AN ABSTRACT OF THE THESIS OF

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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. This experiment was prompted by the observation that multiple use of waste heat discharged in the condenser cooling water of thermal power plants may become an important consideration in the development and siting of these plants. The thermal discharge might be used to achieve increased soil temperature by circulating warm water through a subsurface pipe network.

Objectives of this investigation were: (1) to determine the effect, if any, of buried line heat sources on air temperatures within a crop canopy; (2) to determine the extent to which soil temperature can be elevated with buried line heat sources maintained at various temperatures; (3) to establish the effect of subsurface heating on soil water

regimes and to evaluate a subsurface irrigation system as a means of maintaining high soil water content and hence high rates of heat transfer in the vicinity of heat sources; (4) to evaluate a theoretical model for prediction of energy dissipation rates; (5) to establish the yield response to soil warming for numerous crops; and (6) to evaluate the influence of subsurface heating on soil and air temperatures and crop production in a wood frame, plastic covered greenhouse.

Six individually controlled electrical heating cables were used to simulate a buried pipe network. Thirteen different crops were grown on heated and unheated areas during the four years of this study. Air and soil temperatures were monitored at over 200 locations with thermistors. Readings were taken with a computerized digital data acquisition system. Soil water content was monitored with electrical resistance blocks. Energy inputs were measured for each heating cable with kilowatt-hour meters.

Air temperatures at four heights above the soil surface over bare soil and in a field corn canopy were not appreciably affected by soil warming. Statistically significant temperature increases due to soil warming were observed but they were too small to be of consequence for crop growth.

Soil temperatures in the upper 25 centimeters were more responsive to solar heating than to subsurface heating. Temperature increases due to soil warming were one to five degrees centigrade at the five centimeter depth, depending on heat source temperature, time of year, time of day and crop canopy conditions. A major portion of the root zone was maintained above 20 degrees centigrade during most of the growing season. The greatest temperature increases were observed on a plot where subsurface irrigation was used to maintain high soil water content near the heat sources.

During the summer substantial soil drying occurred in the vicinity of the heat sources, particularly under a field corn crop. Thermal gradients prevented rewetting by sprinkler irrigation. A subsurface irrigation system maintained a wet soil near the heat sources throughout the growing season.

The rate of heat loss from buried heat sources was found to respond to changes in depth and spacing of sources, source temperature, soil surface temperature and soil water content, as predicted by theoretical considerations. A high correlation between mean monthly air temperature and mean monthly heat loss rates was found. The results indicate that the area required to reduce the temperature of circulating warm water, from a 1,000 megawatt thermal power plant, by 10 degrees centigrade would range from 10,000 hectares in the winter to 20,000 hectares in the summer under Willamette Valley climatic conditions. This requirement could be reduced by design modifications or subsurface irrigation.

A wide range in crop response to soil warming was observed for different crops and for some crops in different years. The results obtained with field corn and bush beans suggest that the response to soil heating depends on the degree of adversity to which the crop is subjected. When climatic conditions and management factors are optimum soil heating has a limited effect on crop yields. When one or more of these factors are limiting soil heating becomes more effective and greater yield responses occur. In nearly all cases soil warming resulted in more rapid germination and early growth, and earlier maturation. Double cropping of bush beans and double cropping with summer and winter annual forage crops appear to be feasible with soil warming. Yield increases due to soil warming were above 50 percent for several forage and vegetable crops. Several cropping sequences were suggested. Additional input from agricultural economists and engineers is needed to determine those crop combinations which will result in the greatest economic returns from a soil warming system.

Soil heating did not result in higher air temperatures in a plastic covered greenhouse. Soil temperatures were substantially increased and this resulted in an increase in tomato production of 64 percent compared with a crop grown in the greenhouse with no soil warming. Strawberry yields did not respond to soil warming in greenhouse culture and this was attributed to high air temperatures due to solar heat trapping during daylight hours.

The results of this investigation suggest that soil warming with condenser cooling waters from thermal power plants is feasible. Additional information is needed to evaluate the economic and engineering aspects of a soil warming system. It is unlikely that a soil warming system can fulfill all the needs of a thermal power plant cooling system. Additional studies to evaluate other beneficial uses of waste heat to be used in combination with a soil warming system will be required.

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1. INTRODUCTION

1.1 Source of Waste Heat

While many industries utilize water as a coolant for various processes, the power generating industry is by far the greatest contributor to heat loads being rejected into the environment. In 1970, hydroelectric generation accounted for 16 percent of the total generating capacity in the United States (Warren, 1969). The remaining 84 percent, with a total generating capacity of about 290,000 megawatts, required cooling water to dissipate heat generated at a rate of about two units for each unit of electricity produced. It is anticipated that the demand for electricity will double every 10 years for the next several decades. Most suitable hydroelectric sites have already been developed. The increased capacity must be met by installations which require cooling water. Furthermore, as fossil fuel reserves are depeleted, more and more new installations will utilize nuclear fuel, or generating processes which are still in research and development stages.

With existing technology, conversion efficiencies for fossil fuel generating stations are about 40 percent, compared with 33 percent for nuclear-powered stations. Projections for 1990 (Warren, 1969) indicate that a generating capacity of 1,260,945 megawatts will be met with nuclear fuels accounting for about 40 percent, and fossil fuels accounting for about 44 percent of the generating capacity. In 1970, nuclear fuel accounted for 3 percent and fossil fuel for 76 percent of the generating capacity. If this projection is correct, the rate of waste heat production will increase more than four-fold in two decades. Removal of this heat will require a cooling water flow rate equal to approximately 40 percent of the total runoff in the United States.

Much money and effort are being expended to develop more efficient energy conversion processes. Fast breeder reactors, now in limited use, are capable of conversion efficiencies of 40-43 percent (Diekamp, 1971). Metal magnetohydrodynamics, plasma magnetohydrodynamics, and fusion processes in various stages of development may be capable of efficiencies up to 80 percent. One projection for the year 2050, which assumes an efficiency of 61 percent, indicates a five-fold increase in waste heat rejection from 1970 levels (Boersma, 1970). It is apparent that even with rapidly developing technology in the power generation industry there will be large quantities of waste heat which must be dissipated in some manner.

1.2 Waste Heat Dissipation

Historically most of the condenser cooling water has been discharged directly into rivers, lakes, estuaries, or the open ocean. In 1965, only 116 of 514 central power stations with generating capacities of 100 megawatts or greater utilized auxiliary cooling facilities. In the eastern states, cooling facilities were in use for 18 of 347 stations (U.S. Dept. of Interior, 1968). This arrangement is changing, however, for several reasons. The availability of water to accommodate once-through cooling is fast diminishing in inland areas. There is also a growing concern for protection of our water resources from the potential deleterious effects of discharging warmed water into the aquatic environment.

While cases have been cited where warm water discharges have resulted in improved fishing or other benefits (Alabaster, 1969; Strawn, 1969), it is generally agreed that the total ecological impact of discharging warm water to the aquatic environment is detrimental (Alabaster, 1969; Patrick, 1969; Wurtz, 1969; Mount, 1969; Hedgpeth and Gonor, 1969). Heated effluents not only change the temperature of receiving waters, but also alter other physical and chemical characteristics such as dissolved oxygen content, stratification, salinity, currents and toxicity of various chemicals. In addition, chemicals used to prevent fouling of the cooling system may have biocidal effects on biota of receiving waters.

Temperature tolerances of many freshwater and marine species have been determined in laboratory studies and to lesser extents under natural habitat conditions. Information on food chain organisms, predator-prey relationships, diseases and synergistic and antagonistic interactions of temperature with other environmental parameters are less well understood. Until such time as biologists and ecologists are able to predict the total ecological impact of warm water discharges on the aquatic environment, the continued use of natural bodies of water as a giant heat sink could have adverse consequences.

In response to a growing concern over environmental degradation, and in light of vast amounts of scientific data relating water quality to survival, performance, and reproduction of various aquatic species, both federal and state legislation has been enacted to preserve and protect water quality for all beneficial uses (Stein, 1969; Boardman, 1969). Included in these standards are very specific temperature criteria which stipulate not only maximum allowable temperatures but also allowable rates of change in temperature. Enforcement of these standards will require, in many cases, modification of heated effluent discharge practices. In some instances, installation of auxiliary cooling systems will be required on generating stations now employing once-through cooling. Environmental impact studies on proposed receiving waters will become an important part of pre-installation planning.

While a large fraction of waste heat is dissipated by once-through cooling, there are several cooling systems in use. The simplest and least expensive method is the man-made cooling pond. If the pond is large enough, make-up water is not required and station operation is not dependent on a large, continuous source of cooling water. Disadvantages of cooling ponds include the low heat-transfer rate, which is highly dependent on climatic conditions, and the large land area required.

Spray ponds are more efficient, requiring only 5 percent of the land area needed for a cooling pond (Krenkel and Parker, 1969). Consumptive loss of water is relatively high and performance is limited by the short air-water spray contact time. In addition, undesirable microclimatological conditions such as fog may develop.

Cooling towers have been used in Europe for more than 50 years (Rainwater, 1969). As of 1970 about 35 were in use in the United States. Several types have been developed including natural-draft, mechanical-draft, and dry-cooling towers. While efficiencies and consumptive losses of water vary among types, they are all more favorable than other means of heat dissipation developed to date. Disadvantages of towers in general are high costs, power requirements for operation, effects on microclimate and risk of failure in regions where seismic activity is known to occur.

The technology for dissipation of waste heat without environmental degradation is available. Costs will be high, however, and must be reflected in power rates. Perhaps the greatest cost is the loss of valuable fuel reserves if more efficient generating processes are not developed. The heat produced in the power generating industry must be considered as a valuable resource to be managed for maximum benefit to society, rather than as an undesirable industrial by-product to be disposed of in the least offensive manner.

1.3 Beneficial Use of Waste Heat

1.3.1 General

The concept of beneficial use of waste heat is not new. Extraction of steam for use in refinery processes was an integral part of the design of the Linden Generating Station of Public Service Electric and Gas Company in New Jersey more than 15 years ago (Warren, 1972). The result was an increase in heat efficiency of the generating cycle from 39 to 54 percent concomitant with providing the energy required to refine petroleum products.

Residential space heating with warm water has been practiced in Iceland for more than 40 years (Nutant, 1969). Although the source of warm water in this case is geothermal, the same principles could be applied to generating station effluents. Space cooling in the summer months could be achieved with ammonia or lithium bromide absorption refrigeration mechanisms (Nutant, 1969). Such systems would be particularly attractive in regions where climatic extremes are experienced.

Aquaculture using thermal discharges to increase production rates of channel catfish (Ictalurus punctatus) has been successfully demonstrated (Tilton and Kelley, 1970; Williams, 1972). Thermal effluents from the Long Island Lighting Company are being used to reduce the normal growing period of oysters from four to less than three years by culturing the spat in heated effluent during the four to six months when natural temperatures are too low to sustain maximum growth rates (Timmons, 1971). Many commercially important aquatic species may prove to be suited to thermal aquaculture when some of the associated problems have been solved. Among the most pressing problems are the biocides and possible isotopes in the effluents, shutdowns, and suitable food sources (Yee, 1972).

Other potential uses for thermal discharges have been suggested. Among these are de-icing of harbors and airport runways, defogging of airports, sewage treatment, water distillation, steam-propelled transportation and heating of domestic water (Miller, 1972). There are numerous problems inherent in the application of most of these uses to the solution of the waste heat problem. Some are seasonal uses which may coincide with peak heat rejection periods. Some require either high or low temperatures which may not be available. Others are dependent on a continuous source of constant temperature effluent and cannot accommodate a shutdown for refueling or sudden changes in power production levels. It is apparent that successful schemes for beneficial utilization of thermal discharges will require the integrated systems approach with several alternative uses available.

1.3.2 Use of Waste Heat in Agriculture

Temperatures of thermal effluents from power generating stations are generally in the range of 25-40 C. This is too low for most industrial processes but is ideal for stimulation of many life processes. Crop production in many regions of the world is limited by low air and soil temperatures during part of the growing season. Discharging heat to the soil could lengthen the growing season as well as stimulate growth rates. Not only could higher yields be achieved, but it also might be possible, with the longer season and higher soil temperatures, to grow crops not well suited to a climatic region.

The use of waste heat from power plants for heating greenhouses was considered more than 40 years ago in the USSR and more than 10 years ago in England (Williams, 1972). More recently, investigations in the United States (Jensen, 1972; Williams, 1972) indicate that heating during cool months and cooling during warm months would be more economical utilizing warm water than cooling and heating with methods now used. Williams (1972) estimates that warm water from the Browns Ferry Nuclear Plant in Alabama could provide heating and cooling for 600 hectares of greenhouses and animal enclosures, capable of producing enough tomatoes, lettuce and broilers to supply the needs of five million people. Jensen (1972) points out, however, that while sunlight is not limiting during winter months in the lower latitudes, this may not be true in northern latitudes. This could restrict the crops grown in greenhouse culture to those which do not have long daylight requirements.

Other beneficial uses of waste heat in agriculture have been demonstrated. Using warm water from a nearby industry, a successful frost protection system was developed near Springfield, Oregon (Price, 1972). The demonstration site was a natural frost pocket near the confluence of two rivers. Local farmers experienced frost damage to vegetable, fruit and nut crops about three years of five. Sprinkler irrigation with warm water achieved protection several times over a two-year period while adjacent crops with no protection incurred frost damage. Sprinkler irrigation of several crops with warm water was found to be as good as cold water irrigation in summer months but did not increase yields. Prevention of sunburning of fruit and nut crops was also suggested as a valuable use of the irrigation system. The multi-use system was found to be less expensive than other systems in providing frost protection, plant cooling and irrigation.

Warm water may afford slightly more frost protection than cold water when used over a large area under conditions of low winds. However, Cline, Wolf and Hungate (1969) found that water discharged at 50 C at the nozzle was cooled to ambient air temperature or lower by the time droplets reached the ground surface, under a variety of air temperature and nozzle pressure conditions. Only the largest droplets were able to maintain temperatures above air temperature. These results indicate that limited benefits, if any, will be derived from the heat. This applies to sprinkler frost protection as well as to sprinkler irrigation as a means of transferring heat to the soil.

Surface irrigation with warm water is also an unsatisfactory means for imparting heat to soil. Wierenga, Hagen and Nielsen (1970) found that an application of 13.4 cm of water at 21.6 C initially warmed the surface but the effect was of short duration and later the effect was to cool the soil because of increased evaporation and increased heat capacity. There was very little difference in soil temperature, except for a short period initially, between the plot flooded with warm water and a plot flooded with 13.4 cm of water at 4.1 C. An unirrigated control plot exhibited higher soil temperatures than either of the irrigated plots, again except for an initial temperature increase on the warm water treatment.

In addition to the inability to impart heat to soil with flood irrigation, there is the possibility of heat damage to crops when shallow roots or above ground parts are exposed to hot water. Price (1972) described two incidences where breaks or leaks resulted in flooding of crops with warm water and plants were killed as a result. At the time of flooding, water temperatures were about 60 C. Later experiments with water up to 40 C showed that crops could withstand temporary flooding at these temperatures.

1.4 Soil Warming

Sprinkler or flood irrigation with thermal effluents may be a suitable alternative to once-through cooling in some instances. These methods will not result in full utilization of the available heat. Furthermore irrigation requirements are seasonal in arid regions and non-existent in humid regions. Piping warm water through a network of pipes buried in the soil would result in maximum transfer of heat to the soil. Cooled water leaving the subsurface heating system would then be available for recycling through the plant cooling system or for some other use. In areas where irrigation of crops is required, subsurface irrigation with warm water could be practiced or water taken from the soil heating loop could be applied with sprinklers.

1.4.1 Energy Dissipation by Underground Line 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), ΔT is the temperature difference between pipe surface and soil surface (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.

1.4.2 Thermal Conductivity and 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).

1.4.3 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

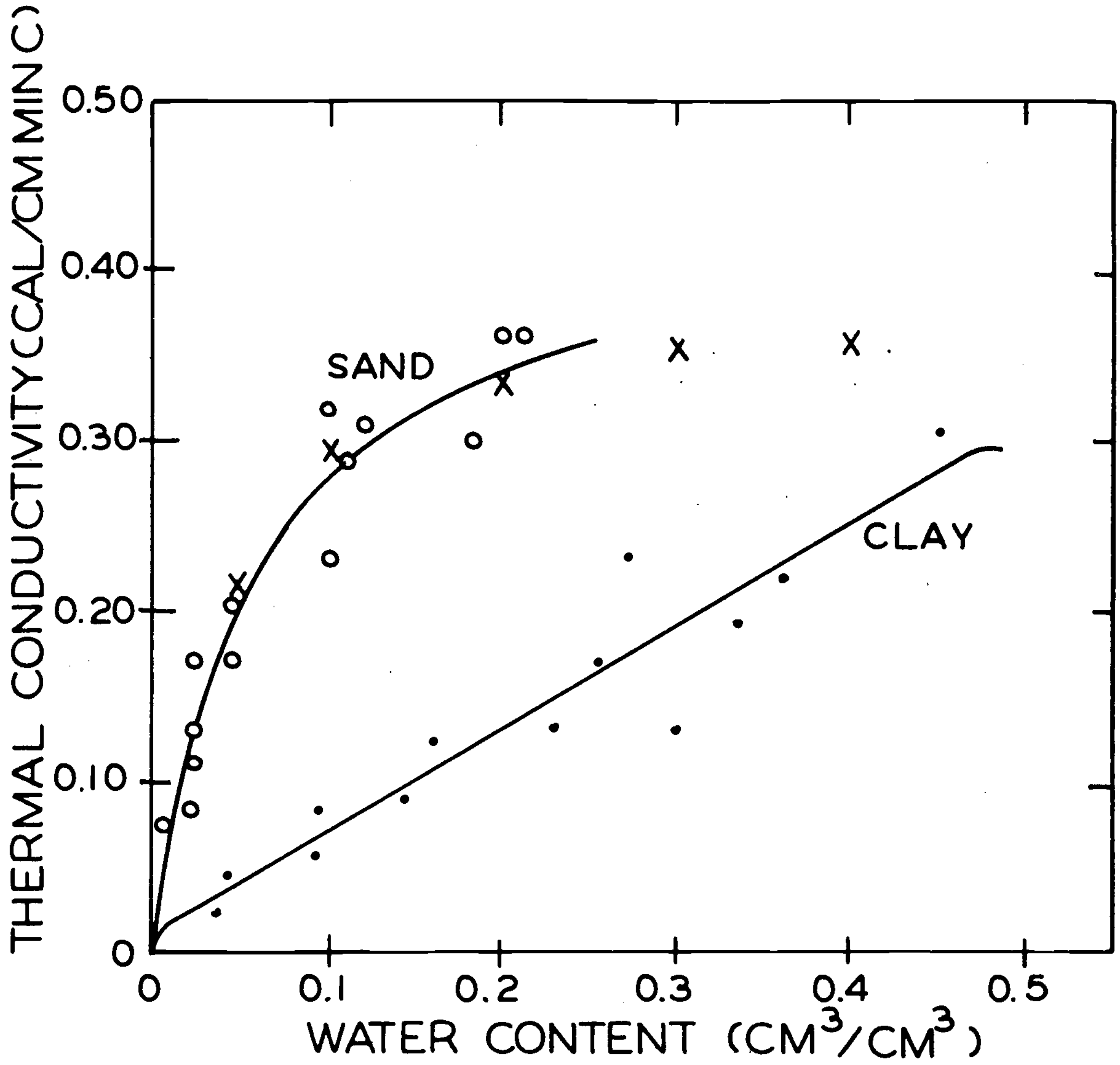

Figure 1. The thermal conductivity of a sandy soil and a clay soil plotted according to De Vries (1966), tables 7.5 and 7.6. The data points are measured values; solid lines represent theoretical values.

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

1.4.4 Effect of Design Parameters on Energy Dissipation 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; $R = 3.0 \times 10^{-2}$ cal/cm^{2}min.

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

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

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

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

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

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

1.5 Crop Growth and Soil Temperature

1.5.1 Temperature Response Mechanisms

Crop growth is the integrated expression of the many processes which supply and incorporate nutrients, water, energy, carbon dioxide, and light into plant material. Soil temperature plays a key role in determining rate of crop growth and exerts its influence in many ways. Much of the recent literature on the effects of soil temperature on growth of various species has been summarized by Babalola (1967), Kuo (1970), Fazilat (1971), Sepaskhah (1971), and Young (1972). Physical and physiological effects have been cited as temperature response mechanisms. Decreasing viscosity of water and cell sap with increasing temperature results in greater uptake of water and nutrients and increased root growth, root and shoot respiration, transpiration and photosynthesis (Sepaskhah, 1971; Young, 1972; Kuo, 1970; Nielson et al., 1961; Cannell et al., 1963; Jensen, 1960; Nelson, 1967; Unger and Danielson, 1967). Increased membrane permeability as a result of increased temperature has been suggested as an important cause of observed temperature effects (Babalola et al., 1968; Kramer, 1940).

An increase in availability of nutrients at root absorption sites at higher temperatures may result from increased diffusion rates, increased solubility of certain compounds, and increased rate of breakdown of mineral and organic sources of ions. Active ion uptake is enhanced by an increase in root respiration at higher temperatures (Laties, 1959; Russell and Barber, 1960). Passive ion uptake benefits from the increase in ion availability and increased rate of root growth. Translocation of nutrients in conducting tissues is favored due to decreased viscosity of the cell sap with increasing temperature (Shtrausberg, 1958). Soil temperature acts indirectly through its effects on water uptake and flow through plant tissues to influence water status in aerial portions of plants and hence transpiration and photosynthesis (Nelson, 1967; Unger and Danielson, 1967). That root temperature influences leaf water content has been well established (Cox and Boersma, 1967; Kramer, 1969; Troughton, 1969). An increase in shoot respiration reported by Kuo (1970) was attributed to increased root permeability and more rapid water absorption at higher soil temperatures. Direct effects of temperature on root respiration can be expected as a result of increased enzymatic activity. Jensen (1960) reported increased root respiration of corn and tomato plants in response to temperature increases from 5 to 30 C. Root growth has been shown to respond to elevated soil temperatures in many species (Nielson et al., 1961; Adams, 1962; Stoffer and Van Riper, 1963). Optimum temperatures vary for different species and cultivars of a given species. Sorghum (Adams, 1962; Rhykerd et al., 1960), corn (Nielson et al., 1961), and spring wheat (Woolley, 1963) showed increased root growth as soil temperatures increased to 26.7 C. Bromegrass root growth increased to 19.4 C.

Root temperature exerts a direct influence on physiological processes by altering enzymatic controlled reaction rates. One effect is related to interconversion of enzymes from the denatured state, devoid of or greatly decreased enzymatic activity, to the native or enzymatically active state (Mahler and Cordes, 1966). The denatured state is found at low and high temperatures. The optimum temperature for the native state varies for different enzymes. A second effect results from the influence of temperature on the kinetics of biochemical reactions. A Q_{10} value of 2.0 or higher is common for enzymatic reactions (Salisbury and Ross, 1969). Temperature affects plant water status. Enzyme activity has been shown to be highly dependent on plant water status (Todd, 1972). Thus through its effect on plant water status, root temperature indirectly influences enzymatic activity and hence metabolic processes. Knoll et al. (1964) studied the influence of root zone temperature on growth and content of phosphorus and anthocyanin in corn seedlings. They concluded that a direct effect of soil temperature on plant cell metabolism was responsible for shoot growth differences. Similar results were obtained with tomato seedlings (Davis and Lingle, 1961; Lingle and Davis, 1959) and strawberry plants (Roberts and Kenworthy, 1956). The many influences of temperature on crop growth are difficult to isolate and quantify. For the objectives of this study it is sufficient to recognize that several response mechanisms have been identified and that they all may be involved in the temperature response of plant growth.

1.5.2 Experiments on Plant Response to Soil Temperature

Most studies on temperature effects on nutrient uptake, root growth, shoot growth, photosynthesis, transpiration, and respiration have been done with young plants under laboratory conditions. Different results may be obtained in field studies where crops are grown to maturity and subjected to normal climatic variability. Mederski and Jones (1963) heated field plots to 29.4 C at 20 cm depth with buried electrical heating cables. They found that the heat treatment doubled the rate of dry matter accumulation of corn, increased the potassium and phosphorus content but decreased the calcium content in plant tissues during the first 60 days. However, when harvested at maturity, yield and nutrient content differences disappeared. The heated crop matured earlier and for some crops this may result in an important marketing advantage.

Fazilat (1971) and Young (1972) evaluated effects of root zone temperature and soil water stress on growth and uptake of N, P, K, Ca and Mg in five week old wheat seedlings. They found maximum growth rate to occur at 23.9 C. The dry matter content of N, P, and K increased with increasing temperature, while Ca decreased and Mg was essentially unaffected by temperature. Results of Mederski and Jones (1963) for corn at 10 cm top height showed the same response of P, K, Ca and Mg to increased temperature. Nielson *et al*. (1961) evaluated mineral composition of corn, bromegrass, and potatoes at four soil temperatures and found the same relationships as above with a few exceptions. Ca content decreased with increasing temperature in all experiments except in the tops of potatoes. The effect on uptake rates was similar to that obtained by Fazilat (1971) and Young (1972).

Walker (1969) measured the effect of temperature on growth and uptake of nutrients in corn seedlings. He found maximum uptake rates for most nutrients between 26 and 34 C. Boron showed no change in rate between 12 and 20 C but increased ten-fold from 21 to 31 C. Although the soil used was high in Ca, plant abnormalities similar to Ca deficiency symptoms, and very low Ca content were observed at the higher temperatures. This agrees with low uptake rates reported by others. Cannell et al. (1963) found no effect of soil temperature on Mg content of tomato leaves, which agrees with the results obtained with wheat seedlings by Young (1972). They found trends similar to those reported by others for most other nutrients except for an increase in Ca content from 10 to 24 C which is at variance with others. Stoffer et al. (1963) evaluated moisture stress and temperature effects on dry matter accumulation and nutrient uptake by sorghum. They found higher uptake rates of N, P, and Fe at high temperature and low soil moisture stress. Growth rate was also highest at the higher temperatures. They found no significant changes in the contents of various nutrients in the plants however.

The objectives of the studies reported here were to determine the influence of temperature on dry matter accumulation under field conditions. No attempt was made to determine nutrient uptake rates or levels of nutrient content in plant tissues.

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 Calhoun, 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 consisting of two resistance heating wires running parallel in a single sheath, both terminating at one end, was used. 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

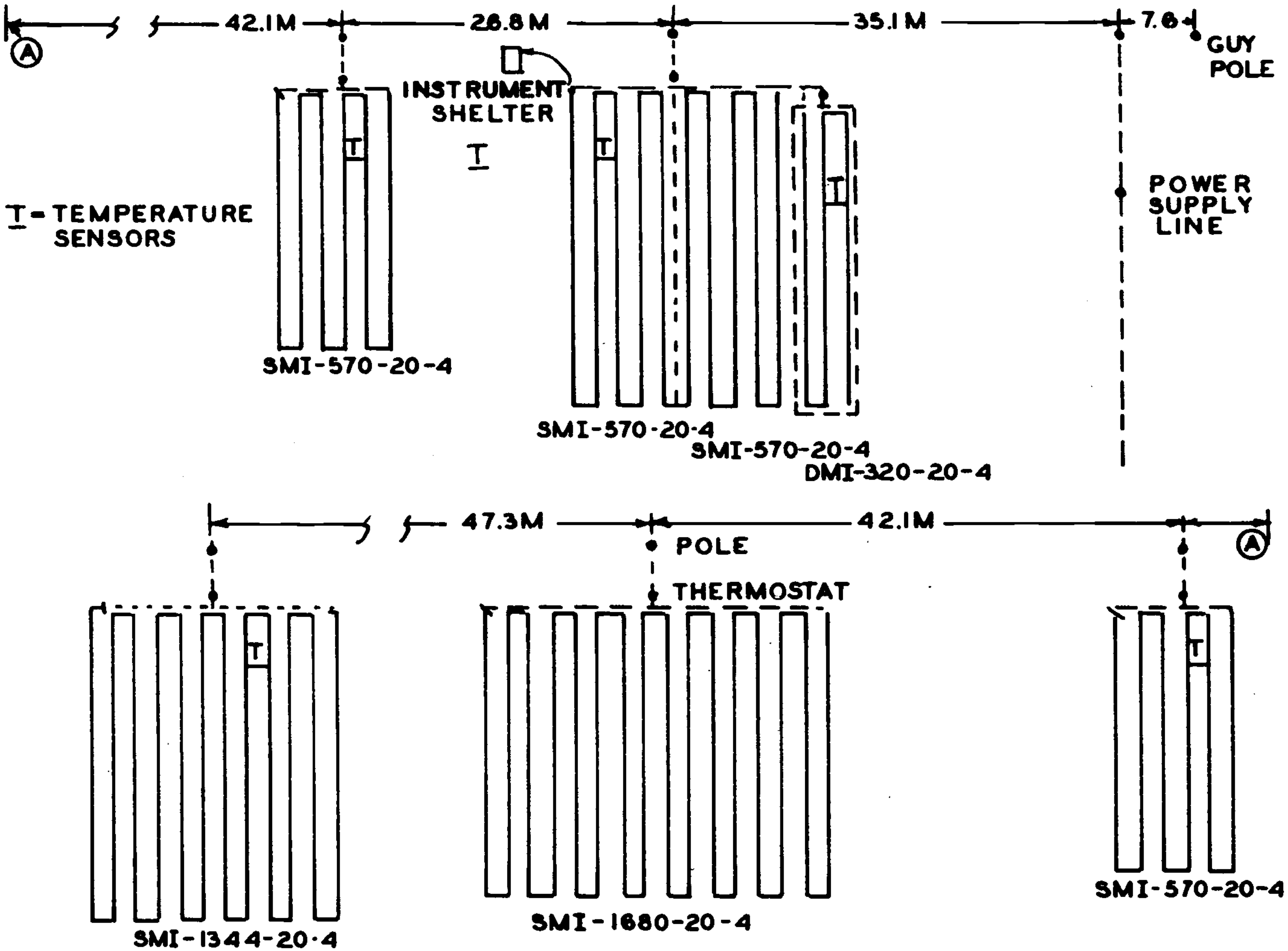

Figure 2. Layout of plots used in the soil warming experiment.

