Crop Response to Warming Soils Above Their Natural Temperatures

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PREFACE

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

The Pacific Power and Light Company of Portland, Oregon, provided funding for initiation of a study of the effect of warming soils above their natural temperatures on crop growth. Additional funding was provided by the Office of Water Resources Research, USDI. The research program was conducted cooperatively by the Oregon State University Departments of Soil Science, Horticulture and Agronomic Crop Science. Research was conducted at the Hyslop Field Laboratory.

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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 depleted, 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 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 activities are 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 nonexistent 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.

The present study was initiated to evaluate the effect of increased soil temperatures on crop production and to study the heat budget of such a system. This report summarizes the effect of increased soil temperatures on crop growth.

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 about 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 is not available at the site. It was therefore decided to simulate the underground system of pipes with warm water flowing through them with a buried network of 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. This transformer had one secondary winding providing 480 volts center tapped to ground with a capacity of 250 kilovolt-amperes. This 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 1. A simplified schematic wiring diagram is presented in Figure 2.

Because of the diverse nature of the heated plots, a variety of heating cables was used, each specified to maintain a constant dissipation rate per unit area. With the exception of the greenhouse, all cables were a single-conductor unit consisting of one resistance heating wire completely surrounded by 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

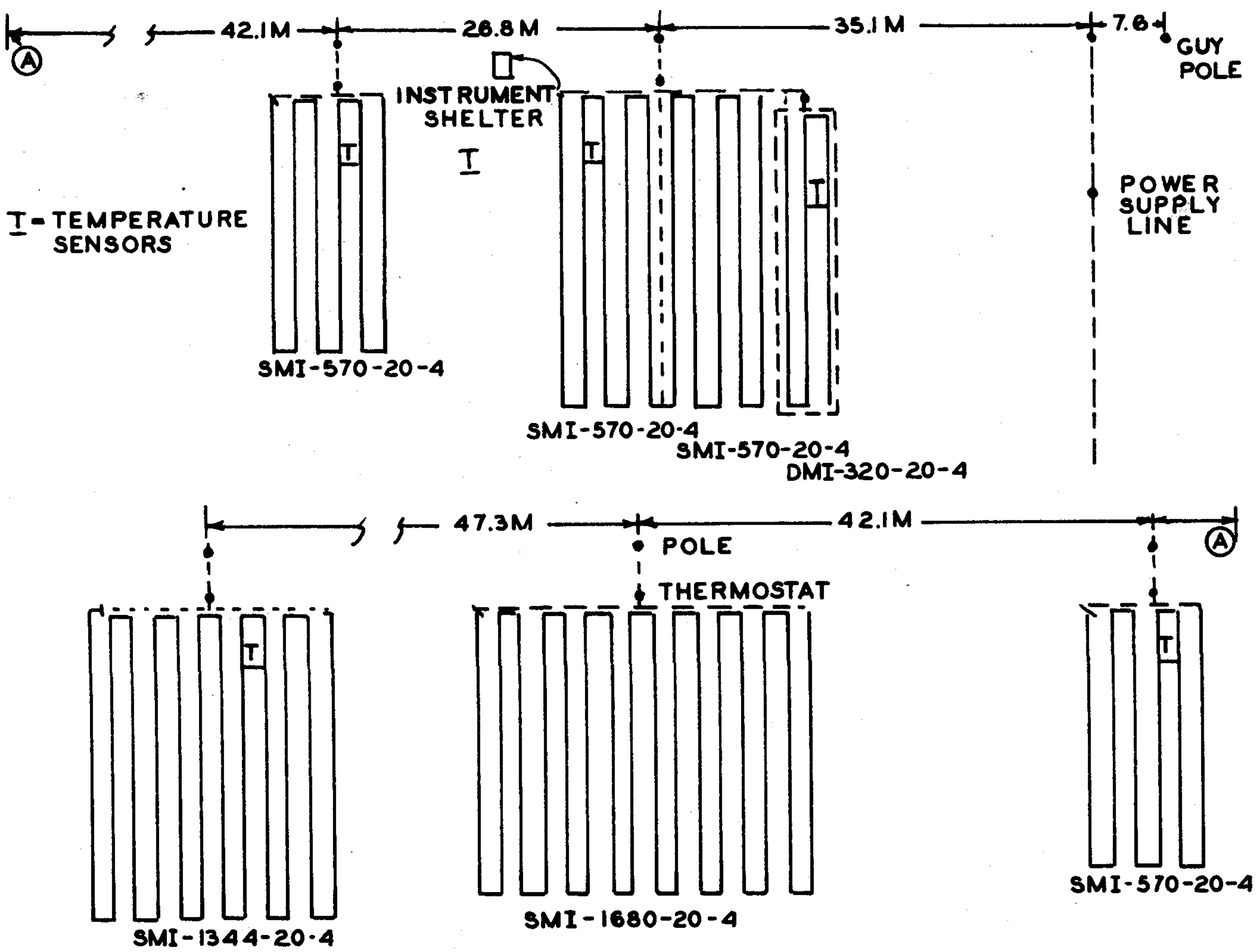

Figure 1. Layout of plots used in the soil warming experiment.

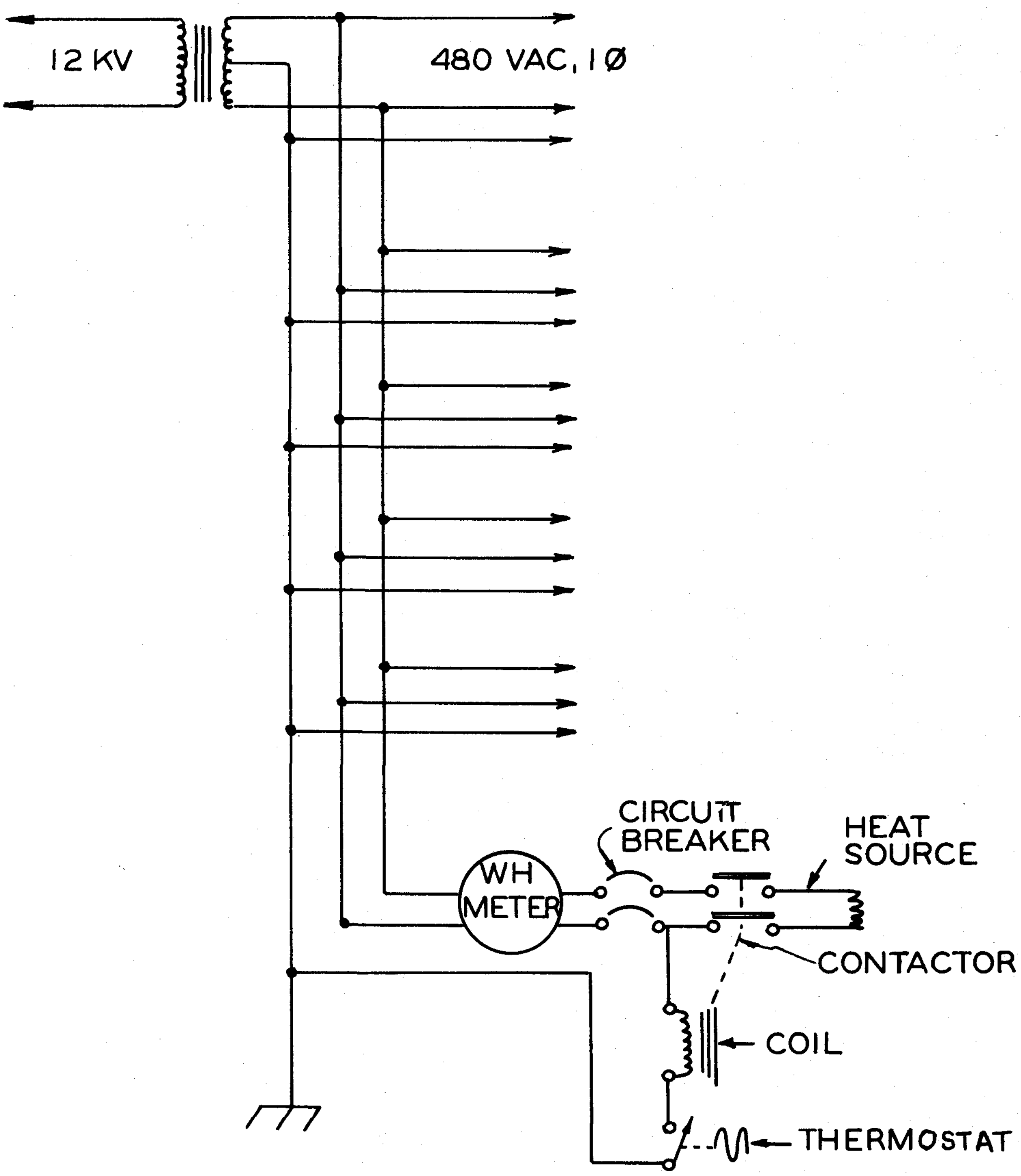

Figure 2. A simplified schematic diagram of the wiring of heat sources and their components to the secondary power source.

wires running parallel in a single sheath and having both terminations 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 of 65.5 watts per linear meter (watts/meter). Cable specifications are presented in Table 1.

Table 1. Heat 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 watt-hour meter and switching equipment fed from the secondary cable. Each circuit was metered by a 480-volt, two-stator, polyphase watt-hour 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. The alloy resistance wires in the shorter cables have a much smaller temperature coefficient and operate at essentially the design power of 65.5 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 watt-hour 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 by one-half of the lateral spacing. For the GRASS and GREENHOUSE locations the designations (1) and (2) refer to original and replacement cable respectively.

