original watthour meters, control switches, and thermostats were retained in both cases.

The area heated and plot dimensions for all cable installations are indicated in Table 2. It was assumed that heated areas extended beyond the outside cable loop a distance equal to one-half the lateral spacing. For the GRASS and GREENHOUSE locations the designations (1) and (2) refer to original and replacement cables, respectively.

Table 2. Plot dimensions and placement of heating cables.

Plot	Cable depth	Cable spacing	No. loops	Plot width	Plot length	Plot area
	cm	cm		m	m	m^2
NO COVER	92	183	10	18.3	33.6	613
CORN	92	183	6	11.0	27.4	301
SUB-IRR	92	183	6	11.0	27.4	301
BEAN	92	183	16	28.1	29.3	820
GRASS (1)	92	183	12	22.0	32.2	709
GRASS (2)	51	122	16	19.5	32.2	628
GREENHOUSE (1)	92	183	3	5.5	31.1	171
GREENHOUSE (2)	55	122	4	4.9	30.5	149

Heating cables designated SMI-574-20-4 in Table 1 were used on NO COVER, CORN, and SUB-IRR plots. Two such cables were wired to one control switch on the NO COVER plot. Cables designated SMI-1680-20-4 were used on the BEAN plot and as the replacement cable on the GRASS plot. The cable originally installed in the GREENHOUSE was DMI-320-20-4. It was replaced with DMI-405-20-4 in 1970.

2.2.2 Trenching

Trenching was done with an industrial trencher (Ditch-Witch, Model J-20) equipped for 10 cm-wide trenches. Horizontal and vertical spacings were maintained within 5 cm of design specifications. Backfilling was done with a tractor-mounted blade and hand tamping. Water was applied during and after backfilling to assist in compacting trenches to the original density.

2.2.3 Thermostat Controls

Temperature control of the heating cables was achieved with industrial thermostats (equivalent to No. A19ANC, Penn Controls, Inc., Oak Brook, Ill.) mounted in watertight enclosures. Each had a three-meter capillary. The sensing bulb was placed in close proximity to the heating cable. The thermostat controlled a magnetic contactor (class 40, Furnas Electric Co., Batavia, Ill.) of appropriate capacity.

Temperature control of the thermostats was with screwdriver slot adjustment. The switch action was an SPDT contact unit. The sensing bulbs were initially located approximately 2 cm from the cable sheath. On August 25, 1969, sensing bulbs were relocated to be in intimate contact with the cable sheaths.

2.3 Power Use Measurement

Meter readings were recorded at regular intervals throughout the four-year study period. During summer months, readings were taken at one- to three-day intervals. In the winter, readings were taken less frequently but at least twice each month. The time at which readings were taken also was recorded. This allowed calculation of the average rate of energy consumption for the period between consecutive readings.

2.4 Operation of the Heat Sources

Heat sources were energized during periods of crop production and on some plots through the winter months. Table 3 shows the periods of operation for each of the six sources, the source temperatures where this information was available. Short-term shutdowns which occurred for various reasons are not indicated. Dates when heat sources were turned on or off are indicated in columns labeled "in use."

Source temperatures indicated in Table 3 are average values for periods when heat sources were in use. On the CORN and GRASS plots, source temperatures fluctuated as much as 6 to 8 C over a period of one or two days. Source temperatures on the other plots were very stable over extended time periods. Sudden changes in source temperatures in Table 3 are indicative of changes in thermostat settings or malfunctions of the heat sources.

2.5 Soil Temperature Measurements

2.5.1 Soil Temperature Sensors

Soil temperature measurements were made with precision disc thermistors with a resistance of 10,000 (± 1 percent) ohms at 25 C and a beta of 3,965 K (Thermonetics 1J13, Cal-R Inc., Santa Monica, California). These were encapsulated in .8 cm diameter copper tubing sections, each 2.5 cm long. One end of the copper tubing was crimped shut and sealed with solder. The copper tubing was filled with low-viscosity epoxy resin to provide a waterproof capsule. Lead wires varying in length from 1.5 to 3 meters consisted of two conductor unshielded cables.

All sensors were connected to the instrument shelter with multi-pair cables. The more distant sites were serviced with standard No. 22 AWG 50-pair, direct burial, telephone cable meeting REA-PE-23 specifications. For the shorter cable runs No. 22 AWG 51-pair cable with a single jacket (Belden 8751, Belden Corp., Chicago, Ill.) was used. These cables were buried sufficiently deep to avoid damage from tillage operations.

All field splices between sensors and signal cables were made with terminal junctions meeting MIL-T-81714 specifications. Use was made of modular blocks accepting eight crimp-type pin contacts, protected with silicone rubber grommets (No. TJ12E-02-02, Deutsch Electronic Components Division, Banning, California). These terminal blocks were assembled in the field and placed in a vertical 10 cm diameter clay tile capped on the upper end with a wooden disc. All signal cables were routed to the instrument shelter, brought above ground in protective conduits, and passed through the shelter wall.

All cable terminations, data acquisition instrumentation, and field office operations were located in an instrument shelter consisting of a permanently placed 6.7 meter mobile office trailer. The trailer was provided with a thermostatically controlled electric heater and a mechanical air conditioning system. Inside temperatures were controlled between 20 and 25 C.

2.5.2 Installation of Soil Temperature Sensors

A soil auger, 2.5 cm in diameter, was used to bore holes to the depth of the deepest sensor in a given stack. A sensor was pressed firmly into place with a tamping tool consisting of a 2.0 cm diameter solid plastic cylinder mounted on a soil auger shaft. Loose soil was then poured into the hole in 3-5 cm increments each, firmly packed with the tamping tool. This was repeated until the depth for the next sensor in the stack was reached. This sensor was then installed in a similar manner and the entire process repeated until all sensors at depths greater than 31 cm were in place.

Wire leads from the sensors were routed to a clay drainage tile 10 cm in diameter and 30.5 cm long, buried vertically with the upper end 30 cm below the soil surface. Wire leads from all sensors below 31 cm entered the tile from the bottom. Leads from sensors above 31 cm entered the tile from the top. This allowed easy access for placing the shallow sensors inside the tile during periods when tillage operations were performed.

Multipair shielded cables entered the tiles from below. Connections between sensor leads and shielded cable leads were enclosed in the tile. Lids made from exterior plywood prevented soil from filling the tiles.

2.5.3 Placement of Soil Temperature Sensors

Soil temperatures were monitored on six different study plots within the experimental area during the course of the study. These locations

Table 3. Timetable of heating cable operation and approximate source temperature.

Month	NO COVER		CORN		SUB-IRR		BEAN		GRASS		GREENHOUSE	
	In use	Source temp.	In use	Source temp.	In use	Source temp.	In use	Source temp.	In use	Source temp.	In use	Source temp.
		C		C		C		C		C		C
1969:												
April	25	--	25	--	25	--	25	--	25	--	no	--
May	yes	--	yes	--	yes	--	yes	--	yes	--	1	--
June	yes	--	yes	--	yes	--	yes	--	yes	--	yes	--
July	yes	--	yes	--	yes	--	yes	--	yes	--	yes	--
August	yes	--	yes	--	yes	--	yes	--	yes	--	yes	--
September	yes	--	18	--	18	--	yes	--	yes	--	yes	--
October	20	--	no	--	no	--	15	--	15	--	27	--
1970:												
April	2	23	2	36	8	26	2	--	2	--	no	--
May	yes	25	yes	43	yes	27	yes	--	yes	--	no	--
June	yes	26	yes	40	yes	32	yes	--	15	--	no	--
July	yes	32	yes	40	yes	36	yes	--	no	--	no	--
August	yes	--	yes	--	21	--	yes	--	no	--	no	--
September	yes	30	11	38	no	--	11	--	14	--	no	--
October	yes	29	no	--	no	--	no	--	yes	--	no	--
November	yes	31	no	--	no	--	no	--	yes	--	no	--
December	yes	31	no	--	no	--	no	--	yes	27	21	--

1971:												
January	yes	32	no	--	no	--	no	--	yes	24	yes	--
February	yes	33	no	--	no	--	no	--	yes	24	yes	--
March	yes	33	no	--	no	--	no	--	yes	24	yes	--
April	yes	33	22	31	22	25	22	--	yes	24	yes	--
May	yes	33	yes	28	yes	31	yes	--	yes	25	yes	--
June	yes	35	yes	35	yes	30	yes	--	yes	32	yes	--
July	yes	35	yes	31	yes	31	yes	--	yes	32	yes	--
August	yes	35	yes	33	yes	33	yes	--	yes	32	yes	--
September	yes	35	17	34	yes	31	yes	--	yes	34	yes	--
October	yes	--	no	--	29	--	21	--	yes	--	21	--
November	yes	--	no	--	no	--	no	--	yes	--	no	--
December	yes	--	no	--	no	--	no	--	yes	--	no	--
1972:												
January	yes	38	no	--	no	--	no	--	yes	46	25	31
February	yes	36	no	--	no	--	no	--	yes	50	yes	34
March	yes	36	no	--	30	--	no	--	yes	52	yes	36
April	yes	36	no	--	yes	27	no	--	yes	54	yes	38
May	yes	--	5	--	yes	--	no	--	yes	--	yes	--
June	yes	37	yes	38	yes	32	no	--	yes	65	yes	34
July	yes	37	yes	32	yes	31	no	--	yes	35	yes	--
August	yes	37	yes	33	yes	31	no	--	yes	34	yes	--
September	14	36	yes	33	yes	31	no	--	yes	34	yes	--
October	no	--	2	--	2	--	no	--	5	--	yes	--

are indicated in Figure 2. The CONTROL plot was on an unheated area with no plant cover. The NO COVER location was on a heated plot maintained bare. Cover on the CORN plot varied from none prior to planting to a full crop of field corn in late summer. The SUB-IRR plot was planted with field corn and bush beans in 1970, maintained bare in 1971, and planted with field corn in 1972. The GRASS plot had ryegrass growing on it during winter months and sudangrass during summer months. GREENHOUSE soil temperatures were monitored under bare soil conditions.

The CONTROL plot temperature sensors were placed in a single stack at depths of 2.5, 7.6, 15.2, 22.9, 45.7, 68.6, 91.4, 114.3, 152.4 and 213.4 cm. These sensors were not moved after their installation in March, 1970.

Sensors were installed at the NO COVER and CORN locations in July, 1969. The original placement of sensors in relation to heat sources and soil surface is shown in Figure 4. The sensors at depths of 2.5 and 22.9 cm in the CORN plot were buried in the clay tile in February, 1970 for protection during tillage operations. They were relocated in April, 1970 according to the scheme shown in Figure 5.

Temperature sensors at 2.5 and 22.9 cm depths in the NO COVER plot were relocated at positions indicated in Figure 5 in June, 1970. These sensors were not disturbed during the remainder of the study period.

In April, 1970, sensors were installed in the SUB-IRR plot at depths of 22.9 cm and greater according to the layout shown in Figure 6. Those at depths of 2.5, 7.6, and 15.2 cm were installed in June, 1971. All sensors at the upper four depths were buried in the clay tile during tillage operations and subsequently relocated as shown in Figure 6.

Temperature sensors were installed on the GRASS plot in October, 1970. Their location with respect to soil surface and heat sources is indicated in Figure 7. Sensors at depths of 2.5, 7.6, and 15.2 cm were buried in a clay tile during tillage operations and relocated at the appropriate positions later.

Four temperature sensors were installed in the GREENHOUSE plot in January, 1972. These were placed at 2.5 and 50.8 cm depths. Two were located directly over the heat source and two were located midway between two adjacent loops of the heat source.

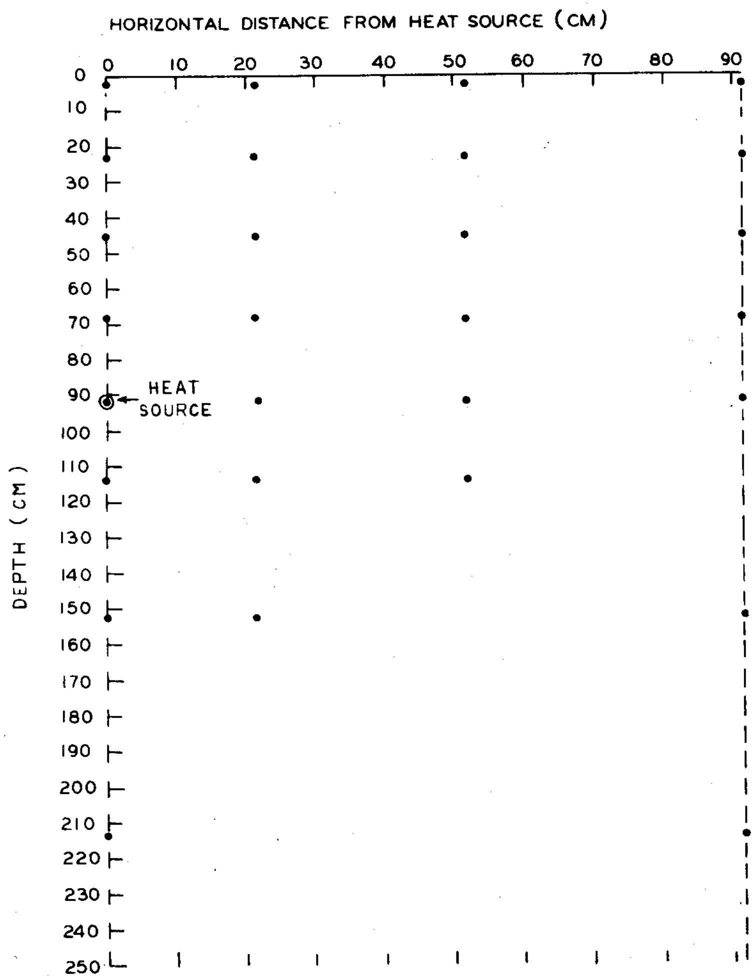

Figure 4. Original location of temperature sensors in NO COVER and CORN plots in relation to the soil surface and heat sources.

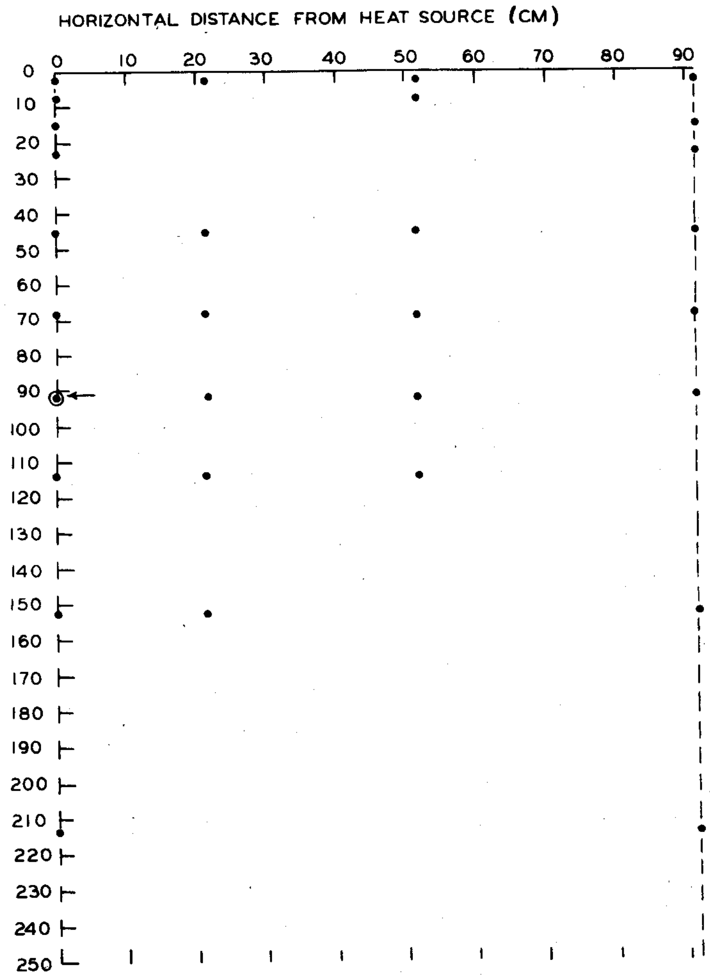

Figure 5. Final location of temperature sensors in NO COVER and CORN plots in relation to the soil surface and heat sources.

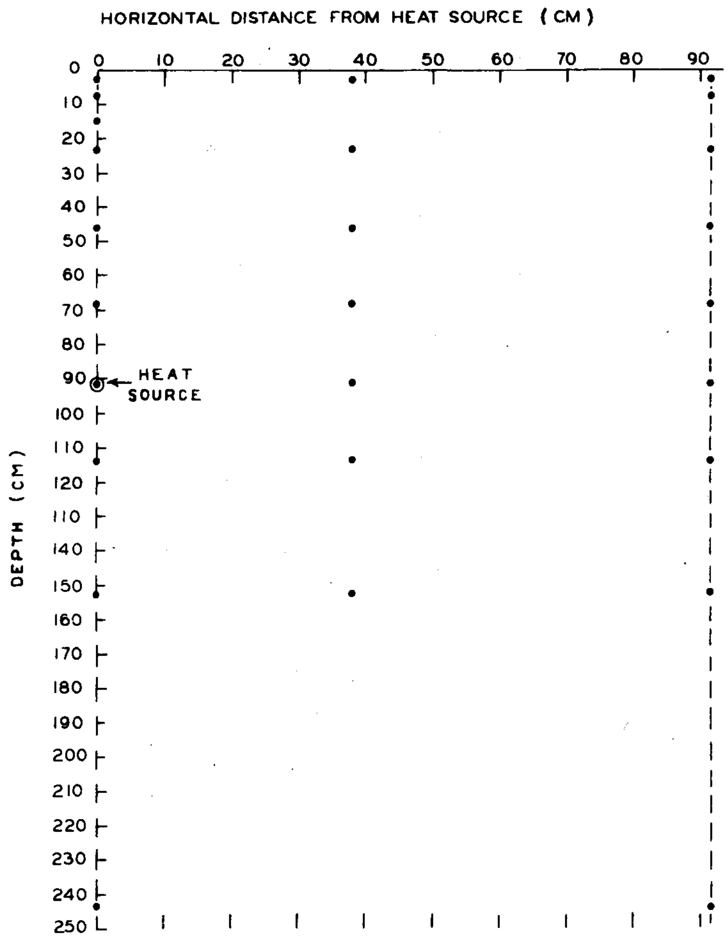

Figure 6. Location of temperature sensors in the SUB-IRR plot in relation to the soil surface and heat sources.

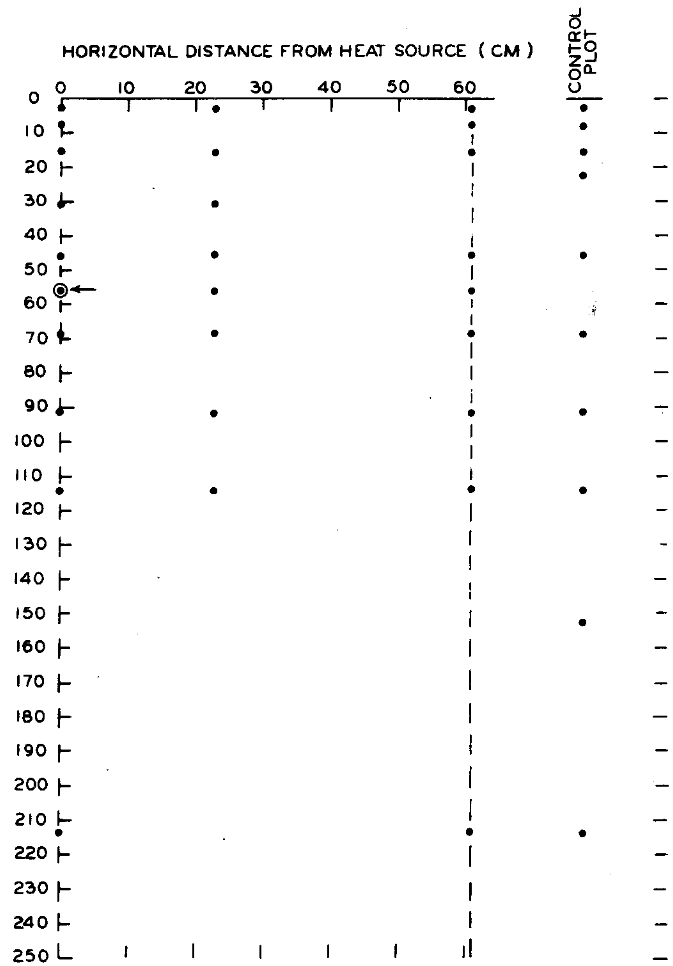

Figure 7. Location of temperature sensors in the GRASS plot in relation to the soil surface and heat sources.

2.5.4 Data Acquisition System Components and Specifications

All sensor measurements were made with a Hewlett-Packard model 2012B data-acquisition system. System components included the following instruments: model 2911 A, B, C crossbar switch, scanner, controller, and programmer; model 2402A digital voltmeter; model 2547A coupler and digital clock; model 5050B digital printer; Kennedy model 1600H incremental magnetic tape recorder.

To provide flexible signal wiring, all splices between the multi-pair signal cables and the crossbar scanner switch were made at a rack mounted set of modular terminal blocks (No. Tj11A-02-01, Deutsch Electronics). All permanent signal wiring to the scanner inputs used two-wire, foil-shielded cable. The guard was left unterminated since the individual signal pairs were not shielded. The scanner was configured for a two-wire and guard 200 channel system. The system programmer was set up as dictated by the experimental requirements.

In general, all thermistors were read on a resistance range of 100,000 ohms with a resolution of 1 ohm. Undesired channels were omitted with the "skip" function. Calibration channels were measured at each scan to determine if system drift had occurred. The system was calibrated against internal standards when required to maintain specified accuracy. The digital clock was adjusted for one-hour scan intervals with an average scanning time of 25 seconds. When required, the digital printer was used for immediate verification. Most data were recorded on magnetic tape for future computer analysis.

The data acquisition system had a manufacturer's specified accuracy of 0.01 percent of reading and 0.005 percent of full scale at the operating ambient temperature. The ohmmeter measurement current was 100 microamperes which can be expected to cause an equivalent self-heating of the thermistors of about 0.01 C in the buried units and about 0.1 C in the air temperature sensors. Variations in lead resistance were not compensated and can be expected to vary from 0.2 ohms to about 16 ohms.

2.5.5 Data Reduction and Output Format

Magnetic tape recorders were processed on the Oregon State University CDC 3300 computer. A number of different programs were used, which in general consisted of a resistance to temperature conversion routine and a formatting routine which printed temperatures in a graphical representation of the field thermistor matrix. Initial measurements involved thermistors that had been individually calibrated against a Hewlett-Packard 2012 Quartz thermometer to an accuracy of one ohm and 0.01 C. Correction coefficients were calculated for each thermistor and used to compensate each measurement during computer analysis. It was found that the thermistors varied by an equivalent temperature of 0.2 C at one standard deviation. Consequently, the correction subroutine was omitted and an average calibration was used for all thermistors.

Where practical, matched thermistors were placed in the field thermistor matrix at mirror image positions. The resistance from each of these two thermistors was converted to equivalent temperatures which were arithmetically averaged. Thus the completed printout represented an average of the folded-over halves of the field matrix. All the data were rounded off to 0.1 C.

2.6 Air Temperature Measurements

2.6.1 Air Temperature Sensors

Thermistors described in Section 2.5.1 were used to monitor air temperatures. The thermistors were protected by a thin conformal epoxy coating. These were incorporated into a modification of the tetraskelion radiation shield described by Bellaire and Anderson (1951). This shield utilizes natural wind, instead of forced draft, to ventilate the temperature sensors and provides temperature errors of less than .1 C at wind velocities greater than 1 knot.

All sensors were constructed with sufficient two-conductor unshielded cable to reach the cable splice points. Temperature measurement sites were serviced with four 11-pair, unshielded cables to the collection tile points. Field splices and connections to the instrument shelter were as described in Section 2.5.1.

Radiation shields in the greenhouse were suspended from the greenhouse frame with wire. Those in field installations were bolted to pipe frames anchored in the soil to depths of 45 cm. This arrangement rendered shields immobile under the highest wind velocities encountered.

2.6.2 Placement of Air Temperature Sensors

Sensors were installed in the greenhouse in January, 1971. These were arranged in three rows of five sensors each, spaced at six meter intervals. One row was positioned 30 cm below the peak along the center of the structure. Two rows, one on each side of the structure, were positioned along the side walls at a height of 1.5 meters above ground and 30 cm from the edge of the frame.

Air temperature sensors were installed 15, 65, 115 and 170 cm above the soil surface at five locations in 1972. Two stacks of sensors were installed three meters apart at each site. Locations included: (1) CONTROL plot: unheated with bare soil around the sensors; (2) NO COVER plot: heated with bare soil around the sensors; (3) CORN plot: heated with sensors located midway between adjacent corn rows; (4) SUB-IRR plot: heated with sensors located midway between adjacent corn rows; and (5) Reference corn plot: unheated with sensors located midway between adjacent corn rows. Measurements were made during the months of July, August, and September.

2.6.3 Data Reduction and Output Format

Data acquisition and reduction for air temperature measurements was essentially identical to that described in Sections 2.5.1 and 2.5.2 for soil temperature measurements. The printed output for greenhouse air temperatures was a representation of the thermistor matrix. An arithmetic average of the temperatures at all 15 locations was calculated in the data reduction program and included in the printout.

The output for the field installations was a representation of the field thermistor matrix. The air temperatures of the two replicates were arithmetically averaged for each height and location.