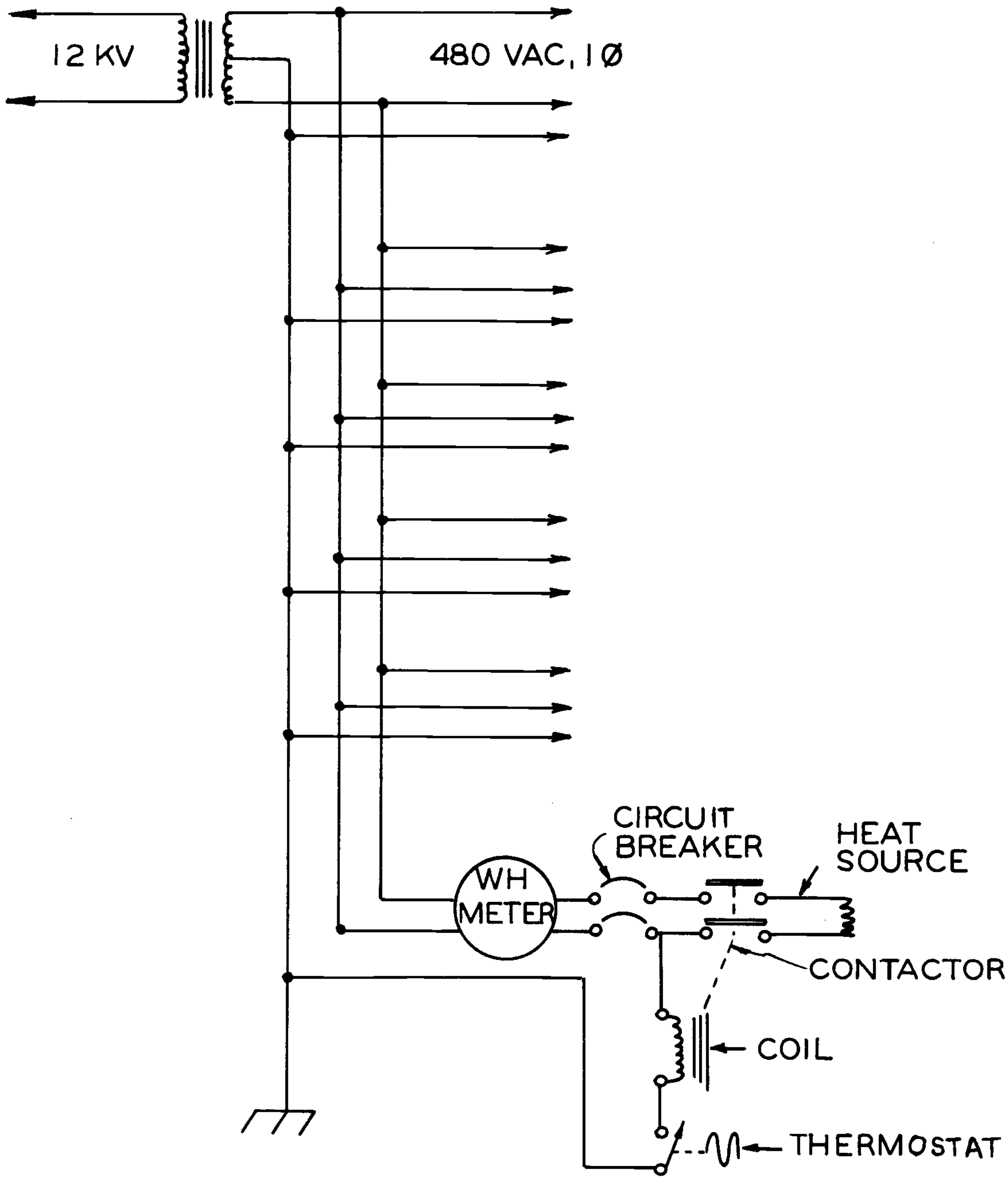

Figure 3. A simplified schematic wiring diagram of the heat sources and their components to the secondary power source.

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
DMI-405-20-4	123	8,060	16.8	.78	18	alloy

Connections were made to contactor 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 Monitoring Power Consumption

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, and 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."

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	--

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 multipair 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 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. The surface sensors were buried and relocated again in 1971 and 1972. Each time they were relocated as 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

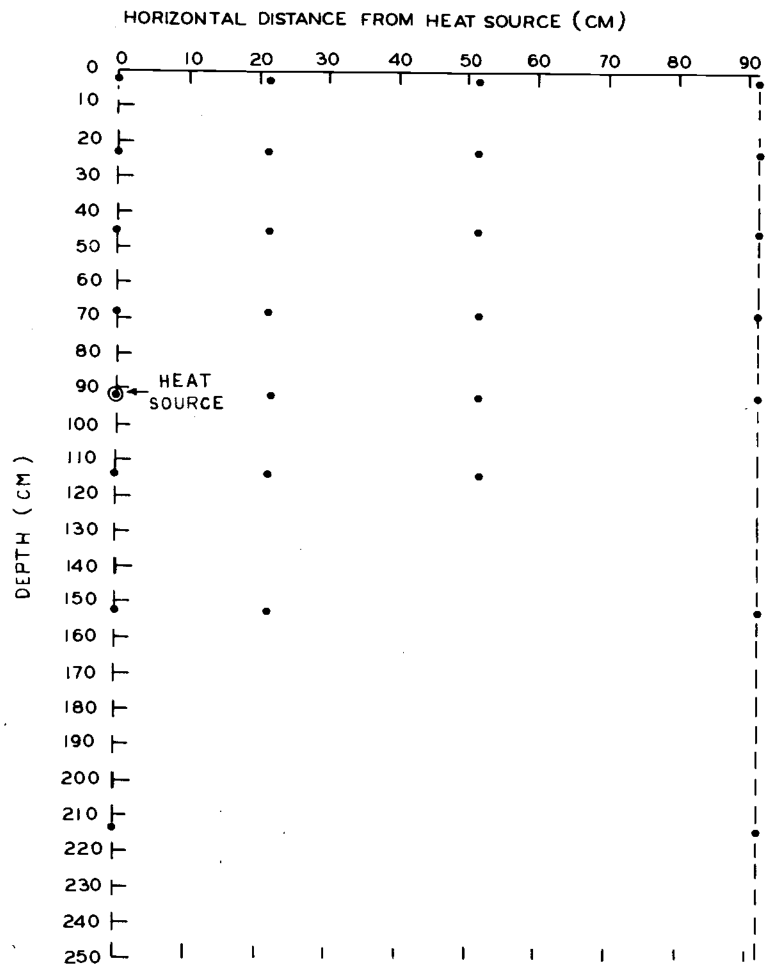

Figure 4. Original location of temperature sensors in NO COVER and CORN plots in relation to the soil surface and heat sources.

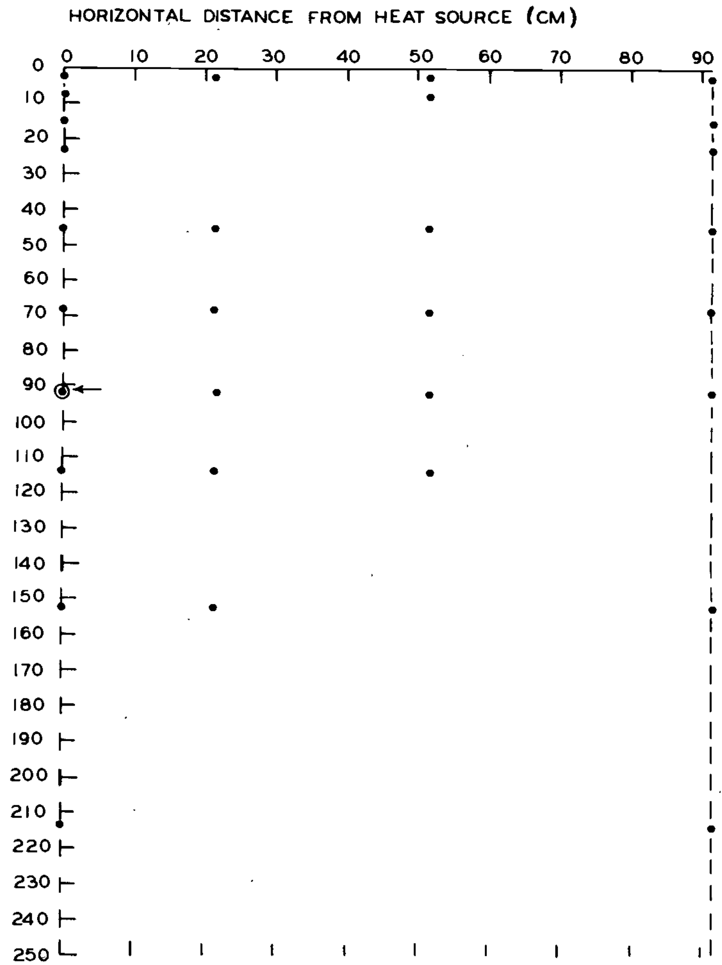

Figure 5. Final location of temperature sensors in NO COVER and CORN plots in relation to the soil surface and heat sources.

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 locations with respect to soil surface and heat sources are 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.

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;

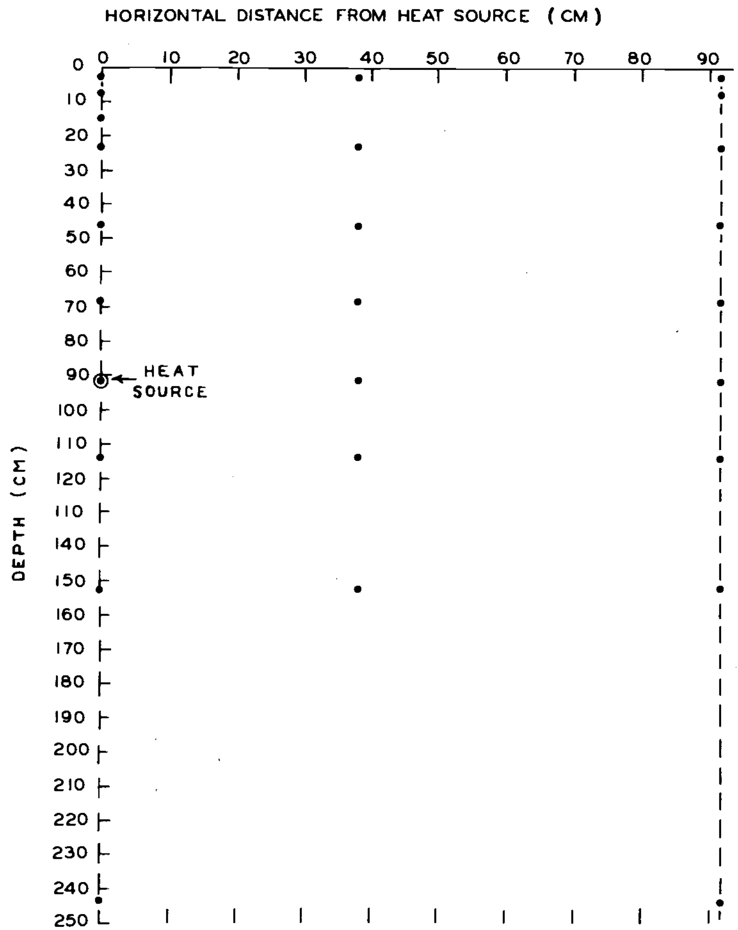

Figure 6. Location of temperature sensors in the SUB-IRR plot in relation to the soil surface and heat sources.

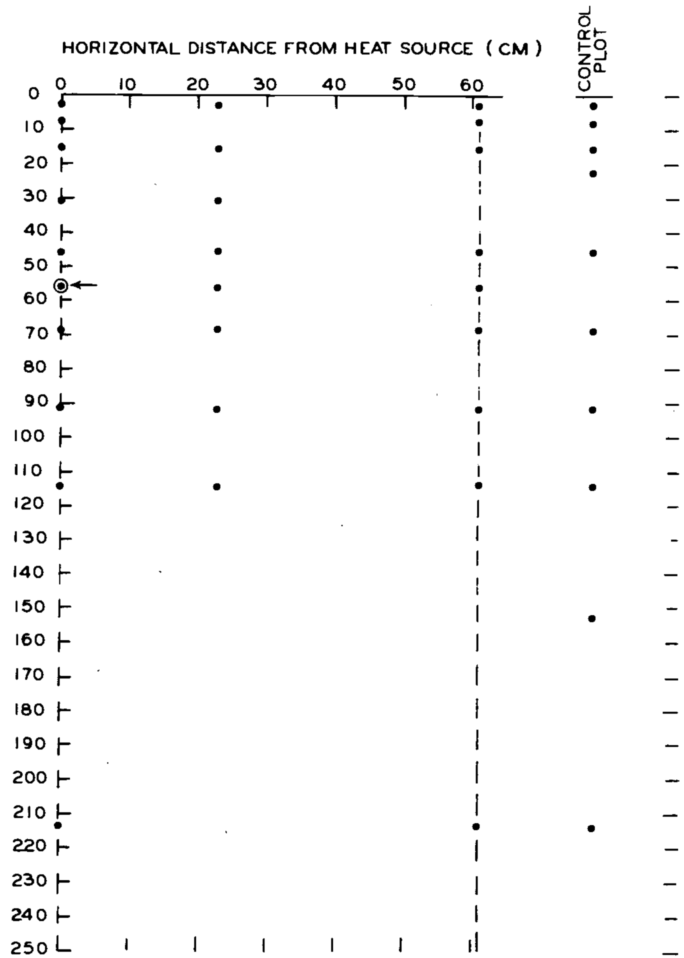

Figure 7. Location of temperature sensors in the GRASS plot in relation to the soil surface and heat sources.

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 records 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 2.5.4 and 2.5.5

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 multi-pin 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, Amphenol 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

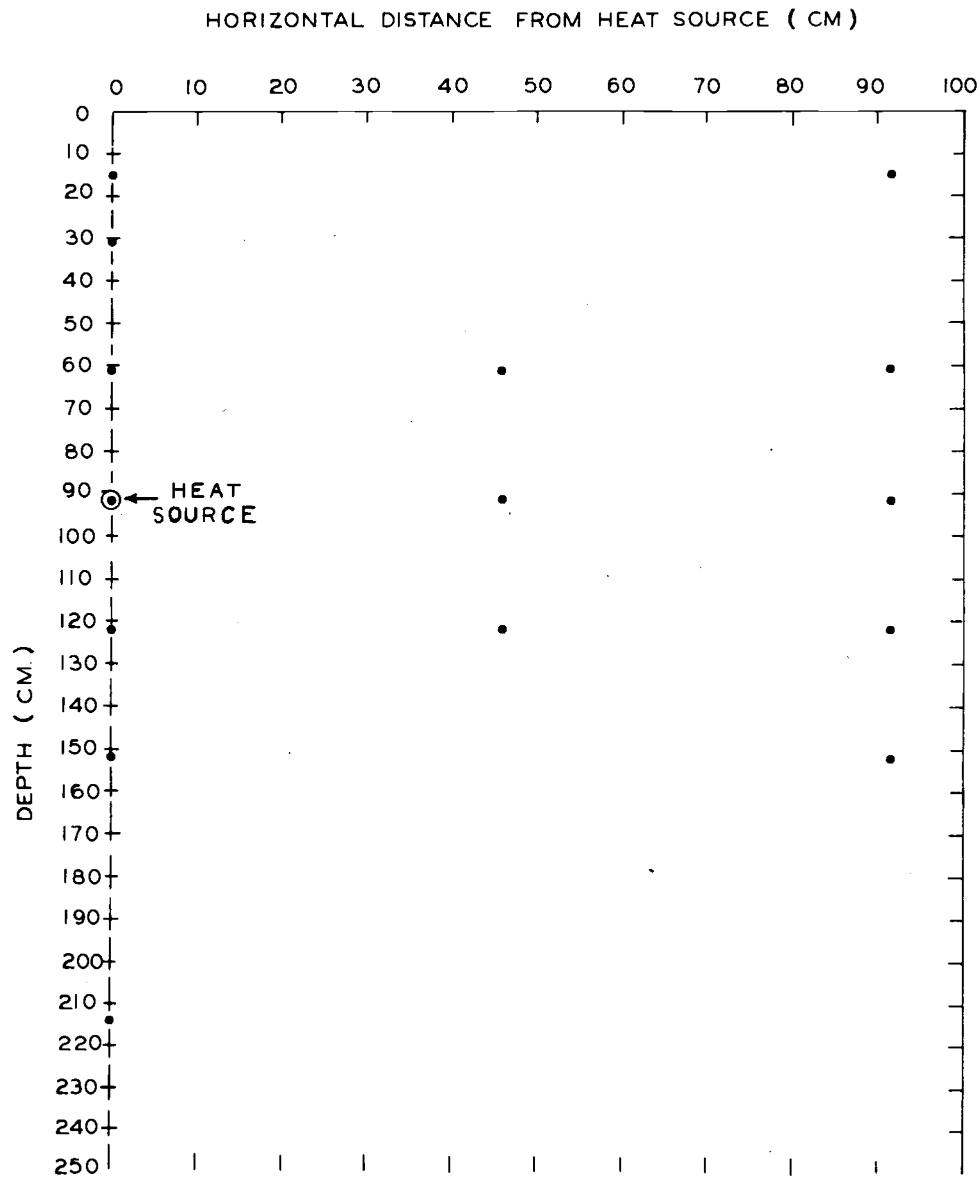

Figure 8. Location of water content sensors in the NO COVER plot in relation to the soil surface and heat sources.

replaced with new sensors.

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 were installed 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 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. Nine days from the months of July, August and September were selected for analysis of the observations. No irrigation or precipitation occurred during any of these days. Maximum, minimum, and average air temperatures over unheated soil 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.

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.

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

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 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		Corn canopy		
	Unheated	Heated	Unheated	Heated	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

A summary of the results 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.

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		Corn canopy		
		Unheated	Heated	Unheated	Heated	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

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 the four locations. Three subunits were used for the 15 cm height including: heated, bare soil; unheated, corn canopy; and

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).

	Bare soil				Corn canopy					
	Unheated		Heated		Unheated		Heated		Sub-Irr	
Time	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	-1.0	.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	.2	-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

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 comparison 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

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

	Time	Level of significance[1/]			
		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	*	*	**	*
	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
	Average	NS	NS	**	**

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

Table 9. Summary of the statistical analyses 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.

	Bare soil, LSDs[1/]	Corn canopy, LSDs	
Time	Unheated vs. heated	Unheated vs. heated	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**

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

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 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 on 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 reduced 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 trapping 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 the 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.

3.3.2.2.1 Height: 15 cm. 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.

3.3.2.2.2 Height: 65 cm. 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.

3.3.2.2.3 Height: 115 and 170 cm. 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. Subsurface 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) the soil temperature at each gridpoint in the soil profile shown in Table 13 for a selected point in time. 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 not enclosed in parentheses were measured in the field. Those 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, 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.

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 profiles 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

The analysis had to be limited to certain selected dates because of time and fund limitations. The major comparisons desired were those between plots at different times of the year for full-day cycles. Several factors were considered in choosing the dates for which temperatures were analyzed. 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

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	65	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	22.7	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

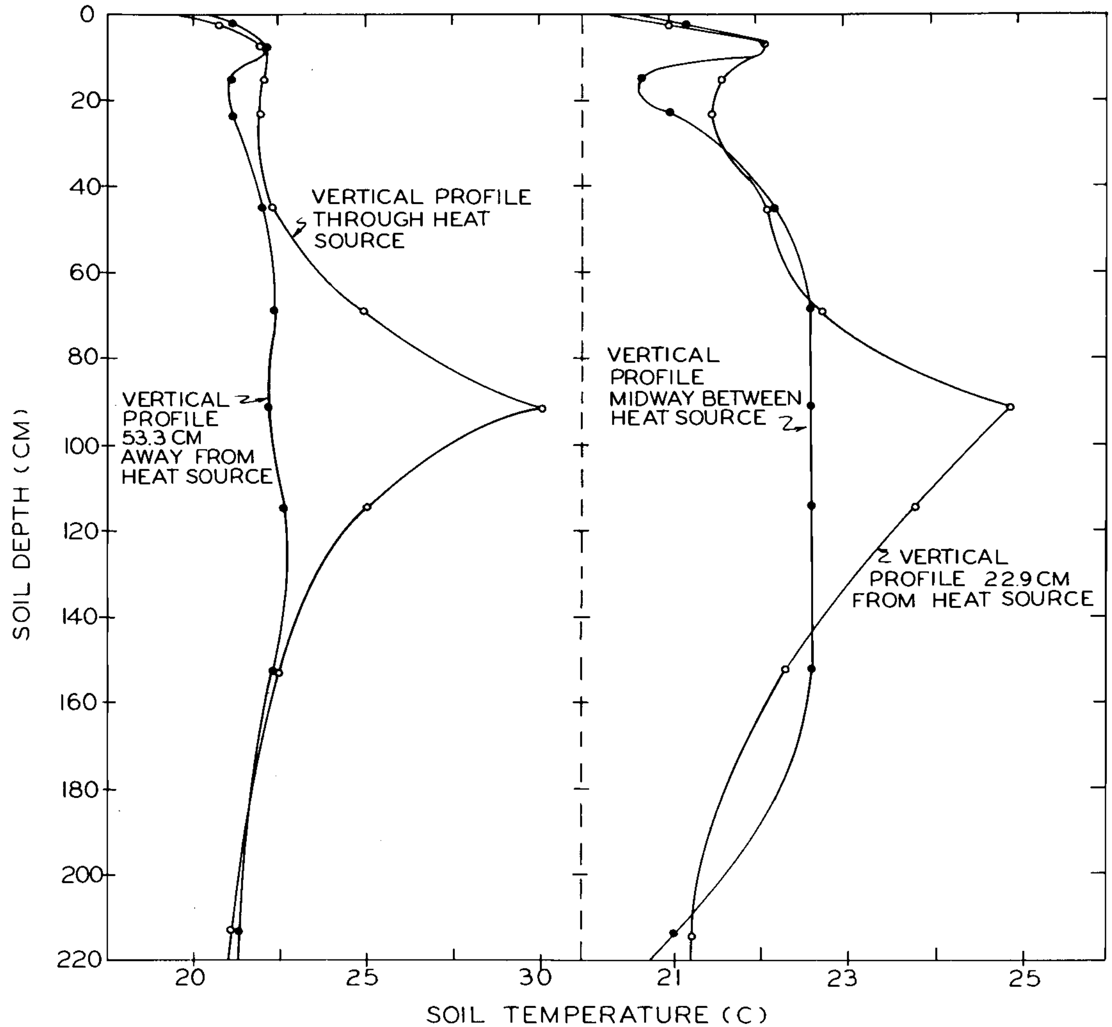

Figure 9. Soil temperature as a function of depth in vertical planes 0, 22.9, 53.3 and 91.4 cm from the heat source. CORN plot, 0000 hours, August 11, 1971. Note the scale change.

no irrigation water was applied. A further criteria was that 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.

Days were selected to represent a hot summer day, a normal summer day and a normal winter day. Similar air temperatures occurred for at least three days prior to each day selected. August 11, 1971 represents a hot summer day. The maximum air temperature recorded at the U.S. Weather Bureau Station was 38 C and the minimum was 12 C. September 16, 1971 was a normal summer day with a maximum air temperature of 27 C and a minimum of 14 C. The winter day used was February 19, 1971 with maximum and minimum air temperatures of 8 and -1 C, respectively (U.S. Dept. of Commerce, 1971).

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.

The change in soil temperatures as a function of distance from the heat source can be seen in Figure 9.

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 are shown for the CORN plot on August 11, 1971. The average temperature in each plane was obtained by taking into account all gridpoint temperatures in that plane so that temperatures at depths not shown in Table 14 were also included in the calculations.

At the 5 cm depth temperatures 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 5 cm 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.

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 solar heating is more important than soil warming in determining soil temperatures in the upper 25 cm of the soil. During the night a noticeable heat source influence is

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

exerted near the surface and the greatest influence occurs in the vertical plane passing through the heat source.

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 5 to 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.

Average temperatures in Table 14 were obtained by taking into account all gridpoint temperatures at a given horizontal spacing. It is apparent that there was almost no difference in temperatures between the 45 and 85 cm distances from the heat source. Average temperatures in this region were about 1 C less than those observed in a vertical 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 (Table 15) for five cases. All data shown are for August 11, 1971 except for the SUB-IRR (field corn) data which was obtained on August 6, 1972. The average temperature was calculated by taking into account all grid-point temperatures at a given horizontal spacing.

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	Avg.
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 the result of the low soil water content at this depth on the CORN 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 horizontal decrease of the soil temperature at the heat source depth on the SUB-IRR plot was less than observed on all other plots. This can be attributed to the higher soil water content which resulted in higher rates of heat transfer and lower temperature gradients. Horizontal variations in temperature decreased at depths below the heat sources. At 185 cm soil temperatures were essentially uniform in the horizontal direction.

The smallest variation for the total of all depths was observed 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 variations occurred on the CORN plot when all depths were considered. 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 generally assumed to be 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 source. 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 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 average hourly temperatures obtained as described above for heated plots.

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.

Temperatures calculated as described above are shown for three day classes in 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.

4.3.1 CONTROL Plot

Characteristics of the daily temperature variations on the CONTROL plot for the three selected days are shown in Tables 16 and 17. The plot surface was free of vegetation at all times. For all days the daily temperature changes were small below the 20 cm depth. The average daily temperature on a given day was nearly constant for the upper 50 cm on all days considered. 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 effect of

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.

Temperature category	Depth	CONTROL	NO COVER	CORN	SUB-IRR 1971	SUB-IRR 1972	GRASS
	cm	C	C	C	C	C	C
Warm day							
Maximum	5	28.2	31.3	22.6	34.7	26.8	--
	15	23.6	28.4	21.8	30.7	25.7	--
	25	22.9	27.2	21.6	29.4	24.9	--
	35	22.3	27.2	21.9	29.2	24.7	--
	45	20.8	27.7	22.3	28.9	25.0	--
	Ave.	17.9	27.8	22.4	26.4	25.1	--
Minimum	5	18.5	17.8	19.5	21.7	22.1	--
	15	20.8	22.8	20.0	25.3	23.6	--
	25	21.9	25.1	20.4	27.2	23.9	--
	35	22.0	26.4	21.0	28.0	24.2	--
	45	20.7	27.4	22.0	28.4	24.5	--
	Ave.	17.4	27.1	22.1	25.6	24.9	--
Daily average	5	22.5	24.0	21.3	27.7	24.2	--
	15	22.3	25.6	21.1	28.7	24.8	--
	25	22.4	26.3	21.2	28.3	24.4	--
	35	22.1	26.8	21.6	28.5	24.3	--
	45	20.8	27.5	22.2	28.6	24.7	--
	Ave.	17.6	27.5	22.3	26.0	25.0	--
Source		--	35	31	33	31	--
Cool day							
Maximum	5	19.7	24.7	17.1	24.0	22.1	18.6
	15	17.1	22.6	17.0	22.4	22.2	19.8
	25	16.8	22.3	17.6	22.6	21.2	20.7
	35	16.7	22.8	19.2	23.4	21.2	21.4
	45	16.5	23.6	21.3	23.9	22.3	22.6
	Ave.	16.2	25.7	22.8	24.1	24.1	21.2
Minimum	5	13.0	14.0	14.7	15.7	19.0	16.4
	15	14.8	18.2	15.5	18.6	21.0	18.7
	25	15.7	20.4	16.6	21.1	20.6	20.1
	35	16.4	22.0	18.9	22.5	21.0	21.2
	45	16.4	23.4	21.1	23.7	22.2	22.4
	Ave.	15.9	25.1	22.5	23.6	23.9	21.0
Daily average	5	15.6	18.1	15.8	19.4	20.4	17.4
	15	16.2	20.3	16.3	20.6	21.5	19.1
	25	16.4	21.3	17.1	21.9	20.8	20.3
	35	16.6	22.3	19.0	23.0	21.1	21.3
	45	16.5	23.4	21.2	23.8	22.2	22.5
	Ave.	16.0	25.4	22.7	23.8	24.0	21.1
Source		--	34	35	31	31	34

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.

	Maximum			Minimum			Daily average		
Depth	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	10.2
Source temp.	-	34	22	-	34	28	-	34	25

the heat sources on the diurnal temperature variations near the soil 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 between 9.6 and 12.5 C with the greatest increase observed on February 19.

4.3.3 CORN Plot

The influence of a corn canopy on diurnal temperature variations and soil warming effects is illustrated in Table 16. 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. 17.8C and 14.7 vs. 14.0 C) on the CORN plot at the 5 cm depth. The lower maximum temperatures can be attributed to the shading effect. The higher minimum temperatures can be attributed to a reduction of long-wave radiation at night due to the corn canopy.

Average daily temperatures were 4 to 5 C lower than those observed on the NO COVER plot on August 11 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 in spite of the dense vegetative cover which provided shading. 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. Apparently the repairs made following a break in the source did not enable the heat source to function normally from that time on. Temperature data were not shown for this plot for August 19 because the heat source temperatures were in excess of 50 C on this date.

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 at 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. Diurnal variations at 5 and 15 cm depths were less on the SUB-IRR plot than on the NO COVER plot. The total profile variations were slightly higher on the SUB-IRR plot while 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. For both days 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 experienced 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. Soil temperatures to a depth of 45 cm 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. On the cooler day temperatures to the 45 cm depth were nearly the same for both cover conditions.