Table 2. Plot dimensions and placement of heating cables

Plot	Cable depth	Cable spacing	No. loops	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 control

Temperature control of each heating cable was achieved with an industrial thermostat (equivalent to no. A19ANC, Penn Controls, Inc., Oak Brook, Ill.) mounted in a watertight enclosure and having 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 adjustments. 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.

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

Month	NO COVER In use	NO COVER Source temp.	CORN In use	CORN Source temp.	SUB-IRR In use	SUB-IRR Source temp.	BEAN In use	BEAN Source temp.	GRASS In use	GRASS Source temp.	GREENHOUSE In use	GREENHOUSE 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	--

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 in operation during periods of crop production and in some cases through the winter months when crops were not being grown. Table 3 shows the periods of operation for each of the six sources, and source temperatures. Short-term shutdowns for various reasons are not indicated. Dates when heat sources were turned on or off are indicated in columns labeled "in use."

Source temperatures indicated in Table 3 are average values for periods when heat sources were in use. On the CORN and GRASS plots, source temperatures fluctuated as much as 6-8 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.

3. YIELD RESPONSE TO SOIL WARMING

3.1 Introduction

3.1.1 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.

3.1.2 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.

3.2 Sudangrass (*Sorghum vulgare sudanense*)

3.2.1 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 15-27 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).

3.2.2 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 4. 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. Harvests were August 14 and October 5. Botanical separates were taken to determine the amount of weeds in the samples. Results are shown in Table 4.

3.2.3 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 4.

Table 4. 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

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 heat 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 4). 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 higher 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.

3.2.4 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 tons/hectare under heated conditions. Soil heating appears to be very important in the establishment and early growth of this crop.

3.3 Sorghum-sudangrass hybrid (*Sorghum vulgare-sudanese* hybrid)

3.3.1 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.

3.3.2 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 3.2.2. Harvesting was on the same dates (July 29 and October 7). Yields of dry matter and percent dry matter are indicated in Table 5.

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 5. Botanical separates were taken to determine the weed content of the harvested material.

3.3.3 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 3.3.1 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.

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

Table 5. 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 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.

3.3.4 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 sundangrass 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. The value of soil warming with respect to the production of this crop is given further consideration in Section 4.

3.4 Common Annual Ryegrass (*Lolium multiflorum*)

3.4.1 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).

3.4.2 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.

Table 6 presents dry matter yields for each of four harvest dates and the total yield over this period.

Table 6. Dry matter yields of Common Annual Ryegrass

Year	Fertilizer treatment	Harvest date	Temperature treatment unheated	Temperature treatment 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

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 1-2 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 6.

3.4.3 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 6. 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.

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 cannot be adequately discussed without a better understanding of the effect of soil temperature on the fate of the sulfur-coated urea fertilizer.

3.4.4 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. This cropping system is considered in Section 4.

3.5 Crimson Clover (*Trifolium incarnatum* L.)

3.5.1 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).

3.5.2 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 7 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 7. 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		

3.5.3 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.

The results suggest that good establishment requires early fall planting. For this reason it is doubtful that double cropping with sorghum-sudangrass and Crimson Clover would be as successful as a rotation with ryegrass. A rotation with bush beans and Crimson Clover is considered in Section 4.

3.6 Tall fescue (*Festuca arundinacea*)

3.6.1 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.

3.6.2 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 8.

3.6.3 Discussion

Levels of significance, least significant differences and relative yields are indicated for each cutting in Table 8. 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 3 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 insufficient fertilization of the plots. A heavy application of fertilizer in July corrected this.

3.6.4 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.

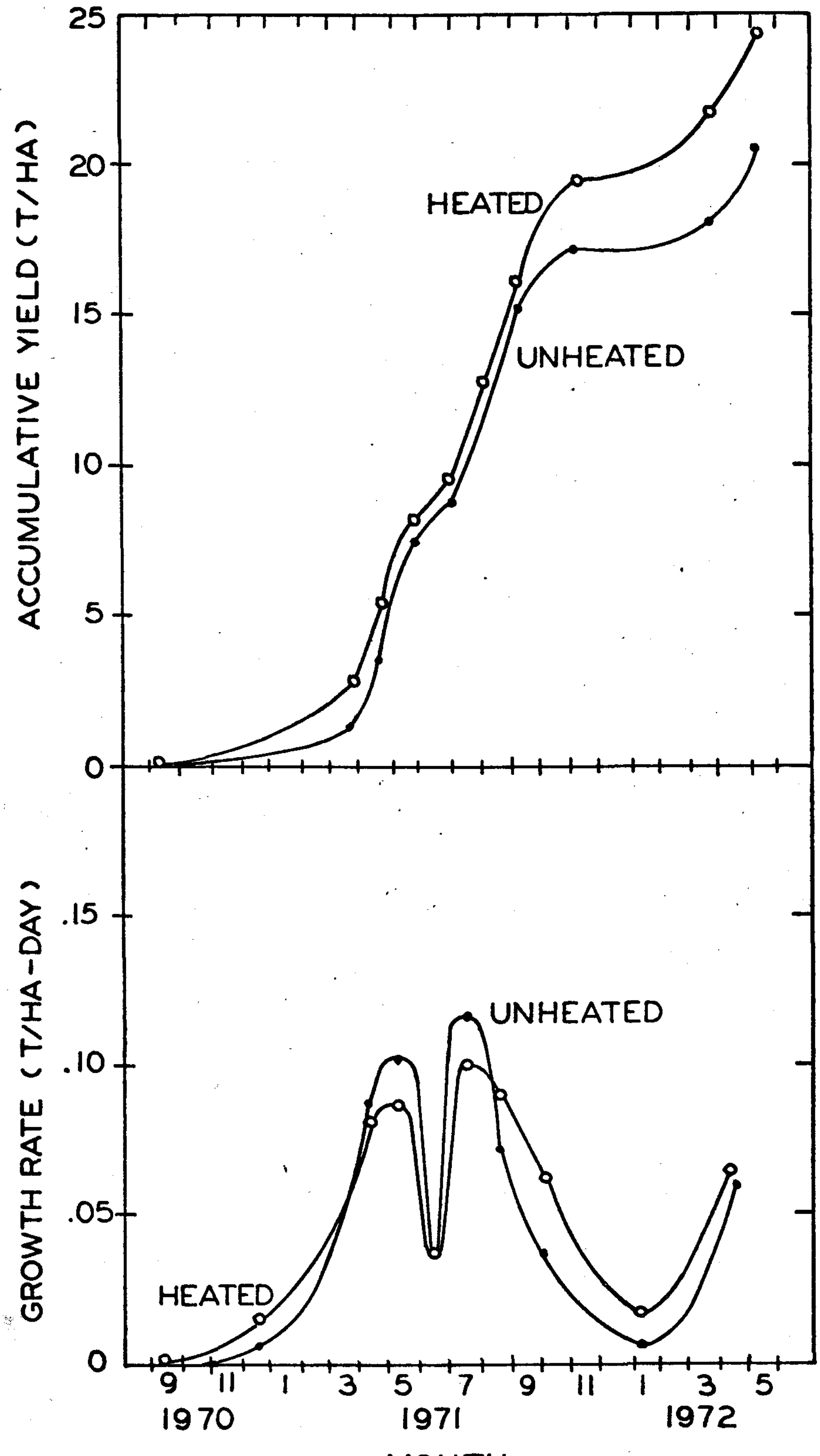

Figure 3. Accumulated yields of Fawn fescue on heated and unheated plots as a function of time and rate of growth of Fawn fescue as a function of time.

Table 8. Fawn fescue dry matter yields

Harvest date	Dry matter yield unheated	Dry matter yield 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.

3.7 Field corn (*Zea mays* L.)

3.7.1 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).

3.7.2 Crop year: 1969

3.7.2.1 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 9. Grain yields shown in Table 10 are adjusted to 15.5 percent moisture in the shelled grain. Kernel moisture for several sampling dates is shown in Table 11.

Table 9. 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 10. 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 11. 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

3.7.2.2 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.

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.

3.7.3 Crop year: 1970

3.7.3.1 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 12. Yields of grain and total dry matter are shown in Table 13. 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 13 are average yields for the heated area obtained by averaging yields from rows between heat sources and over heat sources.

Table 12. 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

3.7.3.2 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 13. 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 4). 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 3.7.2.2) 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.