2.7 Water Content Measurements

2.7.1 Water Content Sensors

Soil water content measurements were made using electrical resistance blocks and an appropriate meter (Delmhorst Instrument Company, Boonton, New Jersey). To facilitate rapid reading of the large number of blocks, an auxiliary selector switch and multipin connector system was used. The moisture meter was mounted on a large clipboard. A two-pole, twelve-position switch was mounted near the meter with the common contacts wired permanently to the meter input circuit. A calibrating resistor was wired to one set of contacts and a short multi-conductor cable wired to the remaining contact. This cable was terminated with a subminiature circular connector (No. 222-11N31, Amphenol Industrial Division, Chicago, Illinois). The meter was modified by removing the "press to adjust" switch and replacing it with a miniature rotary switch providing the external selector switch.

Gypsum blocks were installed in the field in the same manner as soil temperature sensors (Section 2.5.2). The leads were cut to the proper length and crimp-terminated contacts were installed. These leads were grouped together and inserted in a standard pattern into a receptacle that would mate with the moisture meter plug (No. 222-22N31, Amphonel Industrial Division).

2.7.2 Calibration of Gypsum Blocks

Several groups of blocks were calibrated in the laboratory. They were imbedded in soil placed in a pressure plate apparatus. The lead wires were connected to terminal posts outside the pressure chamber by means of electrically insulated hook-up wires passing the chamber wall. Thus readings could be taken while the chamber was pressurized. The soil containing the blocks was initially saturated. The chamber was then closed and the pressure was increased in steps. The water content in the soil was allowed to come to equilibrium at each pressure increment. Readings were taken at regular intervals. Equilibrium conditions were assumed to have been attained when the readings no longer changed with time. Readings were obtained at pressures of 0, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0, and 8.0 bars. Readings at suctions greater than 8.0 bars were obtained by extrapolation.

2.7.3 Placement of Water Content Sensors

Soil water content was monitored on three plots during the course of the study. These were: (1) NO COVER plot: soil warming and bare soil surface conditions; (2) SUB-IRR plot: soil warming, subsurface irrigation, and crops of field corn in 1970, vegetable crops in 1971, and field corn in 1972; and (3) CORN plot: soil warming with a crop of field corn.

Sensors were installed on the NO COVER plot in March, 1970. The location of sensors with respect to heat sources and soil surface is shown in Figure 8. This array of sensors was replicated three times, a distance of three meters separating each set. Sensors located midway between adjacent heat source loops were replicated three times. All other sensors were replicated six times due to the mirror image arrangement. All sensors in this plot remained in place throughout the 1970 and 1971 seasons.

Sensors were installed on the SUB-IRR plot in April, 1970. The arrangement of these sensors was identical to that shown in Figure 8. Three replicates were used on this plot with three meters between each set of 25 sensors. In March, 1971, all sensors at depths of 15.2 and 30.5 cm, and lead wires from the remaining sensors were put into the clay tile to prevent damage during tillage operations. They were relocated in May and sensors at depths of 15.2 and 30.5 cm were replaced with new sensors.

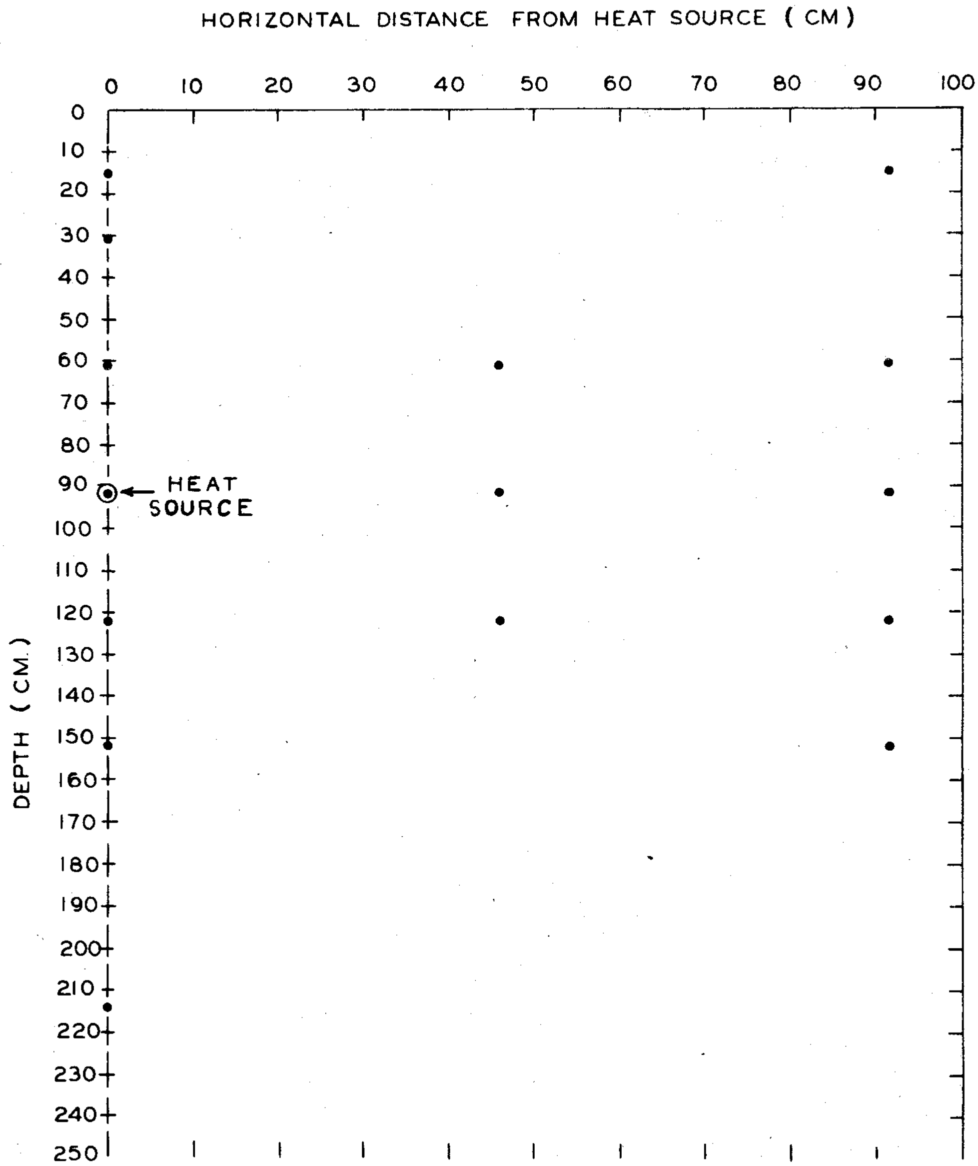

Figure 8. Location of water content sensors in the NO COVER plot in relation to the soil surface and heat sources.

Sensors were replaced on the SUB-IRR plot in June, 1972. Two stacks were located directly over each heat source and midway between each set of adjacent loops at depths of 15.2, 30.5, 45.7, 61.0 and 91.5 cm. There were six parallel heat source lines in this field so that this arrangement resulted in 12 replications at each depth for sensors over the heat sources and 10 replications at each depth for sensors between the heat sources.

Sensors were installed in heated and unheated portions of the CORN plot in June, 1970. Three stacks were installed directly over the heat sources at depths of 15.2, 30.5, 61.0 and 91.5 cm in the heated plot. Three stacks with sensors placed at the same depths were installed in the unheated CORN plot. The sensors were located in the corn rows. New sensors wereinstalled in the heated and unheated CORN plots in 1971. Three stacks were included to monitor the area midway between heat sources at the same four depths. All sensors were located in the corn rows. In 1972 sensors were located directly over the heat sources, midway between heat sources, and in corn rows which were planted 45 cm to the side of the heat sources. They were placed at depths of 15.2, 30.5, 45.7, 61.0 and 91.5 cm. The sensors in the unheated plot were placed in crop rows and between crop rows at the same depths monitored on the heated plots. Each location was replicated three times.

2.7.4 Reading and Recording

Gypsum block readings were taken two or three times each week during the summer months. The NO COVER plot was monitored throughout the year with less frequent readings made during the winter months. Individual meter readings were recorded and subsequently converted to soil water suction values. An arithmetic average soil water suction was then obtained for the replicates of a given location.

2.8 Subsurface Irrigation System

A subsurface irrigation system was installed on one of the heated plots in April, 1970. Modifications of the system were made in 1971 and again in 1972. Only the final design which was in use during the 1972 crop year will be described.

Eleven underground irrigation lines were installed. Six of these were located directly over the heat sources at a depth of 75 cm. The lowest point of the lines was about 15 cm above the heat sources. Five lines were installed at a depth of 60 cm, midway between adjacent heat source loops. All lines were 43 meters long, started at the south edge of the experimental field and extended three meters past the north end of the heat source loops. A water distribution manifold was located at the south end of the system, near the irrigation main line.

Each lateral was a Twin-Wall Hose (Chapin Watermatics, Inc., Watertown, New York) enclosed in a 5 cm diameter, corrugated, plastic pipe (Phillips Products Co., Inc., Watsonville, California). Radial grooves, factory cut at 120° intervals, provided perforations along the entire length. Each line was equipped at the supply end with a PVC elbow and extension which reached to a point flush with the ground surface. The opposite end of each line was closed. The Twin-Wall Hose distribution lines extended the full length of the corrugated pipe. Supply ends were connected to the distribution manifold with .65 cm diameter plastic tubing. Outlet holes were spaced at 98 cm in the inner wall and at 24 cm in the outer wall. The hose was designed to deliver approximately 2.5 liters per minute per 33 meters of line at an operating pressure of .14 kilogram per square cm in the inner wall.

The distribution manifold was a section of 2.5 cm diameter PVC plastic pipe nine meters long. A flow control valve provided the required flow rate into the distribution manifold. The .65 cm diameter tubes going to each lateral were attached to the manifold with poly-tube adapters and brass saddles. Holes were drilled in the PVC pipe at the location of brass saddles. The manifold was connected to the irrigation main line so that the subsurface system could be operated by itself or with the rest of the system in use. The application rate of the subsurface system was .62 cm/hour.

3. CHANGES IN AIR TEMPERATURES

3.1 Results

Air temperatures were monitored at several locations during the summer of 1972. These measurements were made to determine if crop responses observed in 1970 were the result of increases in air temperature over heated plots. They were not intended to represent the effect of a large scale heating system on air temperature. Placement of sensors was described in Section 2.6.2. Nine days from the months of July, August, and September were selected for analysis of the observations. The dates were chosen to represent hot, warm, and cool days. This was done because the effect of soil warming on air temperatures differed for these meteorological conditions. No irrigation or precipitation occurred during any of these days. Maximum, minimum, and average air temperatures recorded over unheated soil at the U.S. Weather Bureau Station on the selected days are shown in Table 4. Hourly air temperatures were also used in the selection of dates. The hourly data showed, for example, September 14 to be a warm day even though maximum and minimum temperatures do not indicate this.

Table 4. Maximum, minimum, and average air temperatures recorded at the U.S. Weather Bureau Station near the experimental site on the 1972 dates chosen for analysis of effect of soil warming on air temperatures (U.S. Dept. of Commerce, 1972).

Date	Air temperatures		
	maximum	minimum	average
	C	C	C
Hot days			
July 16	36	17	27
August 6	39	15	27
August 28	35	16	26
Warm days			
July 13	29	16	23
July 28	33	12	23
September 14	25	10	18
Cool days			
July 6	24	9	17
August 19	27	11	19
September 6	23	9	16

The effect of soil warming on air temperatures was analyzed by comparing the average daily air temperature at the measuring stations over unheated soil with the average daily air temperature over heated soil. Average daily air temperatures were calculated for the five measurement stations (Section 2) at heights of 15, 65, 115, and 170 cm above the ground surface, by averaging nine readings obtained at three-hour intervals starting at 0000 hours. The differences in average daily air temperatures between unheated bare soil and heated soil at several locations and heights above the ground surface are shown in Table 5. All data shown represent average values for two sensors located three meters apart. A minus sign indicates a temperature lower than measured over the unheated bare soil surface. One of the sensors at the 15 cm height in the heated corn plot did not function. Since the data reduction procedure averaged two sensors at each location, invalid numbers were obtained for this location and results are therefore not included in the tabulation.

A summary of the result shown in Table 5 is given in Table 6, where the average daily air temperatures for hot, warm, and cool days over unheated bare soil and the temperature differences between unheated bare soil and other locations are presented. Each temperature category includes an early date, a late date, and a date in the middle of the season so that changes in crop height did not influence this comparison.

The effect of soil warming on air temperatures may be expected to be different during the day than during the night. Therefore, the daily course of air temperatures was considered (Table 7). Averages for the three days of hot and cool day categories and differences between other locations and unheated bare soil are shown.

3.2 Statistical Analysis

Temperature differences between the various cover and heating treatments were small in most cases. However, the data showed trends which appeared to indicate that real temperature differences of less than 1 C occurred. Statistical analyses were performed to evaluate the results obtained.

The statistical model used was a split-plot design with randomized, complete blocks. The whole units were the nine days for which temperatures were analyzed. The subunits were the locations at which temperatures were measured. The A treatment, included in the whole unit, was the three day classes: cool, warm, and hot. For the 15 cm height analyses there were 4 and 12 degrees of freedom associated with the whole unit and subunit error terms, respectively. For all other heights 18 degrees of freedom were associated with the subunit error term and 4 with the whole unit error term. The B treatment consisted of

Table 5. Average daily air temperatures at four heights over unheated bare soil and the difference in average daily air temperature between sensors at the indicated location and the sensors over unheated bare soil for selected days. A minus sign indicates a a lower temperature than measured over the unheated soil.

Date	Bare soil		Corn canopy		
	unheated	heated	unheated	heated	sub-irr
	C	C	C	C	C
15 cm height:					
7/6	15.3	.5	1.4	--	1.7
7/13	21.3	.6	.3	--	.5
7/16	26.0	.7	.3	--	.1
7/28	21.5	.8	.2	--	- .9
8/6	24.6	1.2	- .6	--	-2.0
8/19	17.0	.5	.4	--	- .4
8/28	24.9	.9	-2.1	--	-2.3
9/6	15.6	.2	.0	--	.2
9/14	19.3	.0	- .3	--	- .5
Average	20.6	.6	.0	--	- .4
65 cm height:					
7/6	14.8	- .3	.2	.6	.6
7/13	20.7	.0	.0	.3	.5
7/16	25.7	.0	- .1	-1.0	.0
7/28	21.3	- .1	- .6	- .4	- .6
8/6	24.7	.3	-1.7	- .8	-1.6
8/19	16.7	- .1	- .5	- .1	.1
8/28	24.7	.2	-2.2	-1.9	-1.8
9/6	15.0	.4	- .2	.2	1.3
9/14	19.8	- .4	- .7	- .3	- .7
Average	20.3	.0	- .6	- .3	- .2
115 cm height:					
7/6	14.7	.4	- .1	- .2	.0
7/13	20.8	- .3	- .2	.0	.0
7/16	25.8	.4	- .3	- .8	- .2
7/28	21.4	.3	- .7	- .3	- .6
8/6	25.0	.6	-1.8	- .9	-1.7
8/19	16.7	.4	.0	.2	.3
8/28	24.9	.4	-2.0	-1.0	-1.2
9/6	15.0	.4	- .2	.2	1.3
9/14	20.2	.1	- .9	- .3	- .2
Average	20.5	.4	- .7	- .3	- .2

Table 5. Continued.

Date	Bare soil unheated	Bare soil heated	Corn canopy unheated	Corn canopy heated	Corn canopy sub-irr
	C	C	C	C	C
170 cm height:					
7/6	14.9	.1	-.1	-.1	.2
7/13	21.0	.2	-.2	-.2	.2
7/16	26.0	.1	-.2	-.5	.0
7/28	21.7	-.2	-.7	-.7	-.6
8/6	25.4	.3	-1.6	-1.3	-1.5
8/19	17.1	-.1	-.6	.1	.3
8/28	25.2	.1	-1.9	-1.5	-1.3
9/6	15.2	.1	-.4	.3	1.0
9/14	20.7	-.4	-1.1	-.9	-.5
Average	20.8	.0	-.9	-.5	-.2

Table 6. Average daily air temperatures for three meteorological conditions at four heights over unheated bare soil and the difference in air temperature between sensors at the indicated locations and the sensors over unheated bare soil. A minus sign indicates a lower temperature than measured over the unheated soil.

Day class	Height above surface	Bare soil unheated	Bare soil heated	Corn canopy unheated	Corn canopy heated	Corn canopy sub-irr
	cm	C	C	C	C	C
Hot	15	25.2	.9	-.9	--	-1.4
	65	25.0	.2	-1.3	-1.2	-1.1
	115	25.2	.5	-1.3	-.9	-1.0
	170	25.5	.2	-1.2	-1.1	-.9
Warm	15	21.0	.5	-.2	--	-.6
	65	20.6	-.2	-.4	-.1	-.3
	115	20.8	.0	-.6	-.2	-.3
	170	21.1	-.1	-.6	-.6	-.3
Cool	15	16.0	.4	.6	--	.5
	65	15.5	-.2	-.2	.1	.3
	115	15.5	.4	-.1	.2	.5
	170	15.7	.1	-.3	.1	.5

Table 7. Average hourly air temperature at four heights over unheated bare soil and the difference in air temperature between sensors at the indicated locations and sensors over unheated bare soil for hot and cool days (average of three days).

Time	Bare soil				Corn canopy					
	unheated		heated		unheated		heated		sub-irr	
	hot	cool	hot	cool	hot	cool	hot	cool	hot	cool
	C	C	C	C	C	C	C	C	C	C
15 cm height:										
0000	21.5	11.1	.8	1.0	- .1	1.9	--	--	- .5	1.9
0300	16.9	9.7	.8	.8	1.4	1.1	--	--	1.0	1.2
0600	15.9	11.2	1.2	.5	1.2	1.1	--	--	.7	1.1
0900	25.2	14.2	.8	.2	-1.8	.6	--	--	-2.5	.3
1200	33.6	21.7	.1	.6	-2.4	- .8	--	--	-4.3	-1.3
1500	37.8	25.1	.8	- .3	-3.4	- .3	--	--	-3.7	- .1
1800	34.8	23.0	2.0	.3	-4.6	- .4	--	--	-4.5	.2
2100	22.9	15.3	1.0	.7	.5	.7	--	--	.2	.4
2400	17.7	12.5	1.0	1.3	1.5	1.0	--	--	1.1	.7
Average	25.1	16.0	1.0	.4	- .8	.5	--	--	-1.3	.5
65 cm height:										
0000	22.2	11.5	.0	.2	-1.3	.6	- .5	1.0	- .9	1.1
0300	17.4	9.8	.2	- .1	- .1	.2	.3	.5	.4	.7
0600	16.7	11.1	.3	- .3	- .6	.0	- .5	.5	- .2	.6
0900	24.4	13.7	.0	- .3	-1.9	- .4	-1.6	.1	-1.6	.0
1200	31.4	19.3	- .4	- .5	-1.0	.0	-1.8	.2	-1.1	.1
1500	36.1	22.9	- .1	.2	-2.2	- .3	-2.5	- .2	-2.2	.7
1800	34.8	22.3	.5	- .3	-4.4	- .3	-3.6	- .2	-3.9	.6
2100	23.9	15.4	.6	.0	-1.1	- .3	- .5	.0	- .6	.0
2400	18.7	13.0	.1	- .5	- .4	- .7	- .1	- .3	.2	- .4
Average	25.1	15.4	.1	- .2	-1.5	- .1	-1.2	.2	-1.1	.4

115 cm height:										
0000	22.5	12.4	.5	.4	-1.2	- .1	- .5	.5	- .7	.7
0300	17.8	10.4	.5	.4	- .5	.0	- .1	.4	.1	.6
0600	16.9	11.5	.4	.4	-1.0	.0	- .5	.5	- .6	.6
0900	24.1	14.0	.4	.5	-1.4	- .1	-1.0	.0	-1.3	.3
1200	31.2	19.6	.1	.3	- .8	.2	- .6	.4	- .8	.4
1500	35.9	23.2	.5	.5	-1.8	.0	-1.7	- .1	-1.9	.5
1800	35.0	22.5	.7	.3	-3.4	.0	-2.4	.0	-3.0	.8
2100	24.6	16.2	.9	.5	-1.3	- .4	-1.0	.1	- .8	.5
2400	19.1	13.2	.3	.6	- .8	- .3	- .6	.3	- .2	.6
Average	25.2	15.9	.5	.4	-1.3	- .1	- .9	.2	-1.1	.6
170 cm height:										
0000	22.9	12.5	.1	.1	-1.5	- .6	-1.0	- .1	- .9	.3
0300	18.1	10.3	.2	- .1	- .8	- .7	- .6	- .1	- .3	.3
0600	17.5	11.3	- .1	- .2	-1.6	- .8	-1.3	.2	- .9	.4
0900	24.3	13.8	.0	.0	- .9	- .5	- .8	- .1	01.0	.3
1200	31.2	19.5	- .3	.2	- .3	.6	- .2	.8	- .1	1.1
1500	35.9	22.9	.1	.1	-1.0	.2	-1.2	.1	-1.0	.9
1800	35.3	22.3	.3	.0	-2.6	.2	-2.2	- .1	-2.5	.9
2100	25.3	16.2	.4	.4	-1.5	- .5	-1.6	.2	-1.2	.4
2400	19.5	13.2	.2	.3	-1.1	- .9	-1.0	.1	- .5	.3
Average	25.6	15.8	.1	.1	-1.3	- .3	-1.1	.1	-1.0	.6

the four locations. Three subunits were used for the 15 cm height including: heated, bare soil; unheated, corn canopy; and sub-irrigated, corn canopy. For all other heights the heated, corn canopy treatment was included as a subunit. The blocks were the time of season. Days included in block I were July 6, July 13, and July 16. Block II included July 28, August 6, and August 19, while block III included August 28, September 6, and September 14.

An analysis of variance was calculated for each hour included in Table 7 and for the average daily temperature differences shown in Table 5 at all heights. The results of these calculations are summarized in Tables 8 and 9. Table 8 shows the level of significance found for all sources of variation. Treatment B showed the most frequent source of significant variation.

The least significant differences (LSD) were calculated for treatment B and are shown in Table 9 for three comparisons. No significance was found during the time period from 0900 to 1800 hours for these comparisons. In many cases the largest temperature differences occurred between the heated, bare soil, and unheated, corn canopy. This comparision is meaningless in terms of the influence of soil warming on air temperatures and was not included in Table 9. It does account for the fact that for some cases treatment B was found to be significant in Table 8, but no significant differences were shown in Table 9. The unheated, bare soil treatment was not included in the statistical analyses since all values are zero. Inconsistencies between Tables 8 and 9 also occurred because comparisons between heated and unheated, bare soil appear in Table 9 while this comparison was not shown in Table 8. The use of LSDs makes this a valid comparison, however.

3.3 Discussion

3.3.1 Changes Over a Bare Soil Surface

Most observed temperature differences were less than 1 C (Table 5). However, there are trends evident in the data which suggest that real differences smaller than 1 C occurred. This was confirmed by a statistical analysis. Differences of less than .5 C were found to be statistically significant in some comparisons. Such small differences cannot be expected to be of practical consequence from the standpoint of plant growth, but they are of interest.

3.3.1.1 Height: 15 cm. A slight increase in the average daily temperature over heated bare soil at 15 cm above the ground is shown in Table 5. The largest increases were observed on hot days. Table 7 shows that the increase was uniform throughout the day on hot days. On cool days a diurnal cycle existed with the largest increase occurring at

Table 8. Summary of the statistical analyses of air temperature differences by source of variation for four heights.

Time	Level of significance			
	blocks	day class (A)	treatment (B)	interaction (AB)
15 cm height:				
0000	NS	NS	NS	NS
0300	NS	NS	NS	NS
0600	NS	NS	NS	NS
0900	NS	NS	*	NS
1200	*	NS	**	NS
1500	NS	NS	NS	NS
1800	*	NS	**	NS
2100	NS	NS	NS	NS
2400	NS	NS	NS	NS
Average	*	*	*	NS
65 cm height:				
0000	NS	*	NS	NS
0300	NS	NS	*	NS
0600	NS	NS	NS	NS
0900	NS	NS	NS	NS
1200	NS	NS	NS	NS
1500	*	*	NS	NS
1800	NS	*	**	*
2100	NS	NS	*	NS
2400	NS	NS	**	NS
Average	NS	*	*	*
115 cm height:				
0000	NS	*	**	NS
0300	*	NS	**	NS
0600	NS	NS	**	NS
0900	NS	NS	*	NS
1200	NS	NS	NS	*
1500	**	**	**	NS
1800	NS	NS	**	*
2100	*	**	**	NS
2400	NS	NS	**	NS
Average	NS	*	**	*
170 cm height:				
0000	NS	NS	**	NS
0300	*	*	**	NS
0600	NS	NS	*	NS
0900	NS	NS	NS	NS
1200	NS	NS	NS	NS
1500	NS	NS	NS	NS
1800	NS	NS	*	**
2100	NS	NS	**	NS
2400	NS	NS	**	**

NS Not statistically significant.
* Statistically significant at the 5 percent level.
** Statistically significant at the 1 percent level.

Table 9. Summary of the statistical analysis of air temperature differences for the indicated comparisons at four heights and the indicated times. Temperature differences are shown in Table 7 for hot and cool days. Differences were not significant for the time period from 0900 to 1800 hours.