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

Comparisons of average daily temperatures for various depths 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 10. Data points represent 10-day average temperatures plotted at the midpoint of the 10-day period. All

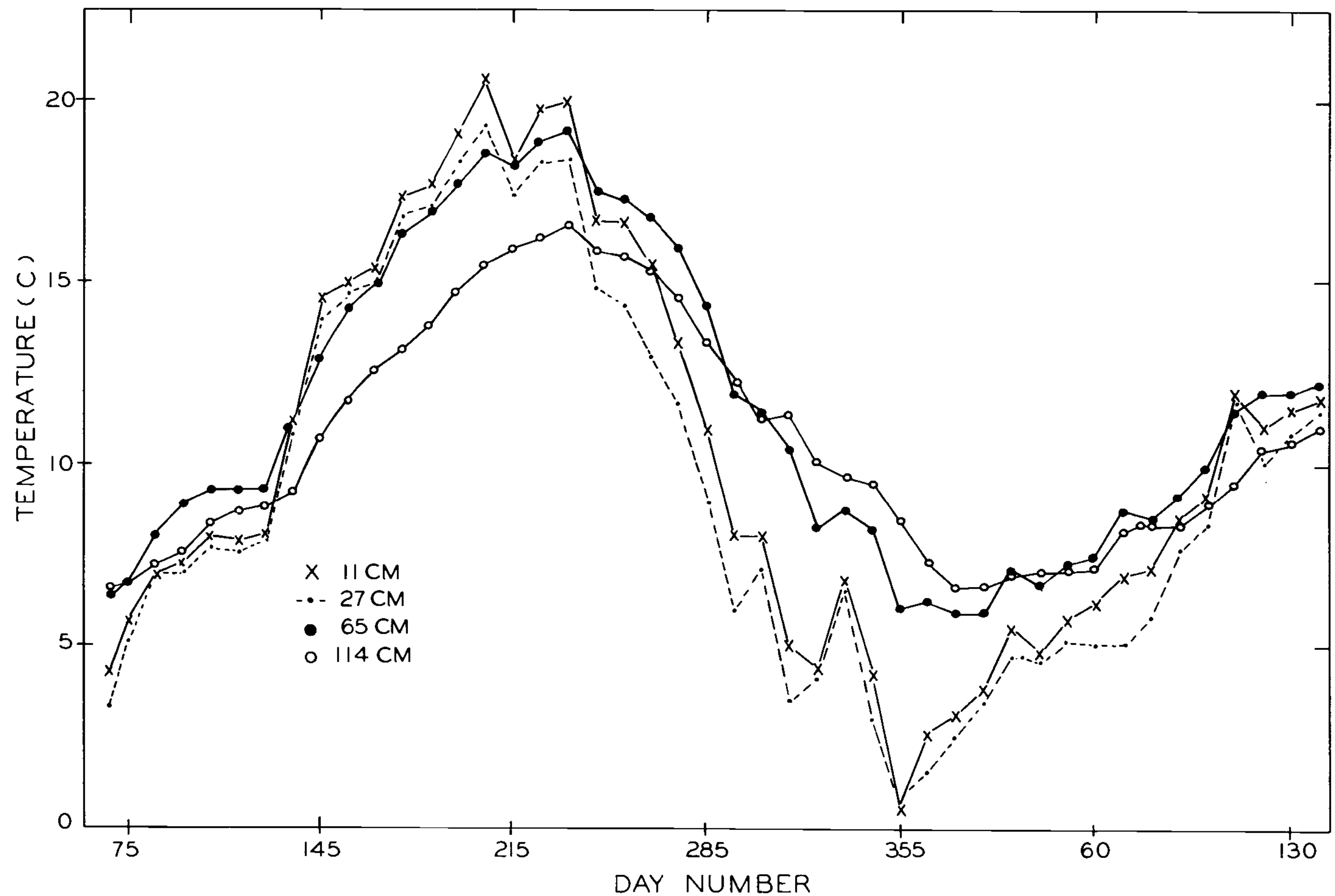

Figure 10. Ten-day average soil temperatures at 11, 27, 68 and 114 cm depths obtained during 1964-1965, after Boersma and Simonson (1970).

measurements were made at 0800 throughout the study period. It was found that at 5 and 15 cm depths observations made at 0800 hours were somewhat below average daily temperatures. At 68 and 114 cm depths temperatures do not change during the day and these temperatures may therefore be assumed to represent daily averages.

Figure 10 illustrates that soil temperatures do not exceed 20 C for an extended time at any depth under natural conditions in the Willamette Valley. Assuming that average daily temperatures at the 11 cm depth were 2 C higher than those reported in Figure 10, temperatures in excess of 20 C would have occurred for about 30 days in 1964 at this depth. 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 are shown for selected days throughout the year in Table 18 and Figures 11, 12 and 13. 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.

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

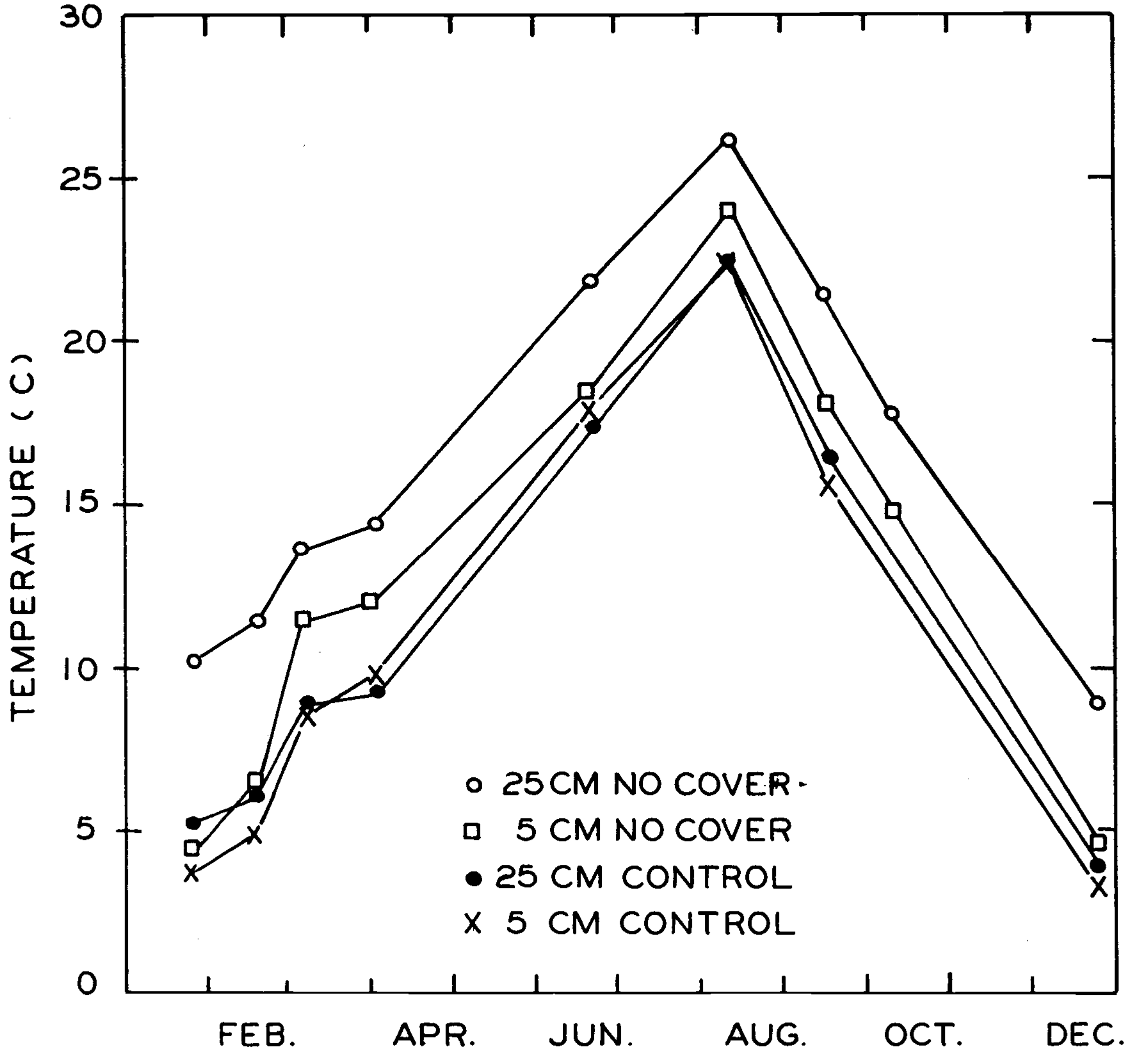

Figure 11. Average daily temperatures at 5 and 25 cm depths on CONTROL and NO COVER plots for selected days throughout the year.

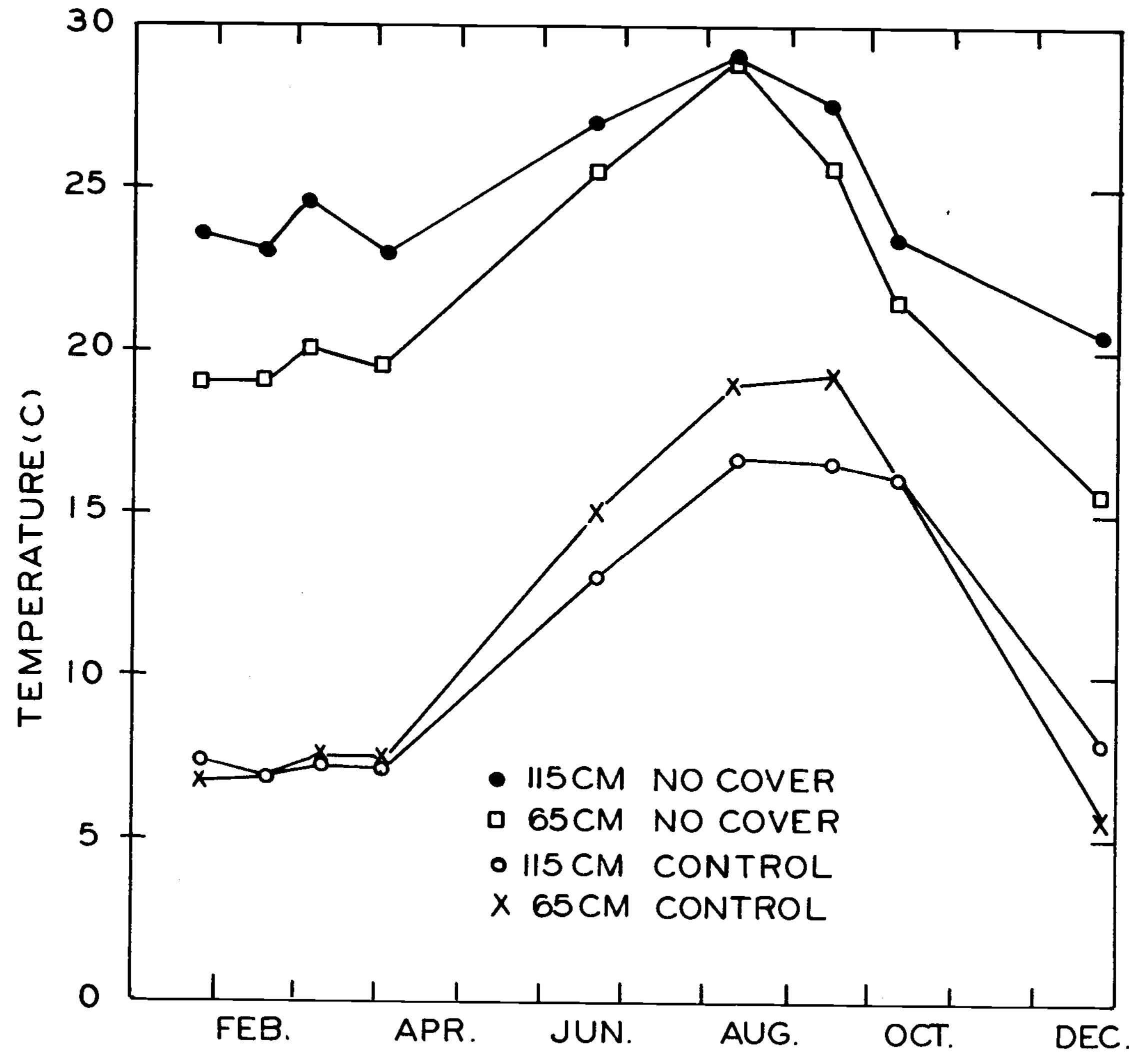

Figure 12. Average daily temperatures at 65 and 115 cm depths on CONTROL and NO COVER plots for selected days throughout the year.

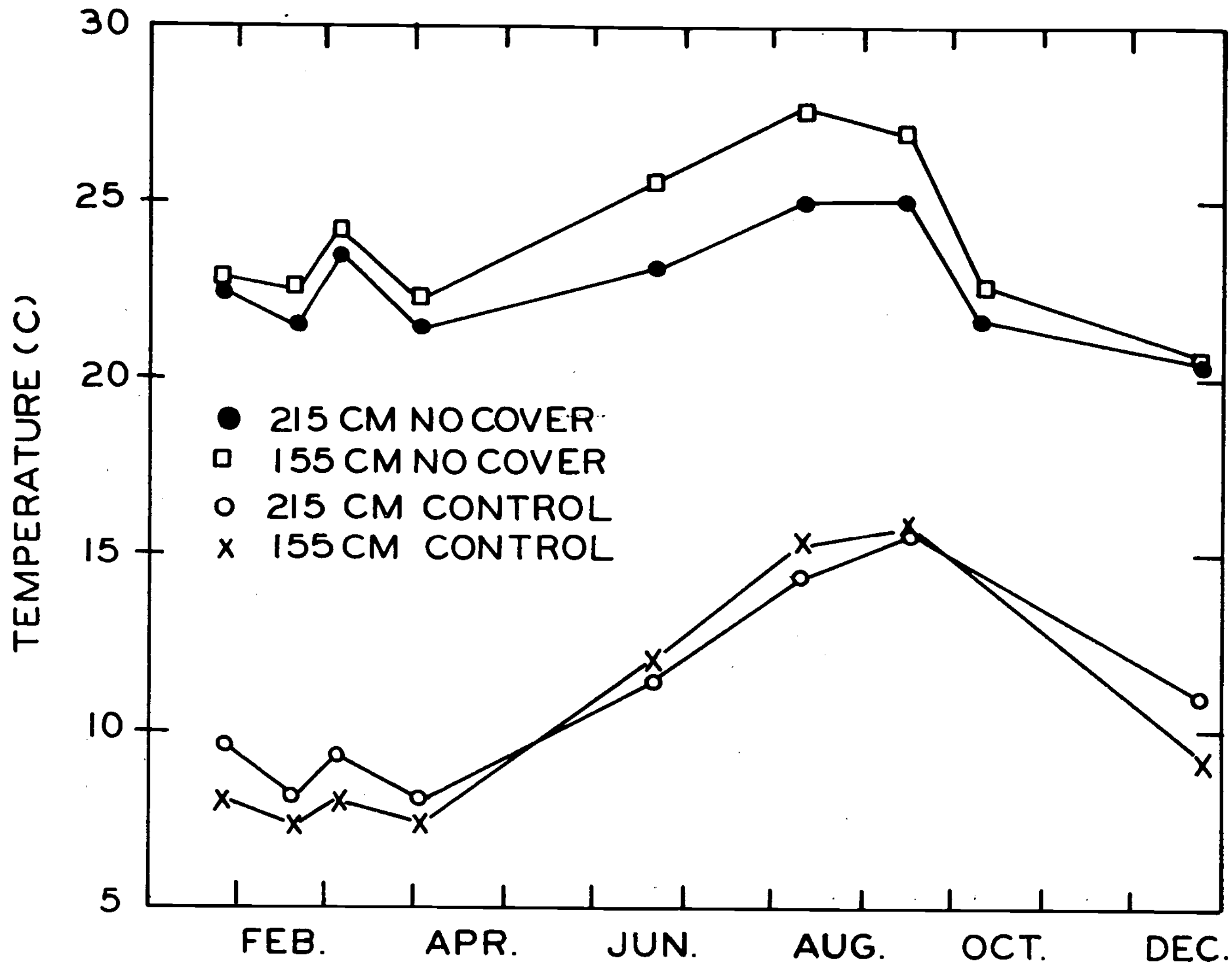

Figure 13. Average daily temperatures at 155 and 215 cm depths on CONTROL and NO COVER plots for selected days throughout the year.

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

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 (Table 18). 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.

CONTROL plot temperatures at all depths show good agreement with those obtained by Boersma and Simonson (1970). The mid-summer peaks in Figures 11 and 12 may be exaggerated somewhat by the choice of an unusually hot day in August. It is again apparent that temperatures in excess of 20 C are experienced infrequently under natural conditions in Willamette Valley soils.

Soil temperatures at depths in excess of 120 cm are probably not

4.5 Summary and Conclusions

It is apparent from soil temperature comparisons between unheated and heated locations that in all cases buried heat sources were effective in maintaining significantly higher temperatures throughout the profile to a depth in excess of 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 held 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 of less than 1 cm diameter. Heated waters from power generating stations would be at a lower temperature during winter months than temperatures maintained at electrical heating cables 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. However, the results of this study indicate that buried heat sources can be effectively used to maintain root zone temperatures at near optimum levels during a large portion of the year under Willamette Valley climatic conditions.

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. Pressure gradients are small under these conditions and vapor phase flow may be expected to be minimal even at elevated temperature gradients. 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 water 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.

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.

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

	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	.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 measurements shown 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 presented by Boersma and Klock (1966) for the 60 to 90 cm depth in Woodburn soil (Figure 14). The results showed 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 only 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	$\gg$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

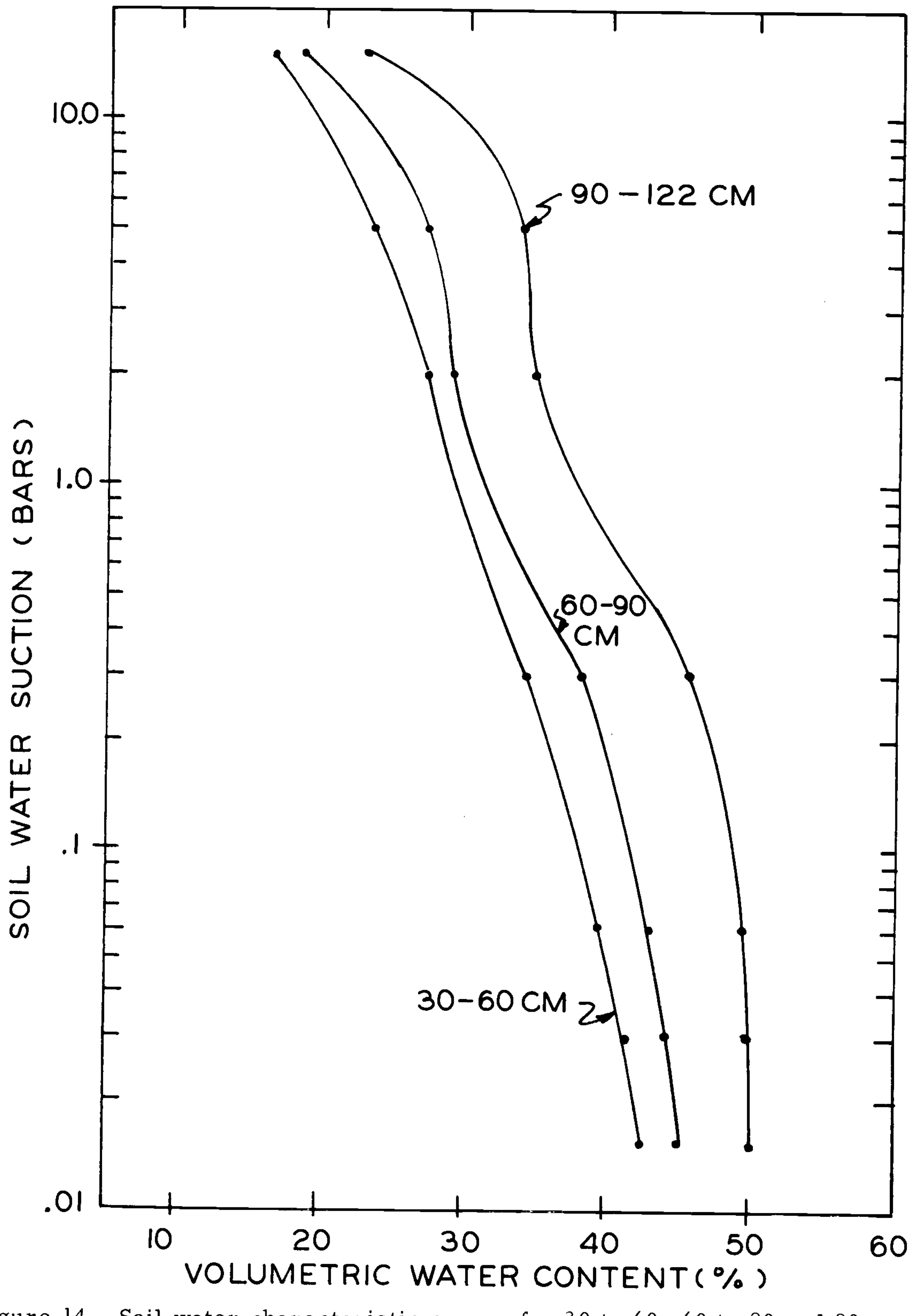

Figure 14. Soil water characteristic curves for 30 to 60, 60 to 90 and 90 to 122 cm zones in a Woodburn soil, constructed from data presented by Boersma and Klock (1966).

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 towards 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. Water contents 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.

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 21 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.

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

	Unheated Depth (cm)				Heated Depth (cm)			
Date	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

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 sytem. 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

Table 23. Soil water suction values obtained midway between crop rows on the CORN plot during 1972. 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	.74	.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	.49	.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

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.

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	1.69	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

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 from the heat sources. Values shown for positions over the heat sources are averages of 12 replications. For positions between

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	61	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	.25	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

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.

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 therefore used for the upper 60 cm of the soil profile. The three soil water characteristic curves are shown in Figure 14.

Energy budget calculations to be made later (Section 6) require estimates of soil water content and changes in soil water content for

55 to 215 cm depth increment. 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 growing season on the SUB-IRR plot and on selected days throughout a one year period on the NO COVER plot. Results of these calculations are shown in Table 27.

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.

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	12/31	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

The changes shown for the SUB-IRR plot in Table 27 were similar to the NO COVER plot for the layer from 106 to 215 cm (46.5 to 44.4 percent). However, much larger changes occurred in the upper layer. The 39.1 to 28.8 percent change in water content which occurred in the 55 to 106 cm layer 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 15 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. Measurements

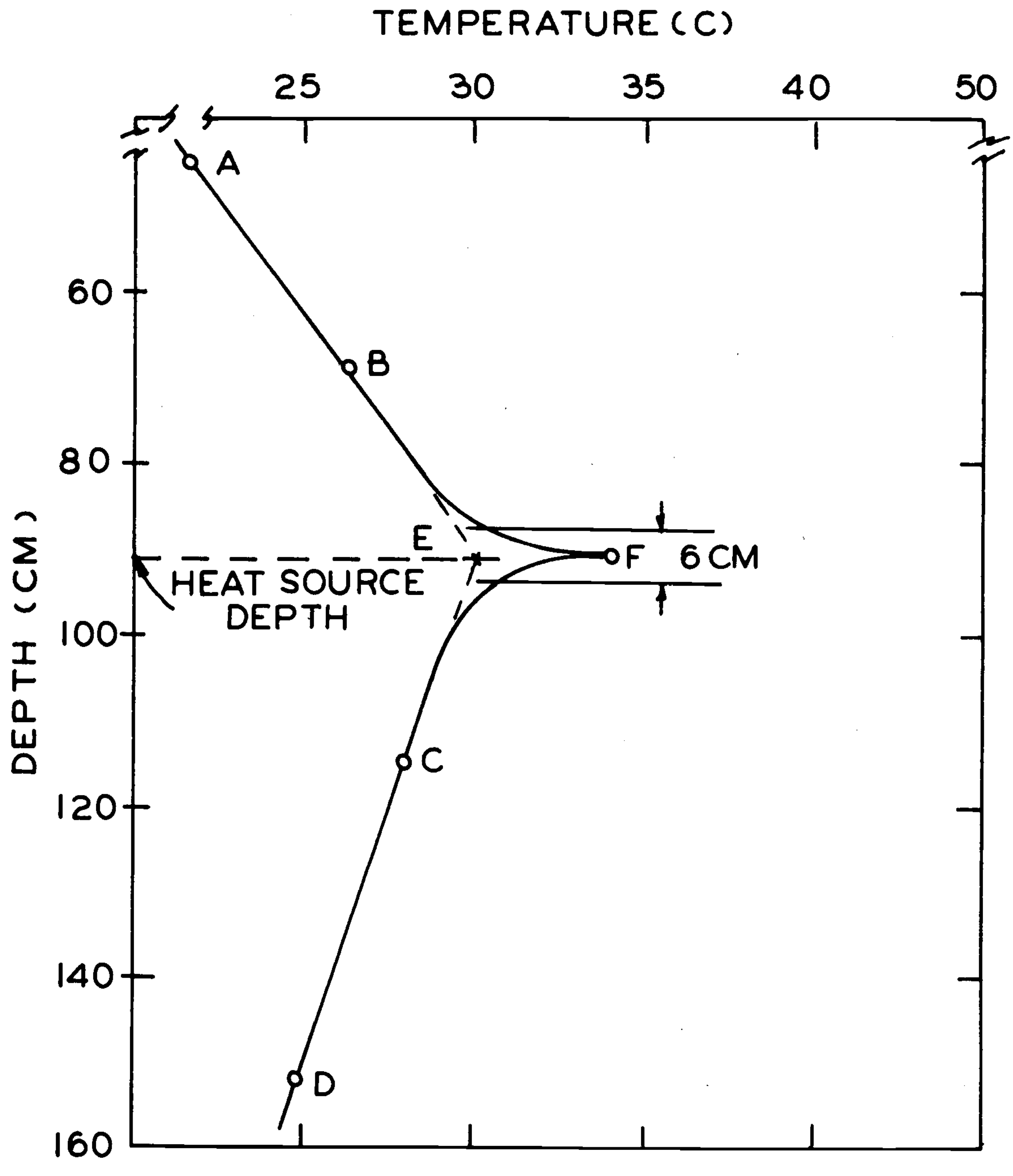

Figure 15. Soil temperatures measured in a vertical plane passing through the heat source. NO COVER plot, August 3, 1972.

to construct the change in soil temperature as a function of soil depth near the heat source (Figure 15) were not available. 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 then drawn, based on the assumption 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 15. 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 is indicated in Figure 15 that the temperature decrease was 2.45 times greater in the 0 to 2 cm zone than in the 2 to 4 cm zone. Thermal conductivities for these two zones were obtained by using Figure 1 and the water contents shown in Table 21. The thermal conductivity increased in the same proportion as the temperature change decreased. 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.

It is important to recognize that if the soil was uniformly at the same water content a heat source temperature of 30 C would produce the observed temperatures at A, B, C and D. 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 16. 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.

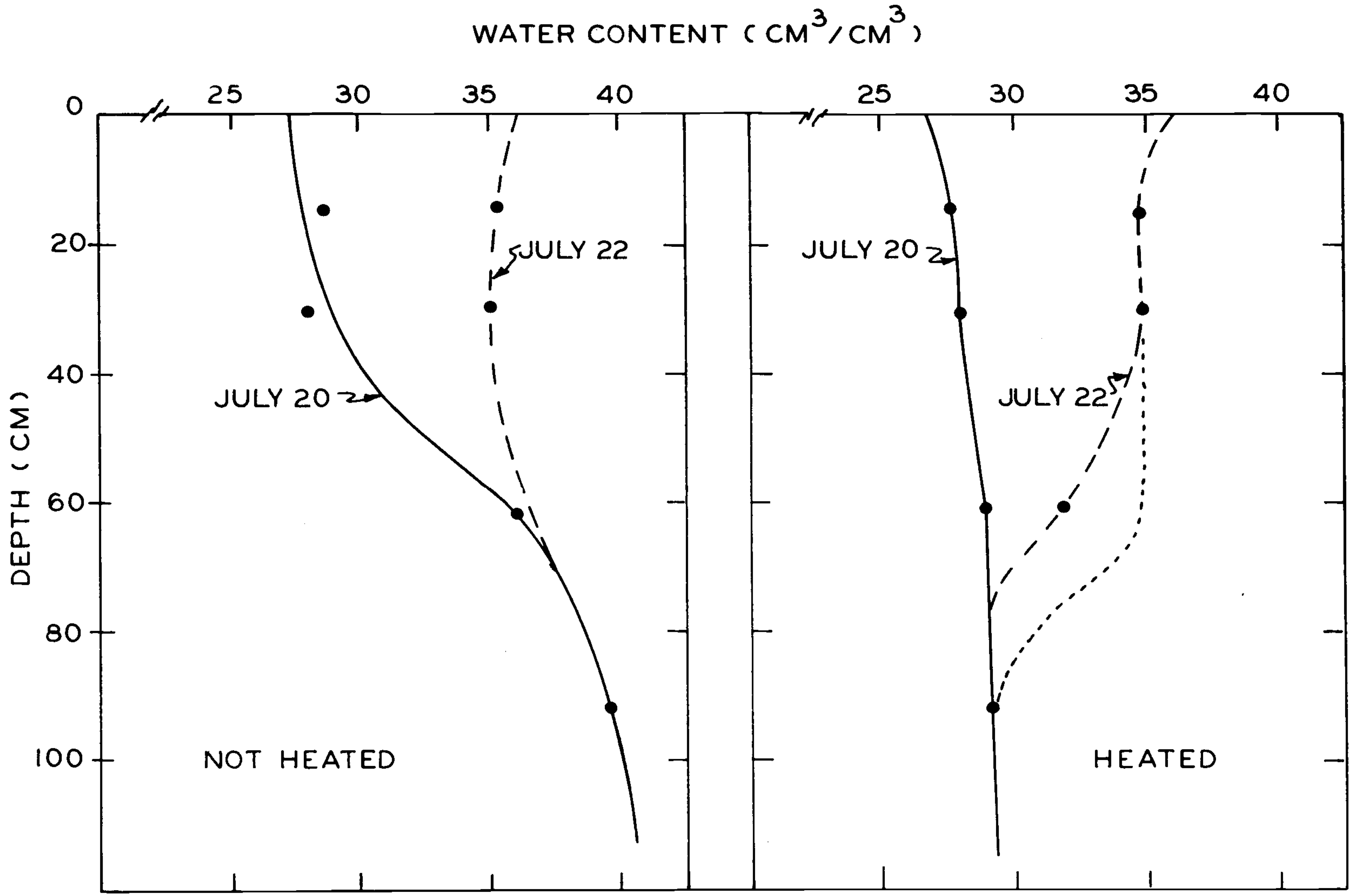

Figure 16. Soil water content before (July 20) and after (July 22) an application of 4.5 cm of irrigation water on unheated and heated CORN plots.