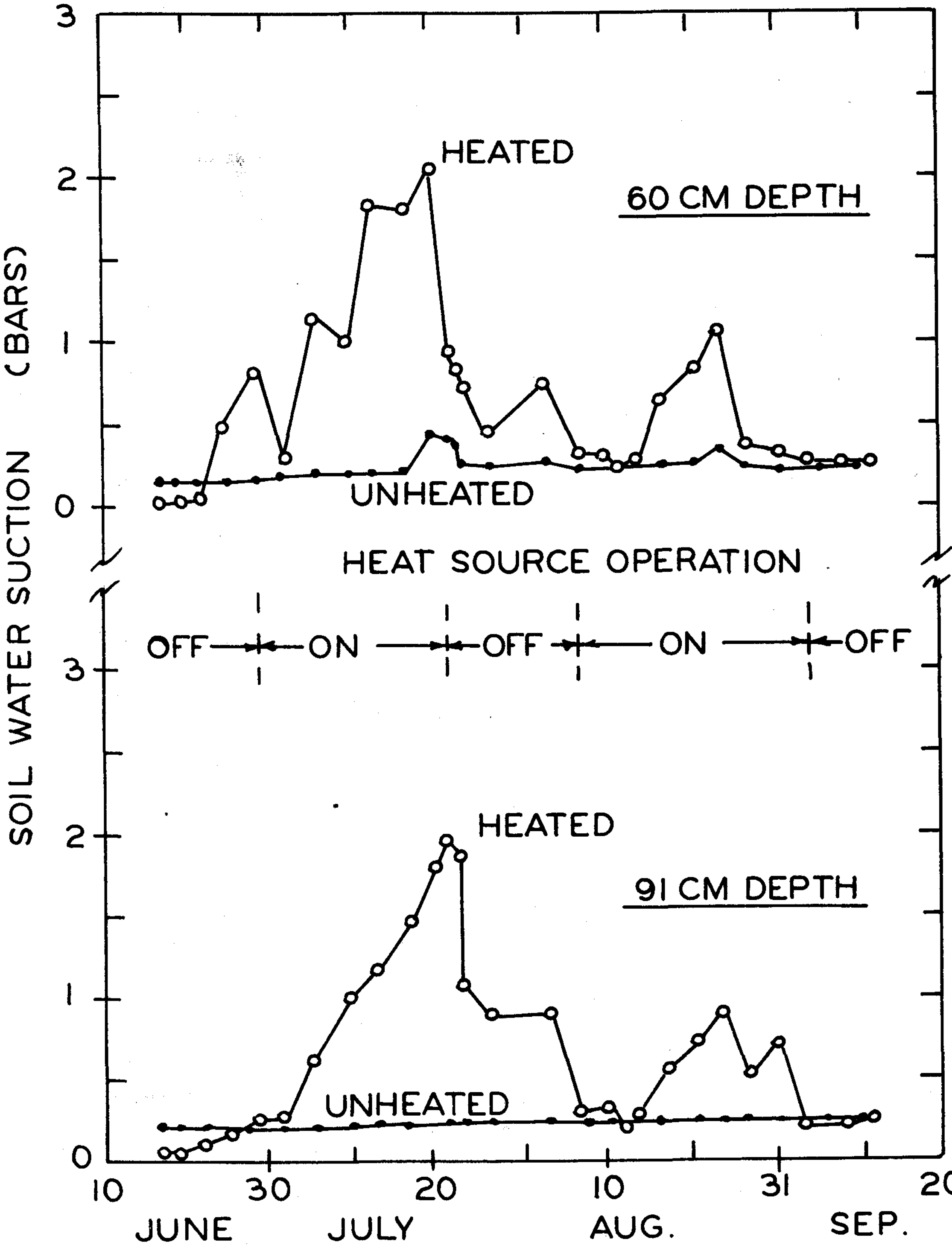

Figure 4. Soil water suction at two depths on unheated and heated CORN plots during 1970.

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 and there were 54 more growing degree days in 1970 (U.S. Dept. of Commerce, 1969, 1970).

3.7.4 Sub-irrigated corn. Crop year: 1970

3.7.4.1 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 12. 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 14. Values shown for heated treatments are averages of harvest rows over heat sources and between heat sources.

3.7.4.2 Discussion. The responses to heating and fertility treatments were not statistically significant. In the previously discussed corn experiment (Section 3.7.3) 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.

Table 14. 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

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.

3.7.5 Crop year: 1971

3.7.5.1 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 15.

3.7.5.2 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 15.

Table 15. Dry matter yield of corn silage and yield of shelled grain at 15.5 percent moisture, 1971

Nitrogen fertilizer rate	Plant component	Unheated	Heated OR	Heated BR	Yield increase OR	Yield increase BR	Yield increase 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

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.

3.7.6 Silage corn. Crop year: 1971

3.7.6.1 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 16.

3.7.6.2 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.

Table 16. 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	7.75	9.54	23
Average	7.55	10.01	33
LSD (P < .01) Heating 2.06			

3.7.7 Crop year: 1972

3.7.7.1 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 32-38 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 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 17. Final yields of silage and grain are shown in Table 18. The percent dry matter of the various plant components is shown in Table 19.

Table 17. 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 18. 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 19. Percent dry matter in stover, grain, and silage and grain shelling percentage, 1972

Treatment	Dry matter			Shelling percentage
	Stover	Grain	Silage	
	%	%	%	%
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

3.7.7.2 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 heating response was significant at the 1 percent level in both measurements. The difference in heat response for silage yields in Table 18 and dry weight per plant in Table 17 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 19. 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.

3.7.8 Sub-irrigated corn. Crop year: 1972

3.7.8.1 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 3.7.7. 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 sub-surface 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 20. Total dry matter yields and the yields of shelled grain at 15.5 percent moisture are shown in Table 21. The percent dry matter of stover, grain, and silage components and shelling percentages are presented in Table 22.

Table 20. Dry matter plant weights at the four indicated sampling dates. Sub-irrigated corn, 1972

Harvest dates	Treatment unheated	heated	Yield increase	LSD
	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 21. 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 22. Percent dry matter in stover, grain, and silage and grain shelling percentage. Sub-irrigated corn, 1972

Treatment	Dry matter			Shelling
	stover	grain	silage	percentage
	%	%	%	%
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		

3.7.8.2 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 3.7.7. 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 18 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 sub-surface irrigation resulted in higher yields than were obtained with heating alone (Table 18). 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 2-3 bars at depths of 60-90 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 without 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 22 shows that in all instances maturity differences were small and less than those reported in Section 3.7.7. 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 plots was slightly more mature.

3.7.9 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 23). 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 from a single crop of corn silage.

Table 23. 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

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.

A wide range of yield responses to soil warming was observed during the four years of experimentation (Table 23). 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 5). These data were fit to linear and quadratic regression models. The linear regression equation calculated was:

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

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 23). The relationship between unheated yields and response to heating appeared to be similar to that observed for silage yields. These data were fitted 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

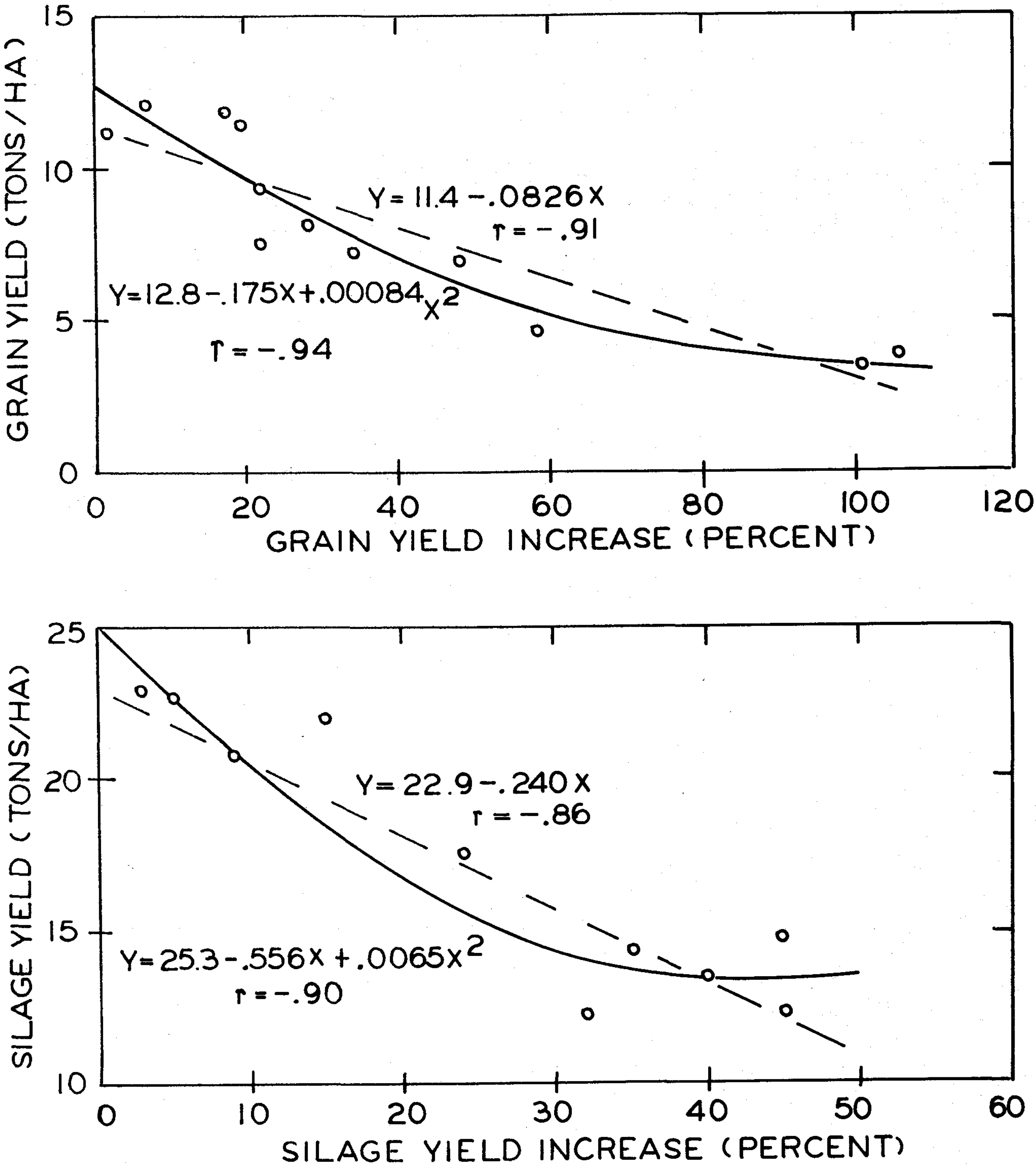

Figure 5. Percent silage yield and grain yield increase obtained on heated plots as a function of silage yield and grain yield obtained on unheated plots.