Time	Bare soil, LSDs unheated vs. heated	Corn canopy, LSDs unheated vs. heated	Corn canopy, LSDs unheated vs. sub-irr
hour	C	C	C
15 cm height:			
0000	.60*	--	NS
0300	.70*	--	NS
0600	.58*	--	NS
2100	.91*	--	NS
2400	.67*	--	NS
Average	NS	--	NS
65 cm height:			
0000	NS	NS	NS
0300	NS	.38*	.38*
0600	NS	NS	NS
2100	NS	NS	NS
2400	NS	.38*	.38*
Average	NS	NS	NS
115 cm height:			
0000	NS	.48*	.48*
0300	.50**	.50**	.50**
0600	NS	.40*	.55**
2100	.52*	NS	.52*
2400	NS	NS	.46*
Average	NS	NS	.39*
170 cm height:			
0000	NS	NS	NS
0300	NS	.36*	.49**
0600	NS	NS	.73**
2100	NS	NS	NS
2400	NS	NS	.66**
Average	NS	NS	.41**

NS Not statistically significant.
* Statistically significant at the 5 percent level.
** Statistically significant at the 1 percent level.

night and a smaller effect occurring during the day. The temperature increase was significant at the 5 percent level from 2100 to 0600 hours (Table 9). The increase in the average daily temperature due to soil warming was not significant.

3.3.1.2 Height: 65 cm. At this height no consistent change in average daily air temperature due to soil warming was found. Fluctuations ranged from an increase of .4 C to a decrease of .4 C on the nine dates analyzed (Table 5). There did not appear to be a diurnal cycle of cool days, but on hot days slight increases were found except at mid-day when decreases were observed (Table 7). The differences that occurred at this height were not significant (Table 9).

3.3.1.3 Height: 115 cm. Average daily air temperatures were consistently higher over the heated bare soil at this height (Table 5). A uniform difference of .4 to .5 C was found throughout the day (Table 7) on hot and cool days. The diurnal cycle in response to soil heating which was evident at 15 cm height did not appear to occur at the 115 cm height. Average daily air temperature increases were not significant, but the increases observed at 0300 and 2100 hours were significant at the 1 and 5 percent levels, respectively (Table 9).

3.3.1.4 Height: 170 cm. There did not appear to be any influence of soil warming on air temperatures at the 170 cm height.

3.3.2 Changes Within a Corn Canopy

3.3.2.1 Unheated Corn. Comparisons between the air temperatures over an unheated bare soil surface and within an unheated corn canopy show that the canopy reduces air temperatures (Table 5). Effects changed during the season as the corn grew taller, as evidenced by the fact that significant differences were found for several cases for blocks in the statistical model (Table 8). Canopy heights were measured three times from June 26 to July 28 (Table 10). By mid-August the canopy was over two meters tall at all locations.

Table 10. Corn canopy heights on unheated, heated, and SUB-IRR locations for three sampling dates. Measurements were made with leaves extended.

Date	Location: unheated	heated	sub-irr
	cm	cm	cm
6/26	37	65	43
7/11	69	140	92
7/28	157	246	206

3.3.2.1.1 Height: 15 cm. Average daily air temperatures were higher in the unheated corn canopy than over the bare soil surface in early July. At this time the canopy was tall enough to provide wind shelter but not tall or dense enough to provide complete shading. The higher temperatures were probably due to the shelter effect. As the canopy height increased, the average daily air temperature at this height gradually became less than over bare soil (Table 5). Day class exerted an influence on the temperature differences. On cool days an increase in average daily air temperature of .5 C was observed. On hot days a decrease of .8 C was found (Table 7). These differences in response must be attributed to shading and wind shelter effects.

The expected daily cycle of cooling by shading during the day and warming by radiant heat trapped during the night is evident in Table 7. Comparison of unheated, bare soil and unheated, corn canopy is not shown in Table 9. The differences were statistically significant in most cases for hourly observations at the 15 cm height. There was no effect of the corn canopy on average daily temperature at this height.

3.3.2.1.2 Height: 65 cm. The average daily temperatures were not affected by the corn canopy early in the season (Table 5). After July 28 varying degrees of temperature reduction occurred. It is apparent from Table 7, which shows small temperature decreases on cool days and larger decreases on hot days, that the differences were influenced more by day class than by canopy height. This is also shown in Table 9 where significance is only shown twice for blocks but four times for day class. A diurnal cycle in the temperature differences occurred at this height on hot and cool days. The greatest effect occurred on hot days due to shading at mid-day (Table 7).

3.3.2.1.3 Height: 115 cm. Similar trends and degree of canopy influence as noted for the 65 cm height were observed, but no daily cycle was found. A constant difference of about .7 C occurred throughout the day. The differences were significant in most cases.

3.3.2.1.4 Height: 170 cm. Temperature differences were about the same as those found at 65 and 115 cm heights for average daily values. However, the daily cycle in temperature differences was reversed (Table 7). On cool days temperatures were warmer during the day time and cooler at night than over unheated bare soil. The differences were significant in most cases. The reversal in daily cycles suggests that at this height the wind shelter effect was more important than shading during the day hours and heat trapping during the night.

3.3.2.2 Heated and Sub-Irrigated Plots. Temperature differences in the corn canopy between unheated, heated and sub-irrigated locations can be attributed to two factors; namely, the heat released from the soil and conservation of heat by the canopy. Soil warming with heat escaping to, and being trapped in, the canopy may result in increased temperatures. It was shown that under conditions of unheated soil a corn canopy reduced air temperatures in most cases. It is reasonable to assume that a taller, denser canopy would result in greater temperature reductions. Therefore, heating effects could be partially offset by cooling effects by the crop cover.

<u>3.3.2.2.1 Height: 15 cm.</u> Average daily air temperatures were slightly higher on the sub-irrigated plot than on the unheated corn plot on July 6 and July 13 (Table 5). The average daily temperatures were lower on the sub-irrigated plot on all other days. Average daily temperatures were the same at both locations on cool days, but lower on the sub-irrigated plot during warm and hot days. None of the differences were statistically significant (Table 9). The observed effect resulted from a reduction in air temperature due to shading. This conclusion is supported by the daily cycles shown in Table 7. The only time average air temperatures on the sub-irrigated plot were higher than on the unheated corn plot was at 1800 hours. If heating exerted an influence at this height, it should have increased temperatures during the night.

<u>3.3.2.2.2 Height: 65 cm.</u> Average daily air temperatures were higher on heated and sub-irrigated plots than on unheated corn plots except on July 16 and July 28. These two days correspond to the time canopy height differences were greatest. On cool days average daily temperatures were .3 and .5 C higher on heated and sub-irrigated plots, respectively. On hot days the differences were .1 and .2 C. Comparisons in Table 7 show that average hourly air temperatures were slightly lower at 0900 and 1200 hours on the heated and sub-irrigated plots. During the remainder of the day the temperatures were higher than those observed in the unheated corn canopy. The differences were significant at the 5 percent level at 0300 and 2400 hours (Table 9). Average daily temperature differences were not significant at this height.

<u>3.3.2.2.3 Height: 115 and 170 cm.</u> Results were similar to those found at the 65 cm height. Temperatures on the heated plots were consistently about .4 C higher. At 115 cm height the sub-irrigated plot was significantly warmer for all hours from 2100 to 0600 while the heated plot was significantly warmer only during the 0000 to 0600 hours period. The average daily temperature difference was significant for the sub-irrigated versus unheated comparison (Table 9). At 170 cm height the heated plot was significantly warmer than the unheated plot only at 0300 hours. The average daily temperature of the sub-irrigated plot was significantly warmer as was average hourly temperature at 0300, 0600, and 2400 hours.

It is interesting to note that on cool days (Table 6) the sub-irrigated plot was slightly warmer than the heated plot. It will be shown in Section 4 that soil temperatures were also higher on this plot. Sub-surface irrigation resulted in a higher rate of heat flow through the soil into the crop canopy.

3.4 Summary and Conclusions

Average daily air temperatures over a bare soil surface increased .6 C at 15 cm height and .4 C at 115 cm height as a result of soil warming. They were not influenced at 65 and 170 cm heights. The greatest increases occurred on hot days at all heights. The change in air temperature due to soil heating showed a diurnal cycle with the largest increases occurring at night at the 15, 65, and 115 cm heights.

Average daily air temperatures in an unheated corn canopy showed no change at the 15 cm height and decreased .6, .7, and .8 C at 65, 115, and 170 cm heights, respectively, compared with unheated bare soil. The smallest temperature changes due to the corn canopy were observed on cool days. Temperature increases were found during the night at 15 and 65 cm heights.

Heating and heating with subsurface irrigation under a corn canopy resulted in slight temperature increases at 65, 115, and 170 cm heights compared with an unheated corn canopy. At the 15 cm height heating with sub-irrigation decreased temperatures slightly.

Significant differences were found for day class, time of season, and heating and cover treatments as well as for the interaction of day class with treatment. The most frequent sources of variation, however, were the heating and cover treatments. Although statistically significant air temperature increases in response to heating were found over bare soil and in a corn canopy, they cannot be considered of consequence for crop growth.

It is recognized that these results are not representative of conditions which would occur in large areas heated with warm water. Air temperatures would probably be increased more over an area of several thousand hectares.

4. CHANGES IN SOIL TEMPERATURES

4.1 Data Reduction

Large variations in soil temperature occur with soil depth, time of day, and season. These are caused by incoming and outgoing radiation. The problem of describing the effect of buried parallel line heat sources is further complicated by its two-dimensional geometry. It was desired as a first step of the analysis to produce from the field measurements (Section 2.5) soil temperature profiles such as shown in Table 13. This was accomplished by using a computer program to fit a temperature surface to sets of data such as shown in Table 11. The temperatures enclosed in parentheses were obtained by interpolation. Sensors were not used at those positions.

The initial approach to the problem of producing the temperature matrix was to describe the vertical temperature distribution for each stack of sensors with a polynomial function and then to develop the temperature surface, based on these three or four functions. The computer printed the temperatures at the gridpoints shown in Table 13. It was learned after some experimentation that due to the complex nature of the vertical temperature variations (Figure 9), no mathematical function could adequately be fitted to the limited number of observations. Additional data preparation was therefore necessary. This consisted of producing from the data shown in Table 11 the set of data shown in Table 12. This transformation was accomplished manually. The data shown in Table 11 were plotted as a function of depth and smooth-fitting curves were drawn by hand (Figure 9). Sets of data such as shown in Table 12 were then obtained from the graphs and used as the basis for the computer program. An example of the outputs obtained is shown in Table 13.

The analysis had to be limited to certain selected dates because of time and fund limitations. Several factors were considered in choosing these dates. They had to be seasonally representative in terms of air temperatures. Since precipitation affects soil temperature, days were selected during which no precipitation occurred and no irrigation water was applied. Climatic conditions during the antecedent day were similar to the one analyzed to eliminate large changes in heat storage. Days were chosen so that the heat source had been in continuous operation at one thermostat setting for several weeks to eliminate large heat storage changes as a source of variation.

Table 11. Soil temperatures measured at the indicated times and depths on the CORN plot. The bracketed temperatures were not measured but estimated.

Date	Time	Depth	Horizontal distance from heat source (cm) 0	22.9	53.3	91.4
	hour	cm	C	C	C	C
8/11/71	0000	2.5	20.8	(21.0)	21.2	(21.2)
		7.6	22.0	(22.1)	22.1	(22.1)
		15.2	22.1	(21.6)	(21.0)	20.7
		22.9	22.0	(21.5)	(21.2)	21.0
		45.7	22.3	22.1	22.0	22.2
		68.6	24.9	22.7	22.4	22.6
		91.4	30.1	(24.9)	22.2	22.6
		114.3	25.0	23.8	22.6	(22.6)
		152.4	22.5	22.3	(22.4)	22.6
		213.4	21.3	(21.2)	(21.1)	21.0
8/11/71	0300	2.5	19.1	(19.4)	19.6	(19.6)
		7.6	21.5	(21.3)	21.1	(21.1)
		15.2	21.6	(21.0)	(20.5)	20.3
		22.9	22.0	(21.0)	(20.5)	20.0
		45.7	22.4	22.2	22.0	22.2
		68.6	24.9	22.9	22.4	22.6
		91.4	30.1	(24.9)	22.2	22.6
		114.3	25.0	24.0	22.6	(22.6)
		152.4	22.5	22.3	(22.4)	22.6
		213.4	21.3	(21.2)	(21.1)	21.0

Table 12. Soil temperatures derived from depth versus temperature curves for 0000 hours on August 11, 1971, on the CORN plot.

Depth	Horizontal distance from heat source (cm) 0	22.9	53.3	91.4
cm	C	C	C	C
0	19.5	20.2	20.7	20.9
5	21.5	21.6	21.7	21.8
10	22.2	22.1	22.1	22.0
20	22.0	21.5	21.0	20.6
30	22.0	22.0	21.8	21.6
40	22.3	22.2	22.0	22.0
50	22.6	22.1	22.0	22.3
60	23.8	22.4	22.2	22.5
70	25.2	22.8	22.5	22.6
80	27.0	23.4	22.5	22.6
85	28.3	23.7	22.4	22.6
90	29.6	24.1	22.2	22.6
95	29.0	24.3	22.1	22.6
100	27.8	24.4	22.2	22.6
110	25.8	24.1	22.5	22.6
120	24.4	23.5	22.6	22.6
140	22.8	22.8	22.4	22.6
160	22.3	22.2	22.2	22.5
180	21.8	21.7	21.8	22.2
200	21.4	21.3	21.4	21.6
220	21.3	21.1	20.8	20.7

Table 13. Example of gridpoint temperature printout resulting from the computer program. CORN plot, 0000 hours, August 11, 1971.

Depth	Horizontal distance from heat source - cm									
	5	15	25	35	45	55	67	75	85	Sum
cm	C	C	C	C	C	C	C	C	C	C
5	21.5	21.5	21.6	21.6	21.7	21.7	21.8	21.8	21.8	195.0
15	22.2	22.0	21.9	21.8	21.7	21.6	21.6	21.5	21.4	195.7
25	21.9	21.8	21.7	21.6	21.5	21.4	21.3	21.2	21.1	193.5
35	22.0	22.0	21.9	21.8	21.7	21.6	21.6	21.5	21.5	195.6
45	22.4	22.3	22.2	22.1	22.1	22.1	22.1	22.1	22.2	199.6
55	23.0	22.6	22.3	22.2	22.2	22.3	22.4	22.5	22.6	202.1
65	23.8	22.9	22.4	22.2	22.2	22.3	22.4	22.6	22.6	203.4
75	25.1	23.7	22.8	22.4	22.3	22.4	22.6	22.7	22.6	206.6
85	27.0	24.9	23.6	22.9	22.6	22.5	22.7	22.8	22.9	211.9
95	27.6	25.6	24.1	23.0	22.4	22.1	22.1	22.2	22.4	211.5
105	26.2	25.0	24.1	23.3	22.7	22.3	22.1	22.1	22.3	210.1
115	24.8	24.2	23.7	23.2	22.8	22.5	22.3	22.3	22.4	208.2
125	23.7	23.5	23.3	23.0	22.8	22.6	22.4	22.4	22.5	206.2
135	23.0	23.0	22.9	22.8	22.6	22.5	22.4	22.4	22.5	204.1
145	22.7	22.9	22.6	22.5	22.4	22.4	22.3	22.4	22.5	202.5
155	22.4	22.4	22.3	22.3	22.2	22.2	22.2	22.3	22.4	200.7
165	22.2	22.1	22.1	22.1	22.0	22.1	22.1	22.2	22.3	199.2
175	21.9	21.8	21.8	21.8	21.9	21.9	22.0	22.1	22.2	197.4
185	21.6	21.6	21.6	21.6	21.7	21.8	21.9	22.0	22.0	195.8
195	21.4	21.4	21.4	21.4	21.5	21.5	21.6	21.7	21.8	193.7
205	21.4	21.3	21.2	21.2	21.2	21.2	21.2	21.3	21.4	191.4
215	21.4	21.3	21.2	21.0	21.0	20.9	20.8	20.8	20.9	189.3
Sum	509.2	499.6	492.7	487.8	485.2	483.9	483.9	484.9	486.3	4413.5

4.2 Temperature Distributions

The lateral spacing between heat sources is an important design criterion for soil warming systems. Sources need to be spaced close enough to maintain adequate temperatures at the midpoint between them. However, for economic reasons, they should be spaced as far apart as possible while still providing adequate heating characteristics. Changes in soil temperature as a function of distance from the heat source are shown in Figure 9. Isotherms measured on the NO COVER plot show the temperature increase achieved on a summer day and a winter day (Figures 10 and 11). Soil temperatures of the unheated control plot are also shown. The heat source was maintained at 35 C for an entire year prior to making the measurements. The largest temperature increase occurred at depths below 30 cm. Little increase in soil temperature occurred near the soil surface. The temperature of the 0 to 5 cm layer responds to climatic conditions and not to the soil warming system. The benefit of the soil warming system would be greatly increased by a mechanism which would enhance the surface temperatures more. Present indications are that this would only be possible by completely covering the soil surface.

A comparison between the soil warming effect on the two dates and with the unheated area may be focused on the 20 C isotherm. On February 17 this isotherm was below the 50 cm depth. It was only 5 cm below the soil surface on August 11. The volume of soil at temperatures above 26 C increased from a small section around the heat source on February 17 to nearly the entire root zone on August 11. The average temperature for the upper 2 meters of soil was about 13 C above that of the unheated soil on both dates.

Figure 12 shows the August 11 temperature distribution on the SUB-IRR plot. The energy released by the heat source provided more heating in the upper soil layers. This section of the profile was at a high water content due to subsurface irrigation, providing for high thermal conductivities and therefore more efficient energy discharge to these layers. The upper soil layers (0 to 100 cm) were warmer than the plot without subsurface irrigation. The lower soil horizons (100 to 200 cm depth) remained colder on the plot with the subsurface irrigation system.

4.2.1 Hourly Measurements

Temperatures obtained at three-hour intervals starting at 0000 hours are shown for several depths below the soil surface in three vertical planes at distances of 5, 45, and 85 cm from the heat source (Table 14). Data shown are for the CORN plot on August 11, 1971. The

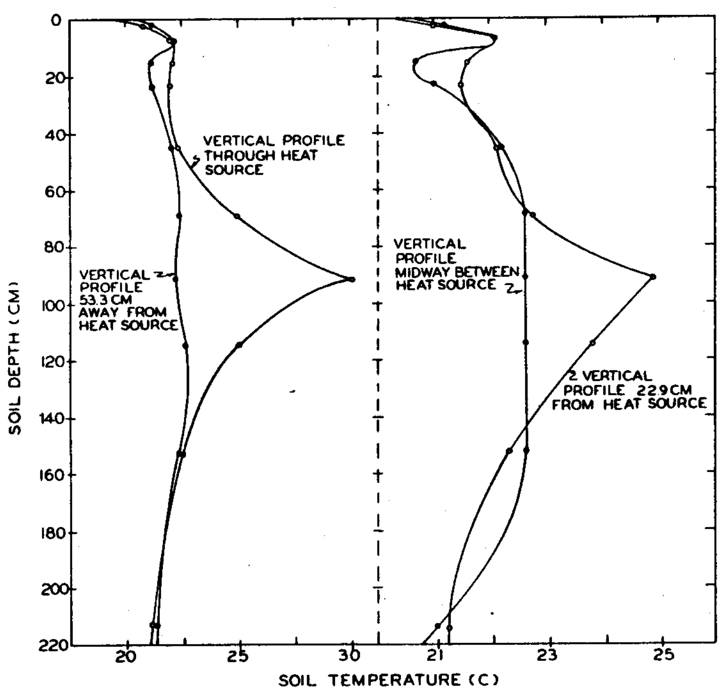

Figure 9. Soil temperature as a function of depth at 0; 22.9; 53.3; and 91.4 cm from heat source. CORN plot, 0000 hours, August 11, 1972 (note difference in temperature scales).

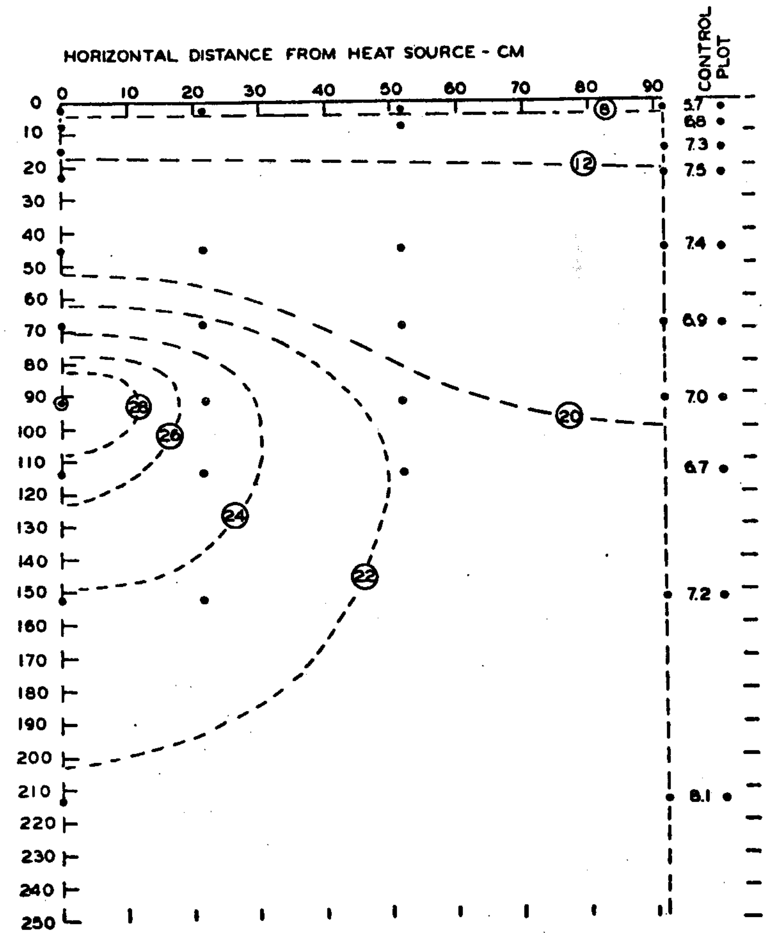

Figure 10. Isotherms of the NO COVER plot based on measurements of February 17, 1971, at 0000 hrs.

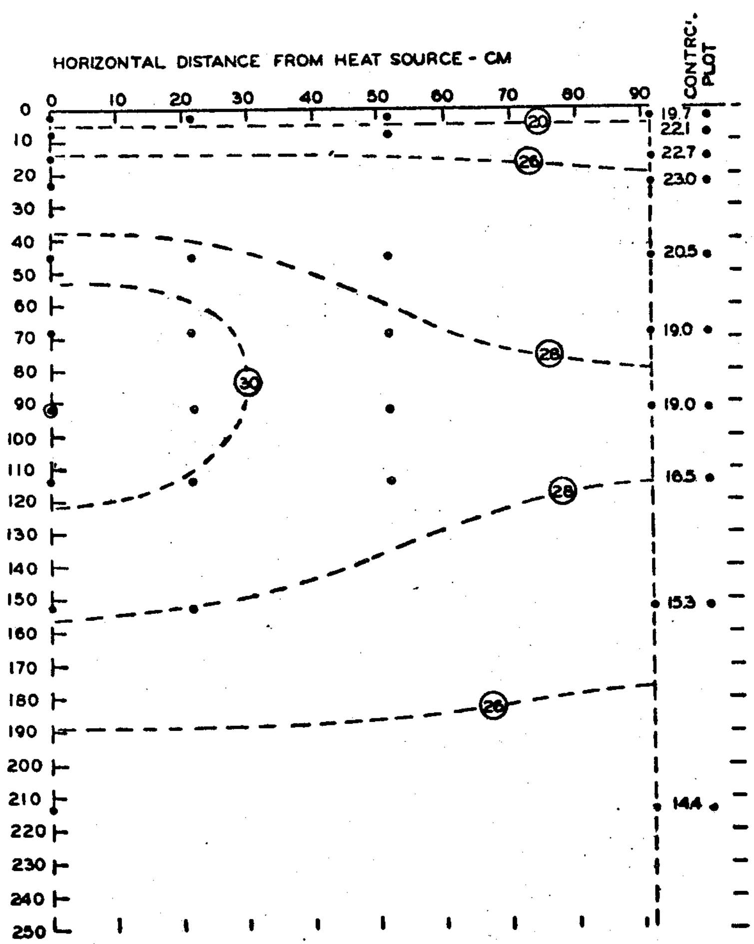

Figure 11. Isotherms of the NO COVER plot on August 11, 1971 at 0000 hrs.

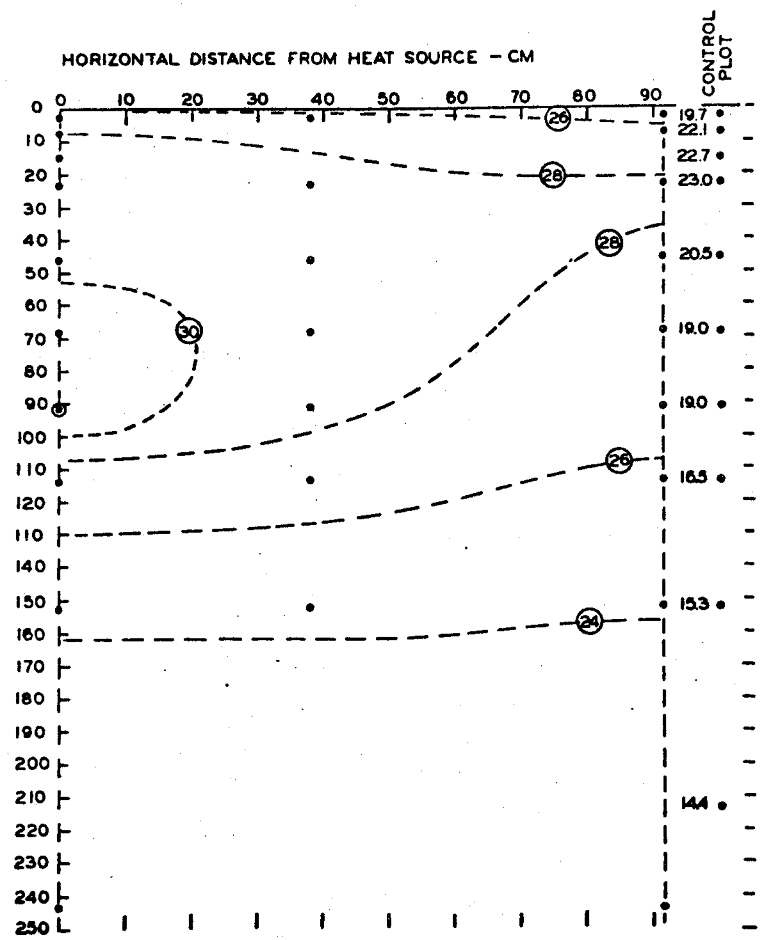

Figure 12. Isotherms of the SUB-IRR plot on August 11, 1971 at 0000 hrs.