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 16. 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.

The rate of energy dissipation on this plot was 2,300 cal/cm^2 day. Only 25 percent of this energy would be required to evaporate the remaining 1 cm of water. It is suggested that the unheated plot did not absorb all available water because of limited pressure gradients. The heated plot did absorb all available water, but part of it was immediately lost due to enhanced evaporation. Rewetting the profile of the heated plot requires higher rates of water application. Similar patterns were observed during other irrigation cycles.

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 suction 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 was observed 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 sub-surface 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 temperature gradients 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 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 the 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.

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

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	C	C	C	C	C	C	C	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

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. Field measurements were obtained at 152 and 213 cm depths at several horizontal distances from the heat source.

The upward temperature gradient was obtained by averaging gradients from 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 horizontal 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 14). 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 .20 cal/cm min C throughout the year was assumed for this region. This conductivity was derived from data presented by De Vries (1966) for a soil containing 55 percent clay. The clay content at this depth in Woodburn soil is less than 25 percent, but fine silts comprise about 50 percent of the soil fraction (Gelderman, 1970).

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 date 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.

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

Date	Temp. change	Mass		Temperature gradient	
		Soil	Water	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	.01	40.3	12.4	.31	1.03
10/10/70	-.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	-0.1	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	Upper	Calculated thermal conductivity
	-------------	cal/day*	------------		cal/cm min C
NO COVER plot:					
1/25/72	7,800	2,500	300	5,000	.08
2/19/71	6,500	- 400	800	6,100	.13
3/5/72	7,800	1,600	600	5,600	.11
4/2/72	6,200	1,400	600	4,200	.11
6/20/71	4,700	1,300	2,100	1,300	.05
8/11/71	3,400	600	2,200	600	.03
9/16/71	4,100	200	1,600	2,300	.09
10/10/70	3,100	- 800	900	3,000	.13
CORN plot:					
8/11/71	4,800	3,900	1,100	- 200	---
9/16/71	3,800	200	1,700	1,900	.10
SUB-IRR plot:					
8/6/72	5,800	2,500	2,000	1,300	.11
8/19/72	6,000	- 200	1,800	4,400	.17

*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.

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 8 percent of the total energy flow on the first four dates and 44 percent on the last four dates. Heat transfer at the upper boundary was about 74 percent of the total on the first four dates but only 47 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 .13 cal/cm min C to a low of .03 cal/cm min C at the end of the summer. These are low for all dates compared to values shown in Figure 1 for soil water contents found throughout the year (Section 5). 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 .21 C/10 cm existed on this date (Table 29). Yet the energy balance shows a downward heat flux of 200 cal/day 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. It is also possible that the thermal conductivity of the lower part of the profile was less than the assumed 0.20 cal/cm min C.

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. The relatively low thermal conductivities calculated for all dates included in the NO COVER and CORN plot analyses suggest that the value of

.20 cal/cm min C assumed for the lower boundary may have been too high for this soil.

6.3 Energy Dissipation as a Function of 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. Energy dissipation rates were obtained from kilowatt-hour meter readings taken periodically throughout the course of the study (Section 2.3). During the summer readings were taken at one to seven day intervals. During the winter readings were taken less frequently but at least twice monthly. 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 extrapolated from existing data 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

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

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 summarzied 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.

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

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 17. Equation 1

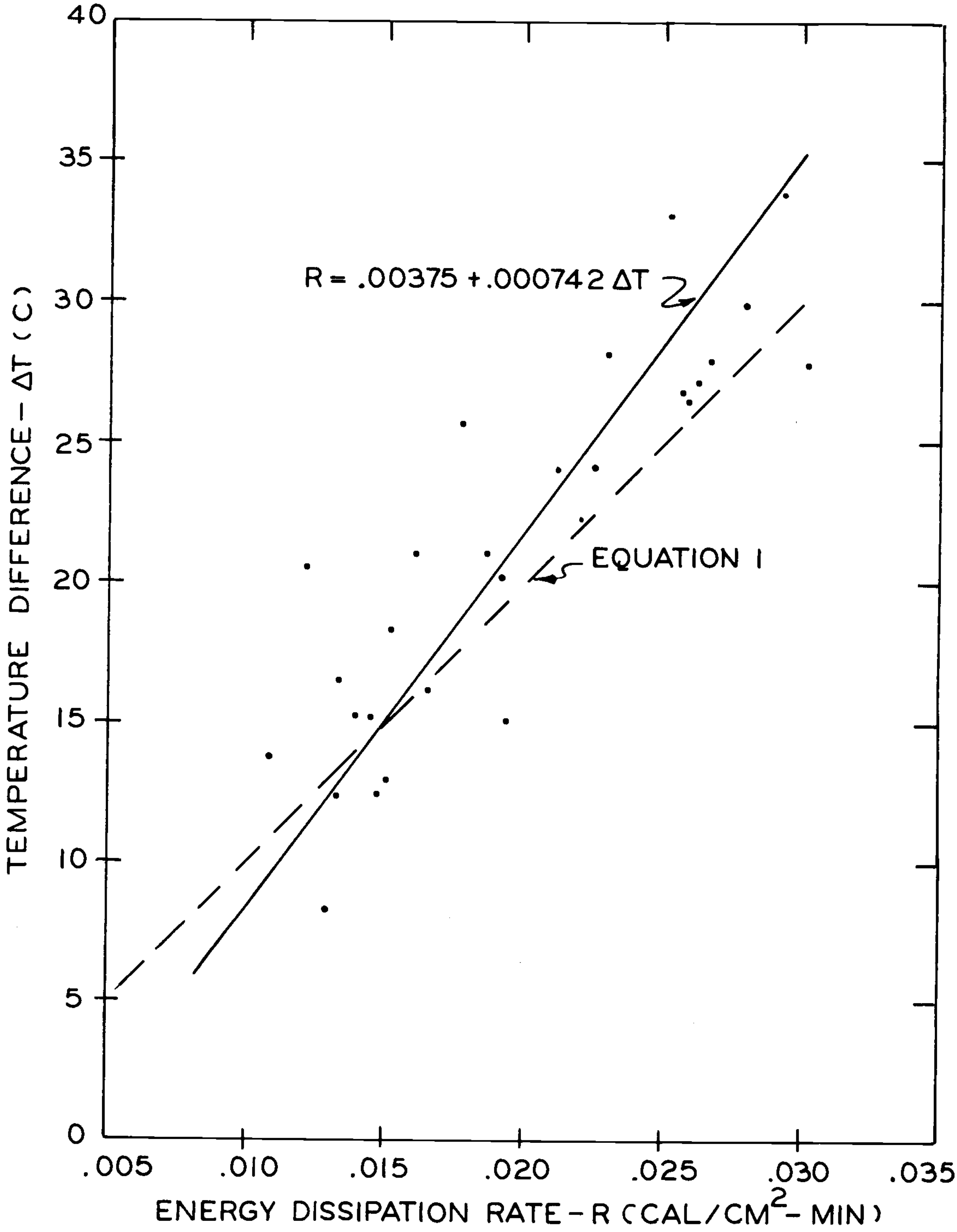

Figure 17. Mean monthly energy dissipation rates as a function of the difference between mean monthly heat source temperature and mean monthly air temperatures measured at the U.S. Weather Bureau Station.

for the conditions of Case IV (Section 1.4) corresponding to the design of the heat source system used on the NO COVER plot is also shown. A constant thermal conductivity of $k = .20$ cal/cm min C was assumed and the temperature difference varied from $\Delta T = 5$ C to $\Delta T = 30$ C.

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. Heat flow to regions below the heat source still occurs when the surface temperature is identical to the heat source temperature. This condition is not described by Equation 1 which was developed for steady state conditions. The rate of downward heat flow was shown in Table 30.

The theoretical model provides a good estimate of energy dissipation rates within the range of temperature differences measured during this study. Departures from the theoretical model can be attributed to two factors. The model assumes steady state conditions and therefore does not allow for changes in heat storage within the soil profile. It also assumes that all heat loss occurs at the soil surface and does not account for heat flow to lower regions of the soil profile.

6.4 Energy Dissipation as a Function of 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 heated 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 made throughout the time period.

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

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/ ΔT x 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

soil surface temperature (T_{su}) was:

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

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.

During September the onset of cooler weather results in a decrease in heat storage. Thus in addition to the energy input from the heat source, stored heat is transferred out of the profile. The result is that dissipation rates are lower than would be expected based on the temperature gradients. 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:

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

<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:

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

6.4.1.5 GREENHOUSE Plot. 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:

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

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.

6.4.2 Discussion

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:

$$R = .00181 + .000914(T_s - T_{su})$$

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 and no energy flow at the lower boundary of the profile 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. It means that more than the measured energy loss contributed to the energy flux

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	--

during the winter so that calculated conductivities should be higher during the winter. Heat flow at the lower boundary of the profile was found to be low during the winter but nearly equal to the rate of flow at the upper boundary during the summer. Taking this into account would result in a small reduction in the thermal conductivity obtained for the winter but a large reduction for the summer.

6.5 Land Area Required to Dissipate the Waste Heat from a 1,000 Megawatt Power Plant

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} cal/cm^{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 requirement of 6,230 ha. During August the average rate of heat dissipation was approximately 2.3 x 10^{-2} cal/cm^2min, corresponding to an area requirements 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 experimental results and Kendrick and Havens' (1973) theoretical predictions.

The results indicate that experimental data and predictions from theoretical models are in quite 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. YIELD RESPONSE TO SOIL WARMING

7.1 Introduction

7.1.1 Selection of Crops for Evaluation

The proposed soil warming system will be expensive to install and operate. Crops that respond with high yield increases or that have a high value will be required to make it economically feasible. Crops currently being grown in a given region may satisfy this requirement. On the other hand, it may become feasible and necessary to introduce new crops which are not adapted to a region under natural soil temperature conditions.

In choosing crops to evaluate the potential of soil warming in the Willamette Valley, consideration was given to present practices as well as possible alternatives. Some high value crops that grow well under natural conditions were used. These included strawberries, bush beans, broccoli, and peppers. Tomatoes and Lima beans are not grown commercially because of climatic limitations. They were grown in this study as alternative high value crops.

Double cropping of bush beans has been tried to a limited extent commercially but has not been successful enough to gain widespread acceptance. The limited success is due to climatic restrictions. This practice was evaluated in this study because the increased soil temperatures might overcome the climatic restrictions. High density plantings of bush beans also were evaluated.

The climate of the Willamette Valley is ideal for beef or dairy cattle enterprises. Mild winters allow nearly year-around grazing and minimize housing requirements. Combining forage production with a livestock enterprise would produce high value milk or meat for local markets. Year-around forage production capability makes this combination seem particularly attractive. Several crops which could play a role in the feeding of beef and dairy cattle were evaluated. Field corn is not grown extensively in the region because of lack of local markets and climatic limitations. This crop provides a possible source of silage and/or grain for a livestock enterprise. Sorghum-sudangrass hybrid and sudangrass were included as possible forage crops for summer production. Common Annual Ryegrass and Crimson Clover are potential winter annual forage crops to be grown in rotation with corn, sudangrass, or sorghum-sudangrass hybrid. Fawn fescue was evaluated as a long-term pasture or hay crop capable of year-around production.

Soybeans are being tested by researchers at several locations in Oregon to determine if sufficient yields can be achieved to justify introduction of this cash crop. Climatic limitations make its feasibility doubtful. This crop was included as a potential cash crop which could also be used as a silage crop for livestock production.

7.1.2 Evaluation of Crop Response

The plot area available for experimentation was limited by the cost of installation of the soil warming system and the cost of operating the system. At the same time it was deemed desirable to grow and evaluate a wide variety of crops. Because of these space and resource limitations it was not possible to evaluate factors other than soil heating. It was recognized that changing soil temperature regimes might require adjustments in other management practices such as plant population, water application rates, fertilization and weed control. To minimize the effects of these factors on production, an attempt was made to optimize management levels based on the best information available for the various crops grown. It was possible to include fertility treatments in some experiments. Space requirements also limited the degree of replication that was possible.

7.2 Sudangrass (*Sorghum vulgare-sudanense*)

7.2.1 Introduction

Sudangrass is the most important temporary pasture crop in the United States. It can be used for grazing, greenchopping, silage or hay. In warm dry climates, sudangrass yields more dry matter than nearly all summer annual forage crops. It was included in this study as a potential source of summer and fall forage in a double-cropping, forage production system. Sudangrass is not grown extensively in the Willamette Valley due to a lack of dairy or beef enterprises requiring crops of this nature.

Sudangrass is a freely tillering annual bunchgrass which is best adapted to a warm climate. Germination is poor in cold wet soil and subsequent growth is slow. Soil temperatures should be several degrees higher at planting time than is recommended for corn, as evidenced by the two to three week later planting date recommended (Martin and Leonard, 1949; Wheeler, 1950).

Optimum temperature for growth has been reported to be about 27 C. At temperatures of 15 C or less, little or no growth occurs (Sullivan, 1961). As temperature increases from 15 to 27 C, the content of crude protein increases and that of lignin decreases. Thus, warmer growing conditions improve the feeding quality.

Sudangrass is highly susceptible to frost damage. High prussic-acid content following a frost poses a hazard for feeding cattle. There would be little chance of frost damage in most years under a double cropping system in the Willamette Valley. The problem can be solved by proper management of grazing or cutting programs (Hanson, 1963).

Sudangrass develops a dense, fibrous root system. This crop grows successfully in regions of low summer rainfall. Experiments have shown that it requires more water to produce a given amount of dry matter than corn. Thus irrigation requirements are high

(Wheeler, 1950).

7.2.2 Methodology and Results

The cultivar Trudy was planted on May 28, 1971. A broadcast application of 54 kilograms per hectare (kg/ha) of actual nitrogen (N), 67 kg/ha of phosphate (P_2O_5) and 50 kg/ha of sulfur was made prior to planting. An additional 93 kilograms/hectare (kg/ha) of actual nitrogen (N) was broadcast on June 30. During the season 35.3 cm of irrigation water was applied with full circle sprinklers. The heat source temperature was maintained near 32 C during most of the growing season.

Plots were harvested on July 29 and October 7. Dry matter yields in metric tons per hectare (tons/ha), percent dry matter and yearly total yields are shown in Table 35. To obtain dry matter content samples were placed in an oven maintained at 70 C for 48 to 72 hours.

The same cultivar was planted on June 13, 1972. A broadcast application of 54 kg/ha of actual nitrogen, 67 kg/ha of P_2O_5 and 50 kg/ha of sulfur prior to planting was followed by an application of 76 kg/ha of actual nitrogen on August 15. During the growing season, 40.9 cm of irrigation water was applied with full circle sprinklers. The heat source temperature was maintained near 35 C during most of the growing season. Harvest dates were August 14 and October 5.

Botanical separates were taken to determine the amount of weeds in the samples. Results are shown in Table 35.

Table 35. Dry matter yield, percent dry matter, and percent weeds for two cuttings of sudangrass.

Harvest date	Treatment	Yield	Dry matter	Weed content	Relative yield
		T/ha	%	%	%
7/29/71	Unheated	5.44	21.5	--	100
	Heated	6.76	20.3	--	124
	LSD (P < .05)	1.21	N.S.		
10/7/71	Unheated	6.59	22.2	--	100
	Heated	10.00	20.6	--	152
	LSD (P < .05)		1.6		
	LSD (P < .01)	1.88			
	Total - Unheated	12.03			100
	Total - Heated	16.76			139
8/14/72	Unheated	4.39	17.4	15	100
	Heated	8.19	15.5	2	187
	LSD (P < .01)	1.41	1.9	6	
10/5/72	Unheated	2.73	18.6	42	100
	Heated	4.56	14.8	2	167
	LSD (P < .05)		2.4		
	LSD (P < .01)	.87		29	
	Total - Unheated	7.12			100
	Total - Heated	12.75			179

7.2.3 Discussion

Yield response to heating in 1971 was significant at the 5 percent level (P < .05) for the first cutting and at the 1 percent level (P < .01) for the second cutting. The decrease in dry matter percent due to heating was small and not significant for the first harvest. The decrease was small but significant at the 5 percent level for the second harvest. Least significant differences (LSD) are indicated in Table 35.

No information was obtained about plant density or weed content in 1971. The heated plots had a higher plant density and few weeds while the unheated area had a less dense stand of sudangrass and a significant weed population. Germination of sudangrass was limited by low soil temperatures on unheated plots. It readily germinated on the heated plots and successfully competed for space and moisture.

The yield response to heating in 1972 was significant at the 1 percent level for both harvests. Higher dry matter percentages were found on unheated plots. These differences were significant at the 1 percent level for the first harvest and at the 5 percent level for the second harvest. Weed content on unheated plots was higher for both harvests than the weed content on heated plots. The differences were significant at the 1 percent level.

The 1972 yields on heated plots were higher for the first harvest than those obtained in 1971. The number of growing days was the same. The heat source temperature was maintained at 60 C during June. Temperatures throughout the profile were much higher in 1972 than in 1971 when the heat source temperature was maintained at 32 C.

Yields from the unheated plots for the first harvest were below those of 1971. These plots again had a significant weed problem but the heated plots did not. This is demonstrated by the results of a botanical separation (Table 35). No measure of weed content was obtained in 1971. The appearance of the plots was the same in both years and it is suggested that weed content and plant density were similar in both years.

The 1972 second harvest yields were low for both treatments. A frost on September 27 stopped growth. The weed content of unheated plots had dramatically increased but remained the same on heated plots.

The average yield increase for the two years from heating was 54 percent. The high response in 1972 was due to higher soil temperatures during the first month after planting. Lower total yield in 1972 resulted from a shorter growing season due to later planting and an early frost.

7.2.4 Conclusions

Results of two years of experimentation suggest that sudangrass planted about June 1 could be harvested twice before October 10, with a total dry matter yield of about 15 metric tons per hectare (tons/ha) under heated conditions. Soil heating appears to be very important in the establishment and early growth of this crop.

7.3 Sorghum-Sudangrass Hybrid (*Sorghum vulgare-sudanense* Hybrid)

7.3.1 Introduction

Sorghum-sudangrass hybrids are similar to sudangrass in yield potential and climatic requirements. They are not grown extensively in the Willamette Valley because of a lack of need for summer annual forages. This crop was included in the study as an alternative to sudangrass or corn for forage production.

Locally adapted cultivars of sorghum-sudangrass hybrids have a yield potential similar to sudangrass cultivars (Hanson, 1963; Wedin, 1970). Under periodic harvest management schemes, Wedin (1970) found the Mor-Su cultivar to have a slightly higher mean yield than five other sorghum-sudangrass hybrids and two sudangrass cultivars. The sorghum-sudangrass hybrids were superior when using a single harvest.

McGuire[1/] found sudangrass cultivars to be slightly superior to sorghum-sudangrass hybrids under two-cutting management in numerous trials in the Willamette Valley. He attributes this to slightly higher heat unit requirements for sorghum-sudangrass hybrids.

[1/] William S. McGuire, professor of agronomic crop science, Oregon State University, personal communication.

7.3.2 Methodology and Results

The Mor-Su cultivar of sorghum-sudangrass hybrid was planted on May 28, 1971. Fertilization, irrigation, and heat source temperature were identical to those discussed for sudangrass in Section 7.2.2. Harvesting was on the same dates (July 29 and October 7). Yields of dry matter and percent dry matter are indicated in Table 36.

Table 36. Dry matter yield, percent dry matter, and percent weeds for two cuttings of sorghum-sudangrass hybrid.

Harvest date	Treatment	Yield	Dry matter	Weed content	Relative yield
		T/ha	%	%	%
7/29/71	Unheated	4.88	20.8	--	100
	Heated	8.26	17.2	--	169
	LSD (P < .01)	2.53	2.2		
10/7/71	Unheated	7.04	21.1	--	100
	Heated	9.30	19.4	--	132
	LSD (P < .01)	1.57	N.S.		
	Unheated - Total	11.92			100
	Heated - Total	17.56			147
8/14/72	Unheated	5.38	14.3	11	100
	Heated	8.42	14.2	2	156
	LSD (P < .05)		N.S.	7	
	LSD (P < .01)	2.32			
10/5/72	Unheated	3.41	18.5	15	100
	Heated	5.37	16.8	2	157
	LSD (P < .01)	1.20	N.S.	9	
	Unheated - Total	8.79			100
	Heated - Total	13.79			157

The same variety was again planted in 1972 on June 13. Fertilization, irrigation and heat source temperatures were the same as discussed for the 1972 sudangrass planting. Yields of dry matter, percent dry matter, and percent weeds are presented in Table 36. Botanical separates were taken to determine the weed content of the harvested material.

7.3.3 Discussion

Yield response to soil heating was significant at the 1 percent level for both cuttings in 1971. The percent dry matter was lowest on heated plots. The decrease was significant at the 1 percent level for the first cutting. The 47 percent increase in total yields due to heating was slightly higher than that achieved with sudangrass. It was indicated in Section 7.3.1 that sorghum-sudangrass hybrid may have slightly higher heat unit requirements than sudangrass. Experimental work done in the Willamette Valley indicates that sudangrass usually produces higher yields than sorghum-sudangrass hybrid under natural soil temperature conditions. Yields of the two crops were nearly the same on the unheated plots. The sorghum-sudangrass hybrid yielded nearly one ton/ha dry matter more than sudangrass on heated plots.

Problems of germination and weed control encountered with this crop were similar to those observed for sudangrass. Unheated areas had poor stands and numerous weeds. Germination on unheated areas was slow. Weeds were not a problem on heated plots because the sorghum-sudangrass hybrid germinated rapidly and competed successfully with the weeds. No measure of weed content was obtained in 1971.

The yield response to heating in 1972, an increase of 57 percent for both harvests, was significant at the 1 percent level. Weed content differences were significant at the 5 percent level for the first harvest and at the 1 percent level for the second harvest.

Yields of the first cutting were slightly higher in 1972 than in 1971 on both heated and unheated plots. The later planting date and higher heat source temperatures were probably the reasons for this. Low yields for the second cutting in 1972 were the result of a September 27 frost. Total yields in 1972 were lower than in 1971 as a result of the shorter growing season. The average yield increase due to heating for the two years was 51 percent. About the same increase was observed for the sudangrass.

The percent dry matter was highest on unheated plots for all harvests of both sudangrass and sorghum-sudangrass hybrid. This was probably due to the higher weed content on the unheated plots. The greatest difference in percent dry matter was observed for the second cutting of sudangrass in 1972 when the weed content was highest.

7.3.4 Conclusions

The yields of sorghum-sudangrass hybrid on heated plots were about 1 ton/ha higher than sudangrass yields in both years. This is contrary to the results obtained by other research efforts involving these crops in the Willamette Valley. This suggests that soil warming may be more beneficial for sorghum-sudangrass and lends support to the suggestion that heat unit requirements may be higher for this crop.

Wedin (1970) found that sorghum-sudangrass hybrids were superior to sudangrass under one-cutting management. The use of these crops as silage in a dairy enterprise would involve one-cutting management. Sorghum-sudangrass hybrid appears to be the best choice between the two crops under both management systems.

7.4 Common Annual Ryegrass (*Lolium multiflorum*)

7.4.1 Introduction

Common Annual Ryegrass is important in the Willamette Valley as a forage crop and for seed production. It establishes very quickly and produces good yields of succulent forage during the winter months and early spring if seeded in early fall. It was included in this study to evaluate the effect of soil warming on winter annual grass production in rotation with sudangrass or sorghum-sudangrass hybrid.

Common Annual Ryegrass is well adapted to the climate of the

Willamette Valley where most of the seed for this crop is produced. However, low soil temperatures in the fall may retard the establishment of ryegrass if it is planted too late (Schoth and Weihing, 1966).

7.4.2 Methodology and Results

Common Annual Ryegrass was planted on September 26, 1970. A broadcast application of 448 kg/ha of ammonium sulfate was harrowed in prior to planting. Additional broadcast applications of 57 kg/ha of actual N, 54 kg/ha of actual N and 67 kg/ha of P_2O_5, and 114 kg/ha of actual N were made on October 14, January 4, and March 31, respectively. The heat source was maintained at 25 C during most of the growing period. The heat source was not energized during a portion of the growing period due to mechanical problems. As a result of a break in the heating cable and subsequent problems in making repairs, the heat source was not in continuous use until early February. Results for 1970-1971 are presented in Table 37.

Common Annual Ryegrass was again planted on November 6, 1971. All plots received broadcast applications of 68 kg/ha of P_2O_5 and 67 kg/ha of potassium (K_2O). Nitrogen was applied at rates of 112, 224, and 336 kg/ha of actual N with a sulfur-coated urea compound. Thus three nitrogen treatments were established. The 1 to 2 millimeter pellets contained 34.5 percent N, 20.5 percent sulfur, and had a dissolution rate of 29.2 percent in 13 days. This slow release nitrogen compound is being tested extensively for use on forage crops. It is intended to be used in lieu of more soluble forms which need to be applied periodically throughout the production period. The heat source temperature was maintained at 40-55 C during the growing season.

The grass was harvested on March 24 and April 27. Yields in tons/ha of dry matter for each harvest and for the total of the two harvests are presented in Table 37.

7.4.3 Discussion

During the first year (1970-1971) the yields were significantly different (at the 5 percent level) only for the second harvest date. The total yields were significantly different at the 1 percent level. The response to heating for the total yield was 18 percent. During the second year, effects of the heating and fertility treatments were significant at the 1 percent level for both cuttings and for the total yield. Least significant differences are indicated in Table 37. The heating by fertility interaction was significant at the 1 percent level for both cuttings and at the 5 percent level for total yield. This was due to the failure of the highest fertility level to increase yields as much on the heated plots as on the unheated plots. The difference in yields between the two highest nitrogen rates was not significant on heated plots while on the unheated plots the additional nitrogen nearly doubled the yields of the second cutting. It is possible that soil heating hastened the dissolution of the sulfur-coated urea so that it was less available for growth after the first cutting.

Table 37. Dry matter yields of Common Annual Ryegrass.

Year	Fertilizer treatment	Harvest date		Temperature treatment Unheated	Heated
				T/ha	T/ha
1970-71	None	12/21		1.39	1.57
		3/24		1.45	2.04
		4/26		2.76	3.04
		5/12		1.30	1.46
		Total		6.90	8.11
1971-72	112 kg N/ha	3/24		0.00	0.63
		4/27		0.43	1.55
		Total		0.43	2.18
	224 kg N/ha	3/24		0.07	1.30
		4/27		1.19	2.28
		Total		1.26	3.58
	336 kg N/ha	3/24		0.36	1.93
		4/27		1.97	2.02
		Total		2.33	3.95
1971 LSD ($P < .05$) heating:		3/24	- .54		
1971 LSD ($P < .01$) heating:		Total	- .87		
1972 LSD ($P < .01$) heating:		3/24	- 0.19		
		4/27	- 0.27		
		Total	- 0.39		
1972 LSD ($P < .01$) fertility:		3/24	- 0.24		
		4/27	- 0.33		
		Total	- 0.48		

Total yields were much lower in the second year due to late planting. First cutting yields were much higher on the heated plots for all nitrogen treatments. This can probably be attributed to the higher soil temperatures. Germination was better on the heated plots and the time required for establishment of the grass was obviously greatly reduced by heating. The nitrogen response can not be adequately discussed without a better understanding of the effect of soil temperature on the fate of the sulfur-coated urea fertilizer.

7.4.4 Conclusions

The yield potential of Common Annual Ryegrass is best illustrated by the 1970-1971 results. In a rotation with sorghum-sudangrass or sudangrass the ryegrass crop could be planted early in October. Four cuttings should be possible. Yields in the 1970-1971 season were undoubtedly reduced on heated plots because of the heating cable problems and low source temperatures when the heat source was energized.

The late planting in the 1971-1972 crop year severely reduced yields. However, soil warming appeared to be effective in promoting establishment. It appears that soil warming would be more beneficial for later planting dates.

These results suggest that double cropping with sorghum-sudangrass hybrid and Common Annual Ryegrass would result in total dry matter yields of approximately 25 tons/ha/year. Planting and harvesting dates for the two crops are compatible. Ryegrass could be planted in early October with the final harvest in May. The sorghum-sudangrass crop could then be planted in early June with the final harvest at the beginning of October.

7.5 Crimson Clover (*Trifolium incarnatum* L.)

7.5.1 Introduction

Crimson Clover is a winter annual legume grown for forage. Although the major region of importance for this crop is the southeastern United States, it is fairly well adapted to the cool, humid coastal regions of the Pacific Northwest. Crimson Clover could be important in the Willamette Valley for livestock forage in the spring, as a green manure crop, or for seed production. Because of its ability to produce high quality forage early in the spring, it could easily fit into a rotation, producing a valuable crop when the land may otherwise be idle.