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 6. Linear 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 6 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 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

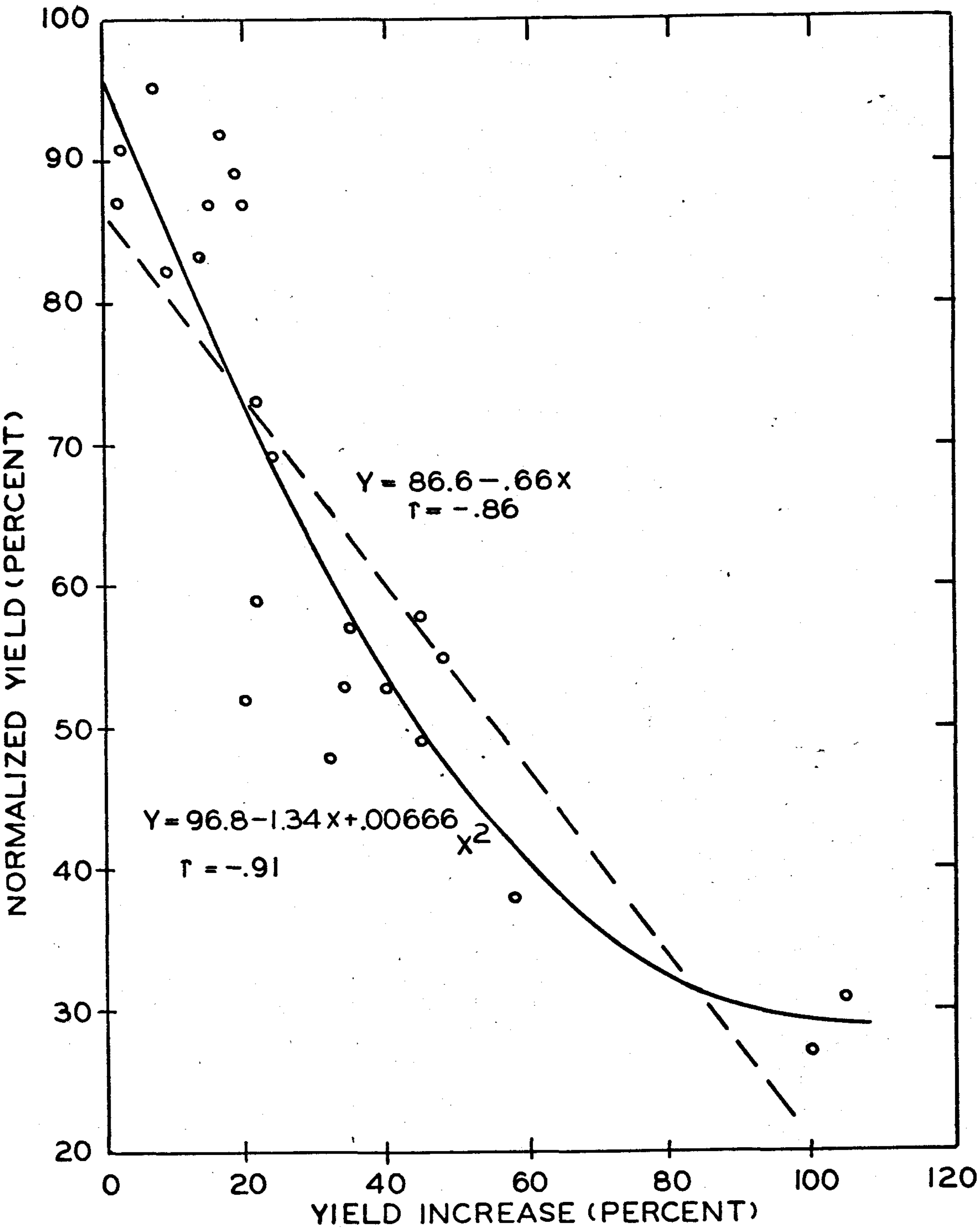

Figure 6. Percent silage and grain yield increase obtained on heated plots as a function of normalized silage and grain yields on unheated plots.

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.

3.8 Soybeans (Glycine max L.)

3.8.1 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.

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

3.8.2 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 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 19. 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 24. The grain yield was 0.9 tons/ha and was not affected by the soil warming treatment.

Table 24. 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 25 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 25. Yield of total dry matter and dry beans. Soybeans, 1971

Plant component	Phosphorous 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)

3.8.3 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.

3.8.4 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 sub-surface heating.

3.9 Bush beans (*Phaseolus vulgaris*)

3.9.1 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.

3.9.2 Crop year: 1969

3.9.2.1 Methodology and results. The cultivator 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, 168 kg/ha of agricultural gypsum broadcast prior to planting, 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 26. 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.

Table 26. 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

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.

Yield of beans and percent of beans passing a number 4 sieve are presented in Tables 27 and 28 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 27. 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

The yields shown in Table 27 were adjusted to a standard of 50 percent of beans passing a number 4 sieve (Table 29). 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 29).

Table 28. 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

Table 29. 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

3.9.2.2 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 28 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.

3.9.3 Crop year: 1970

3.9.3.1 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 30. 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 30. Crop history dates and water applied, bush beans, 1970

Treatment	Planting dates	
	D1	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 31. 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 32.

Table 31. 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

Table 32. 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

3.9.3.2 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.

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.

3.9.4 Sub-irrigated bush beans. Crop year: 1970

3.9.4.1 Methodology and results. Bush beans (cultivar Gallatin 50) were planted on the subsurface irrigated area. Treatments included: no heat, heated with subirrigation, unheated with subirrigation, 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 3.9.3.1. 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. Subirrigated 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 subirrigated 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 subirrigated areas and three in unheated areas. Yields, maturity, adjusted yields, and relative yields are shown in Table 33.

Table 33. Yield of subirrigated 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, subirrigated	19.2	63.8	20.5	102
	Heated, subirrigated	26.2	49.7	26.2	130
111	Unheated	16.4	66.9	18.3	100
	Unheated, subirrigated	17.4	64.4	19.0	104
	Heated, subirrigated	23.3	50.8	23.4	128

3.9.4.2 Discussion. Subirrigation alone did not significantly affect yield or maturity. The slight increase in yield for unheated, subirrigated plots is probably due to more efficient use of irrigation water applied through the subsurface system. Subirrigation 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 3.9.3. 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 3.9.3. This can be explained in part by the previous cropping history. Plantings D1 and D2 discussed in Section 3.9.3 followed bush beans. The subirrigated 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.

3.9.5 Crop year: 1971

3.9.5.1 Methodology and results. The cultivar Oregon 58 was planted on the subirrigated 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 subirrigation system. Nitrogen was applied at the rate of 92 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 34. Harvesting was delayed several days past ideal maturity as shown by the maturity data.

3.9.5.2 Discussion. The yield response to heating with subirrigation was significant at the 5 percent level. Plant populations were 415,000 and 316,000 plant /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 subirrigated plots in 1970.

Table 34. 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			

3.9.6 Summary and conclusions. There years of bush bean experiments are summarized in Table 35. 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. Further consideration will be given to double cropping of bush beans in Section 4.

Table 35. 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 unheated	Adjusted yields heated	Yield increase
	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 7). 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 7. 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 3.7.9. These data are presented in Figure 8, 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 3.7.9 that the relationship between unheated yields and yield response to soil heating might apply not only 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.