Table 14. Hourly temperatures at several depths and horizontal distances from the heat sources for the CORN plot on August 11, 1971.

Time	Horizontal distance	Depth (cm) 5	25	55	95	135	185	Average
hour	cm	C						
0000	5	21.5	21.9	23.0	27.6	23.0	21.6	23.1
	45	21.7	21.5	22.2	22.4	22.6	21.7	22.1
	85	21.8	21.1	22.6	22.4	22.5	22.0	22.1
0300	5	20.5	21.9	23.1	27.7	23.0	21.6	23.1
	45	20.4	21.2	22.3	22.4	22.7	21.7	22.0
	85	20.6	20.5	22.5	22.4	22.5	22.0	22.0
0600	5	19.7	21.6	23.1	28.4	23.0	21.6	23.1
	45	19.5	20.3	22.3	22.4	22.7	21.7	21.8
	85	19.5	19.3	22.6	22.5	22.5	22.0	21.8
0900	5	20.2	21.3	23.2	27.2	23.3	21.7	23.0
	45	20.1	20.3	22.4	22.6	22.7	21.7	21.9
	85	20.2	19.5	22.6	22.3	22.4	22.0	21.8
1200	5	21.6	21.2	23.3	26.6	23.2	21.6	23.0
	45	21.7	20.9	22.4	22.7	22.7	21.7	22.1
	85	21.8	20.9	22.5	22.2	22.4	22.0	22.1
1500	5	22.4	21.5	23.2	28.2	23.2	21.6	23.2
	45	22.6	21.3	22.3	22.5	22.7	21.7	22.1
	85	22.8	21.1	22.4	22.5	22.4	22.0	22.1
1800	5	22.4	21.9	23.2	28.9	23.2	21.6	23.4
	45	22.6	21.4	22.4	22.6	22.7	21.7	22.2
	85	22.8	21.2	22.6	22.6	22.4	22.0	22.2
2100	5	22.1	22.0	23.4	29.8	23.3	21.5	23.6
	45	22.2	21.5	22.4	22.5	22.7	21.7	22.2
	85	22.4	21.2	22.6	22.7	22.4	22.0	22.2
2400	5	20.9	22.0	23.6	30.3	23.4	21.6	23.7
	45	20.9	21.3	22.4	22.5	22.7	21.7	22.1
	85	21.1	20.7	22.6	22.7	22.4	22.0	22.0

average temperature in each plane is the arithmetic mean of all gridpoint temperatures in that plane. Temperatures at depths not shown in Table 14 were also included in the calculations.

Temperatures at the 5 cm depth were similar at all lateral distances indicating that at this depth the soil temperature was not influenced by the heat source. At 0600 hours the temperature at the 5 cm horizontal spacing was .2 C higher than at the 45 and 85 cm horizontal spacings. During the remainder of the day temperatures were slightly higher at 45 and 85 cm spacings. This consistent difference is probably the result of differences in the calibration of the thermistors. It could also be due to placement of the thermistors. The placement is very critical near the soil surface because large temperature changes over short distances occur. At a depth of 25 cm a temperature decrease with increasing distance from the heat sources was observed throughout the day. The greatest difference was found at 0600 and the smallest at 1200 hours. This demonstrates that during the day warming due to solar heating is more important than soil warming in determining soil temperatures in the upper 25 cm of the soil. At the 55 cm depth a small but consistent temperature difference was observed as the horizontal distance from the heat source increased. The slight increase in temperature from 45 to 85 cm spacing may have been due to a systematic experimental error. It was noted in Section 2.5 that an average calibration curve was used for data reduction. This could result in differences of up to .4 C between sensors. At the 95 cm depth a large temperature decrease existed from the 5 to the 45 cm horizontal spacing. The change with time in the 5 cm plane was due to the erratic heating characteristics of the heat source on this plot (Section 6). Horizontal variations at this depth and at greater depths were stable with time.

The average temperatures indicate that no temperature differences existed between the 45 and 85 cm distances from the heat source. Average temperatures in these planes were about 1 C less than those in the plane 5 cm away from the heat source.

4.2.2 Average Temperatures During the Day

The average daily temperatures at several depths below the soil surface and distances from the heat source were tabulated for five plots (Table 15). The average daily temperatures represent the arithmetic means of the computer results obtained at three-hour intervals for each combination of depth and spacing. An average daily soil temperature for each of the three vertical planes was also computed. This average is the arithmetic mean of the computer results obtained at three-hour intervals for all gridpoints in a given vertical plane. All data shown are for August 11, 1971, except for the SUB-IRR plot which were obtained on August 6, 1972.

Table 15. Average daily temperatures at several depths and horizontal distances from the heat sources. The heat source depth was 91 cm except on the GRASS plot where the heat source was placed at 55 cm.

Horizontal distance	Depth (cm) 5	25	55	95	135	185	Average
cm	C	C	C	C	C	C	C
NO COVER							
5	18.1	21.6	26.7	31.6	28.0	26.2	26.4
45	18.2	21.4	24.5	27.3	27.2	26.2	25.3
85	18.2	21.1	22.8	26.1	26.6	25.9	24.5
CORN							
5	16.1	18.7	24.0	32.0	26.0	23.1	27.1
45	15.7	16.9	22.2	24.7	24.8	23.0	24.9
85	15.6	16.2	22.1	23.2	24.0	23.0	24.2
SUB-IRR (bare soil)							
5	19.5	22.5	26.0	29.5	25.4	23.4	26.4
45	19.4	21.7	24.4	26.0	24.8	22.4	25.0
85	19.1	21.7	23.7	25.0	24.6	23.0	24.8
SUB-IRR (field corn)							
5	21.0	21.4	25.2	29.2	25.9	24.2	27.8
45	20.4	20.7	23.3	25.6	25.5	24.0	26.4
85	20.0	20.5	22.8	24.7	25.1	24.0	26.1
GRASS							
5	17.5	20.7	30.2	22.9	21.0	20.2	20.9
25	17.4	20.4	22.8	22.6	21.1	20.0	20.0
55	17.4	20.0	22.4	22.0	21.0	19.9	19.8

The horizontal variation in the average daily soil temperature at the 5 cm depth was less than 1 C for all plots. Solar heating is more important than subsurface heating in determining temperatures near the soil surface. Only the CORN plot had horizontal variations greater than 1 C at the 25 cm depth. This was probably due to the high heat source temperature on this plot. The large temperature change at 55 cm depth on the GRASS plot is due to the shallow depth (55 cm) of the heat source on this plot. Similar large variations occurred at 95 cm on the other plots where sources were buried at 91 cm. The decrease in average daily soil temperature from the 5 cm to the 85 cm plane at the heat source depth was smallest in the SUB-IRR plot (4.5 C) and largest in the CORN plot (8.8 C). Horizontal variations in temperature decreased at depths below the heat sources. Soil temperatures were essentially uniform in the horizontal direction at a depth of 185 cm.

The smallest variation in the average soil temperature for all depths occurred on the GRASS plot where heat sources were spaced at 122 cm. Subsurface irrigation resulted in less variation than was observed on the NO COVER and CORN plots. The greatest horizontal variation in the average of all depths occurred on the CORN plot. These data show that heat sources with a lateral spacing of 183 cm at a depth of 91 cm maintain reasonably uniform temperatures between adjacent lines. This was also substantiated by crop yields. In most cases, yields from rows directly over heat sources were not higher than yields from rows located midway between heat sources.

4.3 Temperature Changes on Individual Plots

Soil temperatures are the same at all points in a horizontal plane at a given time and depth on fields warmed only by the sun. This is not so in fields heated with line heat sources. The temperature distribution shown in Table 11 emphasizes the two-dimensional nature of the problem to be described. Temperature variations occur with respect to distance from the soil surface as well as distance from the line heat sources. It was decided to compare results of soil warming with line heat sources on the basis of average hourly and average daily temperatures at various depths. These averages were obtained from printouts such as those shown in Table 13. They represent the arithmetic mean of all gridpoints at a given depth during the hour being considered for average hourly temperatures and the arithmetic mean of all gridpoints at a given depth for all hours for the average daily temperature. An average temperature for the total profile from 0 to 220 cm depth was also calculated for hourly as well as daily comparisons. This was an arithmetic mean of all gridpoint temperatures. The magnitude of the diurnal variation at a given depth will be assessed on the basis of the average hourly temperatures. Temperatures shown for the CONTROL plot were estimated from plots of hourly temperature measurements versus time. Since horizontal variations at a given depth do not occur on unheated soil, the temperatures shown are for a single point on the CONTROL plot.

Average temperatures were obtained for three day classes (Tables 16 and 17). Table 16 presents measurements obtained on a warm summer day and a cool summer day and Table 17 shows temperatures obtained on a winter day.

Table 16. Average hourly maximum and minimum temperatures and daily average temperatures for several depths for a warm summer day and a cool summer day. All warm day measurements were made on August 11, 1971, except for the SUB-IRR plot in 1972, when August 6 measurements were used, and all cool day measurements were made on September 16, 1971, and August 19, 1972.

Plot	Depth	Warm day (August 11)			Cool day (September 16)		
		Max.	Min.	Ave.	Max.	Min.	Ave.
	cm	C	C	C	C	C	C
CONTROL	5	28.2	18.5	22.5	19.2	13.0	15.6
	15	23.6	20.8	22.3	17.1	14.8	16.2
	25	22.9	21.9	22.4	16.8	15.7	16.4
	35	22.3	22.0	22.1	16.7	16.4	16.6
	45	20.8	20.7	20.8	16.5	16.4	16.5
	Ave.	17.9	17.4	17.6	16.2	15.9	16.0
NO COVER	5	31.3	17.8	24.0	24.7	14.0	18.1
	15	28.4	22.8	25.6	22.6	18.2	20.3
	25	27.2	25.1	26.3	22.3	20.4	21.3
	35	27.2	26.4	26.8	22.8	22.0	22.3
	45	27.7	27.4	27.5	23.6	23.4	23.4
	Ave.	27.8	27.1	27.5	25.7	25.1	25.4
CORN	5	22.6	19.5	21.3	17.1	14.7	15.8
	15	21.8	20.0	21.1	17.0	15.5	16.3
	25	21.6	20.4	21.2	17.6	16.6	17.1
	35	21.9	21.0	21.6	19.2	18.9	19.0
	45	22.3	22.0	22.2	21.3	21.1	21.2
	Ave.	22.4	22.1	22.3	22.8	22.5	22.7
SUB-IRR 1971	5	34.7	21.7	27.7	24.0	15.7	19.4
	15	30.7	25.3	28.7	22.4	18.6	20.6
	25	29.4	27.2	28.3	22.6	21.1	21.9
	35	29.2	28.0	28.5	23.4	22.5	23.0
	45	28.9	28.4	28.6	23.9	23.7	23.8
	Ave.	26.4	25.6	26.0	24.1	23.6	23.8
SUB-IRR 1972	5	26.8	22.1	24.2	22.1	19.0	20.4
	15	25.7	23.6	24.8	22.2	21.0	21.5
	25	24.9	23.9	24.4	21.2	20.6	20.8
	35	24.7	24.2	24.3	21.2	21.0	21.1
	45	25.0	24.5	24.7	22.3	22.2	22.2
	Ave.	25.1	24.9	25.0	24.1	23.9	24.0
GRASS	5	--	--	--	18.6	16.4	17.4
	15	--	--	--	19.8	18.7	19.1
	25	--	--	--	20.7	20.1	20.3
	35	--	--	--	21.4	21.2	21.3
	45	--	--	--	22.6	22.4	22.5
	Ave.	--	--	--	21.2	21.0	21.1

Table 17. Average hourly maximum and minimum temperatures and daily average temperatures for several depths on a winter day. All measurements were made on February 19, 1971.

Depth	Maximum			Minimum			Daily average		
	CONTROL	NO COVER	GRASS	CONTROL	NO COVER	GRASS	CONTROL	NO COVER	GRASS
cm	C	C	C	C	C	C	C	C	C
5	7.5	10.5	8.3	3.0	3.7	4.1	4.9	6.4	6.1
15	6.5	10.8	8.3	4.8	8.1	7.2	5.7	9.5	7.7
25	6.6	11.9	9.5	5.2	10.9	8.5	6.0	11.5	9.1
35	6.8	13.7	10.1	6.3	13.2	9.6	6.6	13.4	9.8
45	7.1	15.5	11.1	6.8	15.2	10.7	6.9	15.3	10.8
Ave.	7.1	19.6	10.4	6.8	19.3	10.1	7.0	19.5	10.5
Source temp.	---	34	22	---	34	28	---	34	25

4.3.1 CONTROL Plot

The plot surface was free of vegetation at all times. The daily temperature change was 9.7 C at 5 cm but only 1.0 C at 25 cm. The average daily temperature, including depths from 0 to 220 cm, was nearly constant on a given day. The influence of soil heating on temperatures at various depths can be determined by comparisons between the heated plots and the CONTROL plot.

4.3.2 NO COVER Plot

Large diurnal temperature fluctuations occurred at the 5 cm depth on each day considered. This result shows the small influence of the heat sources on the soil temperature variations near the surface. Here temperature variations are controlled by meteorological conditions and not by the heat sources. As distance from the surface increased, the diurnal temperature variation decreased. Below 25 cm depth the diurnal variation was less than 1 C in all cases.

Comparison with the CONTROL plot shows that an increase in the average daily soil temperature at the 5 cm depth occurred on each of the three days. These increases were 1.5, 2.5, and 1.5 C for August 11, September 16, and February 19, respectively. At greater depths larger increases were observed. For the total profile to a depth of 220 cm the increases in average daily temperature were 9.9, 9.4, and 12.5 C for August 11, September 16, and February 19, respectively.

4.3.3 CORN Plot

Field corn growing on the CORN plot was over 2 meters tall and provided complete shading of the soil surface on both days. Diurnal temperature variations were much less at the 5 and 15 cm depths than those observed on the NO COVER plot. The maximum temperatures were lower (22.6 vs. 31.3 C and 17.1 vs. 24.7 C) while the minimum temperatures were higher (19.5 vs. 17.8 C and 14.7 vs. 14.0 C) on the CORN plot at the 5 cm depth. The lower maximum temperatures are the result of shading. The higher minimum temperatures can be attributed to a reduction of long-wave radiation at night due to the corn canopy.

Average daily temperatures on August 11 were 4 to 5 C lower than those observed on the NO COVER plot at all depths shown in Table 16. On September 16 CORN plot temperatures were 2 to 4 C lower than on the NO COVER plot. The heat source temperature was 4 C lower on the CORN plot on August 11 and 1 C higher on September 16 compared with heat source temperatures on the NO COVER plot.

4.3.4 GRASS Plot

A dense stand of sudangrass over 1 meter tall completely covered the soil surface on the GRASS plot on September 16, 1971. Table 16 shows that temperature variations were less near the soil surface on this plot than on the NO COVER and CORN plots. Average daily temperatures at all depths to 45 cm were higher than those found on the CORN plot on this date. This was due to the lesser heat source depth. The average daily temperature for the total profile was less than that observed on the NO COVER and CORN plots due to lower temperatures in the lower portion of the profile.

Comparisons between the NO COVER and GRASS plots for February 19 (Table 17) indicate that diurnal temperature variations were less at 5 and 15 cm depths on the GRASS plot. Temperatures were lower throughout the GRASS plot profile due to lower source temperatures and the short period of heat input prior to this date. The daily fluctuation of source temperatures shown for the GRASS plot in Table 17 was characteristic of the operation of this heat source.

4.3.5 SUB-IRR Plot

4.3.5.1 Year: 1971. Effects of soil warming in combination with subsurface irrigation on diurnal temperature variations are shown for bare soil conditions in Table 16. The sub-irrigation system was not used extensively during the months of August and September in 1971. No water was applied through this system from July 30 to August 12 and from August 26 to September 20. Water contents in the vicinity of the heat sources were higher than on the NO COVER and CORN plots on these dates, however.

Average daily temperatures and diurnal variations in average hourly temperatures for the two days in 1971 can best be compared with those observed on the NO COVER plot since soil surface conditions were the same. On August 11 the heat source temperature on the SUB-IRR plot was 2 C lower than on the NO COVER plot. Average temperatures, nevertheless, were higher at all depths to 45 cm on the SUB-IRR plot. The average temperature was 1.5 C lower. The heat source temperature was 3 C lower on September 16 on the SUB-IRR plot and similar results were obtained for average daily temperatures at various depths and for changes in hourly averages. The greatest effect of subsurface irrigation was a reduction in diurnal variations and an increase in temperature in the upper soil layers.

4.3.5.2 Year: 1972. The subsurface irrigation system was used more extensively in 1972. The soil water content near the heat sources was maintained at higher levels than in 1971. Field corn was growing on the plot in 1972. Soil temperature data for August 6, a warm day, and August 19, a cool day, are presented in Table 16. Maximum air temperatures observed at the official weather station were 39 and 27 C and minimum air temperatures were 15 and 16 C for August 6 and August 19, respectively (U.S. Dept. of Commerce, 1972). Irrigation water was applied through the subsurface irrigation system on August 4 and again on August 16.

Air temperatures for the two days chosen in 1972 were nearly identical to those experiences on August 11 and September 16, 1971. For the warmer day the heat source temperature was 2 C higher in 1971. On the other three days the heat source temperature was 31 C. Average soil temperatures at a given depth were consistently 4 C lower under the crop canopy of field corn on the warm day than those observed with a bare surface in 1971. Average temperatures to the 45 cm depth were nearly the same for both cover conditions on the cooler day.

Comparison of CORN plot temperatures (Table 16) with SUB-IRR plot temperatures under corn shows an increase of about 4 C in the average daily temperature of the upper layers due to subsurface irrigation. Heat source temperatures were 4 C higher on the CORN plot on the cool day, making the temperature increase due to subsurface irrigation even larger. The average temperature for the total profile was slightly higher on the SUB-IRR plot for both days.

Diurnal temperature variations under the corn canopy were about the same as those observed on the CORN plot for both days. They were considerably less than on the SUB-IRR plot with bare surface conditions. The greatest decrease in variations occurred at 5 and 15 cm depths.

4.3.6 Summary and Conclusions

Results shown in Tables 16 and 17 indicate that soil warming increased the soil temperature by varying degrees depending on crop canopy, burial depth, soil water content, and weather conditions. The effect was small at the 5 cm depth, but became increasingly greater as the heat source depth was approached. On February 19, 1971, the NO COVER plot was 5.5 and 8.4 C warmer than the CONTROL plot at depths of 25 cm and 45 cm, respectively, while at the 5 cm depth the difference was only 1.5 C.

The greatest temperature increases were achieved on the SUB-IRR plot. The maintenance of a high soil water content resulted in high rates of heat transfer and smaller temperature gradients throughout the upper portions of the soil profile. Under both bare soil conditions and a corn canopy, higher temperatures were maintained on the SUB-IRR plot even though source temperatures were lower than on other heated plots.

4.4 Annual Temperature Changes

4.4.1 Annual Soil Temperature Cycle

Soil temperatures at several depths were monitored daily from the fall of 1963 through the spring of 1965 at 15 sites in Western Oregon (Boersma and Simonson, 1970). Results of these measurements are shown in Figure 13. Data points represent 10-day average temperatures plotted at the midpoint of the 10-day period. All measurements were made at 0800 throughout the study period. Soil temperatures measured at 0800 hours are less than the average daily temperatures for the 5 and 15 cm depths. Temperatures do not change during the day at 68 and 114 cm depths and these temperatures may therefore be assumed to represent the daily averages.

Figure 13 shows that soil temperatures do not exceed 20 C for an extended time at any depth under natural conditions in the Willamette Valley. It is assumed that average daily temperatures at the 11 cm depth were 2 C higher than those shown in Figure 13 to allow for the fact that the 0800 hours observation is less than the daily average temperature. Temperatures in excess of 20 C would have occurred at this depth for about 30 days in 1964. Diurnal fluctuations under natural conditions are 1 C or less below 25 cm, hence little deviation from daily averages can be expected for the 27 cm depth.

4.4.2 Effect of Soil Warming on the Annual Temperature Cycle

Average daily soil temperatures at several depths for the CONTROL and NO COVER plots for selected days throughout the year are shown in Table 18. These temperatures were calculated by procedures discussed in Section 4.3. Maximum and minimum air temperatures recorded at the U.S. Weather Bureau Station and heat source temperatures on the NO COVER plot for the days selected are indicated in Table 19. CONTROL plot temperatures were in good agreement with those obtained by Boersma and Simonson (1970).

The average temperature increases due to soil warming were 1.6, 3.6, and 4.8 C at 5, 15, and 25 cm depths, respectively, for eight days sampled. The 11.5 C increase found for the total profile to a depth of 220 cm reflects the large increases which occurred in the lower portion of the profile. Soil warming resulted in approximately 120 days of temperatures above 20 C at the 25 cm depth (Figure 14). This is well within the rooting zone of many crops and can be expected to have a significant effect on plant uptake of water and nutrients. At the 65 cm depth temperatures were above 20 C for over 200 days and the minimum observed was above 15 C (Figure 15). Soil temperatures at depths below 120 cm are probably not important in determining production levels of annual

Table 18. Average daily temperatures at 5, 15, and 25 cm depths and for the total profile to a depth of 220 cm on the NO COVER and CONTROL plots for selected dates.

	Daily average temperatures							
	5 cm		15 cm		25 cm		Total	
Date	NO COVER	CONTROL	NO COVER	CONTROL	NO COVER	CONTROL	NO COVER	CONTROL
	C	C	C	C	C	C	C	C
1/25/72	4.4	3.7	8.1	4.9	10.2	5.2	19.4	7.2
2/19/71	6.4	4.9	9.5	5.7	11.5	6.0	19.5	7.0
3/5/72	11.4	8.5	12.8	8.9	13.5	8.8	21.2	8.1
4/2/71	12.0	9.7	13.4	9.1	14.3	9.2	20.0	7.8
6/20/71	18.4	17.9	20.8	17.7	21.8	17.4	24.6	13.9
8/11/71	24.0	22.5	25.6	22.3	26.3	22.4	27.5	17.6
9/16/71	18.1	15.6	20.4	16.2	21.3	16.4	25.4	16.0
12/24/70	4.5	3.2	7.2	3.7	8.8	3.8	18.9	7.4
Average	12.4	10.8	14.7	11.1	16.0	11.2	22.1	10.6

crops. They may be important for deep-rooted perennial crops such as alfalfa and certain tree fruits. Figure 16 shows that NO COVER plot temperatures were maintained above 20 C throughout the year at depths of 155 and 215 cm. The maximum temperature observed on the CONTROL plot for these depths was about 16 C and the annual average was about 10 C.

Table 19. Maximum and minimum air temperatures (U.S. Dept. of Commerce, 1971, 1972) and heat source temperature on the NO COVER plot for selected days.

Date	Temperature		
	Maximum	Minimum	Heat source
	C	C	C
1/25/71	9	6	35
2/19/71	8	-1	34
3/5/72	8	-1	37
4/2/72	13	2	35
6/20/71	25	8	35
8/11/71	38	12	35
9/16/71	27	14	34
10/10/70	15	6	29
12/24/70	7	-1	31

Temperature levels achieved throughout the year on the NO COVER plot are not representative of all conditions that would occur under a crop canopy. When the canopy has developed sufficiently to provide shading of the soil surface, lower temperatures can be expected in the upper soil layers. This was demonstrated in Section 4.3. Maintaining high soil water content levels will partially offset the effect of shading.

4.5 Summary and Conclusions

Buried heat sources raised soil temperatures throughout the profile to depths greater than 2 meters. A large percentage of the profile was maintained at 20 to 25 C during most of the year when heat source temperatures were maintained at 30 to 35 C. This is near the optimum temperature level for most agronomically important crops.

Theoretical considerations indicate that a network of warm water pipes, 5 cm in diameter, will increase soil temperatures above levels achieved with electrical heat sources with a diameter of 0.5 cm. Heated water from power generating stations might be at a lower temperature during winter months than the heat source temperatures used during the course of this study. The net effect of substituting warm water pipes for electrical heat sources would be a slight increase in profile temperatures during the summer months and a slight decrease during winter months.