Crimson Clover is adapted to cool, humid weather and mild winters with moderate temperatures. It is important to plant early enough in the fall to enable the crop to establish good growth prior to the onset of cold weather. Optimum soil temperature for germination is about 20 C (Anonymous, 1969).

7.5.2 Methodology and Results

Crimson Clover was planted on September 28, 1970. A broadcast application of 448 kg/ha of ammonium sulfate was harrowed in prior to planting. An additional application of 54 kg/ha of actual N and 67 kg/ha of P_2O_5 was made on January 4, 1971. The heat source was energized September 14. Because of a break in the cable and subsequent problems in making repairs, the heat source was out of use most of the time from mid-October to February. From September 14 through May 12, when the crop was harvested, the heat source was maintained at 25 C when in use.

Two harvest areas of 14 square meters each were cut for each heating treatment. Table 38 presents dry matter yields and percent dry matter for the May 12 harvest. The 64 percent response to heating was significant at the 5 percent level.

Table 38. Dry matter yield and percent dry matter of Crimson Clover.

Treatment	Yield	Relative yield	Dry matter
	T/ha	%	%
Unheated	3.00	100	15.9
Heated	4.93	164	15.9
LSD ($P < .05$):	.77		

7.5.3 Conclusions

Soil heating had a marked effect on fall growth of Crimson Clover. This was reflected in the large differences in yields between unheated and heated plots. Even with soil heating this crop is inferior to Common Annual Ryegrass in yielding ability. Forage quality and its value as a green manure crop may offset yield limitations of the crop.

7.6 Tall Fescue (*Festuca arundinacea*)

7.6.1 Introduction

Tall fescue seed production has been of major economic importance in the Willamette Valley for more than 30 years. The Alta strain of tall fescue was developed at the Oregon Agricultural Experiment Station. In addition to its importance as a seed crop, it is widely grown in western Oregon as a forage crop (Cowan, 1966). Fawn fescue was included in this study to determine if soil warming could enhance winter growth and to see if higher soil temperatures during the summer months would reduce production potential.

Tall fescue is a deep rooted crop which remains green and vigorous in the Willamette Valley when most other grasses go dormant due to high or low temperature extremes and soil water stress (Wheeler, 1950). Forage yields are high and of high quality compared with other perennial grasses grown under similar climatic conditions. The crop maintains a good stand for 5 to 15 years (Cowan, 1966).

Tall fescue is adapted to a wide range of climatic conditions. It requires a minimum annual precipitation of about 40 cm and grows at elevations up to 5,000 feet (Wheeler, 1950). Deep roots enable the crop to withdraw water to depths of 1.5 meters, which explains its ability to sustain growth during the summer months in the Willamette Valley.

7.6.2 Methodology and Results

Fawn fescue was planted September 11, 1970. A broadcast application of 54 kg/ha of actual N and 67 kg/ha of P_2O_5 was made prior to planting. Additional broadcast applications were made as follows: 57 kg/ha of actual N on October 14, 1970; 54 kg/ha of actual N and 67 kg/ha of P_2O_5 on January 4, 1971; 114 kg/ha of actual N on March 31, 1971; 176 kg/ha of actual N and 100 kg/ha of sulfur on July 2, 1971; 113 kg/ha of actual N on September 10, 1971; and 54 kg/ha of actual N and 67 kg/ha of P_2O_5 on March 31, 1972. A total of 44 cm of irrigation water was applied with full circle sprinklers during the 1971 irrigation season. The heat source temperature was maintained near 33 C throughout this period. Yields of dry matter are shown in Table 39.

Table 39. Fawn fescue dry matter yields.

Harvest date	Dry matter yield Unheated	Heated	Relative yield	Significance level 1/	LSD
	T/ha	T/ha	%		T/ha
3/24/71	1.39	2.82	203	1%	.73
4/26/71	2.89	2.64	91	NS	-
5/27/71	3.20	2.69	84	NS	-
7/2/71	1.37	1.28	93	NS	-
8/4/71	3.88	3.31	85	NS	-
9/8/71	2.51	3.16	126	5%	.47
11/3/71	2.04	3.42	168	1%	.68
3/23/72	.87	2.42	278	1%	.48
5/5/72	2.46	2.71	110	NS	-
Total	20.61	24.45	119	NS	-

1/ NS - not statistically significant.

7.6.3 Discussion

Levels of significance, least significant differences and relative yields are indicated for each cutting in Table 39. Heating increased yields during the fall and winter months. Unheated yields were higher from April through August but the differences were small and not significant. The total response to heating over the 14 month harvest period was a yield increase of 19 percent. The growth rates shown in Figure 18 were obtained by dividing total yield by the number of growing days. During winter months the rate of growth was substantially higher on the heated plots. During summer months the rate of growth was depressed slightly by the high soil temperature on the heated plots. The mid-summer growth depression was due to

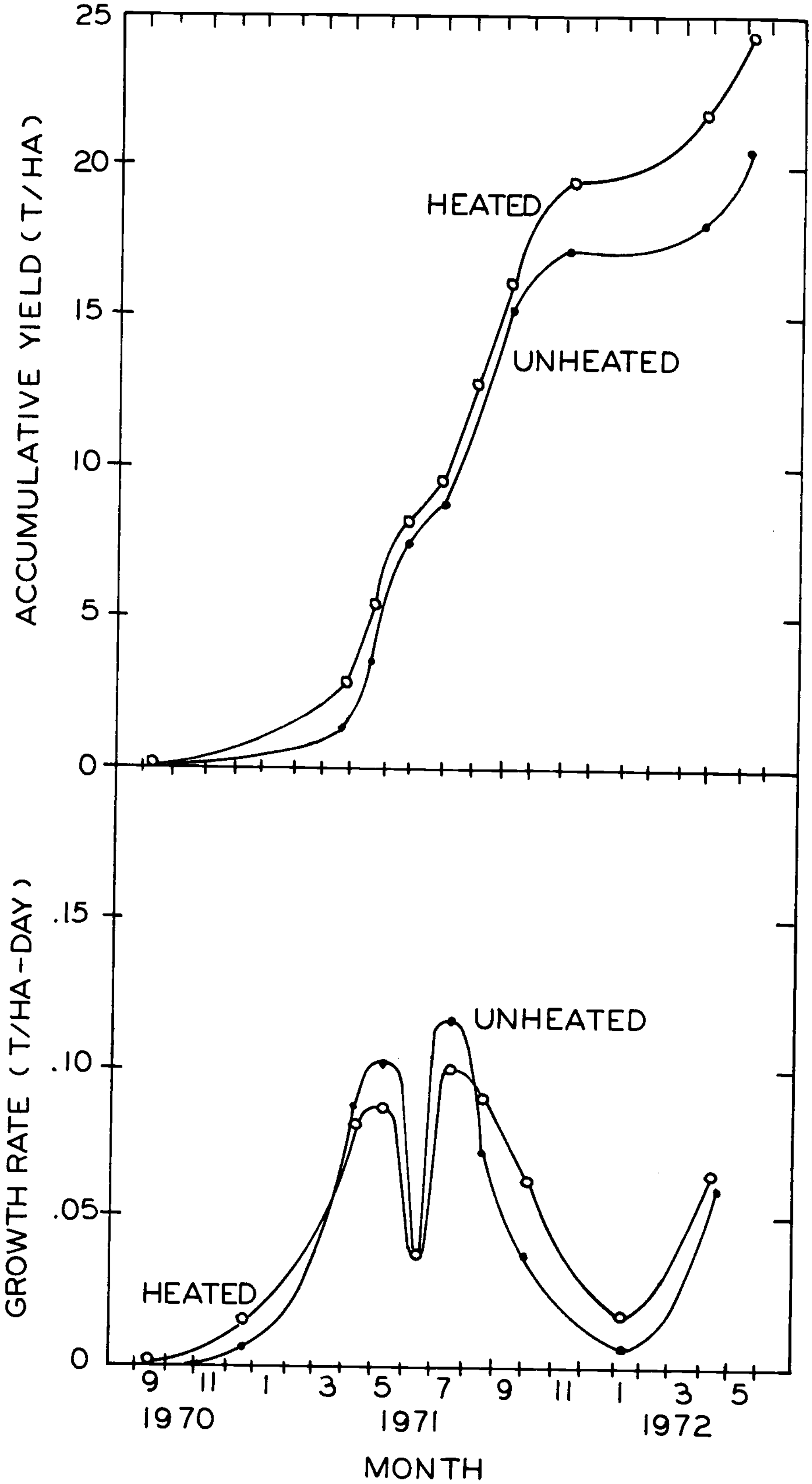

Figure 18. Accumulated yields of Fawn fescue on heated and unheated plots as a function of time and rate of growth of Fawn fescue as a function of time.

insufficient fertilization of the plots. A heavy application of fertilizer in July corrected this.

7.6.4 Conclusions

It is evident that soil warming increased production of Fawn fescue during winter months. The higher soil temperature reduced yields slightly during summer months. Response to heating over a 12-month period was a significant increase in yield. Total dry matter yield under heated conditions appears to be about 20 tons/ha/year. The crop could be used for either pasture or hay in a dairy or beef operation.

7.7 Field Corn (*Zea mays* L.)

7.7.1 Introduction

Field corn is of great economic importance in the United States. Approximately one-fourth of the crop land in the United States is devoted to the production of corn for grain or silage (Martin and Leonard, 1949). By selecting locally adapted cultivars, one can obtain a crop closely suited to the climate of most locations in the United States.

Corn grows best in regions where average June-July-August air temperatures are 20-22 C (Martin and Leonard, 1949). The minimum temperature for appreciable growth is 10 C. An optimum growth range is 30-35 C and temperatures above 45 C cause injury to corn plants (Wilse, 1962). The minimum soil temperature for germination is about 10 C. An increase in soil temperature from 12 C to 15.5 C reduces germination time from 11 to 3 days (Wilse, 1962).

Corn can withstand a light freeze during early seedling growth but will be injured or killed by freezing temperatures after plants are about 15 cm tall (Martin and Leonard, 1949). A wide range in the length of growing season required for corn to mature is provided by the many locally adapted cultivars available. Longer growing season cultivars generally attain higher yields. Cultivars are available for regions with growing seasons ranging from 90 to more than 150 days.

Corn has a high water requirement. Watts et al. (1968) calculated a consumptive use of about 45 cm for corn grown in the Willamette Valley. The most critical time for water use is the five-week period following tasseling, when about one-half of the seasonal water uptake occurs (Martin and Leonard, 1949).

The corn plant develops an extensive root system with seminal, coronal and aerial roots. Roots usually spread laterally one meter and occupy a large portion of the top 45-60 cm of soil. Some roots may extend to depths of two meters or more (Martin and Leonard, 1949).

7.7.2 Crop Year: 1969.

7.7.2.1 Methodology and Results. The cultivar Northcoast Oregon 350, a hybrid dent, was planted on May 12, 1969 at the rate of 86,000 plants/ha. The stand was later thinned to a density of 72,000 plants/ha. The row spacing was 91 cm. Fertilizer was applied at the rate of 114 kg/ha of actual N and 168 kg/ha of agricultural gypsum broadcast before planting, 76 kg/ha of P_2O_5 and 34 kg/ha of K_2O banded at planting and 152 kg/ha of actual N side dressed during June. During the growing season, 25.9 cm of irrigation water was applied with full circle sprinklers. The heat source temperature was not monitored in 1969.

The crop rows were parallel to the heat source and 46 cm to the side. All rows therefore were the same distance from the heat source. Unheated harvest areas were at least five meters from the nearest heat source. Petroleum mulch was applied immediately after planting in 15 cm wide bands over the rows. Information concerning cultural practices is shown in Table 40. Grain yields shown in Table 41 are adjusted to 15.5 percent moisture in the shelled grain. Kernel moisture for several sampling dates is shown in Table 42.

7.7.2.2 Discussion. Seedling emergence occurred one day earlier on heated plots. The vegetative growth and stages of maturity on heated plots differed from those on unheated plots throughout the growing season. In late July, heated corn plants were one meter taller than unheated plants and heated stalks were noticeably thicker. Tasseling and silking occurred four to five days earlier on heated plots.

Table 40. Crop history dates, field corn, 1969.

Treatment	Date
Planted and applied mulch	May 12
Applied Atrazine	May 19
Thinned stand	July 2
Harvested corn silage	September 9
Harvested corn grain	September 25

Table 41. Dry matter yield of corn silage and yield of shelled grain at 15.5 percent moisture, 1969.

Plant component	Unheated	Heated	Yield increase
	T/ha	T/ha	%
Silage (total dry matter)	12.3	17.9	45
Grain (shelled @ 15.5% moisture)	7.2	9.6	34

LSD ($P < .01$): Silage - 2.1 Grain - 0.8

Table 42. Moisture content of the grain (wet weight basis) determined on the indicated dates, 1969.

Treatment	Date 9/9	9/22	9/29	10/7	10/28
	%	%	%	%	%
Unheated	66.25	51.76	41.20	37.50	36.76
Heated	58.93	43.20	33.22	31.05	28.39

The yield response to soil heating was significant at the one percent level for both silage and grain. Yields on heated as well as unheated plots were affected by a shortage of water. The normal irrigation water requirement for corn is about double the amount that was applied in 1969. The heated corn suffered most from this lack of water. It grew faster and put on more dry matter than the unheated corn. The heated corn dried out severely during the first week of September. The unheated corn remained green for several more weeks. The kernels of the heated plots were shriveled and loose in the ears, leading to a suspicion of lower kernel weight than on unheated plots. However, it was found that the heated ears had an average of 17 percent more kernels per ear and the kernel weight was 16 percent higher than that for the unheated corn. This measurement substantiated the observed grain yield increase of 34 percent.

7.7.3 Crop Year: 1970

7.7.3.1 Methodology and Results. The cultivar Northcoast Oregon 350 was planted April 17, at the rate of 70,000 plants/ha in 91 cm rows. Three nitrogen fertility treatments were used. Each treatment received 54 kg/ha of actual N, 67 kg/ha of P_2O_5 and 34 kg/ha of K_2O banded at the time of planting. Additional nitrogen fertilizer was applied as a broadcast application at rates of 38, 132, and 226 kg/ha of actual N to obtain the three nitrogen fertility treatments. During the growing season 63.5 cm of irrigation water was applied with full circle sprinklers. The heat source temperature ranged from 35 to 50 C.

Crop rows were parallel to the heat sources with one row directly over the heat sources and one row midway between them. Unheated harvest areas were at least five meters from the nearest heating cable. Petroleum mulch was applied in a 15 cm wide band over the crop rows immediately after planting. Information concerning cultural practices used is presented in Table 43. Yields of grain and total dry matter are shown in Table 44. The yields of rows planted over the heat sources were not statistically different from the yields of rows between the heat sources. The yields shown in Table 44 are average yields for the heated area obtained by averaging yields from rows between heat sources and over heat sources.

Table 43. Crop history dates, field corn, 1970.

Treatment	Date
Planted and applied mulch	April 17
Applied Atrazine	May 5
Harvested ears	September 15
Harvested stover	September 17

7.7.3.2 Discussion. Neither heating nor fertility treatments had a statistically significant effect on yields. The yield increase resulting from heating was much lower than that observed in 1969.

Emergence occurred six days earlier on the heated plots and a maturity advantage was maintained throughout the growing season. At the time of harvest the percent dry matter in the ears was 56.7 for heated corn and 51.7 for unheated corn. However, during July and August, vegetative growth differences disappeared as warm air and increased soil temperatures enabled the unheated corn to catch up. Fertility levels had little effect on yields. The lowest rate of N gave the highest silage yield on heated plots.

Table 44. Dry matter yield of corn silage and yield of shelled grain at 15.5 percent moisture, 1970.

Nitrogen fertilizer rate	Plant component		Unheated	Heated	Yield increase
kg/ha			T/ha	T/ha	%
92		Silage	21.86	25.22	15
		Grain	11.36	13.53	19
186		Silage	22.69	23.77	5
		Grain	11.67	13.71	17
280		Silage	22.94	23.65	3
		Grain	12.10	12.90	7
	Average	Silage	22.50	24.21	8
	Average	Grain	11.71	13.38	14

Soil water content was monitored throughout the season with gypsum-blocks. Irrigation scheduling was based on observations made in heated plots which lost more water than the unheated plots. As a result the unheated plots were maintained near field capacity most of the time. The soil water suction on the heated plots dropped to two bars near the heat source in July. Replenishment of water by irrigation proved to be difficult. Apparently the temperature gradient offered a great enough resistance to water movement. The heat source was turned off to eliminate the steep temperature gradient. After this was done it was possible to rewet the soil near the heat source. The heat source was again energized but at a lower temperature. It was then possible to maintain the soil water content at higher levels, but they remained well below levels observed in unheated plots (Figure 19). These data suggest that roots in heated soil penetrate to greater depths and utilize a greater volume of the soil for water supply as well as nutrient supply. This could account for the lack of response to fertility treatments on the heated plots.

The water shortage observed in 1969 (Section 7.7.2.2) was probably less severe on heated corn until late in the season because heated roots were withdrawing moisture to a depth of one meter or more while unheated roots apparently occupied only 60-70 percent as much soil volume. When moisture became limiting in August, 1969, heated corn not only had a more extensive root system, but thermal gradients resulting from subsurface heating undoubtedly resulted in vapor flow from regions near the heating cable to upper layers occupied by roots. By the time severe drying occurred on heated plots, growth had essentially ceased.

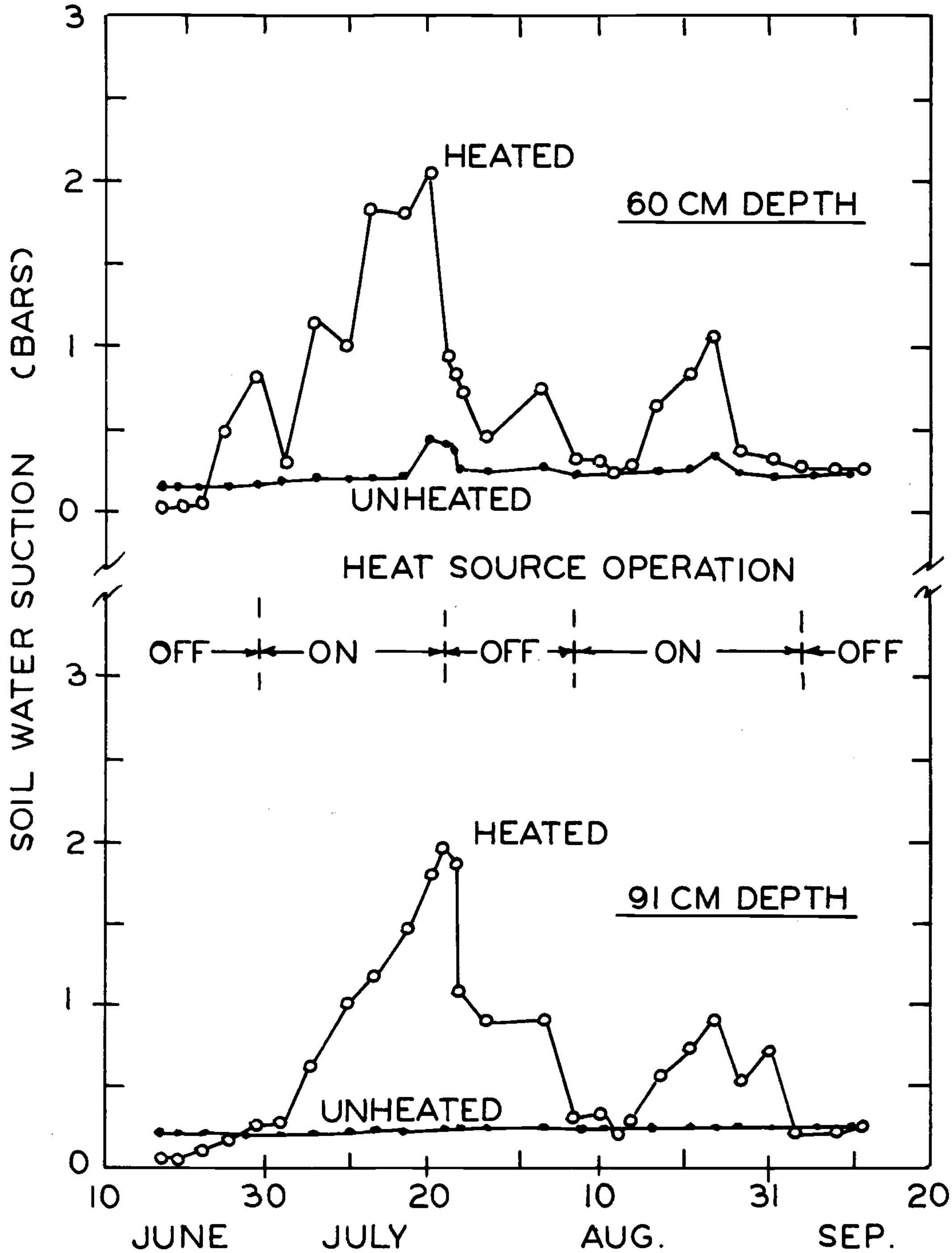

Figure 19. Soil water suction at two depths on unheated and heated CORN plots during 1970.

Ear samples were taken from each plot to determine moisture percentage, number of kernels per ear, and average kernel weight. A 16.5 percent increase due to heating was found for kernel weight, compared with 17 percent observed in 1969. Heated ears contained 5 percent more kernels per ear compared with a 17 percent increase in 1969. However, unheated plots had 8 percent more ears than heated plots. The net result was a 14 percent increase in grain yield. Leaf analysis data taken at time of silking showed no difference in nitrogen content for any of the heating or fertility treatments.

The total dry matter yields were 12.3 and 17.9 tons/ha for unheated and heated plots, respectively in 1969 and 22.5 and 24.2 tons/ha in 1970. The difference between years can be attributed to three factors. The most important factor was the difference in the amount of irrigation water applied. In 1969 the application was 25.9 cm while in 1970, 63.5 cm was applied. In 1970 the corn was planted 25 days earlier, resulting in a longer growing season. Climatic conditions were more favorable during the ear development and maturation period in 1970. Mean daily temperatures were 1.0 and 1.1 C higher in July and August (U.S. Dept. of Commerce, 1969, 1970).

7.7.4 Sub-Irrigated Corn. Crop Year: 1970

7.7.4.1 Methodology and Results. The field corn cultivar Northcoast Oregon 350 was grown on the subsurface irrigated plot.

Cultural practices and crop history dates were the same as those shown in Table 43. Two fertility levels with N rates of 186 and 280 kg/ha were used. Unheated plots received 58.5 cm of irrigation water, applied with sprinklers. Heated, sub-irrigated plots received 50.8 cm applied with sprinklers and 7.7 cm applied through the sub-irrigation system. Heat source temperatures were maintained below 38 C throughout the season on the sub-irrigated plot.

Dry matter yields of silage and grain are presented in Table 45. Values shown for heated treatments are averages of harvest rows over heat sources and between heat sources.

Table 45. Dry matter yield of corn silage and yield of shelled grain at 15.5 percent moisture. Sub-irrigated corn, 1970.

Nitrogen fertilizer rate	Plant component		Unheated	Heated	Yield increase
kg/ha			T/ha	T/ha	%
186		Silage	20.72	22.67	9
		Grain	11.24	11.45	7
280		Silage	17.52	21.75	24
		Grain	9.41	11.49	22
	Average	Silage	19.12	22.21	16
	Average	Grain	10.33	11.47	11

7.7.4.2 Discussion. The responses to heating and fertility treatments were not statistically significant. In the previously discussed corn experiment (Section 7.7.3) all yields were slightly higher than those obtained for this crop. The yield response to heating was higher for total dry matter (16.2 vs. 7.6 percent) but lower for grain (11.1 vs. 14.3 percent). This may have been due to the lower soil temperatures on the heated, sub-irrigated plots.

A yield decrease resulted from the high rate of nitrogen fertilizer in the sub-irrigated plots. The previously discussed 1970 corn crop also showed yield reductions in response to the higher rates of nitrogen fertilizer.

7.7.5 Crop Year: 1971

7.7.5.1 Methodology and Results. The cultivar Northcoast Oregon 350 was planted on April 30 at the rate of 70,000 plants/ha in 91 cm rows. Crop rows were parallel to the heat sources with one row directly over them and one row midway between them. The fertilization program was the same as that used in 1970. The same nitrogen treatments were again used. Petroleum mulch was applied on May 4. During the growing season 34.8 cm of irrigation water was applied with full circle sprinklers. The heat source temperature varied from 31 to 38 C during the growing period.

Rows over the heat sources (OR) and rows between heat sources (BR) were harvested separately. Unheated harvest areas were at least five meters from the nearest heating cable. Plots were harvested on September 16. Total dry matter yields and yields of shelled grain at 15.5 percent moisture are presented in Table 46.

Table 46. Dry matter yield of corn silage and yield of shelled grain at 15.5 percent moisture, 1971.

Nitrogen fertilizer rate	Plant component	Unheated	Heated		Yield increase		
			OR	BR	OR	BR	Avg
kg/ha		T/ha	T/ha	T/ha	%	%	%
92	Silage	13.48	19.94	16.44	48	22	35
	Grain	3.45	7.03	6.90	104	100	102
186	Silage	14.31	19.89	18.79	39	31	35
	Grain	4.82	7.59	7.57	57	57	57
280	Silage	14.81	22.74	20.34	54	37	46
	Grain	3.99	8.27	7.93	107	99	103
	Average (Silage)	14.20	20.85	18.52	47	30	39
	Average (Grain)	4.08	7.64	7.46	87	83	85

LSD ($P < .01$): Heating - Silage 1.75, Grain 0.58; Fertility - Silage 1.81, Grain 0.61

7.7.5.2 Discussion. The effects of heating and rate of nitrogen application were significant at the 1 percent level for both silage and grain yield. Least significant differences are shown in Table 46.

Grain yields over the heat sources did not significantly differ from those between the heat sources, although higher yields over the heat sources were obtained. This difference was greatest for the silage yields. There was a significant yield increase from soil warming. Silage yields were significantly increased by soil warming with the highest yields occurring over the heat sources.

Grain yields were the same for the two highest nitrogen rates and both were significantly higher than the yields at the lowest nitrogen rate. Silage yields were different only between the lowest and highest nitrogen rates. These results are in contrast to the 1970 results when fertility levels had no significant effect on silage or grain yields.

Averaging the OR and BR treatments resulted in a heating response of 39 percent for silage yields and 85 percent for grain yields. The 1971 yields were much lower than those observed in 1970, but about the same as those obtained in 1969. The summer of 1971 was the coolest of the first three years of testing. June 1971 was very cool and wet which resulted in a slow start for the plants. Strong winds following a heavy irrigation in September resulted in a serious lodging problem, particularly on the heated plots where the corn was taller and heavier. Because of the lodging, it was necessary to harvest the crop before the grain was mature. A later harvest date might have resulted in higher grain yields for all treatments. It is possible that the grain yield heat response would have been less than the observed 85 percent.

The differences in nitrogen response between 1970 and 1971 may in part be explained by differences in climatic conditions during the two summers. Higher temperatures in the first three months of 1970 were more favorable for the release of nitrogen from organic reserves. Soil temperatures on the heated plots were higher in 1970 than in 1971. While a slight silage yield increase was observed with higher nitrogen levels on unheated plots in both years, the response on heated plots differed. In 1970, increasing nitrogen rates depressed yields and in 1971 increasing nitrogen rates increased yields.

In addition to the influence of climatic conditions and soil temperatures on nitrogen supplied from organic reserves the level of organic reserves may be involved in the response differences observed. The high soil temperatures of the heated plots undoubtedly promoted rapid release of nitrogen with corresponding depletion of reserves. Since all above ground portions of the crop were removed from the field each year it is possible that a significant reduction of organic nitrogen may have occurred on the heated plots. As a result, the additional nitrogen was needed on the heated plots in 1971.

7.7.6 Silage Corn. Crop Year: 1971

7.7.6.1 Methodology and Results. Northcoast Oregon 350 field corn was planted on May 21 at the rate of 160,000 plants/ha in 46 cm rows to evaluate the effect of soil warming on silage production. Fertilizer was applied at the same rates used in other 1971 corn experiments. A nitrogen fertility treatment with the same three nitrogen rates was included. During the growing season 35.3 cm of irrigation water was applied with full circle sprinklers. The heat source temperature was 32 C during the growing period.

The crop was harvested on August 3. Severe lodging occurred when strong winds followed a heavy irrigation so that early harvest was necessary. Dry matter yields are presented in Table 47.

Table 47. Dry matter yields of high density silage corn, 1971.

Nitrogen fertilizer rate	Unheated	Heated	Yield increase
kg/ha	T/ha	T/ha	%
92	7.21	9.70	35
186	7.70	10.80	40
280	7.72	9.54	23
Average	7.55	10.01	33
LSD ($P < .01$) Heating 2.06			

7.7.6.2 Discussion. The effect of heating was significant at the 1 percent level. Nitrogen rate did not significantly affect yields. Response to nitrogen was similar to that observed with other corn experiments. Yields on heated plots were highest at the intermediate rate of nitrogen application and were depressed at the high rate. Yields on the unheated plots were highest for the highest nitrogen treatment.

The total dry matter yield and the response to heating were similar to that obtained for the first harvest of sudangrass and sorghum-sudangrass hybrid. All three crops were grown in adjacent plots with heat provided by the same heat source.

7.7.7 Crop Year: 1972

7.7.7.1 Methodology and Results. The cultivar Northcoast Oregon 350 was planted on May 12 at the rate of 86,000 seeds/ha in 91 cm rows. Fertilizer rates were the same as those used in the two previous years with nitrogen applied at the rate of 186 kg/ha. During the growing season 43.4 cm of irrigation water was applied with full circle sprinklers. The heat source temperature was 32 to 38 C during the growing season.

Rows were planted parallel to the heat sources and 45 cm to the side. Unheated plots were located at least four meters from the nearest heated area. Total dry matter harvests were taken on June 26, July 11, and July 28 to establish early season growth rates. In a final harvest on October 3, yields of total dry matter and grain were determined.