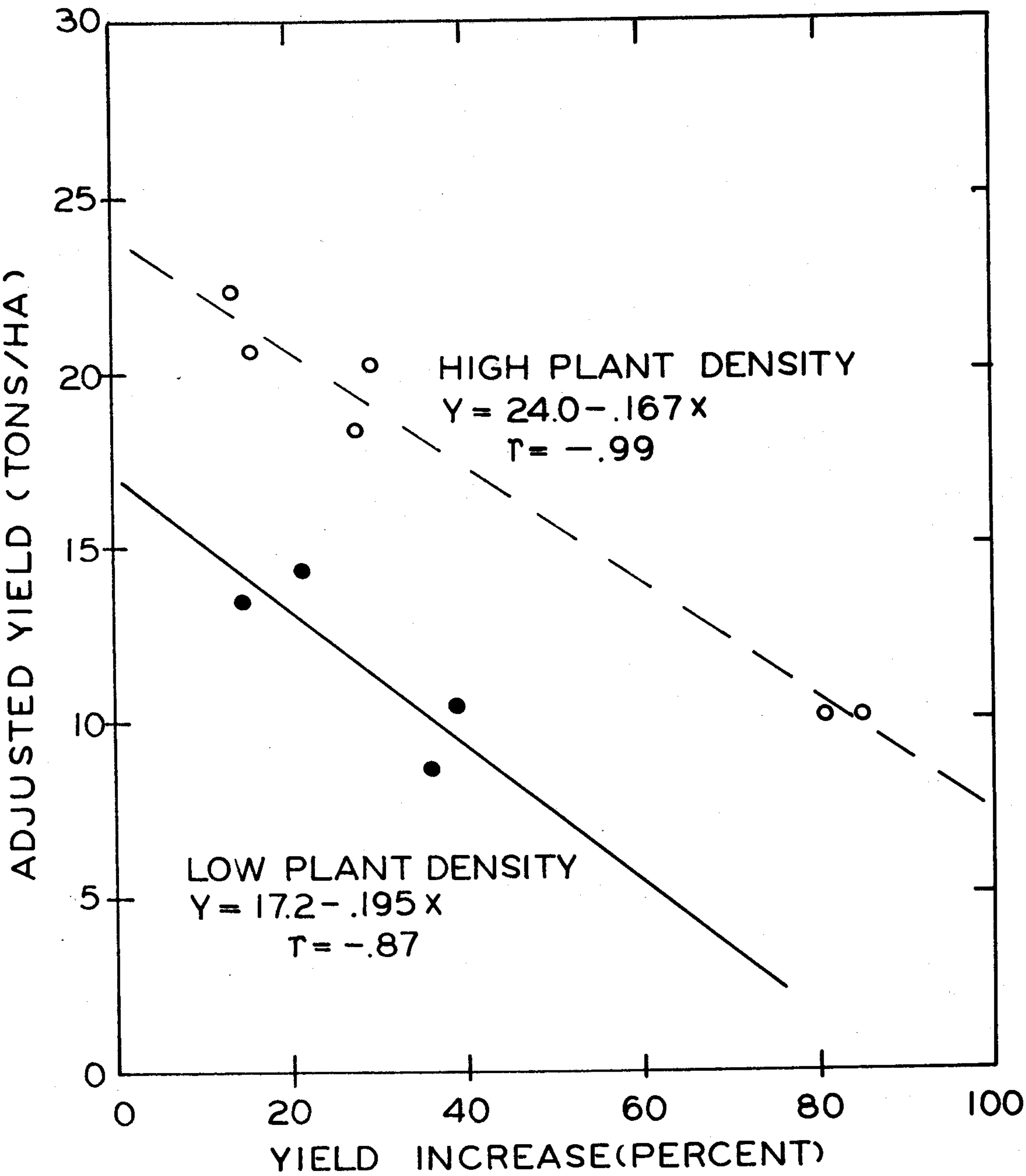

Figure 7. Percent bean yield increase obtained on heated plots as a function of yield obtained on unheated plots.

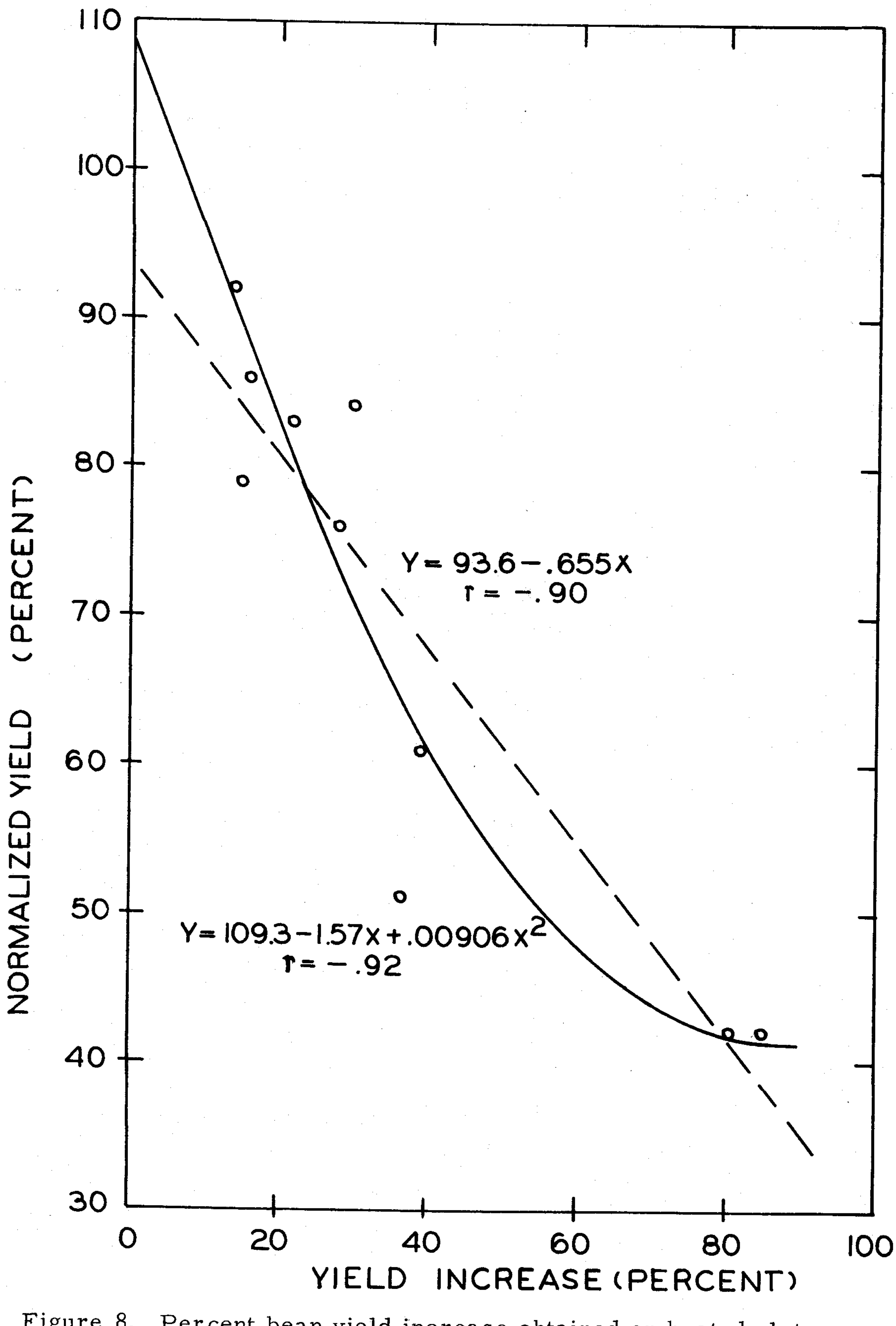

Figure 8. Percent bean yield increase obtained on heated plots as a function of normalized bean yields on unheated plots.

3.10 Lima beans (*Phaseolus lunatus*)

3.10.1 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.

3.10.2 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 36.

Table 36. 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 37.

Table 37. 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

3.10.3 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 and fertility treatments 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 3.9.3.2. 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.

3.10.4 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.

3.11 Tomatoes (*Lycopersicon esculentum* var. *commune*)

3.11.1 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.

3.11.2 Field grown tomatoes

3.11.2.1 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.

3.11.2.2 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 that 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.

3.11.2.3 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.

3.11.2.4 Summary and conclusions. Response to soil warming is summarized in Table 38. 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 38. Yield of tomatoes measured during 1969, 1970, and 1971

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

3.11.3 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 9). Prior to September 8, only ripe fruit was harvested. On the final harvest date all fruit was picked regardless of size or stage of maturity.

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

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

Harvesting of the tomatoes started on July 21 and continued until October 14 when all remaining fruit was picked. Harvest areas were 59.5 square meters. The yield obtained was 184 tons/ha of ripe tomatoes (Figure 9) 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 subsurface heating for greenhouse tomato production.