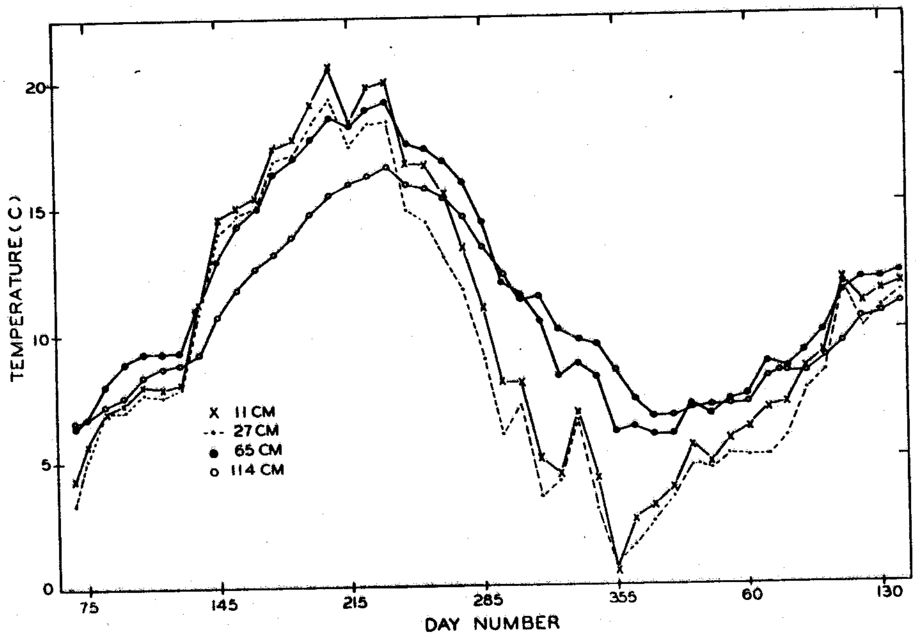

Figure 13. Ten-day average soil temperatures at 11, 27, 68, and 114 cm depths obtained during 1964-1965, after Boersma and Simonson (1970).

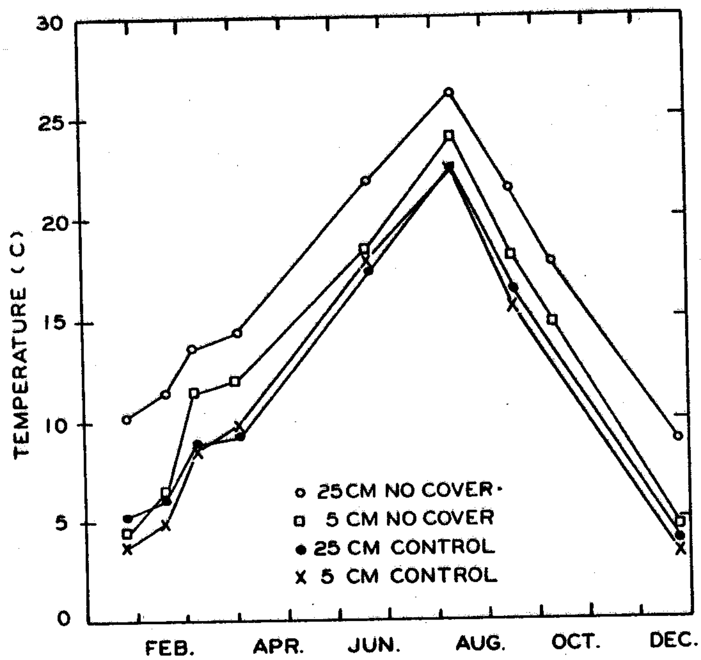

Figure 14. Average daily temperatures at 5 and 25 cm depths on CONTROL and NO COVER plots for selected days throughout the year.

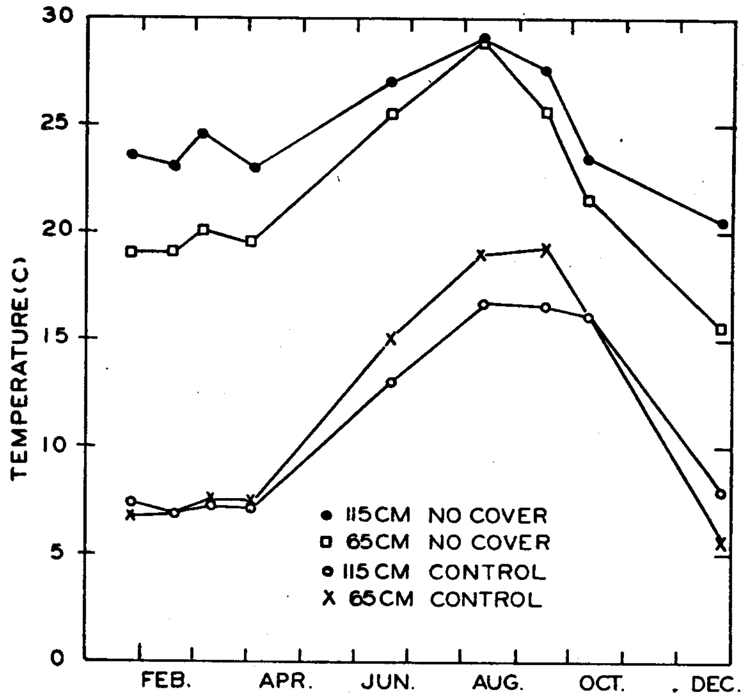

Figure 15. Average daily temperatures at 65 and 115 cm depths on CONTROL and NO COVER plots for selected days throughout the year.

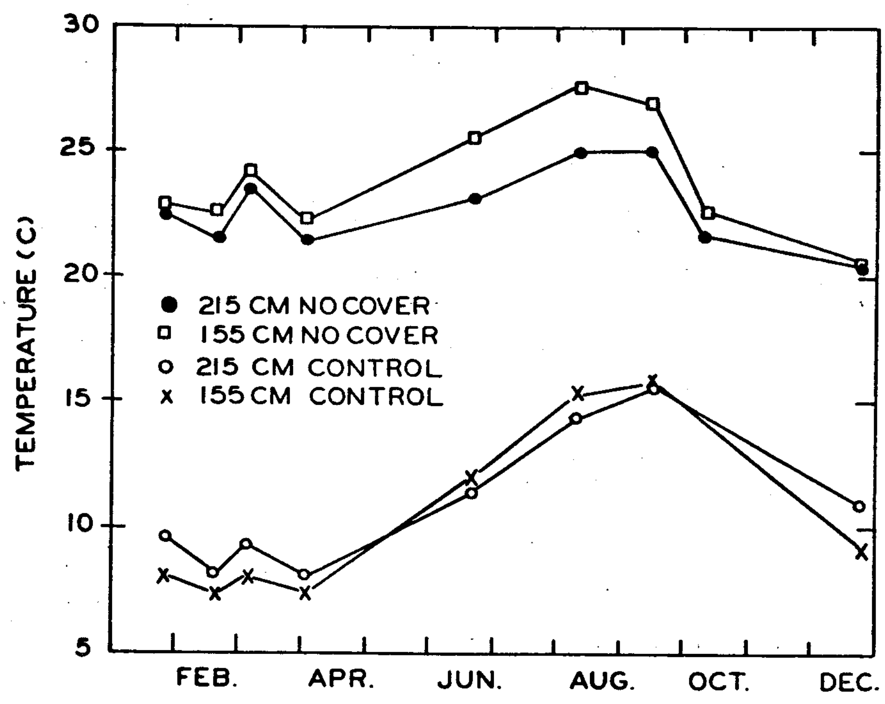

Figure 16. Average daily temperatures at 155 and 215 cm depths on CONTROL and NO COVER plots for selected days throughout the year.

5. CHANGES IN SOIL WATER CONTENT

5.1 Introduction

Water movement in soils occurs in response to temperature gradients and pressure gradients. It was anticipated that underground line heat sources maintained at temperatures above natural soil temperatures would produce changes in the natural soil water regime. Cary (1965) studied the simultaneous flow of energy and water across soil samples under various thermal and pressure gradients. He found that liquid phase flow accounted for most of the water transfer at high water contents. Liquid and vapor phase flow might contribute equally to water movement at lower water content. Water transfer due to thermal gradients may range from zero to several millimeters per day depending on existing temperature and pressure gradients. The relative contribution of liquid phase flow and vapor phase flow is determined by prevailing temperature and pressure gradients.

Frequent rainstorms maintain a high soil water content in the Willamette Valley during the winter. High evapotranspiration rates on cropped fields deplete water supplies during the summer so that large pressure gradients occur. Vapor phase flow may also be large under these conditions and rapid depletion may occur.

Temperature and pressure gradients causing water movement will be in opposite directions in the soil warming system. The temperature gradient existing between heat source and soil surface causes water movement in the vapor phase toward the soil surface. Irrigation water applied at the soil surface will penetrate the soil under pressure gradients existing between the wet soil surface and the drier regions to be rewetted at lower depths. Vapor phase flow toward the soil surface caused by temperature gradients may be equal to or exceed the liquid phase flow downward caused by the pressure gradients. Under these conditions rewetting of the lower soil horizons will be difficult. The very steep temperature gradients existing in the immediate vicinity of the heat sources may make it impossible to rewet this area throughout the year.

Soil water content was monitored extensively on three heated plots during the course of the study. A subsurface irrigation system was installed on one of the plots to evaluate such a system as a means of solving the problem of drying of the soil in the immediate vicinity of the heat sources.

5.2 Results

5.2.1 NO COVER Plot

Electrical resistance block readings were taken at two to four day intervals throughout the period from April to September, 1970, and at one week intervals during the winter months of 1970-1971. Location of sensors was shown in Figure 8. Results for selected locations and dates of the 1970-1971 season are shown in Table 20. Large fluctuations occurred at the 15 and 30 cm depths as a result of frequent irrigation during the cropping season. Soil water suction values for these depths are not shown. Little difference in suction values was found between sensors located in vertical planes 46 and 91 cm from the heat sources. Therefore only data for sensors in vertical planes 0 and 91 cm from the heat sources are shown.

Table 20. Soil water suction values at several depths on the NO COVER plot during 1970-1971.

Date	Over heat sources Depth (cm)					Between heat sources Depth (cm)			
	61	91	122	153	214	61	91	122	153
	Bars					Bars			
5/1	.25	.25	.28	.25	.26	.26	.26	.26	.27
6/1	.31	.32	.27	.25	.25	.27	.26	.27	.27
6/15	.27	.49	.28	.26	.25	.26	.26	.27	.30
7/2	.28	.52	.33	.26	.25	.26	.26	.31	.32
7/13	.30	.50	.33	.28	.25	.26	.26	.31	.33
8/3	.35	.58	.35	.30	.26	.27	.25	.31	.34
8/14	.26	.32	.37	.33	.29	.26	.25	.35	.34
8/31	.27	.24	.25	.33	.30	.25	.25	.28	.33
9/18	.25	.25	.37	.37	.28	.25	.26	.30	.33
10/19	.28	.37	.34	.42	.28	.28	.27	.38	.41
11/3	.26	.25	.26	.26	.25	.27	.26	.26	.27
12/4	.26	.25	.25	.25	.25	.28	.27	.25	.26
12/31	.27	.25	.26	.26	.25	.28	.27	.25	.26
2/5	.26	.24	.26	.26	.24	.27	.26	.25	.25
3/1	.26	.23	.26	.26	.24	.28	.27	.25	.25
4/1	.26	.24	.25	.26	.25	.27	.27	.25	.25

The six sensors located next to the heat sources (91 cm) gave inconsistent results during summer months. Large differences existed among the six replicates. It became obvious that the sensors were not located the same distance from the heat sources. Only large changes in water content over short distances could explain the measured differences.

These differences could be the result of drying in the proximity of the heat sources. On August 3, 1972, a trench was dug to check the position of one set of sensors. The two sensors at the 91 cm depth adjacent to the heat sources were found at the proper depth, but one was located 6 cm to the side of the heat source and at the second position the heat source was found at a depth of 85 cm. All the sensors intended to be located at the 91 cm depth next to the heat sources were probably several cm away from them.

The measurements in Table 20 show the soil near the heat sources to be a little dryer than midway between two adjacent loops, particularly during the summer months. These measurements did not show the extreme drying that was expected to occur near the heat sources. After the position check indicated that the sensors were not very close to the heat sources a gravimetric sampling procedure was adopted. Duplicate samples were taken at several distances from the heat sources for water content determinations (Table 21). Soil water suctions were obtained from soil water characteristic data developed by Boersma and Klock (1966) for the 60 to 90 cm depth in Woodburn soil (Figure 17). The results showed that steep water content gradients existed near the heat source. The 0 to 2 cm cylinder around the heat source was almost devoid of water. The thermal conductivity is very low at this water content (Figure 1). The 2 to 4 cm zone around the heat source contained only about 65 percent of its water content at saturation. The water content of the 4 to 6 cm cylinder was slightly lower than the rest of the soil profile.

Table 21. Soil water content and soil water suction values at several positions near the heat source (average of duplicate samples). Heat source temperature: 34 C.

Vertical distance from heat source	Horizontal distance from heat source	Vol. water content	Soil water suction
cm	cm	%	Bars
0-2	0	9.4	≫15.0
2-4	0	27.0	5.0
4-6	0	30.2	1.3
10-12	0	33.0	0.7
24-26	0	30.7	1.2
0	24-26	38.1	0.3

5.2.2 CORN Plot

Soil water content was not measured on the CORN plot during the 1969 cropping season. Corn growing on the heated area severely wilted toward the middle of August. The nearby unheated corn maintained vigorous growth. Irrigation applications were the same in both areas, indicating that water loss from the heated soil was much higher than from the unheated soil. Soil water suctions were measured on heated and unheated areas during the 1970 growing season (Table 22). Measurements were made in the crop rows. Measurements on the heated area were in a vertical plane passing through the heat source. The results shown are averages of three replications.

Table 22. Soil water suction values obtained on the CORN plot during 1970. Measurements were made in the corn rows.

Date	Unheated Depth (cm)				Heated Depth (cm)			
	15	30	61	91	15	30	61	91
	---------Bars---------				---------Bars---------			
6/29 Heat source energized (40 C)								
6/29	.64	.42	.18	.22	1.30	1.24	.81	.23
7/2	.15	.19	.19	.23	.23	.23	.32	.24
7/6	1.25	.75	.19	.22	1.89	1.29	1.13	.65
7/10	.40	.54	.20	.22	1.03	.57	.99	.98
7/13	1.43	1.45	.21	.21	2.01	1.67	1.84	1.16
7/17	.40	.82	.22	.21	.26	.51	1.81	1.46
7/20	1.24	1.61	.45	.22	1.87	1.60	2.07	1.80
7/22	.23	.99	.42	.23	.27	.25	.92	1.96
7/22 Energy supply shut off								
7/23	.23	.73	.37	.23	.27	.25	.86	1.82
7/24	.18	.34	.28	.23	.27	.25	.69	1.03
7/27	.17	.27	.25	.23	.25	.24	.43	.88
8/3	.21	.26	.28	.24	1.11	.77	.77	.90
8/7	.21	.24	.25	.23	.27	.26	.33	.24
8/7 Heat source energized (40 C)								
8/10	.25	.25	.24	.23	.83	.34	.29	.28
8/14	.23	.23	.25	.23	.71	.35	.27	.28
8/17	.25	.40	.26	.24	.36	.80	.66	.56
8/21	.23	.25	.27	.23	.72	.67	.86	.70
8/24	.61	.49	.37	.24	1.29	1.09	1.07	.94
8/27	.24	.24	.26	.23	.29	.26	.34	.49
8/31	.23	.24	.24	.23	.27	.24	.30	.70

Heat source temperatures were in excess of 40 C much of the measuring period. The heating system was turned off from June 19 to June 29 and from July 22 to August 7. This was done because it was found difficult to rewet the lower portions of the soil profile with irrigation water while source temperatures were high. The heat source temperature during the June 29 to July 22 period was 40 C. During this time soil water suctions at the 91 cm depth increased from 0.28 to 1.96 bars on the heated plot. Irrigation applications of 18 cm from July 29 to August 5 produced rewetting of the soil layers below the 60 cm depth on the heated plots. Soil water suctions decreased from 2.07 and 1.96 to 0.43 and 0.88 bars at the 61 and 91 cm depths, respectively.

Lower heat source temperatures were maintained in 1972 to avoid the drying observed in previous years. The heat source was energized throughout the cropping season. Soil water suction near the heat source remained below one bar until the last week in August (Table 23). A gradual drying occurred nevertheless. Both measurement locations were midway between crop rows. Similar comparisons are shown in Table 24 for data obtained in the crop rows. Crop rows were 45 cm offset from the heat source. Results for a third location, midway between heat sources on heated plots, are not shown. The suctions in the crop rows were slightly higher than between the rows at corresponding depths, showing the effect of root concentration. All values shown in Tables 23 and 24 are averages of three replications.

5.2.3 SUB-IRR Plot

The subsurface irrigation system (Section 2.8) was designed to overcome the problem of drying near the heat source. In 1970 an equivalent depth of 7.7 cm of irrigation water was discharged through this system. Distribution from the system was found to be inadequate and it was not used extensively. As a result soil water contents throughout the profile were similar to those observed on the CORN plot during 1970 (Table 25). Measurement locations for which data are shown were the same as those shown for the NO COVER plot in Table 20. All sensors were positioned in corn rows. The timing and amounts of irrigation water applied on the CORN and SUB-IRR plots differed slightly so that individual days cannot be compared. The measurements show again the drying of the soil over the heat sources at the 61 cm depth and near the heat source at the 91 cm depth. The soil between adjacent heat source loops dried out considerably at these depths. Corresponding measurements on unheated soil planted with corn are shown in Table 22.

The subsurface irrigation system design described in Section 2.8 was used in 1972. An equivalent depth of 28.2 cm of water was discharged through this system from June 23 through September 1. Table 26 presents soil water suctions measured in vertical planes 0 and 92 cm

Table 23. Soil water suction values obtained midway between crop rows on the CORN plot during 1962. Sensors on heated plots were located directly above the heat source.

Date	Unheated Depth (cm)					Heated Depth (cm)				
	15	30	45	61	91	15	30	45	61	91
	---------------Bars---------------					---------------Bars---------------				
6/23	1.02	.51	.27	.22	.25	1.48	.76	.34	.24	.23
6/30	1.35	.65	.31	.25	.27	1.99	1.06	.45	.28	.25
7/7	1.34	.58	.29	.25	.26	2.35	1.52	.80	.38	.24
7/14	.45	.25	.24	.24	.27	2.09	1.07	.65	.40	.25
7/21	.96	46	.23	.22	.26	1.16	1.03	.84	.57	.29
7/28	.54	.44	.27	.23	.25	.96	.81	.73	.60	.34
8/4	.62	.73	.53	.24	.25	1.12	1.58	1.58	1.16	.59
8/11	.28	.30	.44	.34	.25	.31	.45	.81	.98	.58
8/18	.28	.27	.43	.39	.26	.61	.57	1.20	1.27	.92
8/25	.36	28	.37	.35	.26	.86	.99	1.32	1.31	.96
9/1	1.14	1.46	.98	.81	.26	.74	1.35	1.72	1.60	1.07
9/7	.28	.28	1.02	1.21	.45	.50	.62	1.59	1.66	1.10
9/15	.58	.64	.89	1.16	.53	.38	.75	1.44	1.22	1.26
10/6	.61	.71	.80	.99	.59	.91	1.20	1.80	1.67	1.52

Table 24. Soil water suction values obtained in crop rows on the CORN plot during 1972. Sensors on heated plots were located in a vertical plane 45 cm from the heat source.

Date	Unheated Depth (cm)					Heated Depth (cm)				
	15	30	45	61	91	15	30	45	61	91
	-----	-----	Bars	-----	-----	-----	-----	Bars	-----	-----
6/23	1.36	.53	.31	.23	.22	1.61	.83	.30	.24	.22
6/30	1.81	.65	.33	.26	.25	2.57	1.32	.41	.26	.24
7/7	1.72	.64	.31	.25	.25	2.35	1.75	.67	.30	.22
7/14	1.49	26	.27	.25	.26	2.24	1.38	.56	.32	.22
7/21	2.00	.74	.57	.24	.25	.32	.30	.52	.39	.22
7/28	1.14	.68	.51	.24	.24	.60	.45	.34	.34	.22
8/4	1.08	.89	.73	.54	.24	.56	.85	1.27	.80	.24
8/11	.64	.34	.35	.39	.24	.47	.58	.65	.67	.27
8/18	.29	.28	.28	.26	.25	.27	.27	.52	.73	.31
8/25	.99	.51	.48	.31	.25	1.02	1.23	1.19	.95	.35
9/1	1.89	2.03	1.83	1.59	.38	.62	1.21	1.54	1.40	.59
9/7	.28	.35	1.29	1.65	.61	.37	.27	.81	1.20	.77
9/15	.98	1.38	1.64	1.34	.60	.46	1.06	1.46	1.62	.61
10/6	1.02	1.02	1.06	1.20	.61	1.38	1.83	1.72	1.36	.78

from the heat sources. Values shown for positions over the heat sources are averages of 12 replications. For positions between heat sources 10 replications were averaged. Subsurface irrigation distribution lines were at 75 cm depth over the heat sources and at 60 cm depth between heat sources. Comparison of Table 25 with 26 shows that the subsurface irrigation system was very successful in maintaining low soil water suctions or a high soil water content.

Table 25. Soil water suction values at selected locations on the SUB-IRR plot during 1970.

	Over heat sources Depth (cm)					Between heat sources Depth (cm)			
Date	61	91	122	153	214	61	91	122	153
	------------Bars------------					--------- Bars ---------			
5/1	.25	.22	.23	.24	.25	.24	.24	.22	.26
6/1	.32	.27	.25	.24	.24	.28	.25	.25	.28
6/15	.28	.32	.27	.24	.24	.31	.27	.25	.27
7/2	.26	.29	.27	.23	.23	.27	.26	.25	.25
7/10	1.19	.58	.31	.23	.23	.58	.27	.25	.25
7/20	1.97	1.47	.47	.25	.24	2.41	.54	.30	.25
7/27	1.60	1.70	.54	.27	.23	1.99	.68	.33	.25
8/3	2.45	2.27	.74	.29	.23	3.01	1.32	.40	.26
8/10	1.34	2.50	.73	.30	.23	2.00	1.17	.40	.26
8/17	1.17	2.74	.70	.30	.23	2.08	1.17	.41	.26
8/24	2.81	2.86	.97	.33	.23	3.41	1.67	.50	.27
8/31	.45	2.00	.80	.33	.22	1.90	1.21	.47	.27
9/3	.26	.54	.67	.33	.23	1.43	1.08	.44	.27
9/11	.65	.76	.57	.37	.24	1.35	.98	.45	.27
9/29	1.22	1.05	.68	.36	.23	1.50	.82	.45	.27

5.3 Discussion

5.3.1 Seasonal Changes in Soil Water Content

Changes in water content of the soil profile are obtained from the soil water suction values. Soil water suctions were converted to water content on a volume basis by using soil water characteristic data presented by Boersma and Klock (1966) for Woodburn soil. Curves were constructed for the 30 to 60, 60 to 90, and 90 to 122 cm depth intervals. No data for soil layers below 122 cm were available. It was assumed that the data for the 90 to 122 cm layer apply to the 122 to 215 cm depth interval. The soil water characteristic curve for the 30 to 60 cm layer is similar to those for 0 to 9, 9 to 15, and 15 to 30 cm layers and was

Table 26. Soil water suction values obtained on the SUB-IRR plot during 1972.

Date	Over heat sources Depth (cm)					Between heat sources Depth (cm)				
	15	30	45	60	91	15	30	45	61	91
	Bars					Bars				
6/23	1.33	.57	.33	.26	.20	1.51	.58	.33	.26	.20
6/30	1.25	.60	.31	.23	.25	1.37	.57	.31	.25	.25
7/7	1.16	.52	.26	.24	.25	1.16	.44	.28	.25	.24
7/14	.49	.26	.24	.25	.25	.53	.25	.26	.26	.25
7/21	.99	.56	.31	.24	.24	.95	.48	.28	.24	.23
7/28	.36	.35	.31	.26	.24	.34	.34	.30	.24	.24
8/4	.40	.65	.62	.46	.26	.34	.48	.51	.30	.25
8/11	.28	.31	.33	.34	.27	.27	.27	.26	.25	.24
8/18	.28	.40	.38	.32	.25	.28	.30	.30	.25	.24
8/25	.48	.42	.37	.35	.26	.43	.31	.29	.25	.24
9/1	1.21	1.34	1.00	.47	.24	1.76	1.25	.88	.39	.26
9/7	.28	.39	.87	.51	.26	.29	.50	.72	.36	.33
9/15	.43	.44	.66	.52	.29	.44	.35	.43	.36	.31
10/6	.73	.57	.66	.66	.50	.68	.53	.53	.48	.38

therefore used for the upper 60 cm of the soil profile. The three soil water characteristic curves are shown in Figure 17.

Energy budget calculations to be made later (Section 6) require knowledge of soil water content and changes in soil water content for 55 to 215 cm depth increments. A procedure was developed to estimate, for certain days, an average volumetric soil water content for this layer based on observations similar to those reported in Tables 20 through 26. Each observation point was assumed to represent the water content of the volume of soil within horizontal and vertical boundaries obtained by joining the midpoints between adjacent sensor locations. For example, the sensor at the 153 cm depth, midway between heat sources was considered representative of the 137 to 184 cm depth in a region extending 91 cm horizontally to each side. Only one sensor was used at the 214 cm depth. It was assumed to be representative of the 184 to 215 cm depth increment. Weighted average volumetric water contents were calculated for three depth increments on selected days during the 1970 growing season on the SUB-IRR plot and on selected days throughout 1970 and 1971 on the NO COVER plot. Results of these calculations are shown in Table 27.

Table 27. Weighted average volumetric water contents for the indicated layers and dates on SUB-IRR and NO COVER plots.