The dry matter plant weights observed for the several harvest dates are shown in Table 48. Final yields of silage and grain are shown in Table 49. The percent dry matter of the various plant components is shown in Table 50.

7.7.7.2 Discussion. The response to soil warming was significant for all harvest dates. The greatest response was in mid-July. The silage yield increase at harvest time was 20 percent and the final grain yield increased 22 percent as a result of soil warming. The

Table 48. Dry matter weights at the four indicated sampling dates, 1972.

Harvest dates	Treatment Unheated	Treatment Heated	Yield increase	LSD ($P < 0.01$)
	gm/plant	gm/plant	%	gm/plant
6/26/72	2.1	5.3	152.0	1.3
7/11/72	10.4	29.5	184.0	7.6
7/28/72	46.9	82.4	76.0	21.2
10/3/72	149.0	194.0	30.0	30.0

Table 49. Dry matter yield of corn silage and yield of shelled grain at 15.5 percent moisture, 1972.

Plant component	Unheated	Heated	Yield increase	LSD ($P < .01$)
	T/ha	T/ha	%	T/ha
Silage	13.19	15.79	20.0	2.52
Grain	7.61	9.25	22.0	1.57

Table 50. Percent dry matter in stover, grain, and silage and grain shelling percentage, 1972.

Treatment	Dry matter Stover	Dry matter Grain	Dry matter Silage	Shelling percentage
	%	%	%	%
Unheated	18.7	46.0	28.8	83.2
Heated	21.4	52.5	32.9	80.6
LSD ($P < .01$)	2.3	3.3	1.3	2.6

heating response was significant at the 1 percent level in both measurements. The difference in heat response for silage yields in Table 49 and dry weight per plant in Table 48 is the result of slightly higher plant populations on the unheated plots. A difference in maturity due to heating is demonstrated by dry matter and shelling percentages presented in Table 50. All percentages were significantly different at the 1 percent level.

The yields obtained in 1972 were low. Grain yields were depressed somewhat by small ears and the failure of about 20 percent of the kernels to fill out. This may have been caused by an unusually warm period in August when the daily maximum temperature exceeded 34 C for seven consecutive days. A maximum temperature of 41 C occurred during this period (U.S. Dept. of Commerce, 1972).

Soil water supply did not appear to be a limiting factor. Similar results were obtained on sub-irrigated crops where more water was applied. The higher plant density in 1972 may have resulted in smaller individual plants but this does not appear to be very important. The plant density on the sub-irrigated plot was similar to that of previous years and the yields were also low.

7.7.8 Sub-Irrigated Corn. Crop Year: 1972

7.7.8.1 Methodology and Results. The cultivar Northcoast Oregon 350 was planted on the sub-irrigated plot. Planting date, fertilization schedule, and seeding rates were the same as described in Section 7.7.7. During the growing season, heated, sub-irrigated, plots received 34.8 cm of irrigation water applied with full circle sprinklers and 28.2 cm of water applied through the subsurface irrigation system. An adjacent unheated area received 38.6 cm of irrigation water applied with sprinklers. The heat source was maintained near 31 C.

Harvests were made at four dates. Dry matter production in grams/plant is presented in Table 51. Total dry matter yields and the yields of shelled grain at 15.5 percent moisture are shown in Table 52. The percent dry matter of stover, grain, and silage components and shelling percentages are presented in Table 53.

Table 51. Dry matter plant weights at the four indicated sampling dates. Sub-irrigated corn, 1972.

Harvest dates	Treatment		Yield increase	LSD
	Unheated	Heated		
	gm/plant	gm/plant	%	gm/plant
6/26/72	1.5	2.5	67.0	1.0 ($P < 0.05$)
7/11/72	7.6	14.4	90.0	5.7 ($P < 0.01$)
7/28/72	50.3	89.5	78.0	20.4 ($P < 0.01$)
10/3/72	146.0	228.0	56.0	58.0 ($P < 0.01$)

Table 52. Total dry matter yield of silage and yield of shelled grain at 15.5 percent moisture. Sub-irrigated corn, 1972.

Plant component	Unheated	Heated	Yield increase	LSD (P < .01)
	T/ha	T/ha	%	T/ha
Silage	12.19	16.11	32.0	2.10
Grain	6.95	10.27	48.0	1.92

Table 53. Percent dry matter in stover, grain, and silage and grain shelling percentage. Sub-irrigated corn, 1972.

Treatment	Dry matter			Shelling percentage
	Stover	Grain	Silage	
	%	%	%	%
Unheated	18.8	44.3	28.4	79.3
Heated, sub-irrigated	18.4	49.0	30.9	81.6
LSD (P < .05)	N.S.		2.4	2.0
LSD (P < .01)		4.5		

7.7.8.2 Discussion. The heat response of plant growth was significant at the 5 percent level for the first harvest and at the 1 percent level for the next three harvests. For the first two harvests, heated, sub-irrigated and unheated yields were lower than those observed in the parallel planting discussed in Section 7.7.7. For the third harvest, both plantings gave similar results. Final harvest weights were nearly identical on the two unheated treatments while sub-irrigation with heating resulted in a slight increase in plant weight over heating alone. Plant populations were nearly the same on both unheated areas. The plant density on sub-irrigated plots was 80 percent of that on unheated plots while heated plots had 90 percent of the stands achieved on unheated plots. The low plant density on sub-irrigated plots was the result of pheasant damage.

The effect of heating with subsurface irrigation on final silage and grain yield was significant at the 1 percent level. Comparing these yields with those reported in Table 49 shows that unheated yields were slightly less on the sub-irrigated plot. This may have been due in part to the difference in cropping history. Similar results were observed for crops grown on these areas in 1970. Heating with subsurface irrigation resulted in higher yields than were obtained with heating alone (Table 49). Equal stand densities would probably have accentuated this difference. Sub-irrigation made it possible to maintain high water content levels throughout the soil profile. On the heated plots without subsurface irrigation the water content decreased to equivalent soil water suctions of 1 to 2 bars at depths of 60 to 90 cm. This effect also was observed in previous years. Subsurface irrigation resulted in higher soil temperatures in the upper soil layers even though cable temperatures were kept at about the same level in both areas. The small yield differences between heated and heated with sub-irrigation treatments indicate that soil water supply was not a limiting factor in determining crop yields in 1972. The sub-irrigated crop received approximately 50 percent more irrigation water during the growing season.

Table 53 shows that in all instances maturity differences were small and less than those reported in Section 7.7.7. Apparently the higher water content levels maintained in the sub-irrigated areas offset, somewhat, the effect of heating. The dry matter percentage of stover was actually lower on the heated sub-irrigated treatment. Differences in the other three maturity parameters were statistically significant but small. They indicated that the crop on the heated plot was slightly more mature.

7.7.9 Summary and Conclusions

The average yield of total dry matter over four years and several fertility treatments on heated plots was 20.6 tons/ha (Table 54). The response to soil warming was 22 percent. The field corn produced higher yields than sorghum-sudangrass hybrid. Corn silage is also higher in feeding value than sorghum-sudangrass. However, in a dairy or beef enterprise the two crops are not incompatible. Early planting and late harvest reduce the possibility for double cropping with corn. Total dry matter production from a rotation of sorghum-sudangrass and annual ryegrass under heated conditions would probably be slightly higher than for a single crop of corn silage.

The average yield of grain over four years was 10.5 tons/ha on heated plots. The yield increase due to heating was 28 percent. This level of production would justify growing corn for grain.

Table 54. Total dry matter and grain yields obtained on unheated plots and the percent yield increase due to soil warming obtained during the indicated four years of experiments with corn.

Year	Nitrogen fertilizer rate	Total dry matter			Grain		
		Unheated	Heated	Increase	Unheated	Heated	Increase
	kg/ha	T/ha	T/ha	%	T/ha	T/ha	%
1969	266	12.3	17.9	45	7.2	9.6	34
1970	92	21.9	25.2	15	11.4	13.5	19
	186	22.7	23.8	5	11.8	13.7	17
	280	22.9	23.7	3	12.1	12.9	7
1970	186	20.7	22.7	9	11.2	11.5	.2
	280	17.5	21.8	24	9.4	11.5	22
1971	92	13.5	18.9	40	3.5	7.0	100
	186	14.3	19.3	35	4.8	7.6	58
	280	14.8	21.5	45	4.0	8.2	105
1972	186	13.2	15.8	20	7.6	9.3	22
	186	12.2	16.1	32	7.0	10.3	48
Average		16.9	20.6	22	8.2	10.5	28

A wide range of yield responses to soil warming was observed during the four years of experimentation (Table 54). The total dry matter yield (silage yield) increase ranged from 3 to 45 percent of yields on unheated plots. A plot of yield increase due to heating versus unheated yields shows a well defined relationship (Figure 20). These data were fit to linear and quadratic regression models. The linear regression equation calculated was:

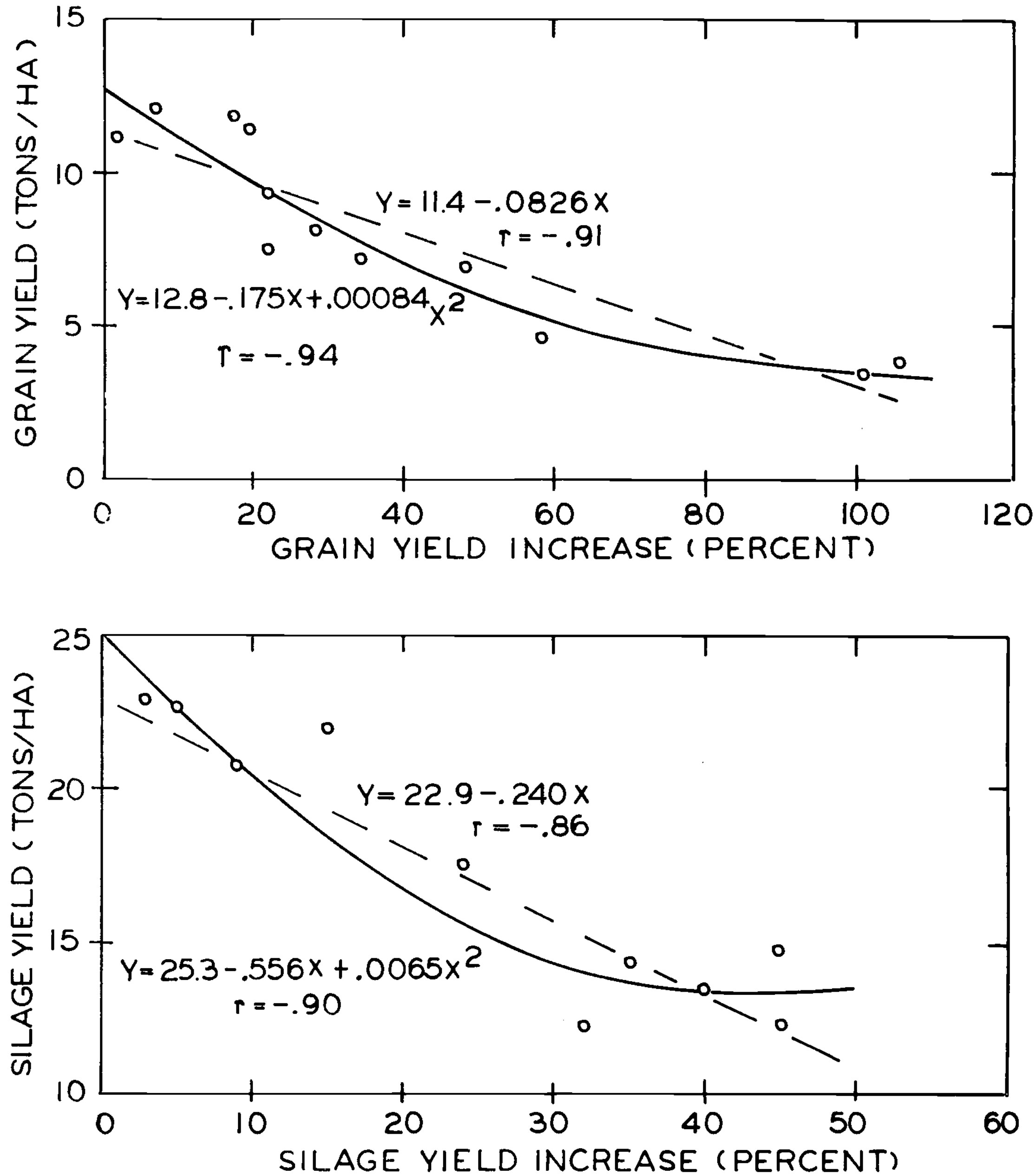

Figure 20. Percent silage yield and grain yield increase obtained on heated plots as a function of silage yield and grain yield obtained on unheated plots.

$$Y_{(S)} = 22.9 - .240X \quad [\text{with } r = -.86]$$

where $Y_{(S)}$ = unheated silage yield and X = percent yield response to soil warming.

This model suggests a maximum unheated yield of 22.9 tons/ha. It accounted for 74 percent of the variation in unheated yields.

The quadratic regression equation calculated was:

$$Y_{(S)} = 25.3 - .5566X + .00646X^2 \quad [\text{with } r = -.90]$$

This model suggests a maximum unheated yield of 25.3 tons/ha. It accounted for 81 percent of the variation in unheated silage yields.

Both models suggest that soil heating can overcome conditions that restrict yields on unheated areas. Among the limiting conditions encountered the most important are climatic conditions, fertility levels, and irrigation. The more severe these limitations are the greater the response to soil heating becomes. However, when conditions are optimum for high yields, these models predict that soil warming will not increase yields.

The range in grain yields observed over the four years of experimentation was greater than the variation in silage yields. Grain yield response to soil warming varied from 2 to 105 percent of unheated yields (Table 54). The relationship between unheated yields and response to heating appeared to be similar to that observed for silage yields (Figure 20). These data were fit to linear and quadratic regression models. The linear regression equation calculated was:

$$Y_{(G)} = 11.4 - .0826X \quad [\text{with } r = -.91]$$

where $Y_{(G)}$ = unheated grain yield and X = percent yield response to soil warming. The linear model accounted for 82 percent of the observed unheated yield variation and predicted a maximum unheated yield of 11.4 tons/ha.

The quadratic regression equation calculated was:

$$Y_{(G)} = 12.8 - .175X + .000838X^2 \quad [\text{with } r = -.94]$$

This model predicted a maximum unheated grain yield of 12.8 tons/ha and accounted for 89 percent of the observed yield variation.

The quadratic regression provided the best fit for silage and grain yields. The correlation coefficients were high. Similarities between the two yield parameters suggested that a single relationship might fit data from both silage and grain yield observations. To prepare a normalized graph, yields on unheated plots were set equal to 100 for the condition of zero yield increase due to heating. These yield values were chosen from the quadratic relationships. The yields obtained on unheated plots were then normalized to a percentage of this maximum yield. Normalized silage and grain yields as a function of yield increase due to soil warming are plotted in Figure 21. Linear

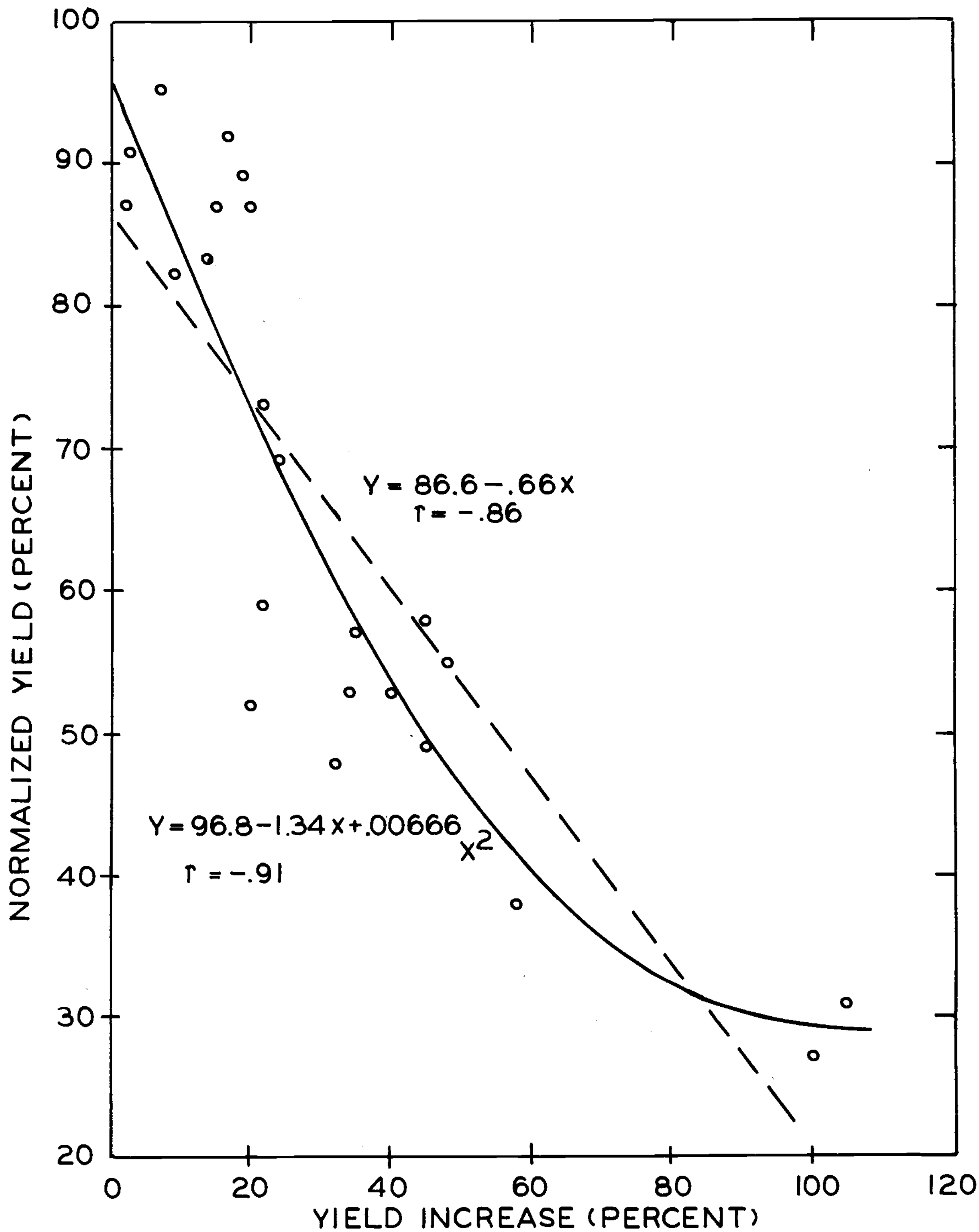

Figure 21. Percent silage and grain yield increase obtained on heated plots as a function of normalized silage and grain yields on unheated plots.

and quadratic regression equations were fit to these data.

The linear regression equation calculated was:

$$Y = 86.6 - .66X \quad [\text{with } r = -.86]$$

where Y = normalized yield as a percentage of maximum yield and X = percent yield increase due to soil warming. This model accounts for 75 percent of the variation in yield. Visual inspection of Figure 21 shows a lack of fit in the two main clusters of data points.

The quadratic regression equation calculated was:

$$Y = 96.8 - 1.34X + .00666X^2 \quad [\text{with } r = -.91]$$

This model accounts for 83 percent of the yield variation and passes close to the center of the two main clusters of data points. The addition of the X^2 term significantly improved the fit.

The relationship between yield level and response to soil warming may not be limited to field corn. It probably applies for all crops. It suggests that the greater the degree of adversity for production of a given crop, the greater will be the response to soil warming. The field corn cultivar used in this experiment was one of the best adapted cultivars available for the Willamette Valley. It is likely that in a good growing season under natural conditions this crop will reach a production level close to its genetic potential or "maximum." For a cultivar adapted to a warmer climate the response to heating may be much higher. This could account for the high responses noted for sudangrass, sorghum-sudangrass hybrid and Crimson Clover, and the relatively low response to heating observed for tall fescue and common ryegrass.

7.8 Soybeans (*Glycine max* L.)

7.8.1 Introduction

Numerous cultivars of soybeans have been grown experimentally in the Willamette Valley. Under natural soil temperature conditions only early season types have been successful. It was postulated that soil warming might result in a longer growing season thus making it possible to grow cultivars which produce higher yields due to their longer growing season.

Soybeans are a warm climate crop with an optimum mean mid-summer temperature of 24-25 C (Martin and Leonard, 1949). Both high and low summer temperatures adversely affect growth depending on the cultivar grown, light conditions, and other factors. Early season temperatures in excess of 35 C may retard node formation and growth of internodes (Cartter and Hartwig, 1963). Low summer temperatures may retard flowering. Soybeans are not seriously affected by light frosts.

Warm soil temperatures are required for good germination.

Cartter and Hartwig (1963) reported emergence in three to five days for seeds germinating at 21 to 32 C compared to 7 to 10 days for emergence at 15.5 C. The number of days required to reach maturity varies widely between cultivars. Some early types mature in 75 days while late types may require 175 days or more to reach maturity (Martin and Leonard, 1949).

Soil water content is particularly important to soybeans during the early growth stages and during the pod-filling stage. Excessive moisture early in the season is detrimental. Soil water stress during pod-filling reduces yields. During the remaining portions of the season soybeans are fairly drought resistant and are not injured by excessive rainfall or irrigation (Cartter and Hartwig, 1963).

While soybean roots may penetrate to a depth of two meters or more (Cartter and Hartwig, 1963), the majority of active roots are found in the upper 30 cm of soil. Stamp[2/] suggests that up to 80 percent of the root system of soybeans may be found in the top 15 cm.

7.8.2 Methodology and Results

The cultivar Chippewa 64 was planted at a rate of 39 seeds per meter in rows with a spacing of 91 cm on May 15, 1969. The stand

[2/] David L. Stamp, assistant professor of agronomic crop science, Oregon State University, personal communication.

was subsequently thinned to 25 plants per meter. The planting received a broadcast application of 114 kg/ha of actual N and 168 kg/ha of agricultural gypsum prior to planting, and 100 kg/ha of P_2O_5 and 34 kg/ha of K_2O banded at time of planting. The herbicide Eptam was applied at a rate of 2.8 kg/ha of active material on May 10. A 15 cm wide band of petroleum mulch was applied over the rows immediately after planting. Rows between parallel heat sources and directly over them were harvested separately. Total dry matter yields and moisture contents are shown in Table 55. The grain yield was 0.9 tons/ha and was not affected by the soil warming treatment.

Table 55. Dry matter yield and moisture content of soybeans, 1969.

Temperature treatment	Yield	Relative yield	Moisture content
	T/ha	%	%
Unheated	5.04	100	70.1
Between cables	8.22	163	70.4
Over cables	8.38	166	70.7
LSD ($P < .01$):	1.10		

In 1971 the cultivar Grant was planted at a rate of 39 seeds per meter on June 7. A broadcast application of 70 kg/ha of K_2O and 38 kg/ha of actual N was made prior to planting. At planting time 54 kg/ha of actual N and 67 kg/ha of P_2O_5 was banded. Additional phosphorus was broadcast at rates of 28, 56, and 84 kg/ha of P_2O_5 to establish three fertilizer treatments. The herbicide Eptam was applied at the rate of 2.8 kg/ha active material on April 29. Heated areas were surrounded by a corn shelter strip.

During the growing season 35.5 cm of irrigation water was applied with full circle sprinklers. No difference in the yields from rows over the heat source and between them was observed in 1969. Harvest areas in 1971 included, therefore, equal portions of rows over and between the heat sources.

Table 56 presents dry matter silage yields and bean yields. Both yield measures were made on October 21. The foliage had been dropped at this time. Thus, silage yields represent weights of stems and beans only.

Table 56. Yield of total dry matter and dry beans. Soybeans, 1971.

Plant component	Phosphorus fertilizer rate (P_2O_5)	Unheated	Heated	Yield increase
	kg/ha	T/ha	T/ha	%
Dry matter	95	7.83	8.49	8
	123	7.80	8.60	10
	151	8.06	8.69	8
Beans	95	1.97	2.14	9
	123	2.01	2.22	10
	151	2.19	2.38	9

LSD ($P < .01$) Heating: .15 Fertility: .19 (Beans)
Heating: .27 (Dry matter)

7.8.3 Discussion

No difference between the yields from plots over the heat sources and between them was observed in 1969. There was an increase in dry matter yield of 63 percent due to soil warming. Plants in the heated plots were taller, had thicker stems and were better nodulated than plants on the unheated plots. There was no difference in moisture content of the plant material between any of the treatments. Soil heating did not affect maturity of the seed or grain yields. The cultivar used in 1969 did not mature early enough to give meaningful grain yields. Bean yields were below one ton/ha for both heated and unheated plots with no difference between treatments.

In 1971, the response to soil warming was significant at the 1 percent level for both silage and grain yield. The yield increase for total dry matter as well as grain was small, however. The cultivar Grant, used in 1971, is a short season cultivar which did mature even though the crop was not planted until June 7. In both years the silage yields on the heated plots were the same. The smaller response due to heating in 1971 resulted from high yields on the unheated plots. The crop was planted much later in 1971. The lower yields on the unheated area in 1969 may have been due in part to poor germination. A small but significant yield increase resulted from the higher phosphorus applications. The response was significant at the 1 percent level.

7.8.4 Conclusions

The yields obtained with this crop were not high enough to justify the expense of soil warming for production of either silage or grain. Several forage crops produce higher silage yields than soybeans in a shorter period of time. Vegetable crops appear to be a better choice for cash crops than soybeans for grain.

The shallow rooting characteristics of soybeans may be the reason for relatively small responses to soil warming. Most of the roots are concentrated in the top 15 cm of the soil profile where soil temperatures are more dependent on solar heating than subsurface heating.

7.9 Bush Beans (*Phaseolus vulgaris*)

7.9.1 Introduction

The bush bean is a warm-season crop which has an optimum mean temperature of 18-24 C for growth (Martin and Leonard, 1949). The optimum temperature for germination is 25 C (Anonymous). At soil temperatures below 15 C the seed may rot in the ground (Thompson and Kelley, 1957). The crop is susceptible to frost damage at all stages. Growing seasons in the Willamette Valley are long enough to make double cropping feasible in some years. One of the main objectives of including this crop in the study was to evaluate the potential for double cropping with soil warming.

Irrigation timing and the amount of water applied are critical to obtain high yields and high quality. Consumptive use for bush beans in the Willamette Valley is about 22 cm (Watts _et al._, 1968). The most critical period for water use is from blossom set to harvest time.

7.9.2 Crop Year: 1969

7.9.2.1 Methodology and Results. The cultivar Oregon 58 was planted at a rate of 30 seeds per meter in 91 cm rows. All treatments received 114 kg/ha of actual N, and 168 kg/ha of agricultural gypsum broadcast prior to planting, and 100 kg/ha of P_2O_5, and 34 kg/ha of K_2O banded at the time of planting. Cultural practices, planting and harvesting dates, the amount of precipitation which fell during the growing season and the total amount of irrigation water applied for four planting dates are shown in Table 57. Planting D4 followed planting D1 on the same ground and was used to evaluate the potential for double cropping. Petroleum mulch was applied in a 15 cm band over the rows immediately after planting. Eptam was applied at the rate of 2.8 kg/ha of active material.

Crop rows on the heated area were located either directly over the parallel heat sources or midway between them. Unheated harvest areas were at least six meters from the nearest heating source. The heat source was energized April 25. The heat source temperature was not monitored on this plot.

Table 57. Crop history dates and amount of water applied, bush beans, 1969.

Treatment	Planting dates D1	D2	D3	D4
Planted and applied mulch	May 12	May 28	June 17	July 25
Applied Eptam	May 19	May 28	May 28	May 19
Harvested	July 20	Aug 2	Aug 20	Oct 9
Irrigation water applied (cm)	15.9	19.3	19.3	27.5
Precipitation (cm)	9.5	6.1	6.1	7.4
Crop days	70.0	67.0	65.0	77.0

Yield of beans and percent of beans passing a number 4 sieve are presented in Tables 58 and 59 for all treatments. These values represent the average of three rows, each five meters long, for planting D1 and four rows, each six meters long, for the remaining plantings.

Table 58. Yield of bush beans, 1969.

Treatment	Planting dates D1	D2	D3	D4
	T/ha	T/ha	T/ha	T/ha
Unheated	13.9	15.2	10.8	7.4
Between cables	15.9	15.7	13.7	14.1
Over cables	18.2	16.8	15.9	12.8
Heated average	17.1	16.3	14.8	13.5

Table 59. Percent of beans passing a number 4 sieve, 1969.

Treatment	Planting dates			
	D1	D2	D3	D4
	%	%	%	%
Unheated	49.2	34.3	47.5	61.3
Between cables	51.3	38.7	44.6	33.6
Over cables	49.0	46.4	49.4	36.6
Heated average	50.2	42.6	47.5	35.1

The yields shown in Table 58 were adjusted to a standard of 50 percent of beans passing a number 4 sieve (Table 60). This adjustment was made by allowing 112 kg/ha of beans for each percent deviation from the standard of 50 percent. Adjusted yields are a better basis for comparing the treatment effects. Relative yields based on setting the yield on the unheated plots equal to 100 percent were calculated (Table 60).

7.9.2.2 Discussion. Statistical analyses showed a heating effect significant at the 1 percent level for unadjusted yields of plantings D3 and D4. Least significant differences were 1.9 and 1.7 tons/ha, respectively. Yields from heated and unheated plots of plantings D1 and D2 were not significantly different. Composite samples were used to determine maturity and statistical analysis of grade determinations was not possible. Table 59 indicates little difference in maturity due to heating for the first three plantings. Beans on the unheated D4 planting were not mature at the time of harvest while beans on the heated plots were at ideal maturity seven days prior to harvest. There was at least a 10-day difference in maturity for this planting. Based on results for planting dates D1 and D4, it appears that two crops of beans could be grown in about 155 days on heated fields allowing five days for harvesting and replanting of the first crop. This would fit well within the growing season for the Willamette Valley.