3.12 Broccoli (*Brassica oleracea* var. *italica*)

3.12.1 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

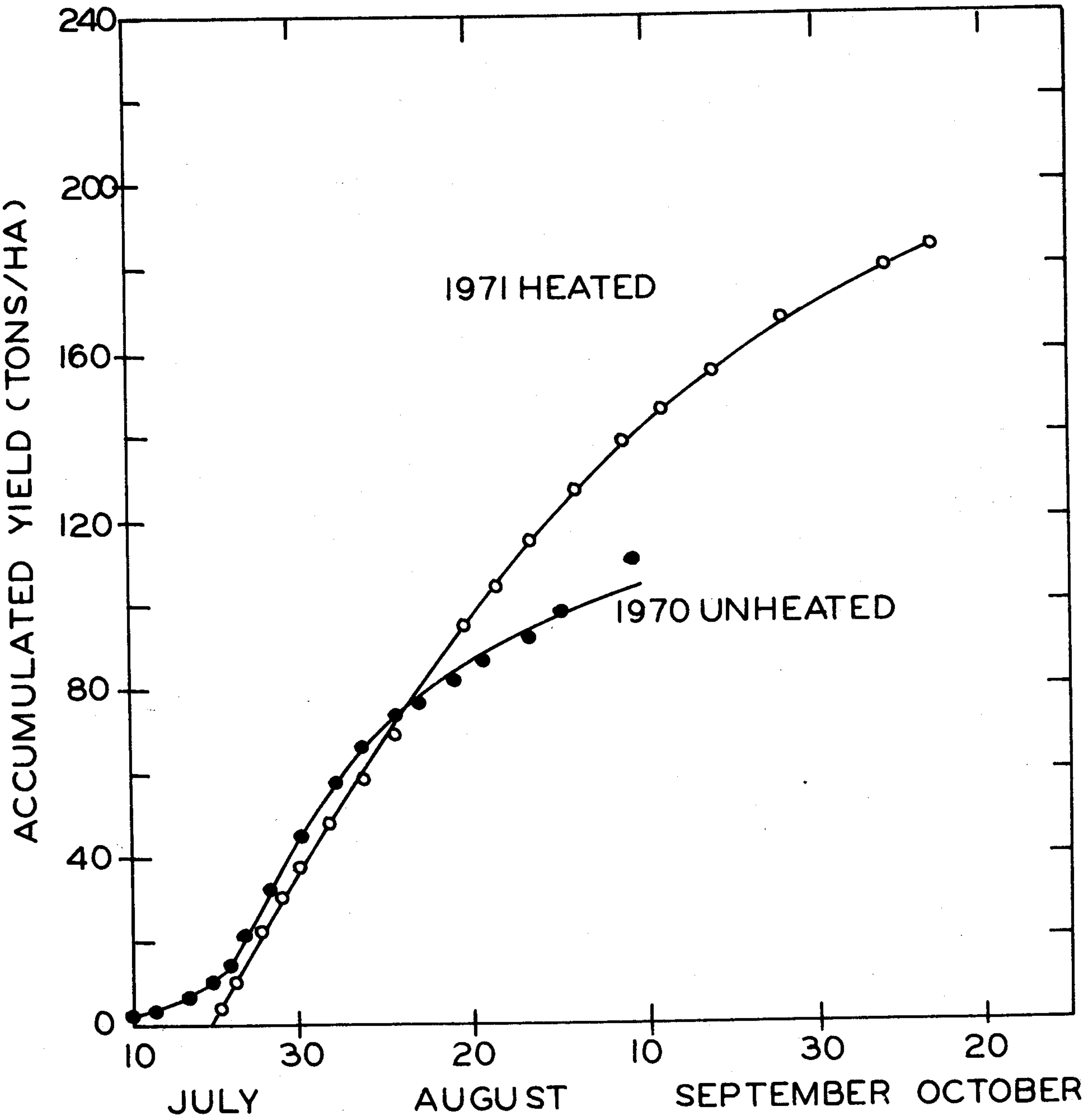

Figure 9. Accumulated yield of unheated greenhouse cultured tomatoes, 1970, and heated greenhouse cultured tomatoes, 1971. Only mature fruit is represented.

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.

3.12.2 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 or 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 39. 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 39. Accumulative yield of broccoli and heat response

Harvest date	Yield unheated	Yield 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

3.12.3 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.

3.13 Peppers (*Capscicum annuum*)

3.13.1 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).

3.13.2 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 subirrigated 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 40 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 40. Accumulative yield of green peppers and heat response

Harvest date	Yield unheated	Yield heated	Response to 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

3.13.3 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 system.

3.14 Strawberries (*Fragaria virginiana*)

3.14.1 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.

3.14.2 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 10 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. 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 10 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

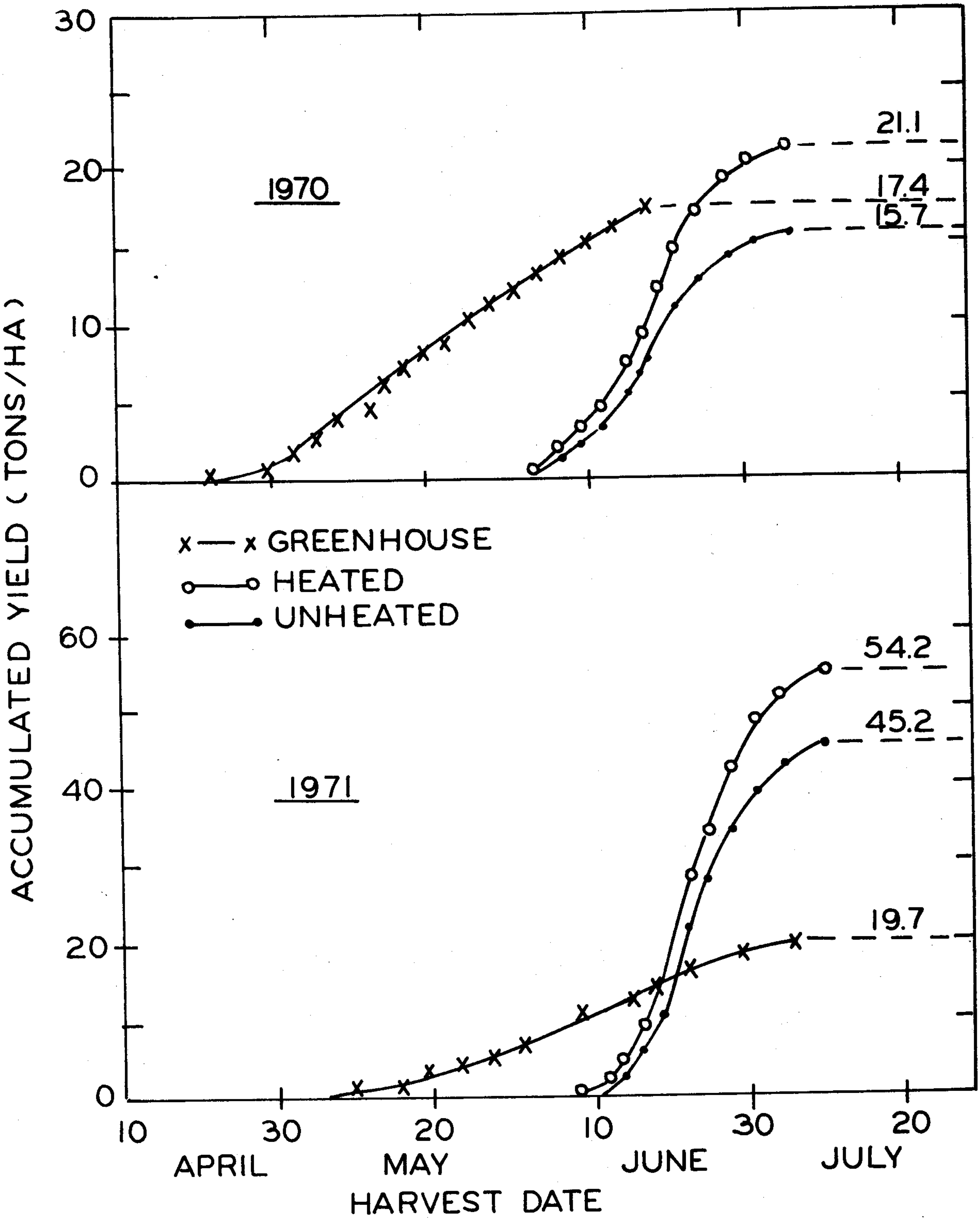

Figure 10. Accumulated strawberry yields on unheated and heated open field plots and in greenhouse culture, 1970 and 1971.

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 has 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 3.14.1 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.

3.14.3 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.

4. ECONOMIC CONSIDERATIONS

4.1 Introduction

Experimental results reported in Section 3 generally indicate that crop yields were increased by open field soil warming. Unheated test plot yields were used as the basis for this observation. These results have posed the following questions: (1) is it more profitable for farmers to produce crops with soil warming methods rather than with conventional (unheated) methods? and (2) which field crops and crop rotations can be profitably produced with soil warming methods?

The economic analyses which follow address each of these questions with respect to a limited number of crop activities. Resource constraints precluded a more extensive analysis.

4.2 Study objective

The specific task of the analysis was to determine if it is more profitable for Willamette Valley farmers to produce selected crops with soil warming methods rather than with conventional (unheated) methods. If soil warming methods are to be more profitable, the value of yield increases which are a direct result of soil warming must at least be equal to the additional annual ownership and operating costs associated with the soil warming system.

4.3 The crop activities

Two cropping sequences and a single crop enterprise were selected for analysis. These were: field corn for silage and grain, an annual rotation of bush beans followed by Crimson Clover silage, and an annual rotation of a sorghum-sudangrass hybrid followed by Common Annual Ryegrass silage.

Field corn was selected for analysis because it is a potentially high yielding concentrate and/or roughage crop ideally suited for ruminant feeding. High yielding field corn cultivars have been climatically adapted to growing conditions in the Willamette Valley. High moisture feed grain (43% DM) rather than cash grain (84.5% DM) production was evaluated because the moisture content of the grain is usually high at the time of harvest. The high moisture content would prohibit economical drying and produce considerable kernel damage during shelling. Many farmers may not consider high moisture corn production as an alternative crop because they do not have adequate storage facilities. However if storage is available, this crop or a corn silage crop in association with a livestock enterprise may prove to be an economically viable crop alternative for some farmers.

The crop sequence of bush beans followed by Crimson Clover silage was selected because bush beans present one of the higher yielding, more profitable horticultural field crops produced in the valley, and the two crops are compatible in an annual rotation. Clover is harvested for silage during the early part of May prior to the planting of bush beans and replanted immediately after the harvest of bush beans in the early fall. The production of bush beans as a single crop was also evaluated since the annual rotation requires a high level of management skills which may preclude many farmers from attempting the rotation.

The annual crop sequence of a sorghum-sudangrass hybrid followed by Common Annual Ryegrass harvested for silage was evaluated because both species are well adapted to the climate of the valley. The crops are easily established and produce good yields of succulent forage throughout the year. The species are compatible in an annual rotation. Ryegrass is harvested two or more times prior to planting the sorghum-sudangrass hybrid in the early summer, and replanted immediately after the last harvest of the hybrid in the early fall. Ryegrass is usually harvested for silage rather than hay because of the high probability of the occurrence of rain in the spring. This rotation also requires a high level of management skills and good field drainage. If both of these conditions are met, this rotation in association with a livestock enterprise may prove to be an economically viable alternative for some valley farmers to ryegrass seed production and the accompanying field burning problem.