	SUB-IRR Soil layer (cm)				NO COVER Soil layer (cm)		
Date	55-106	106-215	55-215	Date	55-106	106-215	55-215
	%	%	%		%	%	%
5/1	39.1	46.5	44.1	5/1	39.0	46.1	43.8
6/1	38.6	46.3	43.8	6/1	38.4	46.1	43.6
6/15	38.4	46.4	43.8	6/15	37.8	46.0	43.4
7/2	38.6	46.4	43.9	7/2	37.6	45.7	43.1
7/10	34.8	46.3	42.6	7/13	37.6	45.6	43.0
7/20	30.9	45.8	41.0	8/3	37.2	45.4	42.8
7/27	30.4	45.6	40.7	8/14	38.7	45.2	43.1
8/3	29.1	45.0	39.9	8/31	38.7	45.5	43.4
8/10	29.7	45.0	40.1	9/18	38.8	45.1	43.1
8/17	29.8	45.1	40.2	10/19	38.2	44.7	42.6
8/24	28.8	44.4	39.4	11/3	38.8	46.2	43.8
8/31	30.1	45.0	40.2	12/4	38.7	46.2	43.8
9/3	33.5	44.8	41.2	10/31	38.7	46.2	43.8
9/11	31.9	44.9	40.7	2/5	38.8	46.3	43.9
9/29	31.0	44.7	40.3	3/1	38.8	46.3	43.9
				4/1	38.8	46.3	43.9

Very small changes in water content occurred at the lower depths of the NO COVER plot throughout the year. The water content varied from 46.3 to 44.7 percent by volume in the 106-215 cm layer. The change was only from 39.0 to 37.2 percent in the 55 to 106 cm layer. Combining these two layers resulted in a total weighted change from 43.9 to 42.6 percent by volume, or an equivalent depth of about 2 cm of water.

Changes on the SUB-IRR plot were similar to those on the NO COVER plot for the layer from 106 to 215 cm (46.5 to 44.4 percent). However, larger changes occurred in the 55 to 106 cm layer. The 39.1 to 28.8 percent change in water content is equivalent to a depth of 5.25 cm of water. Comparing soil water suction values shown for the CORN plot in Tables 22 and 23 with those obtained on the SUB-IRR plot in 1970 (Table 25) shows that the water content fluctuations of the CORN plot were similar to those observed on the SUB-IRR plot in 1970.

The effect of subsurface irrigation on soil water content is clearly shown by comparing soil water suctions observed on this plot in 1970 and 1972 for the 61 and 91 cm depths (Tables 25 and 26). Corn was growing on the plots in both years. The water content did not change at the 91 cm depth throughout the growing season in 1972. A slight increase in suction was noted at the time of the last observation. This can be attributed to the fact that the last subsurface irrigation application was made on September 1. The subsurface system was successful in maintaining a high soil water content throughout the growing season.

5.3.2 Soil Drying Around the Heat Sources

The existence of a very dry core around the heat source was demonstrated by data presented in Table 21. This core was limited in extent to a distance of a few cm from the heat source. The reason for large variations in suctions measured with sensors located near the heat source is clear. The very large change in water content over a small distance made placement of the sensors critical. When these sensors were installed, no effort was made to precisely locate the heat source. The position was determined by measurements at the soil surface. Figure 18 was prepared to show the effect of the change in water content as a function of distance from the heat source (Table 21) and emphasize its effects on temperature gradients. The temperature distribution curves shown for the region near the heat source (80 to 100 cm depth) were drawn by hand. It was assumed that temperatures changed linearly with depth from A to B and from D to C. The two resulting lines intersect at the heat source depth at E and indicate a temperature of 30 C at that depth. The measured heat source temperature was 34 C as indicated by the data point F. The solid lines showing the change in temperature near the heat source were drawn, based on the assumption

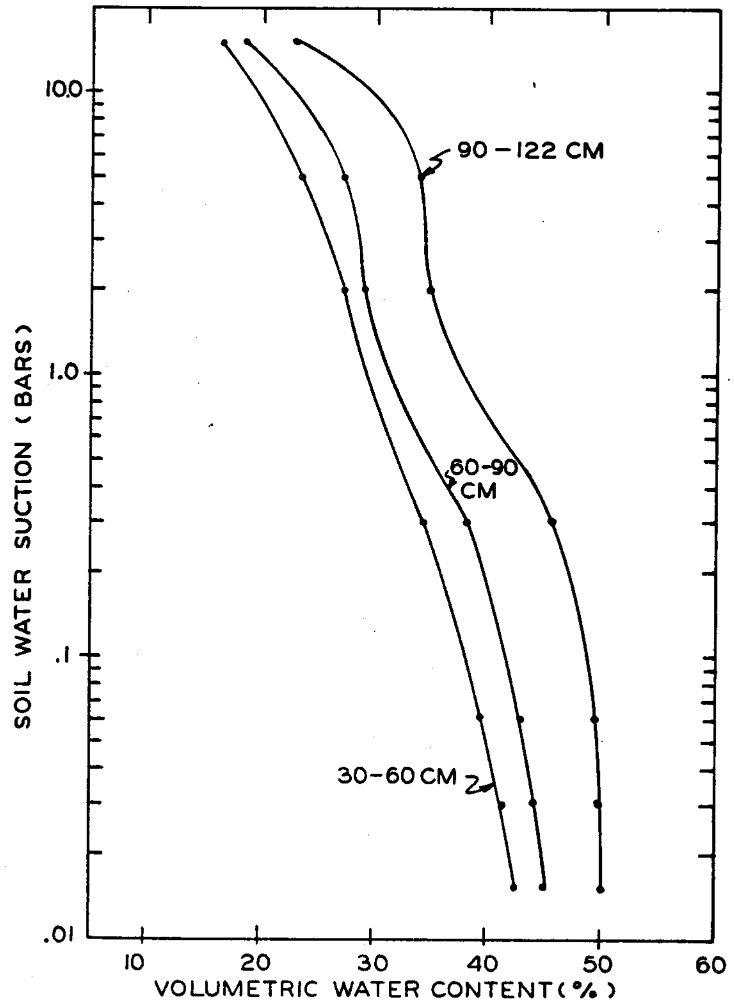

Figure 17. Soil water characteristic curves for 30 to 60, 60 to 90, and 90 to 122 cm zones in a Woodburn soil, constructed from data presented by Boersma and Klock (1966).

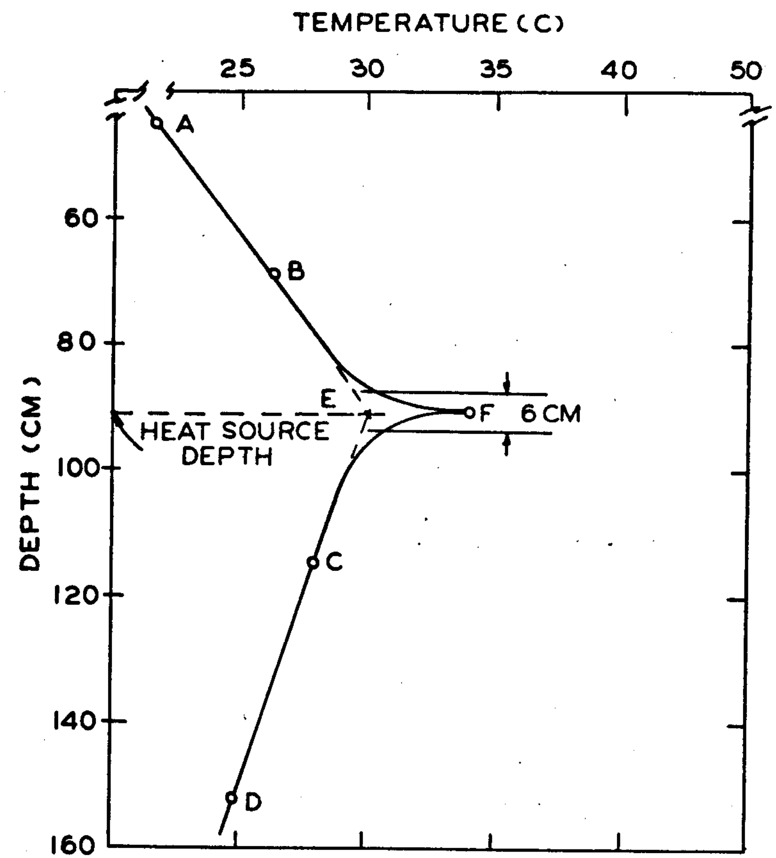

Figure 18. Soil temperatures measured in a vertical plane passing through the heat source. NO COVER plot, August 3, 1972.

that the temperature decreased rapidly over the distance of 0 to 3 cm which forms the dry core around the heat source. This zone is indicated as the 6 cm wide band in Figure 18. The high temperature gradient near the heat source is caused by the low thermal conductivity of that region. The rate of temperature decrease should be inversely proportional to the change in thermal conductivity under steady state conditions. It can be deduced from Figure 18 that the temperature decrease was 2.45 times greater in the 0 to 2 cm zone than in the 2 to 4 cm zone. The thermal conductivity increased in the same proportion as the temperature change decreased. Thermal conductivities for these two zones were obtained by using Figure 1 and the water contents shown in Table 21. The temperature decrease of the 2 to 4 cm zone was 1.38 times greater than the temperature change of the 4 to 6 cm zone. The thermal conductivity of the 4 to 6 cm zone was 1.38 times greater than in the 2 to 4 cm zone. The ratios were 1.14 and 1.11 for the temperature change and thermal conductivity change, respectively. These data indicate that the rapid decrease in temperature near the heat source is caused by the low thermal conductivity of the dry soil. A heat source temperature of 30 C would produce the observed temperatures at A, B, C, and D if the soil had the same water content throughout. Maintaining a high water content near the heat source improves its efficiency in raising soil temperatures appreciably.

5.3.3 Changes in Soil Water Content in Response to Irrigation

Measurements shown in Table 22 show that in 1970 the soil on the unheated CORN plot was maintained at a high water content while the soil on the heated CORN plot gradually dried out. Frequent irrigations did not prevent the soil from drying out on the heated plot and failed to rewet the soil. Soil water content conditions and the water distribution following irrigations are shown in Figure 10. Measurements made on July 20 show the water content to be about 27 percent above a depth of 40 cm and gradually increasing from 35 to 40 percent at depths below 60 cm on the unheated plot. This condition may be considered typical for a well-irrigated plot. The water content on the heated plot was about 27 percent from 0 to 100 cm on the same day. Both plots were irrigated with 6 cm of water on July 21 and water content measurements were again made on July 22, with results shown as broken lines in Figure 10. The irrigation increased the water content in the unheated plot to a depth of 60 cm to slightly higher than 35 percent. The increase in water content shown required 3 cm of water. Assuming an application efficiency of 75 percent means that 4.5 cm of water was available for irrigation so that 1.5 cm did not penetrate the soil. The infiltration rate of the Woodburn soil is very low. The water content was more or less uniform with depth indicating that no pressure gradients existed. This is confirmed by Table 22 which showed suctions of about 0.25 bars at all depths. The excess water remained on the soil surface and eventually evaporated. The same irrigation increased the water content of the heated plot to about 35 percent at depths above 40 cm, as it had on the unheated plot. The irrigation water increased the water content at depths below 40 cm to a lesser degree and very little water passed the 60 cm depth. The increase in water content shown required 3.5 cm so that on this plot 1.0 cm of water remained on the soil surface. The existing pressure gradients should have been sufficiently high to move the remaining 1 cm of water into the soil. The additional wetting it would have provided is shown in the diagram by the dotted line. Even with this additional wetting the profile still would have been much drier than the unheated plot. Penetration of the remaining 1 cm of water into the soil was prevented by opposing thermal gradients.

Suctions of 2.01, 1.67, 1.84, and 1.16 bars were measured at the 15, 30, 61, and 91 cm depths, respectively, on July 13, 1970 (Table 22). Four cm of irrigation water was applied on July 14. Two days later suctions had decreased to .25 and .51 bars at the 15 and 30 cm depths but were 1.81 and 1.46 bars at 61 and 91 cm depths, respectively. The increase in water content to a depth of 30 cm accounts for approximately 2 cm of the 4 cm of irrigation water applied. The remaining 2 cm should have been adequate to reduce suctions at the 60 cm depth to below one bar. However, this did not occur because of enhanced evaporation.

The heat source was turned off on July 22, 1970, and 3 cm of irrigation water was applied on July 23. Measurements made on July 24 showed that water from this irrigation did move to the 91 cm depth. Suction decreased from 1.82 to 1.03 bars. After an additional 3.5 cm application of irrigation water on July 30, suctions of 1.11, .77, .77, and .90 bars were observed at 15, 30, 61, and 91 cm, respectively, on August 3. On August 5 an application of 5.5 cm reduced these suctions to .27, .25, .33, and .24 bars, measured on August 7. Thus with the heat source turned off irrigation water penetrated to the heat source depth and reduced soil water suction to about .3 bars.

The heat source was energized again on August 7. Table 22 shows that the soil did not dry out as much as it did after the heat source was energized on June 29. During that cycle the soil water suction at the 91 cm depth had increased from .24 to 1.96 bars in 24 days. During the heating period following August 7 the suctions at the 91 cm depth were maintained below 1.00 bar. This was mainly accomplished by maintaining a rate of water application high enough to counteract the evaporation from the plot.

5.3.4 Irrigation Management with Soil Heating

Corn had been irrigated with 25.9 cm of water in 1969. This was sufficient to maintain growth on the unheated area, but the crop growing on the heated plot showed severe water stress in September. In 1970, 63.5 cm of irrigation water was applied to corn growing on the same plots. On the unheated area suctions remained near .3 bars throughout the season at all depths to 91 cm. On the heated area suctions of .5 to 2 bars were common throughout the profile (Table 22) and the 60 to 90 cm zone could be rewet only after the heat source was turned off. A companion crop grown on the heated, sub-irrigated area experienced similar suctions (Table 25) with a total application of 58.5 cm of irrigation water. Only 7.7 cm of water was applied through the sub-irrigation system in 1970. In 1972, 43.5 cm of irrigation water was applied to corn on these plots. Once again the unheated areas were maintained at high water contents while on the heated areas suctions rose above one bar (Tables 23 and 24). A companion crop on the heated, sub-irrigated plot received 38.6 cm of irrigation water applied with sprinklers and 28.2 cm applied through the subsurface irrigation system. This maintained suctions below .3 bars in the vicinity of the heat source and kept the entire profile at a high water content throughout the season.

The wide range in water application rates on the heated corn plot did not appear to alter the drying tendencies observed for the region below 60 cm. It appears that sprinkler irrigation is not a satisfactory means of maintaining high soil water content for crops with high water requirements and deep rooting systems, when grown on heated soils. With subsurface irrigation it was possible to keep the entire profile wet throughout the season.

5.4 Summary and Conclusions

Soil heating was found to increase soil water suction in the 60 to 90 cm layer. A small but very dry core developed around the heat source in summer months. Crops which withdraw water from the 60 to 90 cm layer decrease water content more than on a bare plot. Sprinkler irrigation was not a satisfactory method for maintaining high soil water content in the 60 to 90 cm layer. A subsurface irrigation system maintained a wet soil at all depths throughout the growing season in a field corn crop. Soil heating will increase irrigation requirements for deep rooted crops.

6. ENERGY DISSIPATION

6.1 Introduction

A theoretical model for prediction of heat loss rates as a function of design parameters, soil thermal conductivity and temperature difference between line heat source and soil surface was presented in Section 1.4 (Equation 1). Solutions for several sets of design parameters were given.

Equation 1 indicates that heat loss rates fluctuate seasonally as a result of changes in the temperature gradient and soil thermal conductivity. Large seasonal temperature fluctuations occur in the Willamette Valley. Precipitation, and hence soil water content, also shows seasonal changes. High rates of heat loss occur during the winter when air temperature is low and soil water content is high. The high soil water content can be expected to result in high soil thermal conductivity. Low rates of heat loss occur during the summer. Temperature differences between the soil surface and heat sources are low at that time and the soil water content is lower than during the winter because of lack of rainfall. Equation 1 was used as a model for evaluating seasonal changes in energy dissipation rates and their relationship to climatic factors. Three procedures were used to evaluate the energy dissipation data. The first involved a detailed energy balance analysis to determine rates of energy dissipation in relation to upward and downward temperature gradients at different times of the year. Two procedures were then used to correlate dissipation rates measured at different times of the year with temperature gradients and to calculate thermal conductivities.

6.2 The Energy Balance

6.2.1 Methods of Analysis

The purpose of the energy balance analysis of the soil warming system was to quantify contributions of various heat transfer components to the dissipation of energy. The analysis was based on temperature profiles obtained from the computer analysis discussed in Section 4.1. Vertical temperature gradients were calculated using temperature differences between adjacent gridpoints. These differences were tabulated in the form shown in Table 28 for each set of measurements. Temperature differences in the upper 50 cm varied during the day in response to diurnal temperature fluctuations resulting from the daily course of solar heating and long-wave radiation from the soil surface. The differences in the lower part of the profile remained constant throughout the day.

Table 28. Example of gridpoint temperature difference printout produced by a computer program. CORN plot, 0000 hours, August 11, 1971.

Depth	Horizontal distance from heat source - cm								
	5	15	25	35	45	55	65	75	85
cm	C								
5- 15	.7	.5	.3	.2	.0	-0.1	-0.2	-0.3	-0.4
15- 25	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	0.3	-0.3
25- 35	.1	.2	.2	.2	.2	.2	.3	.3	.4
35- 45	.4	.3	.3	.3	.4	.5	.5	.6	.7
45- 55	.6	.3	.1	.1	.1	.2	.3	.4	.4
55- 65	.8	.3	.1	.0	.0	.0	.0	.1	.0
65- 75	1.3	.8	.4	.2	.1	.1	.2	.1	.0
75- 85	1.9	1.2	.8	.5	.3	.1	.1	.1	.3
85- 95	.6	.7	.5	.1	-0.2	-0.4	-0.6	-0.6	-0.5
95-105	-1.4	-0.6	.0	.3	.3	.2	.0	-0.1	-0.1
105-115	-1.4	-0.8	-0.4	-0.1	.1	.2	.2	.2	.1
115-125	-1.1	-0.7	-0.4	-0.2	.0	.1	.1	.1	.1
125-135	-0.7	-0.5	-0.4	-0.2	-0.2	-0.1	.0	.0	.0
135-145	-0.3	-0.3	-0.3	-0.3	-0.2	-0.1	-0.1	.0	.0
145-155	-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1
155-165	-0.2	-0.3	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1
165-175	-0.3	-0.3	-0.3	-0.3	-0.1	-0.2	-0.1	-0.1	-0.1
175-185	-0.3	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.2
185-195	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.2
195-205	.0	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.4
205-215	.0	.0	.0	-0.2	-0.2	-0.3	-0.4	-0.5	-0.5

Computer outputs such as shown in Table 28 were used to calculate an upward and downward heat flux component for a given day. The downward gradient was obtained by averaging gradients for the six 10 cm thick layers from 155 to 215 cm depths. All horizontal increments at each hourly observation were averaged to obtain the gradient for a given day. A total of 486 observations were included in this estimate for one day. By choosing the region from 155 to 215 cm depths errors introduced by data extrapolation were minimized.

The upward temperature gradient was obtained by averaging gradients for the 10 cm thick layer from 55 to 65 cm. All horizontal increments at each hourly observation were averaged to obtain the upward gradient for a given day. A total of 81 observations were included in this estimate.

This analysis considered a column of soil of unit thickness extending from 55 to 215 cm below the soil surface and from the midpoint between adjacent loops on one side of the heat source to the midpoint between adjacent loops on the opposite side of the heat source, a distance of 182 cm. The upper boundary was chosen at the 55 cm depth to avoid having to consider diurnal temperature fluctuations due to solar heating. The lower boundary was the deepest point in the soil profile for which temperature data were available. The vertical boundaries were planes of symmetry at which no horizontal heat transfer into or out of the column of soil occurred. All boundaries were far enough from the heat source that energy input surges did not alter temperature regimes.

The rate of energy addition to the soil was obtained from kilowatt-hour meter readings taken at one to three day intervals. The analyses were made for 24-hour periods starting at 0000 hours. The energy dissipation rates were based on measurements taken several days apart. The rates were found to remain constant over periods of two weeks or longer except during the first month after heat sources were energized or after thermostat settings were changed.

The energy required to raise the soil temperature depends on the mass of soil and water in the profile, the specific heat of soil and water components, and the temperature increase. The soil mass was calculated assuming a uniform bulk density of 1.4 gm/cm^3 for the entire profile (Simonson and Knox, 1965). The water mass was estimated from soil water suction measurements (Section 5) and the soil water characteristic curves constructed from data obtained by Boersma and Klock (1965) for Woodburn soil (Figure 17). The specific heat of the soil solids was assumed to be .4 calories per gram per degree C (cal/gm C) (De Vries, 1966). The specific heat of water is 1.0 cal/gm C. Changes in soil temperature were obtained from gridpoint temperatures obtained with the procedure described in Section 4. The daily temperature change was obtained from the average temperatures at 0000 and 2400 hours. The average temperature was the mean of the 153 gridpoint temperatures within the soil column considered. It was assumed that solar heating did not influence the average profile temperature over a one-day period so that changes in profile temperature were attributed to heat source energy inputs only.

Energy not contributing to an increase in soil temperature must be transferred out of the profile by conduction or mass flow of water in liquid or vapor form. Soil water measurements (Section 5) indicated that water content remained constant throughout the year at the lower boundary. Heat flow at this boundary was therefore assumed to be entirely due to conduction. The rate of heat flow past the lower boundary was calculated as the product of temperature gradient and thermal conductivity. A constant thermal conductivity of .16 cal/cm min C throughout the year was assumed for this region. This conductivity was derived from data presented by Sepaskhah (1973).

6.2.2 Results

Energy balances were calculated for eight dates spaced throughout the year for the NO COVER plot and for two summer days on the CORN and SUB-IRR plots. Maximum and minimum air temperatures measured on the 1971 dates (U.S. Dept. of Commerce, 1971) were shown in Table 19. Maximum air temperatures were 39 and 27 C and minima were 15 and 11 C for August 6 and August 19, 1972, respectively (U.S. Dept. of Commerce, 1972). Values of parameters used to partition energy balance components for each data and plot analyzed are shown in Table 29. The magnitude of heat source energy input, changes in heat storage, heat flow at the lower and upper boundaries, and thermal conductivities at the upper boundary are shown in Table 30.

6.2.3 Discussion

Results presented in Table 30 for the NO COVER plot show the seasonal trends in magnitude of energy dissipation components. Heat transfer at the lower boundary accounted for approximately 7 percent of the total energy flow on the first four dates and 39 percent on the last four dates. Heat transfer at the upper boundary was about 76 percent of the total on the first four dates but only 52 percent on the last four dates. An increase in heat storage was observed on all but two dates. The average contribution to heat storage was about 20 percent. Thermal conductivities calculated for the upper boundary of the profile ranged from a high in the winter of .73 cal/cm min C to a low of .03 cal/cm min C at the end of the summer. The high value corresponds to a very

Table 29. Estimates of the parameters used to partition the energy flow into heat storage, downward flow, and upward flow components. *

Date	Temp. change	Soil	Water	Temperature gradient Lower	Upper
	C/day	--gm x 10^3--		------C/10 cm------	
NO COVER plot:					
1/25/72	.12	40.3	12.7	.05	2.32
2/19/71	-.02	40.3	12.7	.16	1.82
3/5/72	.08	40.3	12.7	.12	1.93
4/2/72	.07	40.3	12.7	.07	1.42
6/20/71	.06	40.3	12.5	.40	.97
8/11/71	.03	40.3	12.4	.57	.68
9/16/71	-.04	40.3	12.2	.18	.92
CORN plot:					
8/11/71	.20	40.3	11.5	.22	.21
9/16/71	.01	40.3	11.5	.33	.76
SUB-IRR plot:					
8/6/72	.12	40.3	12.4	.38	.45
8/19/72	-.01	40.3	12.4	.34	.99

*Per soil column of unit thickness 182 cm wide, with the upper boundary at 55 cm and the lower boundary 215 cm below the soil surface.

Table 30. Energy balance components and thermal conductivities calculated from data shown in Table 29.

Date	Energy input	Change in heat storage	Heat flow out of profile Lower	Heat flow out of profile Upper	Calculated thermal conductivity
	-------------	-------------cal/day*	-------------	-------------	cal/cm min C
NO COVER plot:					
1/25/72	7,800	2,500	200	5,100	.09
2/19/71	6,500	- 400	700	6,200	.13
3/5/72	7,800	1,600	500	5,700	.11
4/2/72	6,200	1,500	500	4,200	.11
6/20/71	4,700	1,300	1,700	1,700	.07
8/11/71	3,400	600	2,300	500	.03
9/16/71	4,100	200	1,300	2,600	.10
10/10/70	3 100	- 800	700	3,200	.13
CORN plot:					
8/11/71	4,800	3,900	900	0	---
9/16/71	3,800	200	1,400	2,200	.11
SUB-IRR plot:					
8/6/72	5,800	2,500	1,600	1,700	.15
8/19/72	6,000	- 200	1,400	4,800	.19

*Per soil column of unit thickness 182 cm wide, with the upper boundary at 55 cm and the lower boundary 215 cm below the soil surface.

wet soil and was the same as that assumed for the lower boundary. The low value corresponds to a very dry soil and indicates that during the summer the rate of energy dissipation is controlled by a dry zone near the heat source. The results show the anticipated trend of low values in the summer and high values in the winter.

The results shown for the CORN plot on August 11 are clearly invalid. An upward temperature gradient of .2 C/10 cm existed on this date (Table 29). Yet the energy balance shows a zero heat flux at this boundary. The discrepancy can probably be attributed to the assumptions made in establishing the energy budget. A temperature increase of .07 C in the layer from 55 to 215 cm was measured on the CONTROL plot on August 11, 1971. This could only be produced by solar heating. If a portion of the .20 C increase shown for the CORN plot on this date was caused by solar heating rather than heat source energy input the change in heat storage shown in Table 30 would be less and a positive upward flux would result.