Table 60. Yields of bush beans adjusted to 50 percent passing a number 4 sieve, and relative yields obtained by setting the yield on unheated plots equal to 100 percent, 1969.

Treatment	Planting dates D1	D2	D3	D4
	T/ha	T/ha	T/ha	T/ha
Unheated	14.3	13.5	10.5	8.7
Between cables	16.8	14.6	13.2	12.3
Over cables	17.9	16.4	15.9	11.2
Heated average	17.4	15.5	14.6	11.8
	Relative yield			
	%	%	%	%
Unheated	100	100	100	100
Between cables	117	108	126	141
Over cables	125	122	151	128
Heated average	121	115	139	135

7.9.3 Crop Year: 1970

7.9.3.1 Methodology and Results. The cultivar Gallatin 50 was planted on a 12.6 x 12.6 cm spacing with a precision planter.

Plantings were made on May 30 and July 3. All treatments received a band application of 54 kg/ha of actual N and 67 kg/ha of P_2O_5 and a broadcast application of 58 kg/ha of P_2O_5 and 70 kg/ha of K_2O prior to planting. Additional nitrogen was broadcast at rates of 0, 38, and 57 kg/ha of actual N to establish three nitrogen treatments. Cultural practices and crop history dates are shown in Table 61. Irrigation scheduling was based on gypsum block readings taken in both heated and unheated plots. Heat source temperature was not monitored on this plot.

Table 61. Crop history dates and water applied, bush beans, 1970.

Treatment	Planting dates D1	Planting dates D2
Applied Eptam	April 15	July 2
Planted	May 30	July 3
Harvested	Aug 1	Sept 12
Irrigation water applied (cm)	30.5	26.7
Precipitation (cm)	1.7	1.2
Crop days	62.0	71.0

Harvested areas on heated plots of planting D1 were 91 cm wide, six meter long strips centered either directly over heat sources or midway between them. Harvest areas of planting D2 included rows over the heat sources as well as between them. Yields from these two positions were not obtained separately. All unheated plots were the same size and were at least five meters from the nearest heat source.

Bean yields, percent of beans passing a number 4 sieve, and adjusted yields for the May 30 planting date are shown in Table 62. Data analysis showed that yields from rows between the heat sources, and over the heat sources were not significantly different. Therefore, the results were averaged and shown as results for the heated area. The same data for the July 3 planting date are shown in Table 63.

Table 62. Yield of bush beans, percent of beans passing a number 4 sieve, and adjusted yields for the May 30 planting, 1970.

Nitrogen fertilizer rate	Treatment	Yield	% Passing #4 sieve	Adjusted yield	Relative yield
kg/ha		T/ha	%	T/ha	%
54	Unheated	12.6	57.6	13.5	100
	Heated	16.3	40.7	15.3	113
92	Unheated	9.0	59.7	10.1	100
	Heated	19.2	41.9	18.3	181
111	Unheated	8.1	67.4	10.1	100
	Heated	18.4	53.3	18.7	185

LSD ($P < .01$) Heating: 2.4

7.9.3.2 Discussion. The yield difference between unheated and heated plots was significant at the 1 percent level for the May 30 planting. Increasing the rate of nitrogen resulted in a decrease in the maturity of the beans. The highest yield on the unheated plots was obtained at the lowest rate of nitrogen fertilizer. Additional nitrogen fertilizer depressed the yield on the unheated plots. The yield on the heated plots was increased by the increase to 92 kg/ha of nitrogen. Further increase did not affect yields. Although fertility treatments did not affect yields significantly, interaction between heating and nitrogen rate was significant at the 1 percent level.

Table 63. Yield of bush beans, percent of beans passing a number 4 sieve, and adjusted yield for three fertility levels for the July 3 planting, 1970.

Nitrogen fertilizer rate	Treatment	Yield	% Passing #4 sieve	Adjusted yield	Relative yield
kg/ha		T/ha	%	T/ha	%
54	Unheated	18.7	61.3	20.0	100
	Heated	12.1	59.4	13.1	66
92	Unheated	19.2	64.9	20.9	100
	Heated	18.4	50.7	18.5	89
111	Unheated	19.5	61.1	20.7	100
	Heated	23.5	54.6	24.0	116
LSD (P < .01) Fertility: 2.0					

In 1969, the planting made on May 28 showed a 15 percent yield increase with the beans on unheated plots being slightly more mature than those on heated plots. The May 30 planting in 1970 resulted in a 56 percent yield increase with the beans from the heated plots being considerably more mature at the time of harvest. Two factors contributed to the difference in response to soil warming between 1969 and 1970. In 1969, asphalt mulch was applied. This treatment has been shown to increase soil temperature and moisture retention in the vicinity of crop seeds. It could have been more effective in promoting early germination and rapid initial growth than the soil warming treatment. In 1970, mulch was not applied and any differences in germination and early growth can be attributed solely to the soil warming effect.

Although soil temperatures were not monitored on the bean plots, it is apparent that temperatures were higher in 1970. Energy discharged on this plot was about 50 percent greater in 1970 than in 1969.

Much higher yields were obtained from the July 3 plantings. The low yield on the heated treatment at the lowest fertility level was the result of severe water damage during blossom set which occurred when a sprinkler head became stuck in one position for several hours. Less extensive water damage was incurred on the intermediate fertility treatment. The beans on the heated plots were slightly more mature but no response to heating was observed for this planting date. The lack of response may be due to the water damage. Nitrogen levels did not affect maturity but significantly increased yields on the heated plots. At the highest level of nitrogen, heating increased yield by 16 percent. The interaction between nitrogen and heating was not significant. Rate of nitrogen fertilizer did not affect the yield on the unheated plots.

It is of interest to compare the sum of the yields from the May 30 and July 3 planting with the sum of the yields from the D1 and D4 planting in 1969. The total yield was about 11 tons/ha higher in 1970. This was due primarily to the greater plant density achieved with the 12.6 x 12.6 cm spacing. Average plant populations in 1969 were about 200,000 plant/ha compared with 480,000 plants/ha in 1970. A 100 percent stand on the close spacing would result in a density of 620,000 plants/ha. The results of 1970 indicate that double cropping on heated soil with optimum fertilization and good stands could result in bush bean yields of 50 tons/ha. In 1970, the two-crop total for the highest nitrogen rate was 43 tons/ha. This would probably have been lower if the first planting had been in April.

Comparison of the highest yield obtained for heated and unheated plots for both plantings in 1970 shows an 18 percent combined yield response to soil heating for a two-crop sequence. A similar comparison for plantings D1 and D4 in 1969 resulted in a 27 percent combined response.

7.9.4 Sub-Irrigated Bush Beans. Crop Year: 1970

7.9.4.1 Methodology and Results. Bush beans (cultivar Gallatin 50) were planted on the subsurface irrigated area. Treatments included: no heat, heated with sub-irrigation, unheated with sub-irrigation, and two nitrogen rates. The rates of nitrogen were 92 and 111 kg/ha of actual N. Phosphorus and potassium fertilization was as discussed in Section 7.9.3.1. The beans were planted on May 30 with a precision planter on a 12.6 x 12.6 cm spacing. Unheated plots received 30.5 cm of irrigation water applied with full circle sprinklers. Sub-irrigated treatments received 26.6 cm of irrigation water applied with full circle sprinklers and 7.7 cm of water applied through the subsurface irrigation system. The heat source temperature was near 35 C during the growing period.

Harvest areas on sub-irrigated plots included equal length of rows between heat sources and over them. The unheated plots were located at least six meters from the nearest heat source. Four harvest strips were taken in sub-irrigated areas and three in unheated areas. Yields, maturity, adjusted yields, and relative yields are shown in Table 64.

Table 64. Yield of sub-irrigated bush beans, percent passing a number 4 sieve, and adjusted yield for two fertility levels, 1970.

Nitrogen fertilizer rate	Treatment	Yield	% Passing #4 sieve	Adjusted yield	Relative yield
kg/ha		T/ha	%	T/ha	%
92	Unheated	18.1	68.6	20.2	100
	Unheated, sub-irrigated	19.2	63.8	20.5	102
	Heated, sub-irrigated	26.2	49.7	26.2	130
111	Unheated	16.4	66.9	18.3	100
	Unheated, sub-irrigated	17.4	64.4	19.0	104
	Heated, sub-irrigated	23.3	50.8	23.4	128

7.9.4.2 Discussion. Sub-irrigation alone did not significantly affect yield or maturity. The slight increase in yield for unheated, sub-irrigated plots is probably due to more efficient use of irrigation water applied through the subsurface system. Sub-irrigation with soil heating resulted in a highly significant yield increase. Statistical analysis of maturity was not possible because composite samples were taken, but heating appeared to advance maturity. The heated beans were mature at harvest while unheated beans were about five to seven days away from ideal maturity.

The high rate of nitrogen decreased unheated yields as it did on the parallel planting of May 30 discussed in Section 7.9.3. The high rate of nitrogen also decreased yields on the heated plots. This is in contrast to its effect on the heated plots of the parallel planting discussed in Section 7.9.3. This can be explained in part by the previous cropping history. Plantings D1 and D2 discussed in Section 7.9.3 followed bush beans. The sub-irrigated block was planted to alfalfa in 1969. A good stand of alfalfa was plowed down in April 1970, contributing a high level of organic material to the soil.

7.9.5 Crop Year: 1971

7.9.5.1 Methodology and Results. The cultivar Oregon 58 was planted on the sub-irrigated area and on an adjacent unheated area. Seeds were planted 5 cm apart in 20 cm rows on June 30. The heated plot was surrounded by a corn shelter strip. Unheated beans received 27.4 cm of irrigation water applied with sprinklers. Heated plots received 24.4 cm applied with sprinklers and 6.4 cm applied through the sub-irrigation system. Nitrogen was applied at the rate of 95 kg/ha of actual N. The fertilization was identical to that used in 1970 crops. The heat source temperature was 31 C during the growing season.

The area harvested in all plots was 8.4 square meters. Unheated plots were at least five meters from the nearest heat source. Yields and percent of beans passing a number 4 sieve are presented in Table 65. Harvesting was delayed several days past ideal maturity as shown by the maturity data.

Table 65. Yield of bush beans, percent passing a number 4 sieve, and adjusted yield, 1971.

Treatment	Yield	% Passing #4 sieve	Adjusted yield	Relative yield
	T/ha	%	T/ha	%
Unheated	25.5	19.3	22.2	100
Heated	29.6	12.3	25.3	114
LSD ($P < .05$):	2.9			

7.9.5.2 Discussion. The yield response to heating with sub-irrigation was significant at the 5 percent level. Plant populations were 415,000 and 316,000 plants/ha on unheated and heated plots, respectively. This difference may explain in part the failure of heating response to be as high as that observed on sub-irrigated plots in 1970.

7.9.6 Summary and Conclusions.

Three years of bush bean experiments are summarized in Table 66. The average response to soil warming was a 19 percent yield increase. The average heated yield was 18.6 tons/ha. High density plantings in 1970 and 1971 resulted in much higher yields than were achieved with conventional plant densities.

Table 66. Adjusted bush bean yields and yield increase due to soil warming obtained during the indicated three years of experiments.

Planting date	Nitrogen fertilizer rate	Adjusted yields		Yield increase
		Unheated	Heated	
	kg/ha	T/ha	T/ha	%
5/12/69	114	14.3	17.4	22
5/28/69	114	13.5	15.5	15
6/17/69	114	10.5	14.6	39
7/25/69	114	8.7	11.8	36
5/30/70	54	13.5	15.3	13
5/30/70	92	10.1	18.3	81
5/30/70	111	10.1	18.7	85
7/ 3/70	54	20.0	13.1	-34
7/ 3/70	92	20.9	18.5	-12
7/ 3/70	111	20.7	24.0	16
5/30/70	92	20.2	26.2	30
5/30/70	111	18.3	23.4	28
6/30/71	92	22.2	25.3	14
Average		15.6	18.6	19

The wide range in yield response to soil warming for three years of bush bean experiments is similar to the results obtained with field corn (Figure 22). The lowest fertility treatments in 1970, the planting where water damage reduced heated yields, were omitted in the analysis. It is apparent that two separate populations are represented. The high density crops of 1970 and 1971 were treated separately from the 1969 crops.

Linear regression equations were calculated and are plotted in Figure 22. For the high density crops the correlation coefficient was: $r = -.99$. The correlation coefficient was $r = -.87$ for the 1969 crops. Quadratic regression equations did not give significantly higher correlation coefficients.

The relationships obtained suggest that maximum yields for the low density and high density cropping systems are 17.2 and 24.0 tons/ha respectively. At these production levels, zero response to soil warming is predicted. The unheated yields were normalized to obtain a percentage of maximum yield in the same manner as discussed in Section 7.7.9. These data are presented in Figure 23, with linear and quadratic regressions shown. The quadratic regression equation accounted for 85 percent of the variation in normalized yields and had a correlation coefficient of $r = -.92$.

It was postulated in Section 7.7.9 that the relationship between unheated yields and yield response to soil heating might apply not only

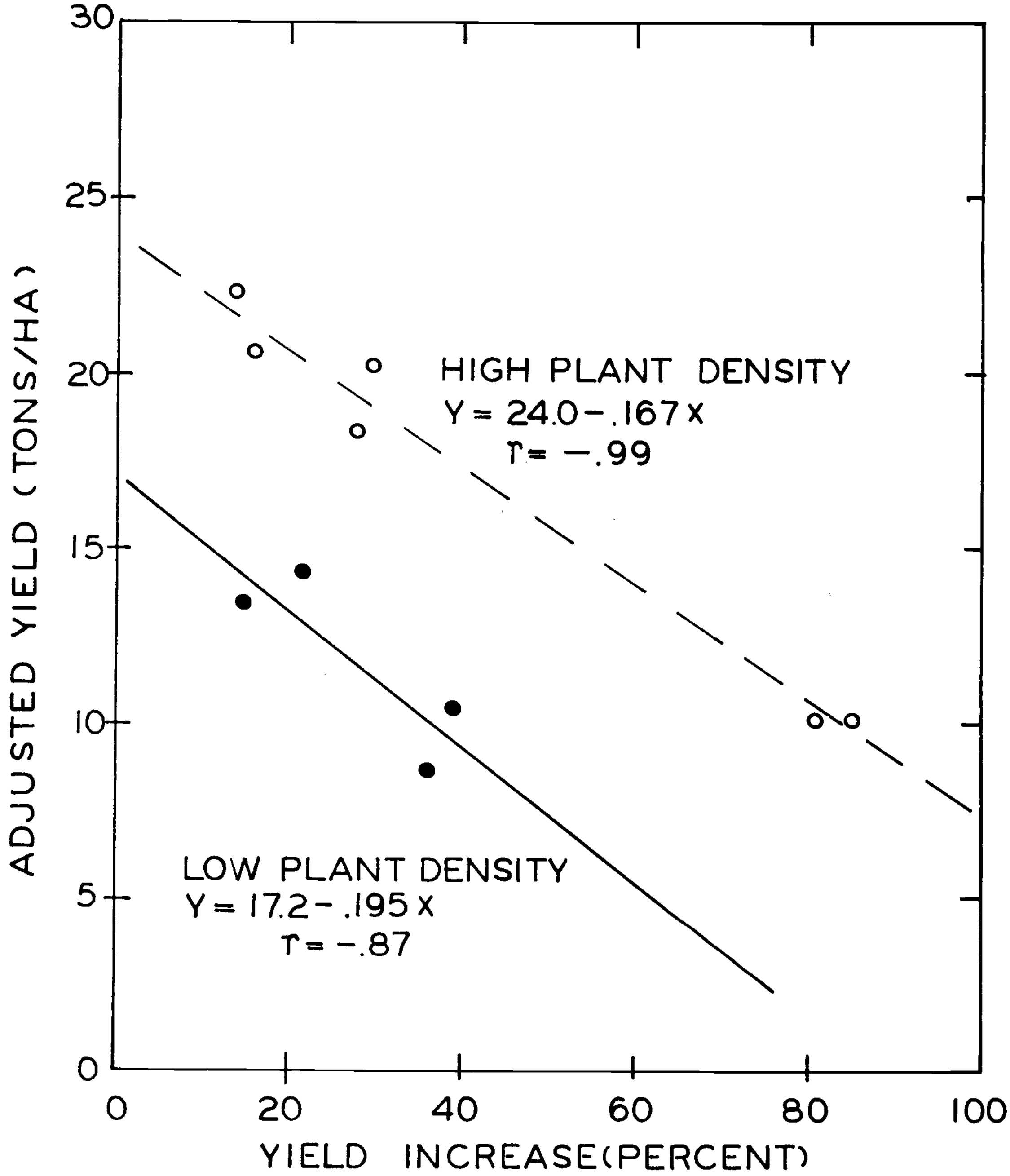

Figure 22. Percent bean yield increase obtained on heated plots as a function of yield obtained on unheated plots.

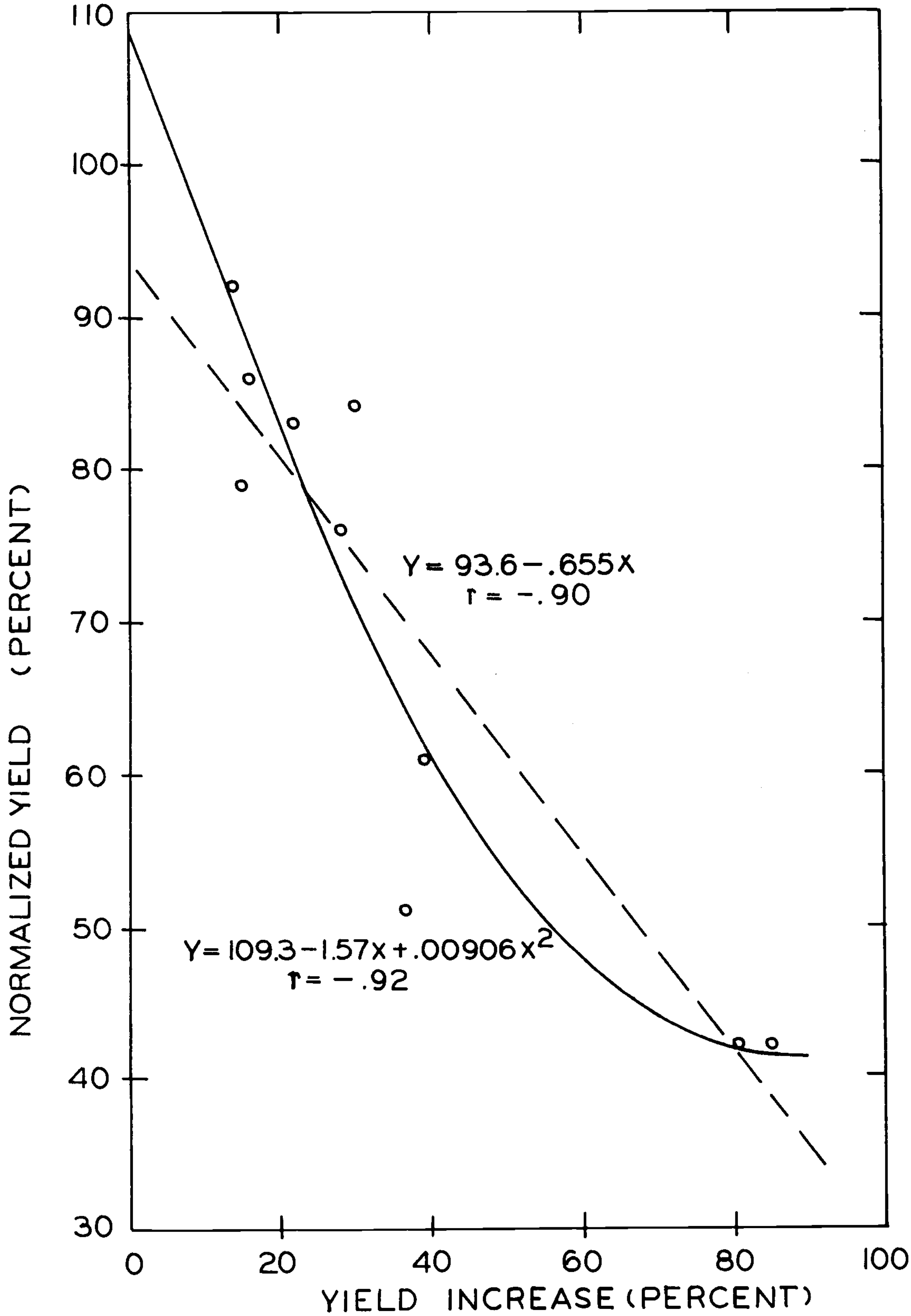

Figure 23. Percent bean yield increase obtained on heated plots as a function of normalized bean yields on unheated plots.

to field corn but to all crops. To test this hypothesis, the normalized yields and heat responses were combined with the 22 pairs of data from field corn including silage and grain yields. The resulting quadratic regression equation, based on 32 pairs of observations, was:

$$Y = 98.1 - 1.26X + .00606X^2 \quad [\text{with } r = -.89]$$

This compares quite closely with the relationship calculated for corn yields alone:

$$Y = 96.8 = 1.34X + .00666X^2 \quad [\text{with } r = -.91]$$

The close agreement between these two crops suggests that the response to soil warming is similar.

7.10 Lima Beans (*Phaseolus lunatus*)

7.10.1 Introduction

Green Lima beans are an important crop for the fresh and processed vegetable markets. The climatic requirements for this crop are more stringent than for common beans. Production of Lima beans in the Willamette Valley is limited by the cool summer temperatures. They were grown in this study to determine if soil warming could overcome temperature limitations of the region for this high value vegetable crop.

Lima beans require warm weather and particularly, warm nights to achieve maximum yields. The crop is highly susceptible to frost damage at all stages of growth. Successful germination requires soil temperatures of at least 15.5 C, and preferably 18 C or above (Knott, 1955; Thompson and Kelly, 1957). Extended periods of hot weather can result in poor blossom set.

Because of the extensive root system this crop develops, water can be withdrawn to considerable depths. As a result, irrigation requirements are less than for more shallow rooted crops. A longer growing season is required for Lima beans than for common cultivars of snap beans because the seeds must reach a more mature state.

7.10.2 Methodology and Results

The cultivar Early Thoragreen was planted on May 15, 1969, at a rate of 30 seeds per meter of row with a row spacing of 91 cm. A broadcast application of 168 kg/ha of agricultural gypsum and 114 kg/ha of actual N was made prior to planting. At planting time 100 kg/ha of P_2O_5 and 34 kg/ha of K_2O was applied in bands. Petroleum mulch was applied in 15 cm wide bands over the rows immediately after planting. The herbicide Eptam was applied at a rate of 2.8 kg/ha active material on May 19. A total of 47.0 cm of irrigation water was applied with full circle sprinklers during the growing season.

Unheated harvest areas were located at least five meters from the nearest heating cable. Rows directly over heat sources and between them were harvested separately. Three rows 4.6 meters long were harvested for each treatment on September 4. Yields are shown in Table 67.

Table 67. Yield of Lima beans, 1969.

Treatment	Yield	Yield increase
	T/ha	%
Unheated	4.9	
Between cables	5.8	18
Over cables	5.4	10

In 1971, the cultivar Early Thoragreen was planted on May 21, at a rate of 39 seeds per meter of row with a row spacing of 91 cm. A broadcast application of 56 kg/ha of P_2O_5 was made prior to planting. At the time of planting 54 kg/ha of actual N, 67 kg/ha of P_2O_5 and 69 kg/ha of K_2O was banded. In addition nitrogen was broadcast at rates of 0, 38, and 57 kg/ha of actual N, to establish three fertility treatments. The herbicide Eptam was applied at a rate of 2.8 kg/ha active material on April 29. Heated areas were surrounded by a corn shelter strip. During the growing season 35.6 cm of irrigation water was applied with full circle sprinklers.

The rows on the heated area were planted at a distance of 46 cm from the cables. This was done because in 1969 the yield was the same for rows over the heat sources and rows between them. Unheated plots were located at least five meters from the nearest heating cable. Three areas were harvested for each treatment. These consisted of two rows each 6.1 meters long. The crop was harvested on September 22. Yields are presented in Table 68.

Table 68. Yield of Lima beans, 1971.

Nitrogen fertilizer rate	Unheated	Heated	Yield increase
kg/ha	T/ha	T/ha	%
54	5.00	6.43	29
92	5.33	8.60	61
111	4.32	5.69	32

7.10.3 Discussion

The yields obtained from rows over the heat sources and from rows between them were not statistically different in 1969. Averaging the two heated treatments results in a 14 percent response to heating. There did not appear to be any effect of soil heating on maturity even though emergence occurred two days earlier on heated plots.

Heating treatment and fertility treatment affected yields significantly at the 1 percent level in 1971. The medium fertility level gave the highest yield on heated as well as unheated plots. The high level of nitrogen stimulated vegetative growth but depressed the yield of beans. At the medium fertility level, soil heating increased the yield of beans by 61 percent. There appeared to be a maturity difference of at least 10 days between unheated and heated plots.

Unheated yields were similar in 1969 and 1971, but yields on heated plots were higher in 1971. It is possible that the effect of soil warming was enhanced by the shelter provided by the corn. The use of petroleum mulch in 1969 and the failure to use it in 1971 are also likely to be important as discussed in Section 7.9.3.2. The heat source temperature was maintained higher in 1971 which resulted in higher soil temperatures at all depths. Soil temperatures were not measured on this plot.

7.10.4 Conclusions

Results of two years of experimentation with Lima beans suggest that soil warming with optimum fertilization results in substantial yield increases. A 61 percent yield response to heating on this high value crop might justify the expense of a soil warming system. Lima beans could be used in a double-cropping rotation with a winter annual forage crop such as annual ryegrass or Crimson Clover.

7.11 Tomatoes (*Lycopersicon esculentum* Var. *commune*)

7.11.1 Introduction

The commercial importance of tomatoes in the Willamette Valley is limited due to the relatively long growing season and warm temperatures required for good yields and quality. This crop was included in field and greenhouse experiments to evaluate the potential of soil warming for lengthening the growing season and providing more favorable temperature regimes for warm-season crops. A minimum night temperature of 15 C is required for fruit set. Temperatures below 10 C and above 32 C reduce pollen production resulting in blossoms dropping off prior to fertilization. Temperatures below 13 C seriously reduce fruit ripening (Knott, 1955).

Tomato plants are deep rooted and, therefore, can withdraw soil water from a large volume of soil. Early season irrigations should wet the soil to depths reached by the roots. Irrigation during ripening can cause cracking of the fruit and should be kept to a minimum (Thompson and Kelley, 1957).

Since tomatoes require a three to four month growing season and are susceptible to frost damage, field planting is accomplished with transplants. Seeds are germinated in a greenhouse or hotbed and kept there for three to five weeks. Plants are then moved to cold frames for at least one week prior to transplanting, to promote plant hardening.

7.11.2 Field Grown Tomatoes

7.11.2.1 Methodology and Results. Crop Year: 1969. In 1969 the cultivar Willamette was planted on June 11. Plants were set out at 30.5 cm intervals in rows spaced 183 cm apart. Heated rows were located directly over the parallel heat sources. The unheated area was located six meters from the nearest heat source. A broadcast application of 116 kg/ha of actual N and 350 kg/ha of P_2O_5 was made one week prior to planting. During the growing season 19.5 cm of irrigation water was applied with full circle sprinklers.

Yields were obtained by harvesting a 12.2 meter strip in one row. All tomatoes were picked September 25 regardless of size or state of maturity of the fruit. The yields were 72 and 108 tons/ha for unheated and heated plots, respectively. This represents a 50 percent yield increase due to soil heating. There was no evidence that soil heating advanced maturity. It did appear to increase the average size of the tomatoes and the number of tomatoes per plant.

7.11.2.2 Methodology and Results. Crop Year: 1970. The cultivar Victor Cross was planted in field plots on June 2 in rows 183 cm apart with 30.5 cm spacing in the row. The area received a broadcast application of 116 kg/ha of actual N and 350 kg/ha of P_2O_5.

The tomatoes received 36.8 cm of irrigation water applied with full circle sprinklers. The source temperature was maintained at 33 C during the growing season. This was a lower temperature than was maintained during the 1969 season. The harvested area was 28 square meters. The plots were harvested on September 27. All fruit was harvested at this time.

Yields on field plots were 79 and 100 tons/ha for unheated and heated treatments, respectively. This represents a 28 percent response due to soil heating. The response to heating was smaller than was measured in 1969. This may in part have been the result of the lower soil temperatures maintained in 1970. Energy dissipation rates in 1970 were about 60 percent of the 1969 rate. Heating did not appear to influence maturity but did have an effect on size of fruit and number of tomatoes per plant.

7.11.2.3 Methodology and Results. Crop Year: 1971. The cultivar Willamette was planted on June 16 in rows spaced 183 cm apart with a 30.5 cm plant spacing in the rows. All areas received 116 kg/ha of actual N and 350 kg/ha of P_2O_5 broadcast prior to planting.

The unheated plot received 38.4 cm of irrigation water applied with full circle sprinklers and the heated plot received 35.0 cm of water applied with full circle sprinklers and 10.2 cm applied through the subsurface irrigation system. The heated plot was surrounded by a border of field corn. This was planted to evaluate the effect of a wind shelter on air temperatures near the ground. It was hypothesized that the shelter might trap heat from the heat sources to maintain higher air temperatures. The harvest area was 50.2 square meters.

The first picking was on September 10. The final picking of all fruit was on October 28. The yields obtained were 59 and 77 tons/ha on unheated and heated plots, respectively. This represents a 31 percent response to soil heating. Soil temperatures during the 1971 season were lower than they had been in previous years. The heat source temperature was maintained at 31 C during the growing period. This may account for the smaller yield increase observed in 1971. It is possible that sub-irrigation may have influenced yield levels slightly.