4.4 Production costs

For the purposes of this study production costs were categorized as "cultural" and "soil warming" costs. Cultural costs include expenses normally incurred by the farmers in producing either a marketable or storable crop. Soil warming costs include expenses related to ownership, operation, and maintenance of a commercial-scale soil warming system. Total crop production costs related to conventional production methods are synonymous with cultural costs since soil warming costs are not incurred. Total crop production costs associated with soil warming production methods include both cultural and soil warming costs. The relevant costs for purposes of this study, are soil warming costs since it is assumed that cultural costs are similar for a crop produced by either production method. This assumption was used because of limited experimental research. The exception to this statement occurs in the evaluation of bush bean production.

4.4.1 Soil warming costs

Annual soil warming costs include fixed ownership and variable operating costs. Ownership costs consist of depreciation, interest on the investment, maintenance, taxes, and insurance. These costs are fixed because they are incurred regardless of the use of the system. Operating costs vary directly with the use of the system. Items related to this category include possible charges for the energy and the cost of electricity for pumping.

The annual ownership cost items of a commercial-scale soil warming system are itemized in Table 41. The total ownership cost is about $670 per hectare per year. The basis for calculating each cost component appears in footnotes to the table. The indicated costs are representative for a 50.6 hectare commercial-scale installation. It is expected that these costs, expressed on a per hectare basis, are also representative costs for installations varying in size from 32 to 100 hectares.

A typical 50.6 hectare installation consists of 220, 5.1 cm diameter, schedule-40, plastic pipes, each pipe being approximately 1,249 meters long, with 2,052 meters of large diameter (43.2 to 83.8 cm) steel pipe serving as main and return lines. The system requires 80 horsepower of pumping capacity, and numerous connectors and reducers.[1/] The plastic pipes are spaced parallel to each other on 1.8 meter centers and buried about 0.9 meters deep. The main and return lines are also buried. These lines have connectors, which are used to attach the plastic pipe, every 1.8 meters. The pumps are the only part of the system visible above ground. The total investment cost of this system is about $411,361.[2/] The cost of individual components is shown in Table 42.

The operating cost of the soil warming system consists mainly of the cost for electricity used in pumping warm water through the underground pipe network and is about $0.27 per hectare per day.[3/] A charge for warm water was not included in the operating cost structure.

[1/] This initial design of a soil warming system was prepared by Lorin R. Davis, associate professor of mechanical and nuclear engineering, Oregon State University.

[2/] Personal Communication. Marvin N. Shearer, Extension Irrigation Specialist, Oregon State University.

[3/] Personal Communication. Lorin R. Davis, associate professor of mechanical and nuclear engineering, Oregon State University.

Table 41. The annual ownership cost of a 50.6 hectare soil warming installation.

Item	Cost
Depreciation[a/]	$ 6,805.00
Interest on the average investment[b/]	20,568.00
Maintenance[c/]	206.00
Taxes and insurance[d/]	6,335.00
Total ownership costs	$33,914.00
Ownership cost per hectare	$670.24

[a/] Depreciation is calculated by the straight line method. The PVC pipe and connectors have an initial cost of $322,685, an estimated 50 year life, and an estimated salvage value of $159.027. The relatively high salvage value reflects the pipe's unique resistance to deterioration. Salvage value would even be higher were it not reduced because of obsolescence and the cost of the salvage operations. The coated steel pipe has an initial cost of $84,926, an estimates 25 year life, and an estimated net salvage value of $849. The pumps and associated equipment have an initial cost of $3,750, and estimated 20 year life, and a $375 salvage value.

[b/] The average investment is half of $411,361. A 10 percent interest rate reflects the opportunity cost of investment capital.

[c/] These costs primarily reflect maintenance of pumps, controls, and starters.

[d/] The soil warming system is considered real property and taxed at or near its market value. However the Department of Environmental Quality may approve a tax exemption for a substantial portion of the market value of this system because it may reduce air pollution due to the operation of cooling towers (Personal communication with DEQ staff). In this study it is assumed that 30 percent of the system's market value is tax exempt. The true market value of the system is estimated at $411,361 (i.e., the system's total initial investment and installation cost). A tax rate of $22 per $1,000 of taxable market value is used to estimate annual taxes. Insurance costs are negligible and are not estimated.

Table 42. The total initial investment and installation costs of a 50.6 hectare soil warming installation (1973 costs).

Item	Quantity	Cost
Schedule-40 PVS pipe, 5.1 cm diameter[a]	276,485 meters	$317,405
Steel pipe, 10 gauge, approximately 83.8 cm diameter[b]	1,650 meters	71,726
Steel pipe, 10 gauge, approximately 61 cm diameter[c]	201 meters	7,419
Steel pipe, 10 gauge, approximately 43.2 cm diameter[d]	201 meters	5,778
Outlet connections[e]	440 connections	5,280
Pumps, controls, starters, and wiring	80 Hp.	3,750
Total cost		$411,361
Approximate capital investment per hectare		$ 8,130

[a] PVC pipe cost about $0.820 per meter and it costs $0.328 per meter to trench, glue, and pull.

[b] Installation costs are about $14.27 per meter. The pipe costs about $29.20 per meter.

[c] Installation costs are $13.94 per meter. The pipe costs $22.97 per meter.

[d] Installation costs are $13.94 per meter. The pipe costs $14.80 per meter.

[e] Installation and material cost is about $12.00 per connection.

4.5 Economic feasibility of production

Evaluation of the economic feasibility of using a soil warming system was based on the criterion that the value of yield increases attributable to soil warming must at least equal the additional annual costs associated with this method of production. The most direct method of making this comparison is on the basis of average yields and costs per hectare. This technique was used in the analyses that follow. The values of the estimated yield increases were based on prices received by farmers in the Willamette Valley during the 1973 crop production year.[4/] Should other prices be more appropriate, they should be used to evaluate the economic feasibility of soil warming production. The yield levels reported in this study are test plot yields; however, it is expected that these yield levels can be attained in commercial production.

4.5.1 Field corn silage

Field corn silage grown on heated soil would require approximately 183 days of soil heating during a growing season normally beginning in the middle of April and continuing until the latter weeks of October. Hence, additional annual ownership and operating costs resulting from soil warming would be approximately $720 per hectare. Included in this total is a $50 charge for electricity used in pumping warm water through the soil warming system. The remaining costs are the fixed ownership costs (Table 41).

According to experimental data reported in Table 23, the average yield of total dry matter obtained during the four years, 1969-72, at several fertility treatments was 20.6 metric tons per hectare on heated plots and 16.9 metric tons per hectare on unheated plots. Thus, the response to soil warming was 3.7 tons per hectare. The value of this yield increase is about $104 per hectare assuming corn silage is valued at $28 per metric ton of dry matter.

Because the value of the yield increase resulting from soil warming is less than the additional cost incurred with soil warming, it is concluded that it is presently not economically feasible to produce field corn silage with soil warming methods. In order to be economically feasible, the yield increase attributable to soil warming would have to be at least 25.7 metric tons per hectare assuming crop value and production costs remain the same. In other words corn silage yields obtained with open field soil warming must be at least 152 percent more than yields obtained with conventional production methods.

4.5.2 High moisture corn grain

The additional total annual cost of producing high moisture corn grain by soil warming methods is similar to the cost incurred in producing field corn silage by this production method since the two growing seasons are identical. This cost is approximately $720 per hectare.

[4/] Personal Communication. R.K. Ganger, specialist county statistics, extension service, agricultural economics, Oregon State University.

The average yield of total dry matter high moisture corn over four years was 8.9 metric tons per hectare on heated plots, and 6.9 metric tons per hectare on unheated plots. The direct response to soil warming was 2.0 tons per hectare. The value of this yield increase is about $264 per hectare assuming high moisture corn is valued at $132 per ton of dry matter.

The value of the yield increase is less than the additional costs incurred with this method of production. Consequently, high moisture corn grain production with soil warming methods is presently not economically feasible. In order to be economically feasible, the yield increase attributable to soil warming would have to be at least 5.5 metric tons per hectare assuming crop value and production costs remain the same, or corn grain yields obtained by open field soil warming must be at least 80 percent greater than yields obtained by conventional methods.

These conclusions were based on a single crop per year. Should another crop be compatible with field corn in an annual rotation, corn production with soil warming methods may be economically feasible. The evaluation of such a rotation was precluded in this study because such a crop was not evaluated in the test plot experiments.

4.5.3 Bush beans

According to experimental data shown in Table 26, soil warming production methods extend the cropping year so that two crops of bush beans can be produced. Usually only one crop is produced during a growing season with conventional production methods because of risks associated with early frosts and immature fruit. Test plot results indicate that beans planted late on unheated plots were not mature at the time of harvest (Section 3.9.2.2). Hence, the evaluation of this crop is based on these intensities of production. In the analysis it was assumed that the bush bean crop can be marketed either for the process market or for the fresh market. The process market, however, would require coordinating the planting and harvest dates to processor's schedules.