The results for September 16, 1971 were nearly the same on the NO COVER and CORN plots. The energy input was slightly less on the CORN plot. Downward temperature gradients were about the same but the upward temperature gradient was higher on the NO COVER plot, resulting in a slightly lower thermal conductivity than was shown for the CORN plot.

The influence of subsurface irrigation on heat loss rates is shown in Table 30. The energy input was much higher on the SUB-IRR plot on the two dates shown than on the CORN and NO COVER plots for days in 1971 with similar meteorological conditions. Heat flow in the upward direction was higher with the result that calculated thermal conductivities were also higher. This is consistent with the high soil water content shown for the SUB-IRR plot in 1972 (Section 5).

The energy balance analysis shows that changes in heat storage account for a large portion of the total energy input at certain times of the year. The downward heat flow is important during the summer and may account for as much as 50 percent of the total energy input. This component contributed little to the total energy flow during the winter. The upward heat flux component accounts for most of the energy dissipation during the winter but less than half of the total during the summer.

Thermal conductivities at the upper boundary were low during summer months and high during winter months. This is consistent with changes in soil water content during the year.

6.3 Energy Dissipation and Air Temperatures

6.3.1 Results

The NO COVER plot heat source was energized nearly continuously from April, 1970, through August, 1972. During this time no extended shutdowns occurred and only minor changes were made in the thermostat setting. Average monthly energy dissipation rates were calculated and are shown in Table 31. Mean monthly air temperatures and monthly precipitation measured at the U.S. Weather Bureau Station located .4 kilometers from the experimental site are presented (U.S. Dept. of Commerce, 1970, 1971, 1972). Average monthly heat source temperatures are also shown. The values enclosed in parentheses were obtained by extrapolation for periods when soil temperatures were not measured.

The data in Table 31 were analyzed with a stepwise multiple regression program. The energy dissipation rate (R) was used as the dependent variable. Independent variables used included heat source temperature (T_s), mean monthly air temperature (T_a), total monthly precipitation (P), temperature difference (T_s-T_a), ln (T_a), $\sqrt{T_a}$, and P^2. The results of the regression analyses are summarized in Table 32. The addition of dependent variables to the three models shown did not significantly improve the ability of the models to describe the data.

6.3.2 Discussion

The square of the correlation coefficients shown in Table 32 represents the percent of variation in energy dissipation rates attributable to variation in the dependent variables of the model. Models (II) and (III) give about the same degree of fit and explain more of the variation than model (I). However, model (I) has a better physical basis. It is analogous to Equation 1, Section 1.4, assuming that the soil surface temperature closely follows the air temperature. The regression equation for model (I) is shown in Figure 20. Equation 1 for the conditions of Case IV (Section 14.) corresponding to the design of the heat source system used on the NO COVER plot is also shown. A constant thermal conductivity of k = .16 cal/cm min C was assumed.

One obvious difference between model (I) and Equation 1 is that Equation 1 predicts zero energy dissipation at $\Delta T = 0$ while model (I) predicts that a small heat loss occurs. Departures from the theoretical model can be attributed to two factors. The model assumes steady state conditions which were not achieved in the experiments. Changes in heat storage occurred and, more importantly, the downward heat flow changed during the year. It was high during the summer and low during the winter. This annual cycle exists and must be accounted for in Equation 1.

Table 31. Energy dissipation rates, heat source temperatures, mean air temperatures, and total precipitation for monthly periods from April, 1970, through August, 1972 (NO COVER plot).

Year month	Energy dissipation rate	Heat source temp.	Mean monthly air temp.	Total monthly precip.
	$cal/cm^2 min$	C	C	cm
1970				
April	.0194	23	7.8	6.8
May	.0147	25	12.4	2.8
June	.0128	26	17.7	1.4
July	.0150	32	19.0	0.3
August	.0133	(31)	18.6	0
September	.0139	30	14.8	2.7
October	.0152	29	10.7	10.2
November	.0212	31	6.9	18.5
December	.0256	31	4.2	31.6
1971				
January	.0303	32	4.1	27.2
February	.0267	33	5.0	13.6
March	.0262	33	5.8	15.7
April	.0225	33	8.8	11.1
May	.0192	33	12.7	5.9
June	.0186	35	13.9	6.3
July	.0165	35	18.8	0.1
August	.0145	35	19.7	1.2
September	.0161	35	13.9	7.9
October	.0177	(36)	10.3	7.1
December	.0251	(37)	3.9	25.7
1972				
January	.0294	38	3.6	25.7
February	.0279	36	6.1	13.0
March	.0258	36	9.4	16.4
April	.0229	36	7.9	10.8
May	.0221	(36)	13.7	6.0
June	.0121	37	16.4	2.6
July	.0133	37	20.5	0.2
August	.0108	37	23.2	0.6

Table 32. Regression models obtained from data in Table 31 and correlation coefficients, r.

Regression model	r
(I): $R = .00375 + .00742(T_s - T_a)$	.873
(II): $R = .0316 + .00281(T_s - 3.26 \ln T_a)$	.921
(III): $R = .0282 + .000323(T_s - 18.33 \sqrt{T_a})$	.926

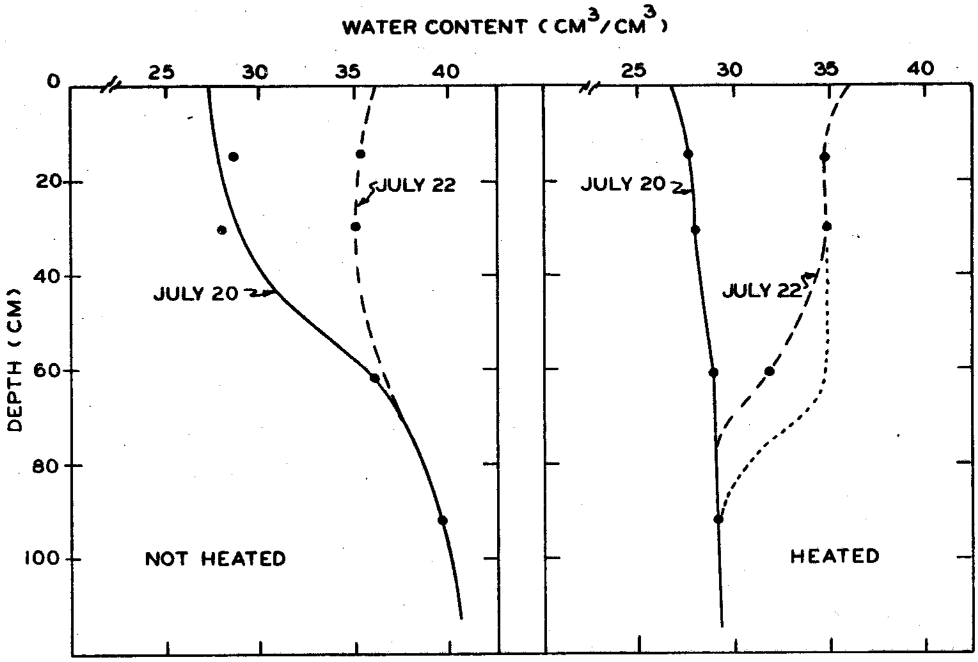

Figure 19. Soil water content before (July 20) and after (July 22) an application of 4.5 cm of irrigation water on unheated and heated CORN plots.

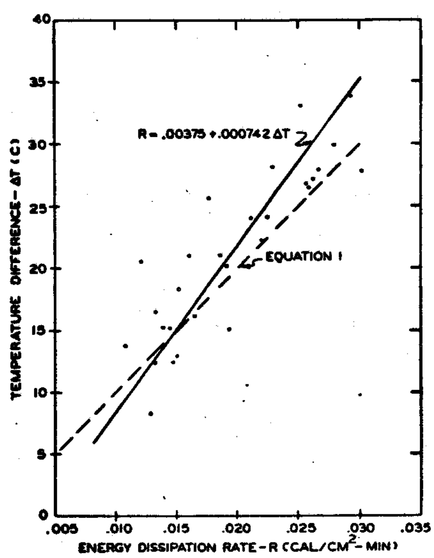

Figure 20. Mean monthly energy dissipation rates as a function of the difference between mean monthly heat source temperature and mean monthly air temperatures measured at the U.S. Weather Bureau Station.

6.4 Energy Dissipation and Soil Surface Temperatures

6.4.1 Results

The correlation between soil surface temperatures and rate of heat loss was investigated for several time periods on five of the six heat plots. The periods of one to three days were chosen to cover a range of climatic conditions during 1971 and 1972. The heat source energy input was obtained from kilowatt-hour meter readings taken at the beginning and at the end of the time periods considered (Table 33). Soil surface temperatures were measured directly above the heat source at a depth of 2.5 cm. Surface temperatures and heat source temperatures shown in Table 33 are the average of hourly measurements for the time period considered.

6.4.1.1 NO COVER Plot. Source temperatures remained within a narrow range of 32.8 to 37.5 C on the NO COVER plot while soil surface temperatures at 2.5 cm depth varied from 6.2 to 29.7 C. Heat loss rates varied three-fold over the time periods studied. Since this heat source was energized continuously over the two-year period no sudden changes in heat storage occurred. The ratio of rate of heat loss to temperature difference ranged from about .00080 in September to .00120 in June. The linear regression between rate of heat loss (R) and the difference between the heat source temperatures (T_s) and the soil surface temperature (T_{su}) was:

$$R = .00181 + .000914(T_s - T_{su}) \qquad [\text{with} \quad r = .88]$$

indicating that the rate of heat loss is closely correlated with the temperature difference between the heat source and the soil surface. This model is very similar to that obtained for the correlation between rate of heat loss and temperature difference between heat source and air temperature. Calculation of the linear correlation between heat loss rate and the temperature difference with September observations omitted resulted in $r = .95$, a substantial improvement.

6.4.1.2 CORN Plot. The CORN plot heat source was energized only during the growing season. Sufficient time was allowed for equilibrium conditions to be achieved. Therefore, time periods prior to July were not analyzed. Average source temperature for the periods of measurement ranged from 30.5 to 35.1 C. The range of dissipation rates and temperature differences was narrower than observed on the NO COVER plot since observations were limited to summer months. Linear regression between heat loss rate and the temperature difference is given by:

$$R = .00430 + .000547(T_s - T_{su}) \qquad [\text{with} \quad r = .89]$$

Table 33. Rate of heat loss, soil temperature at 2.5 cm and at the heat source, temperature difference, and ratio of heat loss to temperature difference.

Time period	Rate of heat loss R	Ave. temp. at 2.5 cm	Ave. temp. of source	Temp. difference	Ratio $R/\Delta T \times 10^{-3}$
	cal/cm^2 min	C	C	C	cal/cm^2 min C
NO COVER:					
1971:					
2/3-2/5	.0278	6.2	34.9	28.7	.97
2/22-2/24	.0252	6.6	33.3	26.7	.94
3/19-3/22	.0255	8.4	32.9	24.5	1.04
4/12-4/14	.0232	11.8	32.8	21.0	1.10
4/22-4/23	.0218	9.7	33.0	23.3	.94
4/28-4/29	.0211	13.4	32.9	19.5	1.08
5.10-5/11	.0185	18.2	33.5	15.3	1.21
6/21-6/23	.0178	21.6	35.1	13.5	1.32
7/8-7/9	.0172	18.0	35.2	17.2	1.00
7/29-7/30	.0146	22.1	36.0	13.9	1.05
8/23-8/25	.0149	18.7	35.1	16.4	.91
9/1-9/2	.0157	14.2	34.8	20.6	.76
9/13-9/15	.0161	16.1	34.6	18.5	.87
9/22-9/24	.0157	15.4	34.4	19.0	.83
1972:					
2/14-2/17	.0302	9.3	35.4	26.1	1.16
3/8-3/10	.0257	11.1	35.9	24.8	1.04
6/17-6/19	.0160	22.0	36.5	14.5	1.10
6/26-6/28	.0151	23.9	36.6	12.7	1.19
7/10-7/12	.0133	24.1	37.2	13.1	1.02
7/26-7/28	.0111	28.3	37.6	9.3	1.19
8/9-8/11	.0105	29.7	37.6	7.9	1.33
8/29-8/30	.0106	25.8	36.6	10.8	.98
9/5-9/6	.0111	18.6	36.1	17.5	.63
CORN:					
1971:					
7/8-7/9	.0113	19.5	32.2	12.7	.89
8/23-8/25	.0136	16.9	33.4	16.5	.82
9/1-9/2	.0139	15.4	32.7	17.3	.80
9/13-9/15	.0155	15.6	35.1	19.5	.79
1972:					
7/10-7/12	.0124	20.0	33.4	13.4	.93
7/26-7/28	.0120	19.0	32.3	13.3	.90
8/9-8/11	.0106	19.7	31.1	11.4	.93
8/29-8/30	.0108	17.6	30.5	12.9	.84
9/5-9/6	.0115	16.3	32.5	16.2	.72

Table 33. Continued.

Time period	Rate of heat loss R	Ave. temp. at 2.5 cm	Ave. temp. of source	Temp. difference	Ratio $R/\Delta T \times 10^{-3}$
	cal/cm^2 min	C	C	C	cal/cm^2 min C
SUB-IRR:					
1971:					
7/8-7/9	.0264	19.3	31.2	11.9	2.22
7/29-7/30	.0229	23.5	32.6	9.1	2.53
8/23-8/25	.0215	22.2	32.7	10.5	2.05
9/1-9/2	.0218	15.4	32.0	16.6	1.38
9/13-9/15	.0224	17.8	31.4	13.6	1.65
1972:					
7/10-7/12	.0242	21.4	32.7	11.3	2.14
7/26-7/28	.0228	22.1	32.4	10.3	2.22
8/9-8/11	.0224	21.9	32.1	10.2	2.20
8/29-8/30	.0225	21.0	29.9	8.9	2.53
9/5-9/6	.0218	19.0	32.2	13.2	1.65
GRASS:					
1971:					
2/22-2/24	.0199	7.3	24.4	17.1	1.16
3/19-3/22	.0183	8.6	25.0	16.4	1.12
4/12-4/14	.0158	11.4	24.4	13.0	1.22
4/22-4/23	.0141	9.4	23.9	14.5	.97
4/28-4/29	.0128	12.9	24.7	11.8	1.08
5/10-5/11	.0102	16.3	24.0	7.7	1.32
6/21-6/23	.0222	22.2	36.4	14.2	1.56
7/8-7/9	.0147	20.8	33.8	13.0	1.13
7/29-7/30	.0182	22.3	36.3	14.0	1.30
8/23-8/25	.0131	18.5	32.5	14.0	.94
9/1-9/2	.0136	16.1	31.9	15.8	.85
9/13-9/15	.0231	15.5	37.5	22.0	1.05
1972:					
7/10-7/12	.0103	23.2	34.4	11.2	.92
7/26-7/28	.0116	21.8	35.4	13.6	.85
8/9-8/11	.0121	20.6	36.1	15.5	.78
8/29-8/30	.0111	22.0	32.7	10.7	1.04
9/5-9/6	.0137	17.9	33.6	15.7	.87
GREENHOUSE:					
1972:					
2/14-2/17	.0421	14.8	35.5	20.7	2.03
3/8-3/10	.0340	17.9	36.4	18.5	1.84
6/17-6/19	.0210	25.4	33.4	8.0	2.62
6/26-6/28	.0206	23.1	32.7	9.6	2.15

<u>6.4.1.3 SUB-IRR Plot</u>. The data for the SUB-IRR plot (Table 33) indicate that subsurface irrigation increased the rate of heat loss compared with CORN and NO COVER plots. The temperature differences between heat source and soil surface temperature were smaller. The range in heat loss rates on the SUB-IRR plot was too small to allow a correlation between heat loss rate and temperature difference. The ratio of heat loss rate to temperature difference is higher than observed on the CORN and NO COVER plots. This can be attributed to higher thermal conductivity resulting from higher soil water content in the vicinity of the heat source (Section 5).

<u>6.4.1.4 GRASS Plot</u>. Heat source temperatures varied from 23.9 to 37.5 C on this plot for the time periods analyzed over the two-year period. The ratios of heat loss rates to temperature differences were similar to those observed on the NO COVER plot. The high ratios during the period June 21 to June 23, 1971 were due to a rising heat source temperature which resulted in a large change in heat storage. The linear regression between rates of heat loss and temperature differences for the GRASS plot was:

$$R = .00191 + .000926(T_s - T_{su}) \qquad [\text{with} \quad r = .72]$$

<u>6.4.1.5 GREENHOUSE Plot</u>. Soil temperatures were monitored in the GREENHOUSE during the first six months of 1972. A wide range in temperature differences and rates of heat loss was observed during this period (Table 33). The linear regression between rates of heat loss and temperature differences was:

$$R = .00643 + .00162(T_s - T_{su}) \qquad [\text{with} \quad r = .98]$$

It is evident that this plot exhibited a different response in heat loss for a given temperature difference than was found for the other plots.

<u>6.4.2 Discussion</u>

The rate of heat loss, R should be proportional to the temperature difference, ΔT, for heat transfer in an isotropic medium under steady state conditions (Kendrick and Havens, 1973). The relationship between the two parameters should be:

$$R = a + b\Delta T$$

where $a = 0$. The value of b can be calculated from Equation 1 for different designs of the soil heating system. For the NO COVER and CORN plots, $b = .00495k$, where k is the thermal conductivity in cal/cm min C. For the GRASS plot, $b = .00842k$ and for the GREENHOUSE plot, $b = .00913k$. The average thermal conductivity for the included time periods can be calculated for each plot using regression coefficients calculated above. The results are: k = .185, .111, .110, and .177 cal/cm min C for NO COVER, CORN, GRASS, and GREENHOUSE plots, respectively.

Close agreement between k values for the NO COVER and GREENHOUSE plots indicates that the difference in heat loss rates between these two plots was the result of different system designs. The low thermal conductivity obtained for the CORN plot is in agreement with results shown in Section 6.2.2. Thermal conductivity was low due to the low water content maintained on this plot. The reasons for the low thermal conductivity on the GRASS plot are not certain. The time periods included from 1972 were during the summer. At this time low soil water contents similar to those on the CORN plot may have existed. The sudangrass crop growing on this plot has high water requirements. Soil water content determinations were not made on the GRASS plot. During the winter of 1971 the soil water content should have been high due to frequent rainstorms. However, energy dissipation rates observed during winter were not correspondingly higher as evidenced by low ratios of heat loss rate to temperature differences (Table 33).

Thermal conductivities were also calculated for each time period included in Table 33 for NO COVER, CORN, GRASS, and GREENHOUSE plots using values of R and $(T_s - T_{su})$ shown in Table 33 and the intercept (a) from the appropriate linear regression model. The regression equation for the NO COVER plot:

$$R = .00181 + .00914(T_s - T_{su})$$

or

$$R = .00181 + .00495k(T_s - T_{su})$$

can be rearranged to:

$$k = \frac{R - .00181}{.00495(T_s - T_{su})}$$

where R is the rate of heat loss, $(T_s - T_{su})$ is the corresponding temperature difference between the heat source and the soil surface, and k is the thermal conductivity for a given period of measurement. Results shown in Table 34 indicate that the thermal conductivities calculated in this manner did not vary much during the year. The lowest values were found during August and September. These values are higher than those shown in Table 30. Results shown in Table 34 were obtained by a procedure which assumes that no change in heat storage occurred. It was shown in Section 6.2 that heat content of the plots increased from March until August and decreased from September until early in the spring. This means that not all of the measured energy loss contributed to heat flow in the summer so that the calculated thermal conductivities should be lower for that time period.

Table 34. Thermal conductivities calculated from regression equations.

Time period	NO COVER	CORN	GRASS	GREENHOUSE
	------------- cal/cm min C ---------------			
1971:				
2/3-2/5	.183	--	--	--
2/22-2/24	.177	--	.125	--
3/19-3/22	.195	--	.119	--
4/12-4/14	.206	--	.127	--
4/22-4/23	.173	--	.100	--
4/28-4/29	.200	--	.110	--
5/10-5/11	.220	--	.128	--
6/21-6/23	.239	--	.170	--
7/8-7/9	.181	.111	.117	--
7/29-7/30	.186	--	.138	--
8/23-8/25	.161	.114	.095	--
9/1-9/2	.136	.112	.088	--
9/13-9/15	.156	.116	.114	--
9/22-9/24	.148	--	--	--
1972:				
2/14-2/17	.220	--	--	.189
3/8-3/10	.195	--	--	.163
6/17-6/19	.198	--	--	.199
6/26-6/28	.211	--	--	.162
7/10-7/12	.177	.121	.089	--
7/26-7/28	.202	.117	.085	--
8/9-8/11	.222	.112	.078	--
8/29-8/30	.164	.102	.102	--
9/5-9/6	.107	.090	.089	--

6.5 Land Area Requirements for Energy Dissipation

The land area required to dissipate the waste heat from a 1,000 megawatt power generating station can be calculated from data presented in Table 33. Data obtained for the NO COVER plot will be used. A 1,000 megawatt generating station operating at an efficiency of 34 percent rejects heat at a rate of 1,941 megawatt or 2.77×10^{10} cal/min. During January the rate of heat dissipation on the NO COVER plot was approximately 3×10^{-2} calcm^{2}min, or 3×10^6 cal/ha min. Hence the area required to dissipate 2.77×10^{10} cal/min is 9,230 ha. The measured rate of heat dissipation was obtained with a heat source which had a diameter of 0.5 cm. Equation 1 shows that the rate of energy dissipation increases as the heat source diameter increases. A warm water pipe system would have a diameter of 5.0 cm. Making adjustment for the increase in source diameter from 0.5 to 5.0 cm results in an area requirements of 6,230 ha. During August the average rate of heat dissipation was approximately 2.3×10^{-2} calcm^{2}min, corresponding to an area requirement of about 14,400 ha.

These results are based on a constant heat source temperature of 35 C. The source temperature of a warm water pipe network would decrease along the pipe and the rate of heat loss would be lower at the end of the pipe. Thus the area required to dissipate the waste heat would increase. If a final water temperature of 25 C is to be achieved, the required area would increase by about 50 percent.

Kendrick and Havens (1973) calculated an area requirement of about 7,000 hectares for a system of a 5 cm diameter pipe network with 61 cm depth and 91 cm spacing. They assumed an initial source temperature of 37 C and a final source temperature of 27 C with a surface temperature of 18 C. To adjust Kendrick and Havens' (1973) data to a depth and spacing comparable to those of the NO COVER plot would require an increase in area requirement of approximately 50 percent for spacing and 45 percent for depth. These adjustments must be compounded and the combined adjustment results in an increase of approximately 122 percent giving a final area requirement of about 15,000 ha.

The average source to surface temperature difference for Kendrick and Havens' (1973) calculations was 15 C. Data in Table 33 indicate that on the NO COVER plot during August the difference was about 10 C. A 50 percent increase in dissipation rates should result if the temperature difference was increased to 15 C on the NO COVER plot. However, a 50 percent decrease in rates can be expected as a result of the adjustment for decreasing source temperature along the pipe length, as discussed above. Hence this adjustment of NO COVER plot data for changing temperature of the heat source is offset by the difference in temperature gradients so that good agreement is observed between the experiment results and Kendrick and Havens' (1973) theoretical predictions.

The results indicate that experimental data and predictions from theoretical models are in close agreement. A warm water pipe network with depth and spacing similar to the NO COVER plot and a pipe diameter of 5 cm could dissipate enough heat to reduce water temperatures about 10 C within an area of 10,000 to 20,000 hectares, depending on the time of year being considered. This requirement could be significantly reduced by increasing pipe density, reducing pipe depth, or increasing the soil water content. Separate studies have shown that the thermal conductivity can be increased three-fold with a properly designed subsurface irrigation system.

6.6 Summary and Conclusions

For a continuously energized heat source the seasonal variation in energy dissipation rates was found to be a three-fold increase from a minimum in late summer to a maximum in the winter, coincident with low air temperatures and high soil water content. A decrease in heat source depth and an increase in source density was found to increase dissipation rates as predicted by the theoretical models. Subsurface irrigation was successful in maintaining high soil water content during periods of high evapotranspiration losses, and therefore maintaining high heat transfer rates.

An energy budget analysis was performed for several dates and three different plots. The results show that the soil and water mass can absorb large heat inputs by very small increases in temperature. During the winter the majority of heat flow out of the soil was in an upward direction. During the summer a large fraction of the energy input was dissipated as heat flow to lower regions in the soil profile. A gradual temperature increase during spring and summer and decrease during fall and winter results from seasonal climatic cycles. Therefore, the assumption of steady state conditions made in the development of theoretical models to predict energy dissipation rates is invalid.

Experimentally determined rates of energy dissipation were quite close to predictions based on theoretical considerations presented by Kendrick and Havens (1973) and Schmill (1967). Although simplifying assumptions make it impossible to partition the various heat transfer components active in the soil medium, gross heat loss predictions based on these models were found to be accurate within reasonable limits in most cases.

Mean monthly air temperatures were found to be highly correlated with mean monthly energy dissipation rates for a continuously energized heat source. This suggests that prediction of energy dissipation rates from readily available climatological data is possible.

7. GREENHOUSE HEATING WITH UNDERGROUND HEAT SOURCES

7.1 Experimental Procedure

Warming of greenhouse soil with buried pipes through which warm water is circulated has been practiced for several years in the Netherlands. The air temperature in most of these houses is controlled with steam heat. The network of buried pipes is used for additional heating of the soil, not for controlling the air temperature. It is also used for sterilization of the soil. For this application steam is circulated through the pipes after the soil has been covered with a tarp. This provides the high soil temperatures needed for complete sterilization of the beds.

A plastic covered greenhouse was constructed over a set of heating cables used in the Pacific Power and Light supported soil warming research project. The purpose of the experiment was to obtain experimental data for later verification of a theoretical analysis of the energy balance of greenhouses.