7.11.2.4 Summary and Conclusions. Response to soil warming is summarized in Table 69. The average response to soil heating for three years of tomato production was 36 percent. The yields obtained in field plots may be unrealistic in view of the fact that immature fruit was included. However, with the use of hot caps or similar protection devices, it would be possible to make plantings two to three weeks earlier in most years. This would undoubtedly result in increased yields and earlier maturation.

Table 69. Yield of tomatoes measured during 1969, 1970, and 1971.

Year	Treatment		Yield increase
	Unheated	Heated	
	T/ha	T/ha	%
1969	72	108	50
1970	79	100	28
1971	59	77	31

7.11.3 Greenhouse Grown Tomatoes

Tomatoes were planted in a plastic covered greenhouse heated with buried heat sources during the 1970 and 1971 growing seasons. Fertilization was the same as for field grown tomatoes. 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 24). 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

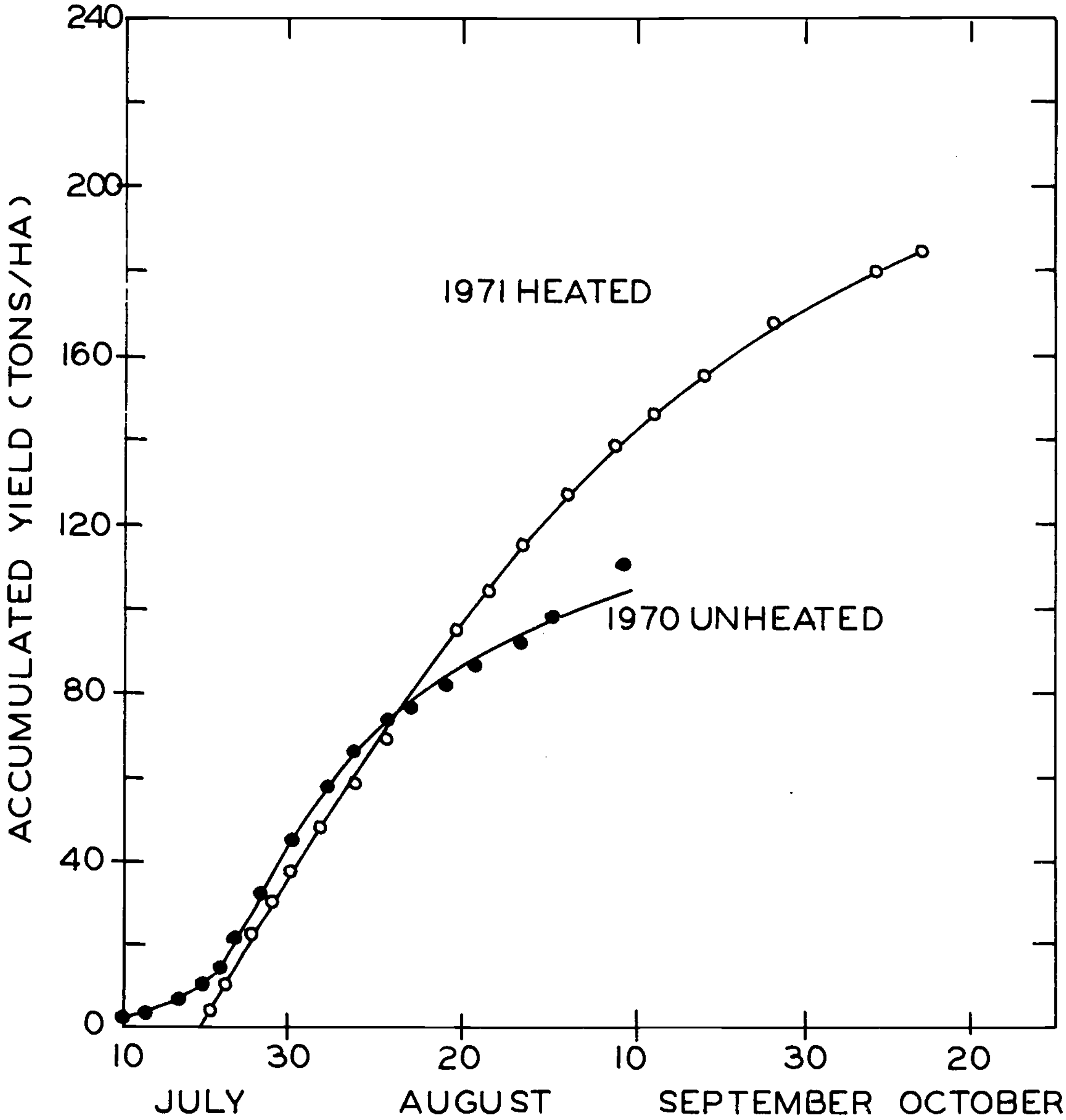

Figure 24. Accumulated yield on unheated greenhouse cultured tomatoes, 1970, and heated greenhouse cultured tomatoes, 1971. Only mature fruit is represented.

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 24). and an additional 22 tons/ha of immature fruit picked on October 14.

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 sub-surface heating for greenhouse tomato production.

7.12 Broccoli (*Brassica oleracea* Var. *italica*)

7.12.1 Introduction

Broccoli is a cool season vegetable crop which is grown extensively in the Willamette Valley. It has less severe climatic requirements than tomatoes. It was included in this study to determine the effect of soil warming on a crop fairly well suited to the natural climatic conditions of the region. The cole crops, including broccoli, are best adapted to cool weather. They can withstand frosts if hardened prior to being set in the field. Plants are sometimes started in hot beds and hardened in cold frames although direct seeding is gaining popularity.

Hot weather during the harvest period may result in leafiness and openness in the heads. This is not as severe for broccoli as other members of the cole crop family (Thompson and Kelley, 1957). Heads and lateral shoots will form at temperatures as low as 7 C provided the plants were well developed previous to this (Knott, 1955). The development of lateral shoots results in an extended harvest period with several cuttings.

7.12.2 Methodology and Results

The cultivar Waltham 29 was planted on July 7, 1971. The plants were set out at 61 cm intervals in rows 61 cm apart. The fertilizer was broadcast and included 168 kg/ha of actual N, 168 kg/ha of P_2O_5, 84 kg/ha of K_2O, 50 kg/ha of sulfur and 2.2 kg/ha of boron. Commercial plant starter solution was used at planting time at the rate of 500 cm^3 per plant.

The heated plot was in the sub-irrigated area. It was surrounded by a corn shelter strip. The unheated area received 39.4 cm of irrigation water during the growing season, applied with full circle sprinklers. The heated plot received 35.0 cm of irrigation water applied with full circle sprinklers and 10.2 cm applied through the subsurface irrigation system. The heat source temperature was maintained at 31 C during the growing season.

Five cuttings were made from September 2 to October 28. Harvest areas were 22.3 and 11.2 square meters on the unheated and heated plots respectively. Accumulated yields are shown in Table 70. The yields of 2.28 and 4.86 tons/ha for unheated and heated plots, respectively represent a 113 percent response to soil heating. It was observed that soil heating had an effect on the maturity of the crop. Although quality determinations were not made, heated heads were consistently larger.

Table 70. Accumulative yield of broccoli and heat response.

Harvest date	Unheated	Heated	Response to Heating
	T/ha	T/ha	%
9/2	.58	1.77	204
9/10	.96	2.17	126
9/21	1.52	3.43	126
10/5	1.79	3.94	120
10/28	2.28	4.86	113

7.12.3 Conclusions

The large yield increase achieved with soil heating on broccoli suggests that cole crops may be among the most responsive crops to soil warming systems. They are also high value crops and warrant consideration as cash crops to be included in any soil warming system.

7.13 Peppers (*Capsicum annuum*)

7.13.1 Introduction

Peppers, like tomatoes, are grown commercially in the Willamette Valley only to a limited extent. Temperature requirements are not as severe as those for tomatoes. This crop was included to represent a high value vegetable crop with minor climatic limitations for this region.

Peppers are susceptible to frost and like tomatoes are set out as five to seven week old transplants in cool climate regions. Cochran (1936) found that peppers held at 10-15.5 C made no appreciable growth and did not flower. Even plants which developed blossoms at higher temperatures did not develop normal fruit when transferred to an environment with temperatures from 10-15.5 C.

Low humidity and high temperatures cause excessive transpiration and water deficits in pepper plants. This results in blossom drop. It is essential to maintain a moist soil, particularly from blossom set to harvest (Thompson and Kelley, 1957).

7.13.2 Methodology and Results

Green peppers were transplanted from cold frames July 7, 1971 in 61 cm rows with a row spacing of 61 cm. Fertilizer was broadcast and included 168 kg/ha of actual N, 168 kg/ha of P_2O_5, 84 kg/ha of K_2O, 50 kg/ha of sulfur and 2.2 kg/ha of boron. In addition, each plant received 500 cm^3 of a commercial plant starter solution at transplanting time.

The heated plot was in the sub-irrigated block. It was surrounded by a corn shelter strip. The unheated plot received 39.4 cm of irrigation water during the growing season, applied with full circle sprinklers. The heated plot received 35.0 cm of irrigation water applied with full circle sprinklers and 10.2 cm applied through the subsurface irrigation system. The heat source temperature was maintained at 31 C during the growing season.

Harvesting began on August 30 and continued until October 19. Harvest areas were 22.3 and 11.2 square meters for unheated and heated plots, respectively. Accumulative yields presented in Table 71 indicated that heating resulted in rapid early growth. Unheated plants caught up later in the season. The total yields of 6.32 and 8.92 tons/ha for unheated and heated plots, respectively, represent a 41 percent response to soil heating.

Table 71. Accumulative yield of green peppers and heat response.

Harvest date	Yield: Unheated	Yield: Heated	Response heating
	T/ha	T/ha	%
8/30	.22	.43	95
9/2	.34	.74	118
9/10	.45	1.59	253
9/14	1.12	2.58	130
9/18	1.84	3.70	101
9/21	3.09	5.31	72
9/26	3.92	6.00	53
9/30	4.64	6.12	32
10/5	5.08	6.68	31
10/10	5.38	7.10	32
10/19	6.32	8.92	41

7.13.3 Conclusions

As was found with broccoli, the greatest yield response occurred early in the season. This crop was found to be quite responsive to soil warming. A large yield increase combined with the high value of green peppers suggests that this crop would be a suitable cash crop to include in a soil warming scheme.

7.14 Strawberries (*Fragaria virginiana*)

7.14.1 Introduction

Strawberries are the chief small fruit crop grown in the Willamette Valley. Western Oregon and Washington is the world's leading strawberry production area. This crop was included in this study because of its economic importance in the region.

The strawberry is one of the most adaptable crops grown. Cultivars are available which grow in such extremes as the interior of Alaska and in semi-tropical climates (Darrow, 1966). The cultivar Northwest was developed in western Washington in 1949 and is now grown on most commercial fields in the northwestern region of the United States.

The strawberry is a perennial crop. Roots and leaves die in winter months. New roots and leaves develop from the crown when favorable temperatures occur in the spring. The degree of bud formation is determined by temperature and moisture conditions in late summer and fall of the previous year. Cultivars have characteristic day-length requirements which must be met to initiate floral formation and the growth of runners.

The crop is susceptible to frost injury after flower formation in the spring. Flowers of commercial cultivars are killed by temperatures of -2 C or lower (Darrow, 1966). However, since not all flowers develop at the same time, total loss of a crop seldom occurs (Shoemaker, 1948).

The time required to progress from flowers to mature fruit is highly dependent on temperature. Darrow (1930) found the optimum temperature for growth to be 23 C during daylight hours for nine cultivars representing northern, southern and middle latitude regions. Growth rates were much lower below 20 C and above 26 C.

Plants are normally restricted to narrow rows spaced about one meter apart. Correlations between leaf area and yield have frequently been made (Darrow, 1966; Shoemaker, 1948). Increasing plant density in beds can be expected to increase yields. It also increases labor requirements for harvesting.

7.14.2 Methodology and Results

The cultivar Northwest was planted June 13, 1969. The plants were set out in 183 cm rows with a 92 cm spacing in the rows. A broadcast application of 58 kg/ha of actual N and 175 kg/ha of P_2O_5 fertilizer was made prior to planting. An additional application of 36 kg/ha of actual N and 45 kg/ha of P_2O_5 was made in the fall of 1970.

In 1969 all blossoms were pinched off to stimulate vegetative growth. Runners were trained to fill the beds with a blanket stand, except for a 30 cm wide path separating 122 cm wide beds. Thus by 1970 the beds occupied 80 percent of the soil surface. In most commercial beds the plants are maintained in 91 cm rows which results in beds occupying about 30 percent of the soil surface.

Irrigation water was applied with full circle sprinklers. During the 1969 growing season 29.5 cm of irrigation water was applied. The amounts for 1970 and 1971 were 40.7 cm and 10.2 cm, respectively. The low application in 1971 reflects the fact that the beds were abandoned after the 1971 harvest.

Three strawberry areas were established. One of these was an unheated control plot. The average distance from the unheated plot to the nearest heat source was six meters. The second plot was on an area with parallel heat sources with the original rows located directly over the heat source. The third plot was established in a plastic covered greenhouse heated with buried heat cables. Two separate heat source systems were used in heating the plots inside the greenhouse and those in the open field. In 1969 the outside heat source was energized from April 25 to October 20 while in the greenhouse the source was used from May 1 to October 27. In 1970 the heat source in the greenhouse did not work because of a malfunction. A new cable was installed in December 1970 at a depth of 51 cm and spacing of 122 cm and was energized during the 1971 growing season. The open field heat source was used throughout the 1970 and 1971 seasons.

Harvesting of the greenhouse plot began on April 22 in 1970 and continued through June 18. The harvest area was 56 square meters. Figure 25 shows the accumulative weight of fruit harvested for the greenhouse plot as well as heated and unheated open field plots. A total yield of 17.4 tons/ha was obtained in the greenhouse plot. The greenhouse harvest was about one month ahead of the field harvest.

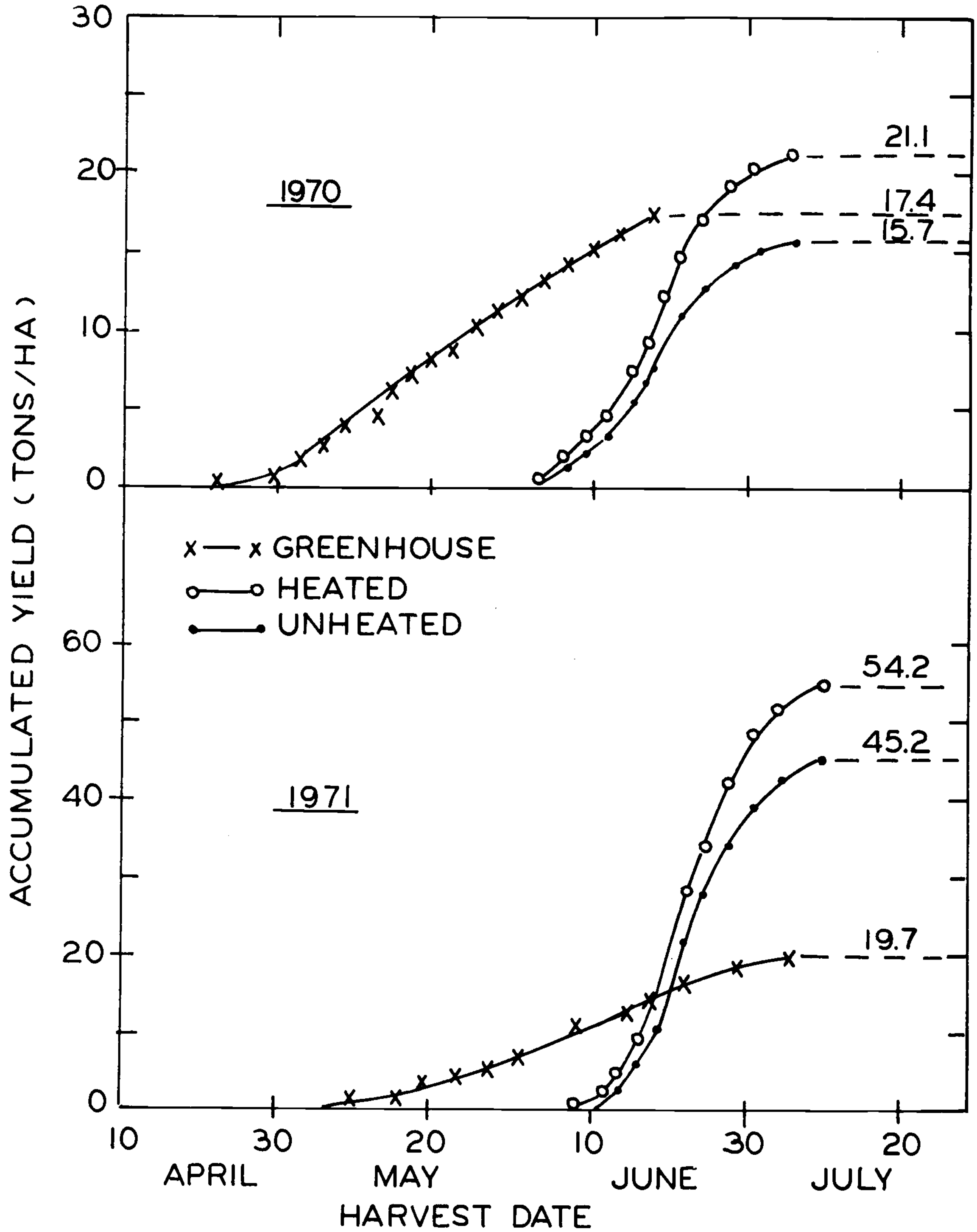

Figure 25. Accumulated strawberry yields on unheated and heated open field plots and in greenhouse culture, 1970 and 1971.

The greenhouse crop was limited in yield by water damage from condensation on the plastic and subsequent dripping on the fruit. Fungus growth was also a problem in the greenhouse plot. Control of these two factors might have resulted in higher yields.

Field plots of 56 square meters were harvested from June 3 to July 6 in 1970. The berries on the heated and unheated plots matured at about the same time. Final yields of 21.1 and 15.7 tons/ha for heated and unheated plots, respectively, represent a 35 percent yield response to soil heating. No fruit quality determinations were made. It was apparent that berries from the heated plots were much larger than those from the unheated plots throughout the harvest period. No disease problems were encountered in the field plots.

The beds in the field plots were more densely populated in 1971, which resulted in higher yields. The greenhouse plot was severely disturbed when the new heating cable was installed. The fungus problem was more severe than it had been in 1970. Figure 25 shows that the harvest period for the greenhouse plot was from May 4 to July 6. The field plots were harvested from June 12 to July 10. Thus harvesting commenced 12 days later in the greenhouse and nine days later in the field than during the 1970 season. It appears that soil heating did not hasten maturity in the greenhouse. This seems reasonable in view of the fact that heated field plots did not mature ahead of unheated plots.

The greenhouse crop matured more than one month earlier than the field plots, as had been observed in 1970. Total yields were much higher in field plots, however, for the reasons discussed above. Yields were 19.7, 45.2, and 54.2 tons/ha, respectively, for greenhouse, unheated and heated plots. The response to soil heating in the field plots was 20 percent. The yield increases of 5.4 and 9.0 tons/ha for 1970 and 1971, respectively, represent a substantial increase for a high value crop.

The most important effect for greenhouse culture of strawberries appears to be the impact on maturity. In addition to the problems discussed above, it is quite possible that high temperatures may have had an adverse effect on yield in the greenhouse. It was noted in Section 7.14.1 that air temperatures above 26 C reduce growth. Comparisons between 1970 and 1971 yields do not provide evidence for evaluation of soil heating response in the greenhouse because of other complicating factors. However, it would appear that soil heating in the greenhouse probably did not increase strawberry yields.

7.14.3 Conclusions

It is apparent that high plant densities can greatly increase strawberry yields in both heated and unheated open field culture. The yield increase achieved with soil warming would probably justify the expense of soil heating because of the high value of the crop. The increase in berry size attributed to heating is also an indication of improved quality.

Greenhouse culture of strawberries is attractive because of the early harvest. However, it appears that some sacrifice in yield potential would accompany the early market advantage. Soil heating in greenhouse culture of strawberries does not appear to provide an added advantage.

7.15 Summary and Conclusions

Thirteen different crops were grown on heated and unheated areas. Field corn and bush beans were grown in each of the four years of the study. Most others were grown during at least two years. A wide range in yield response to soil heating was observed for different crops and for some crops in different years. The results obtained with field corn and bush beans suggest that the response to soil heating depends on the degree of adversity to which the crop is subjected. If weather conditions, fertilization, irrigation and other management practices are optimum soil heating has a limited effect on yields. When one or more of these production factors is limiting, soil heating becomes more effective and greater responses occur. Soil heating is most beneficial for crops which have climatic limitations for a given area. In nearly all cases soil warming resulted in earlier maturation. This can be attributed to faster germination and greater growth rates early in the season when soil temperatures are limiting.

Two summer annual forage crops, sudangrass and sorghum-sudangrass hybrid were evaluated. Two years of trials indicate that the highest yields and the greatest heat response will be achieved with sorghum-sudangrass hybrid. Two winter annual forage crops, Crimson Clover and Common Annual Ryegrass, were tested. The highest yields were obtained with Common Annual Ryegrass but the highest response to soil warming was found for Crimson Clover. Both crops could be grown in rotation with summer annuals making use of land which may otherwise be idle during the winter months. A rotation of ryegrass and sorghum-sudangrass hybrid appears to be feasible. Crimson Clover could be planted in early fall following a crop of vegetables such as Lima beans or bush beans. The clover could then be harvested as a high quality forage crop or plowed down as a green manure crop in early May. One perennial forage crop, Fawn fescue, was harvested over a 14 month period. Soil warming substantially increased winter growth rates but slightly reduced yields during summer months. A total yield response of about 20 percent for 12 months appears to be possible with soil heating.

Field corn was evaluated for total dry matter and grain yield. Wide ranges in yields and response to soil heating were observed. While this crop produced the highest dry matter yields the long growing season required eliminates the possibility of following a corn crop with a winter annual forage crop. In a beef and dairy enterprise, field corn and a double cropping system including winter and summer annual forage crops would appear to be desirable. The corn crop could be followed by an early planted spring crop such as bush beans or Lima beans.

Three bean crops including soybeans, Lima beans and bush beans were evaluated. The response to soil warming for soybeans does not appear to be great enough to justify growing this crop in the Willamette Valley either for silage or grain. The length of growing season and air temperature requirements of this crop apparently cannot be substituted for by elevating soil temperatures. Lima beans responded well to soil heating in terms of yield as well as time to maturity. This crop could be harvested early enough to follow it with a fall planting of Crimson Clover or Common Annual Ryegrass. Bush beans were grown at two plant densities and double cropping was evaluated. An unheated crop planted on July 25 did not mature to a marketable commodity. A heated crop planted on the same date following an early planting easily matured to marketable size with substantial yields. High density plantings resulted in very high yields. It is suggested that double cropping with high density plantings and optimum fertilization can result in yields of 45 to 50 tons/ha on heated soil. The second crop could be harvested early enough to plant ryegrass in the fall.

Tomatoes were grown in open field as well as greenhouse culture. Open field plantings were not made early enough to mature a high percentage of the fruit. Soil warming increased yields by about 35 percent and appeared to improve quality, but did not hasten maturity. Earlier plantings with hot caps or other frost protection devices may result in a sufficient increase in maturity to justify growing this crop on heated soil. Tomatoes were grown in a wood-frame, plastic covered greenhouse with and without soil heating. High yields of high quality fruit were produced in both cases but soil heating increased the yield of marketable fruit by 64 percent.

Broccoli and green peppers were grown during one year of the study. Soil heating more than doubled the yield of broccoli and increased maturity of this high value vegetable crop. The yield response for peppers was not as dramatic but similar effects on maturity were noted. These results suggest that cole crops and other vegetables may be among the most responsive crops to be grown with a soil warming system.

Finally one small fruit crop, strawberries, was evaluated in open field and in greenhouse culture with and without soil heating. Greenhouse yields were reduced by fungus growths, water damage due to condensation on the plastic and subsequent dripping on the fruit, and by disturbances to the bed when a new heating cable was installed. Soil heating did not affect the yield of greenhouse grown strawberries.

The greenhouse advanced maturity by about one month in comparison with open field cultured fruit. In open field culture soil warming increased yields about 25 percent and resulted in larger berries throughout the bearing season. No difference in maturity was found between unheated and heated crops.

An economic evaluation of crop response to soil heating is required to make meaningful interpretations of the results of this study. Such an analysis could be used to determine the cropping systems which would result in the greatest possible beneficial use of subsurface heating. This analysis is beyond the scope of this investigation and will require additional inputs from agricultural economists, engineers and others.

8. GREENHOUSE HEATING WITH BURIED HEAT SOURCES

Climate control of greenhouses with power generating station cooling waters has been suggested as a possible beneficial use of waste heat (Williams, 1972; Jensen, 1972). Heating and cooling can be achieved by circulating the air within the greenhouse through a spray of warm water. Using water at approximately 27 C, greenhouses in Arizona are maintained at near optimum temperatures for tomato production year around (Jensen, 1972). The cost of climate control with a system utilizing warm water is competitive with other heating and cooling systems in use in this area. Year around crop production is possible in greenhouses in southern latitudes where light intensity and duration are adequate during the winter. In northern latitudes natural light may be insufficient to sustain winter production. The high cost of installing and operating a warm water spray, air circulation system may not be jusitifed in regions where year around crop production is not possible.

An alternative to the elaborate and expensive design described by Jensen (1972) is to construct wood frame, plastic covered greenhouses, or air supported plastic bubbles, and heat the soil with warm water circulating through buried pipes. This system was evaluated as part of this study from the standpoint of air and soil temperatures achieved as well as in relation to production of two crops, viz., strawberries and tomatoes.

A plastic covered greenhouse was constructed over a set of heating cables used in the soil warming research project. It was realized that the rate of heat loss from these underground heat sources was small and probably not sufficient to maintain the air temperature in the house much above ambient temperatures. The greenhouse that was built 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 at the positions described in Section 2.6 in five cross sections at equal distances along the length of the house. 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 72).

Table 72. 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	0.0	-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	12.6	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	7.9	--	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
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

Table 72. 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
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
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

Table 72. 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
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

8.1 Daily Temperature Comparisons

8.1.1 January 24

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 source temperature of 30 C. On this day the inside and outside air temperatures were very 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 slightly higher inside the greenhouse throughout the day. The soil temperature at a depth of 51 cm was the same inside and outside the greenhouse.

These measurements emphasize the rapid rates 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.

8.1.2 February 19

Even though the soil temperatures had reached an equilibrium condition on this day, little influence was being exerted on the air temperature inside the greenhouse. 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, however. The largest contribution from soil warming was the increase in the soil surface temperature inside the greenhouse.

8.1.3 February 21

On this day the soil profile was at equilibrium with the heat source temperature. 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.

8.1.4 March 8

A second layer of plastic was added over part of the house in such a way that an air space of about one inch 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 in this manner better advantage might be taken of the energy provided by the heating cables. 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 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 temperature midway between the heat sources, indicating that the energy flow was directed downward over most of the profile during this period. At the higher soil surface 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 temperature of the heat source is maintained at a very high level or if the air temperature in the greenhouse is very low.

8.1.5 March 10

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 this sort of application. The surface temperature of the soil in the greenhouse remained high throughout this period indicating very small temperature gradients toward the soil surface and consequently only a small energy flow was available for warming the air.

8.1.6 April 16 and June 8

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.

8.2 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 73 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 emphasizes the relative inertia of the soil. It should be emphasized, however, that the soil profile inside the greenhouse was extremely dry. More rapid equilibration would have been attained in a wetter soil. Increasing temperatures at this depth on later dates reflect changes in equilibrium conditions as seasonal warming of both air and soil temperatures occurred.

8.3 Summary and Conclusions

Characteristics of the energy requirements of greenhouses in the Willamette Valley are demonstrated in Table 72. March 8 represents a day on which a very cold night was followed by a warm day. The air temperatures 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

Table 73. Soil temperature midway between two heating cables at the depth of the heating cable.

Day no.	Date		Soil temp.	Day no.	Date		Soil temp.
			C				C
20	January	20	--	45	February	14	17.1
21		21	--	46		15	17.4
22		22	--	47		16	17.6
23		23	--	48		17	17.9
24		24	--	49		18	18.4
25		25	--	50		19	18.6
26		26	9.8	51		20	18.8
27		27	9.8	52		21	18.9
28		28	11.3	53		22	19.0
29		29	--	54		23	19.0
30		30	--	55		24	18.9
31		31	11.3	56		25	18.8
32	February	1	--	57		26	19.0
33		2	--	58		27	19.2
34		3	12.2	59		28	19.4
35		4	12.5	60		29	19.8
36		5	12.9	61	March	1	19.9
37		6	13.1	62		2	19.5
38		7	13.6	63		3	19.4
39		8	14.3	64		4	19.3
40		9	14.9	65		5	19.3
41		10	15.7	66		6	19.8
42		11	15.9	67		7	20.5
43		12	--	68		8	20.5
44		13	16.7	69		9	20.7
				70		10	20.9

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 72 indicate that the heat exchange with the outside environment is rapid. This suggests that any heating system used in greenhouses should have a rapid response time. Criteria for ideal heating systems for greenhouses therefore appear to be (1) rapid response, (2) wide range in capacity, and (3) provide cooling during certain times of the day. The soil warming system does not appear to meet any of these criteria.

The effect of soil warming on greenhouse production of tomatoes and strawberries was discussed in Section 7. It was concluded that soil warming did not enhance greenhouse production of strawberries. The reason for this may be the high air temperatures experiences in the greenhouse. Air temperatures above 26 C have been shown to reduce growth rates (Darrow, 1930). A substantial yield increase was obtained with tomatoes in response to soil warming in the greenhouse. This suggests that for tomatoes, and possibly other crops, the soil warming system may be attractive even though it does not significantly affect air temperatures within the greenhouse structure.

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