The greenhouse consisted of a wood frame covered with 4 mil clear plastic. The span of the individual rafters was 6.7 meters. They were placed at one meter intervals. The house was 30 meters long. Fans were used to maintain adequate circulation of the inside air. Temperature measurements were made at 15 positions inside the structure. Sensors were placed in three rows of five sensors each spaced at six-meter intervals. One row was positioned 30 cm below the peak along the center of the structure. Two rows, one on each side of the structure, were positioned along the side walls at a height of 1.5 meters above ground and 30 cm from the wall. Measurements were made at hourly intervals.

Temperature measurements obtained at the 15 positions showed that no temperature stratifications existed. The average of the 15 measurements was therefore used in the analysis of the results. Comparisons between inside and outside soil and air temperatures are provided by the tabulation of measurements made on several days during the winter and spring of 1972 (Table 35).

7.2 Daily Temperature Comparisons

7.2.1 January 24, 1972

The heat source was energized shortly after 10:00 a.m. on January 24. This can be seen by the rapid increase of the heat source temperature. The thermostatic control was set to maintain a heat

Table 35. Soil and air temperatures measured inside and outside the greenhouse.

Date and time	Air temperatures			Soil temperatures			
	Out	In		Depth: 2.5 cm		Depth: 51 cm	
		Single	Double	Out	In	Cable	Midpoint
	C	C	C	C	C	C	C
January 24:							
1800	5.5	4.8	--	4.7	7.2	10.3	10.2
2000	3.8	4.0	--	4.6	6.6	10.3	10.2
2200	4.1	3.5	--	4.2	6.3	10.2	10.3
0000	4.8	4.1	--	4.5	6.3	10.3	10.1
0200	4.1	3.8	--	4.3	6.0	10.2	10.0
0400	3.6	3.3	--	4.1	5.9	10.2	10.0
0600	2.5	2.1	--	3.4	5.2	10.2	10.0
0800	1.1	1.5	--	3.0	4.8	10.2	9.9
1000	2.7	5.4	--	4.3	6.4	10.2	--
1200	2.9	10.5	--	4.2	9.5	26.9	9.8
1400	3.7	12.0	--	4.9	12.2	30.8	9.8
1600	2.8	8.8	--	4.4	11.2	32.7	9.7
1800	0.4	1.3	--	2.4	8.3	32.1	--
2000	-1.0	-0.8	--	1.6	6.0	32.5	9.7
2200	0.1	-0.1	--	1.3	4.8	29.8	--
2400	-0.6	-0.1	--	1.2	3.7	29.5	--
February 19:							
0000	6.7	7.2	--	6.8	13.5	35.0	18.5
0200	6.6	7.4	--	6.9	12.9	35.8	18.6
0400	7.0	7.8	--	7.1	12.8	35.4	18.7
0600	7.2	7.8	--	7.1	12.5	35.6	18.7
0800	7.9	8.7	--	7.6	12.5	36.9	18.7
1000	10.3	15.4	--	9.6	15.0	34.9	18.6
1200	11.5	18.3	--	11.7	18.4	34.9	18.6
1400	12.5	15.5	--	11.2	18.3	37.7	18.6
1600	12.0	15.5	--	10.8	19.1	37.1	18.6
1800	8.3	10.4	--	7.9	16.6	34.9	18.7
2000	7.6	9.2	--	7.6	15.2	36.0	18.7
2200	6.2	7.3	--	7.2	14.3	37.1	18.7
2400	5.5	6.7	--	6.5	13.4	36.3	18.8
February 21:							
0000	1.5	2.9	--	3.9	12.4	35.9	18.9
0200	1.2	2.5	--	3.5	11.3	37.8	19.0
0400	0.9	2.0	--	3.2	10.5	38.5	19.0
0600	1.5	3.3	--	3.9	10.2	37.3	19.0
0800	3.3	5.5	--	5.1	10.5	37.0	19.0
1000	5.3	11.4	--	7.6	13.2	36.7	19.0
1200	7.9	17.6	--	9.5	15.2	37.7	19.0

Table 35. Continued.

Date and time	Air temperatures			Soil temperatures			
	Out	In		Depth: 2.5 cm		Depth: 51 cm	
		Single	Double	Out	In	Cable	Midpoint
	C	C	C	C	C	C	C
February 21; continued							
1400	12.3	22.5	--	10.1	20.7	35.0	18.9
1600	12.3	20.4	--	10.8	21.1	36.8	18.9
1800	9.1	12.3	--	8.3	18.3	36.8	18.8
2000	7.7	10.1	--	7.7	16.2	36.3	18.9
2200	7.4	9.0	--	7.5	15.1	35.4	19.0
2400	6.4	7.8	--	6.9	14.1	35.8	19.0
March 8:							
0000	2.0	4.6	6.6	4.5	14.6	37.0	20.5
0200	1.6	2.8	5.0	3.8	13.0	37.3	20.5
0400	0.3	2.0	4.1	3.2	11.9	37.6	20.6
0600	0.2	1.4	3.5	2.7	11.0	36.6	20.6
0800	2.7	9.0	11.7	4.2	11.5	35.2	20.6
1000	8.3	23.5	27.0	8.4	16.2	36.7	20.6
1200	12.5	32.1	36.8	11.1	22.2	37.3	20.6
1400	16.3	36.4	41.0	12.2	26.4	38.4	20.6
1600	15.7	28.6	32.1	12.2	26.9	35.3	20.6
1800	12.7	18.1	20.7	10.7	23.8	35.0	20.6
2000	11.4	13.3	15.4	9.2	20.7	34.9	20.6
2200	9.8	11.2	13.0	8.3	18.7	37.7	20.6
2400	8.2	9.1	11.0	7.5	17.2	35.3	20.6
March 10:							
0000	8.2	9.1	11.0	7.5	17.2	35.3	20.6
0200	8.7	9.8	11.4	7.8	16.2	35.0	20.6
0400	8.1	9.1	10.6	7.4	15.6	37.9	20.6
0600	7.6	8.8	10.3	7.4	15.0	37.8	20.6
0800	9.4	11.5	12.7	8.7	15.2	37.4	20.6
1000	10.2	14.5	15.9	10.0	16.7	36.6	20.7
1200	11.4	18.0	19.4	11.8	18.4	37.6	20.7
1400	11.7	17.1	18.5	11.6	19.2	35.1	20.7
1600	11.7	15.5	17.0	11.2	19.2	36.7	20.7
1800	11.7	13.4	14.8	10.6	18.3	38.0	20.7
2000	11.6	12.5	13.5	10.1	17.2	37.2	20.7
2200	11.9	11.3	12.3	9.5	16.6	34.8	20.7
2400	11.9	11.5	12.4	9.7	16.1	37.1	20.7

Table 35. Continued.

Date and time	Air temperatures			Soil temperatures			
	Out	In		Depth: 2.5 cm		Depth: 51 cm	
		Single	Double	Out	In	Cable	Midpoint
	C	C	C	C	C	C	C
April 16:							
0000	4.9	7.8	--	7.9	16.8	36.7	23.4
0200	3.2	4.4	--	6.3	15.2	39.3	23.4
0400	3.2	4.5	--	6.1	14.3	38.6	23.4
0600	2.6	3.9	--	5.9	13.4	36.6	23.4
0800	4.5	11.9	--	7.9	16.1	39.4	23.4
1000	6.4	24.0	--	12.1	22.6	36.1	23.4
1200	5.8	22.2	--	11.6	28.0	36.2	23.2
1400	6.5	24.5	--	12.7	28.4	36.3	23.2
1600	7.5	27.3	--	12.7	31.7	38.0	23.0
1800	5.2	18.3	--	10.4	27.3	39.5	23.0
2000	3.1	7.8	--	7.6	22.0	37.9	23.0
2200	2.7	6.6	--	7.9	19.2	39.4	23.0
2400	2.4	4.3	--	6.0	17.0	36.7	23.0
June 8:							
0000	14.4	15.5	--	16.8	22.6	36.1	25.5
0200	12.5	13.9	--	15.8	21.4	36.0	25.6
0400	12.4	12.9	--	15.0	20.3	35.4	25.6
0600	13.6	16.6	--	15.8	20.1	35.7	25.6
0800	19.0	25.1	--	19.7	22.1	34.3	25.6
1000	22.2	32.1	--	24.6	25.0	33.4	25.5
1200	23.7	36.7	--	27.4	28.8	34.3	25.5
1400	21.7	33.4	--	27.6	30.0	32.8	25.4
1600	21.7	32.7	--	25.1	31.0	32.6	25.4
1800	19.6	26.4	--	21.9	29.6	33.5	25.4
2000	14.7	16.6	--	18.9	27.6	35.9	25.6
2200	13.0	16.6	--	17.5	24.3	34.6	25.7
2400	12.5	15.0	--	16.5	23.2	35.6	25.8

source temperature of 30 C. This setting was later changed to 35 C. On this day the inside and outside air temperatures were nearly the same. Only during the day when heating of the greenhouse resulted from incoming radiation did the inside air temperature rise above the outside air temperature. The soil temperature near the surface was from two to three degrees higher inside the greenhouse throughout the day. The soil temperature at a depth of 5 cm was the same inside and outside the greenhouse.

The measurements emphasize the rapid rate at which heat is lost from a structure of this kind. At 1600 hours the inside temperature was 8.8 C and the outside temperature was 2.8 C. The greenhouse was about 6 C warmer than the outside air, yet at 1800 hours the difference in air temperatures was less than 1 C. The heat stored as a result of the sun's radiation was rapidly lost after the sun set. The soil surface temperature in the greenhouse increased as the air temperature increased. The difference between air temperature and soil temperature at 2.5 cm below the surface remained the same throughout the day.

7.2.2 February 19, 1972

The soil temperatures had reached an equilibrium condition at this time. Little influence was being exerted on the air temperature inside the greenhouse by the energy released from the underground heat sources. The increase in air temperature as a result of soil warming was less than one degree during the night. During the day the air temperature in the greenhouse was higher than the outside air temperature as a result of solar radiation. The increase as a result of solar radiation was small on this day and limited to the 1200-1600 hour period. The major contribution from soil warming was a small increase in the soil surface temperature inside the greenhouse. The soil temperature at a depth of 2.5 cm was about 3 C higher than it would have been without soil warming during the night. This observation is based on a comparison of soil temperatures at 2.5 cm measured on January 24 and February 19.

7.2.3 February 21, 1972

The inside air temperature remained about 1.5 C above the outside air temperature during the night indicating a small effect of soil warming. During the day considerable heating from solar radiation occurred leading to a maximum difference between the inside and outside air temperature of at least 10 C. The greatest contribution from the soil warming system was the much higher soil temperature even at the soil surface. During the night the surface temperature of the soil remained about 7 C above the outside soil surface temperature. The difference increased during the day when the air temperature in the greenhouse increased as a result of incoming radiation. On this day the outside air temperatures and outside soil surface temperature were nearly the same at all hours.

7.2.4 March 8, 1972

A second layer of plastic was added over part of the house in such a way that an air space of several cm existed between the two layers of plastic. This was done to provide for a lower rate of heat exchange between the inside air and outside air. It was hoped that better advantage might be taken of the energy provided by the heating cables. Only part of the greenhouse was covered in this manner to provide a comparison between the single and double layer of plastic. Measurements showed the air temperature inside the section covered by the double layer of plastic to be about 2 C higher than the part covered with a single layer of plastic and about 3 C higher than the outside air temperature. The influence of the double layer of plastic was greatest during the day. The highest air temperature recorded inside the greenhouse occurred at 1400 hours. The soil temperatures were obtained in the part of the greenhouse covered with a single layer of plastic.

The course of the soil surface temperature inside the greenhouse should be considered carefully. The soil temperature midway between the heat sources at a depth of 51 cm was 20.6 C throughout the day. The soil surface temperature during the period of about 0800 hours to 2200 hours was higher than the soil temperature at a depth of 51 cm midway between the heat sources, indicating that the energy flow was directed downward over part of the profile during this period. At the higher air temperatures, e.g., 18 C or above, the surface temperature of the soil in the heated greenhouse will also be close to 18 C or possibly higher. Under these conditions, little energy flow to the soil surface can occur. It appears that soil warming can only be an effective method of heating greenhouses if the air temperature in the greenhouse is very low or if the heat source temperature is quite high.

7.2.5 March 10, 1972

This was a cold day with little solar heating and low air temperatures. The double layer of plastic still gave some advantage but seemingly hardly sufficient to justify the cost of adding it. The surface temperature of the soil in the greenhouse remained high throughout this period indicating very small temperature gradients toward the soil surface so that only a small energy flow was available for warming the air.

7.2.6 April 16 and June 8, 1972

Measurements made during these two days show the gradual increase in day length. The effect of solar heating occurred much earlier in the day and lasted longer. As a result of the generally higher air temperatures, cable temperature and soil temperature increased as well.

7.3 Equilibration of the Soil Temperature

Changes in the soil temperature midway between adjacent heat source loops at the heating cable depth provided an opportunity to evaluate the rate of temperature equilibration of the soil after energizing the heat sources. Table 36 shows the temperature at this position during the month of February and early March. It appears that 19 C represents the equilibrium temperature. It was first reached on day number 53 or 28 days after energizing the heat sources. It emphasized the relative inertia of the soil. The soil profile inside the greenhouse was extremely dry. More rapid equilibration would have been attained in a wetter soil. The thermal inertia of the soil makes it difficult to use this system for regulating air temperatures over the period of one day.

7.4 Theoretical Considerations

The rate of heat exchange between the greenhouse space and the outside air for steady state conditions is given by

$$QA_s = UA_r(T_i - T_o) \tag{2}$$

where

T_i = inside air temperature (C)

T_o = outside air temperature (C)

Q = rate of heat discharge from the soil warming system (cal/min cm^2)

A_s = heated soil surface area (cm^2)

U = rate of heat loss through the greenhouse wall (cal/cm^2min)

A_r = surface area of greenhouse exposed to the outside air.

For the experimental greenhouse $A_r/A_s = 1.75$ so that

$$T_i = T_o + \frac{Q}{1.75U} \tag{3}$$

The value of U is generally assumed to be 1.5 BTU/hr ft^2F (or 0.012 cal/cm^2min C) for a single layer of plastic and 1.1 BTU/hr ft^2F (or 0.009 cal/cm^2min C) for a double layer of plastic. The increase in air temperature achieved for four rates of heat discharge from the soil surface is shown in Table 37. These results were obtained with equation (3). Table 38 shows measurements made in the experimental greenhouse. The measured rate of heat discharge was 0.025 cal/cm^2min. The temperature differences predicted by equation (3) would be 1.20 C. The observed differences were in good agreement with this prediction. The difference between outside and inside air temperature was from two to three times greater when a double sheet of plastic was used. This is larger than the increase resulting from the use of a double sheet of plastic predicted by equation (3). The air space between the two layers of plastic used in the experimental greenhouse was much wider than the air space assumed in the development of Table 38. The greater difference is therefore in agreement with predicted results.

Table 36. Soil temperature midway between two heating cables at the heating cable depth. The heating cable was energized on January 24.

Day no.	Date		Soil temp	Day no.	Date		Soil temp
			C				C
20	January	20	--	46	February	15	17.1
21		21	--	47		16	17.6
22		22	--	48		17	17.9
23		23	--	49		18	18.4
24		24	--	50		19	18.6
25		25	--	51		20	18.8
26		26	9.8	52		21	18.9
27		27	9.8	53		22	19.0
28		28	11.3	54		23	19.0
29		29	--	55		24	18.9
30		30	--	56		25	18.8
31		31	11.3	57		26	19.0
32	February	1	--	58		27	19.2
33		2	--	59		28	19.4
34		3	12.2	60		29	19.8
35		4	12.5	61	March	1	19.9
36		5	12.9	62		2	19.5
37		6	13.1	63		3	19.4
38		7	13.6	64		4	19.3
39		8	14.3	65		5	19.3
40		9	14.9	66		6	19.8
41		10	15.7	67		7	20.5
42		11	15.9	68		8	20.5
43		12	--	69		9	20.7
44		13	16.7	70		10	20.9
45		14	17.1				

Table 37. Values of the temperature difference $(T_i - T_o)$ calculated with equation (3).

Rate of energy dissipation Q	U (cal/cm^2 min C)	
	single (0.012)	double (0.009)
cal/cm^2 min	C	C
.020	0.95	1.25
.050	2.38	3.13
.100	4.76	6.25
.200	9.52	12.50

Table 38. Values of $(T_i - T_o)$ measured in the experimental greenhouse covered with single and double layers of plastic and the ratio of $(T_i - T_o)$ for a double layer (d) and a single layer (s).

Date	Time	$T_i - T_o$		$\frac{(T_i - T_o)d}{(T_i - T_o)s}$
		Single	Double	
March 8	0000	2.6	4.6	1.77
	0200	1.2	3.4	2.83
	0400	1.7	3.8	2.24
	0600	1.2	3.3	2.75
	2200	1.4	3.2	2.29
	2400	0.9	2.8	2.00
March 10	0000	0.9	2.8	3.11
	0200	1.1	2.7	2.45
	0400	1.0	2.5	2.50
	0600	1.2	2.7	2.25
	2200	0.4	1.4	3.50
	2400	0.6	1.5	2.50

7.5 Energy Requirements

Characteristics of the energy requirements of greenhouses in the Willamette Valley are shown in Figure 22. March 8 represents a day on which a very cold night was followed by a warm day. The air temperature remained near freezing during the night but rapidly increased to above 35 C during the day. Assuming a desired air temperature of 25 C, heating was required from midnight until shortly after 1000 hours and again from 1700 hours until midnight. The heating requirements varied substantially during this period. Energy dissipation was required from 1000 hours until 1700 hours. On March 10 heating was required throughout the day. The heating requirements again varied considerably throughout the day. Large variations in energy requirements not only occur from day to day but also during the period of one day. The measurements shown in Table 35 indicate that the heat exchange with the outside environment is rapid. This suggests that any heating system used in greenhouses must have a rapid response time.

Criteria for ideal heating systems for greenhouses are: (1) rapid response, (2) wide range in capacity, (3) provide cooling during certain times of the day. The soil warming system does not appear to meet any of these criteria. It does not have the rapid response to changing conditions. It does not have a range in capacities. It does not provide the needed cooling. Sufficient cooling can only be obtained by ventilation, which would not be sufficient during periods of high air temperatures.

7.6 Tomato Yields

Tomatoes were planted in a plastic-covered greenhouse heated with buried heat sources during the 1970 and 1971 growing seasons. The heat source in the greenhouse was not energized during the 1970 season. That year the cultivar Willamette was planted on April 9. Periodic harvests were made throughout the summer. Harvesting commenced on July 7 and continued until September 8 (Figure 21). Prior to September 8, only ripe fruit was harvested. On the final harvest date all fruit was picked regardless of size or stage of maturity.

Mature fruit harvested accounted for 71 percent of the total harvest of 155 tons/ha. Greenhouse culture not only increased yields drastically over open field culture, but more importantly it resulted in early harvest.

In 1971 the same cultivar was planted on March 29 in the greenhouse in 122 cm rows with 46 cm plant spacing in the rows. Rows were located directly over the heating cables, which were energized during the entire growing season.

Harvesting of the tomatoes started on July 21 and continued until October 14 when all remaining fruit was picked. Harvest areas were 59.5 square meters. The yield obtained was 184 tons/ha of ripe tomatoes (Figure 21) and an additional 22 tons/ha of immature fruit picked October 14.

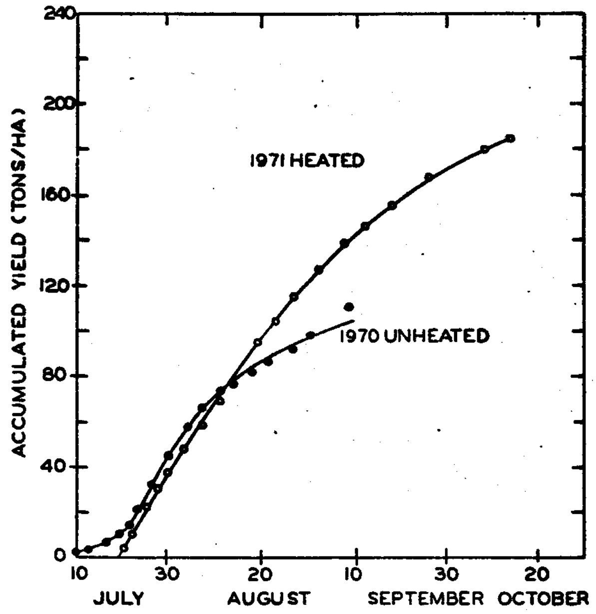

Figure 21. Yield of tomatoes grown in an unheated greenhouse (1970) and a heated greenhouse (1971). The heating system consisted of underground heat sources at 35 C placed at a depth of 50 cm, 120 cm apart. Only the weight of mature fruit was recorded. Each data point represents a harvest of mature fruit.

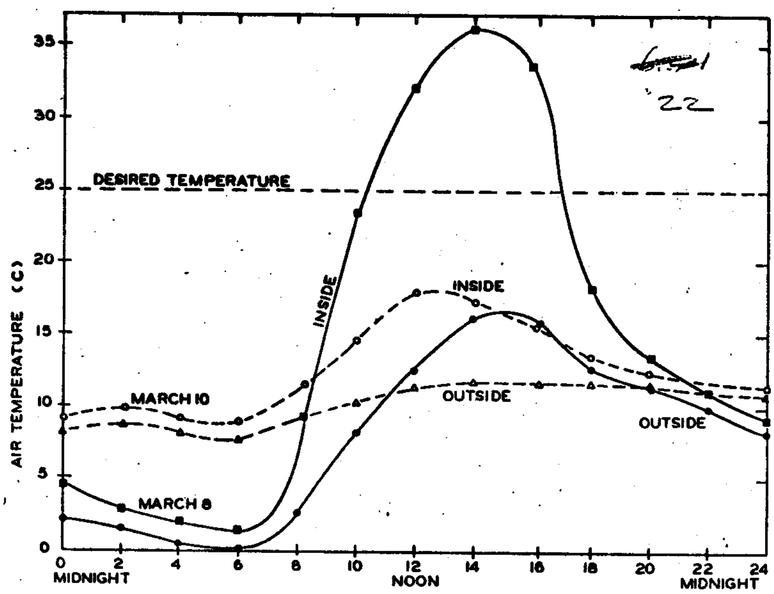

Figure 22. Air temperatures inside and outside the plastic covered greenhouse on a clear day (March 8) and a dark day (March 10). A cooling requirement existed in the clear day for several hours.

Comparison of greenhouse tomato production in 1970 and 1971 demonstrates the effect of soil heating on yield in greenhouse culture. Yield of mature fruit increased from 112 to 184 tons/ha while total yield increased from 155 to 206 tons/ha as a result of soil heating. It would appear that the increase in production and the economic advantage of early marketing could easily justify the expense of subsurface heating for greenhouse tomato production.

LITERATURE CITED

Bates, Earl M. and Wheeler Calhoun, Jr. 1971. Local climatological data for Oregon State University. Rev. ed. Oregon Agricultural Experiment Station. Special Report 277. 42 numb. leaves.

Bellaire, F. R. and L. J. Anderson. 1951. Thermocouple psychrometer for field measurements. Bulletin American Meteorological Society. Vol. 32, No. 6. p. 217-220.

Boersma, L. and G. O. Klock. 1966. Progress of irrigation research on Willamette Valley soils. Oregon. Agricultural Experiment Station. Special Report 212. 60 numb. leaves.

Boersma, L. and G. H. Simonson. 1970. Characterization of water tables in Oregon soils with reference to trafficability. Oregon State University. Dept. of Soils. Data report no. 1 on U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. Contract no. DA-22-079-eng-356 under DA Project no. 1V021701A046, Task 02, and DA Project no. 1V025001A131.

Cary, J. W. 1965. Water flux in moist soil: Thermal versus suction gradients. Soil Science 100:168-175.

De Vries, D. A. 1966. Thermal properties of soils. In: W. R. Van Wijk (ed.). Physics of Plant Environment. North-Holland Publishing Company, Amsterdam. p. 210-235.

Kendrick, J. H. and J. A. Havens. 1973. Heat transfer models for a subsurface, water pipe, soil-warming system. Journal of Environmental Quality. 2:188-197.

Kolfat, Tor D. 1969. Natural body cooling water techniques. In: M. Eisenbud and G. Gleason (eds.). Electric power and thermal discharges. Gordon and Breach. New York, N. Y. p. 295-350.

Nakshabandi, G. A and H. Kohnke. 1965. Thermal conductivity and diffusivity of soils as related to moisture tension and other physical properties. Agricultural Meteorology 2:271-279.

Rykbost, K. A., L. Boersma, H. J. Mack, and W. E. Schmisseur. 1974. Crop response to warming soils above their natural temperatures. Oregon Agricultural Experiment Station. Special Report. 98 numb. leaves.

Schmill, J.V. 1967. Variable soil thermal resistivity-steady state analysis. IEEE Trans. PAS 86(2):215-223.

Simonson, G.H. and E.G. Knox. 1965. Willamette basin general soil association map and report. Corvallis, Soils Department, Oregon State University.

Smith, W.O. and H.G. Byers. 1938. The thermal conductivity of dry soils of certain of the great soil groups. Soil Sci. Soc. Amer. Proc. 3:13-19.

U.S. Department of Commerce. 1970. Climatological data. Oregon. Vol. 76.

__________ 1971. Climatological data. Oregon. Vol. 77.

__________ 1972. Climatological data. Oregon. Vol. 78.

Van Wijk, W.R. and D.A. De Vries. 1966. Periodic temperature variations in a homogeneous soil. In: W.R. Van Wijk (ed.). Physics of plant environment. 2nd ed. North-Holland Publishing Company. Amsterdam. p. 102-143.