Bush beans produced by soil warming methods would require approximately 152 days of soil heating during a growing season normally beginning in the middle of May and continuing until the middle of October. Additional annual ownership and operating costs associated with soil warming are about $711 per hectare. Included in this cost is a charge of about $41 for the electricity used to pump warm water through the soil warming system. Additional cultural costs of about $705 per hectare are incurred to produce and harvest the second crop of bush beans. These costs, itemized in Table 43 must also be charged against the value

Table 43. Additional cultural costs incurred to produce the second crop of bush beans in an annual two crop bush bean sequence--1973.[a/]

	Inputs per hectare					
	Labor			Other		
	Hours	Value	Mach.	Item	Value	Total cost
Cultural operations						
Heavy discing	1.48	$ 4.45	$ 6.67			$ 11.12
Fertilize	.64	1.92	1.06	Mtl.	$ 15.12	18.10
Disc & harrow (3x)	1.48	4.44	4.55			8.99
Plant	Custom		20.31	Mtl.	180.26	200.57
Cultivate (2x)	.99	2.97	2.35			5.32
Irrigate	3.80	11.40	2.89	Mtl. and electricity	14.94	29.23
Other weed control	2.47	7.41	---			7.41
Harvest operations						
Picking	Custom		296.00			296.00
Hauling	Custom		68.00			68.00
Other charges						
Interest on additional operating capital (10%)					9.88	9.88
General farm overhead (8% cash costs)					50.18	50.18
Total costs		$32.59	$401.83		$270.38	$704.80

[a/] Data source: "Enterprise Data Sheets," Extension Farm Management, Oregon State University.

of the yield increase resulting from soil warming. Total costs of producing two crops per year on heated ground are then $1,416.

According to experimental data shown in Table 29, the total adjusted yield for bush beans during 1969 was 29.2 metric tons per hectare on heated plots and 14.3 metric tons per hectare on unheated plots. Thus, the response to soil warming was 14.9 tons per hectare. The total annual yield on the heated plots represents the combined yields of the early and late plantings. The yield on the unheated plots represents the yield of the early crop only. These yields were obtained with conventional plant densities. The value of the additional yield increase (14.9 tons per hectare) ranges from $4,589 to $1,967 per hectare depending on whether the crop is sold for fresh or processed products. This range is based on a process market price of $132 per metric ton and a fresh market price of $308 per metric ton of adjusted yield.

The value of the yield increase directly attributable to soil warming methods was greater than the additional costs associated with this method of production in both marketing situations. Bush bean production with soil warming methods would be economically feasible. This is primarily a result of the production of an additional crop of bush beans in the same crop year. A fee for the use of warm water was not included in this analysis. Should such a fee be imposed, bush bean producers could pay a substantial fee per hectare per year for warm water.

The yield response to soil warming for a single crop during the growing season was 3.1 tons per hectare (Table 29). The value of this yield increase ranges from $955 to $409 per hectare depending on whether the crop is sold for fresh market consumption or processed products. The additional annual ownership and operating costs directly associated with producing a single crop of beans with soil warming methods are about $687 per hectare. Included in this cost is a charge of about $17 for the electricity used to pump warm water through the soil warming system.

The process market value of the yield increase is less than the additional cost incurred by soil warming so that it would not be economically feasible to produce a single crop of bush beans for the process market with soil warming methods. In order to be economically feasible, the yield increase would have to be at least 5.2 metric tons per hectare assuming the crop value and production costs remain the same. In other words the yield of a single crop of bush beans must be increased at least 36 percent by soil warming. The fresh market value of the yield increase is greater than the additional cost resulting from soil warming, so that it would be economically feasible to produce a single crop of bush beans for the fresh market with soil warming methods. This conclusion is based on the assumption that there is no fee for warm water. The producer could pay a fee per hectare for the use of warm water (less than $268 per hectare).

4.5.4 Bush beans--Crimson Clover silage annual rotation

The economic feasibility of producing this annual crop sequence with soil warming methods was evaluated by comparing the value of the clover silage yield increase which results from soil warming with the additional operating cost of running the system during the time clover is growing. This procedure was used because bush bean production with soil warming methods had already been evaluated.

The addition of clover silage to the bush bean crop requires an additional 182 of soil heating since the crop's growing season runs from October through the first two weeks in May. The cost of soil heating which can be attributed to clover production is about $49.14 per hectare. This cost is based on an electrical pumping charge of $0.27 per hectare per day.

The experimental data of Table 7 indicate that the yield increase of clover resulting from soil warming was 1.93 metric tons per hectare. The total dry matter yield of unheated and heated clover plots was 3.00 and 4.93 tons per hectare respectively. The value of the 1.93 ton yield increase is about $71 per hectare assuming clover silage is priced at $37 per metric ton of dry matter.

Since the value of this additional yield is greater than the cost attributed to soil warming production, it is concluded that it would be economically feasible to produce a winter clover silage crop following bush beans with soil warming methods. No charge for the use of the warm water was assumed. The producer would be able to pay a fee of less than $22 per hectare per year.

4.5.5 Sorghum-sudangrass hybrid-common annual ryegrass silage annual rotation

This rotation produced by soil warming methods requires approximately 334 days of soil heating since the growing season includes all 12 months of the calendar year. The additional annual costs which are directly attributed to soil warming are approximately $760 per hectare. Included in this cost is a charge of about $90 for the electricity used to pump warm water through the soil warming system.

The experimental data of Tables 5 and 6 indicate that the yield response of sorghum-sudangrass hybrid and common annual ryegrass directly attributable to soil warming was 5.3 and 1.2 metric tons per hectare respectively. The average total dry matter yields of unheated and heated sorghum-sudangrass hybrid plots were 10.4 and 15.7 metric tons per hectare respectively, and the total dry matter yields of unheated and heated common annual ryegrass plots in the 1970-71 crop year were 6.9 and 8.1 metric tons per hectare respectively. This rotation produced almost 24 metric tons of dry matter per hectare annually with soil warming methods, while 17.3 metric tons of dry matter was produced using conventional production methods. The value of the additional production directly attributable to soil warming was about $243 per hectare assuming sorghum-sudangrass hybrid silage and common annual ryegrass silage are valued at $40 and $26 per metric ton of dry matter respectively.

The values of these yield increases are appreciably below the additional annual costs incurred with this method of production; therefore, it presently is not economically feasible to produce this forage rotation with soil warming methods.

4.5.6 Summary

Based on the results of the economic analyses of Section 4, it is concluded that it would not be economically feasible to produce field corn for either silage or high moisture grain, a single crop of bush beans for process products, or an annual rotation of sorghum-sudangrass hybrid--followed by Common Annual ryegrass silage, with soil warming methods in the Willamette Valley. The value of the respective yield increases resulting from soil warming did not equal the additional annual costs associated with this method of production even though no charge for the energy used to heat the soil was included. Field corn production was evaluated on a single crop per year basis. Should another crop be compatible with field corn in an annual rotation, field corn production with soil warming methods might be economically feasible. The feasibility of such a rotation was not evaluated.

It appears economically feasible to produce a double crop of bush beans for either fresh or process markets or a single crop of beans for the fresh market with soil warming methods. These conclusions are based on the assumption that there is no fee for the energy. Should such a fee be imposed, however, producers of the double crop could pay a rather substantial fee for warm water while producers of the single, fresh market crop could only pay a more modest sum per hectare for the use of warm water. It further appears feasible to produce a winter clover silage crop following bush beans with soil warming methods.

The preceding conclusions are considered as first approximations since they are based on limited research and information. When soil heating energy requirements are more precisely determined, warm water charges are established, and the tax status of the soil warming system is known, more reliable conclusions can be advanced. It should be emphasized that these conclusions do not imply that the economically feasible crop activities are the most profitable cropping alternatives for the farmers. These comparisons were not made in this study because the opportunity costs of production capital, returns to risk, and product supply-market price effects were not considered.

5. SUMMARY AND CONCLUSIONS

5.1 Crop response

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 their development and siting. The thermal discharge might be used to achieve increased soil temperature by circulating warm water through a subsurface pipe network.

The Pacific Power and Light Company, Portland, Oregon, provided funding for a research project to evaluate the effect of warming soils above their natural temperatures on crop growth. The objectives of the research were (1) to measure the effect of increasing soil temperatures on crop growth in the Willamette Valley and (2) to measure rates of heat loss and describe the energy balance of soils heated with condenser cooling water flowing through an underground pipe network. This report deals with the first objective. The second objective is considered in a separate report.

The soil heating experiment was at the Hyslop Crop Science Field Laboratory, 10 kilometers northeast of Corvallis, Oregon. Warm water was not available at the site. It was therefore decided to simulate the underground system of pipes with warm water flowing throughout them with a network of electrical heating cables. The heating cables were installed at the depth of 92 centimeters (cm) with 183 cm spacing between adjacent lines or at a depth of 51 cm with 122 cm spacing between adjacent lines. The temperature of each of six cables was controlled with thermostats. The heat sources were energized during periods of crop production.

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.

Thirteen different crops were grown on heated and unheated areas. Field corn was grown in each of the four years of the study and bush beans were grown during three years. Most others were grown during 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. 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. In a beef or 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 to time of 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 size. 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 the open field as well as in the greenhouse. Open field planting 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 promising crops to be grown with a soil warming system.

Strawberries were 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.

5.2 Economic feasibility

Economic analyses were performed for three cropping sequences. It was found that soil warming was not economically feasible for corn for silage or grain or for a cropping sequence of sorghum-sudangrass silage and Common Annual Ryegrass silage, even though the warm water was supplied to the user at no cost. Assuming that double cropping of bush beans is possible on heated fields but not on unheated fields soil warming was found to be economically feasible for the production of fresh market and process market bush beans. A profit could be realized at a substantial fee for the use of warm water. A Crimson Clover crop following bush beans was also found to give a net profit when grown on heated fields.

These results indicate that in general soil warming will not be economically feasible for forage crops or other low value crops. However, high value crops, such as vegetables, which show large yield responses to soil warming may be profitably grown with soil warming methods even if the producer is assessed a fee for the use of warm water.

An examination of the reasons for the poor economic returns follows. Results of the analyses are summarized in Figure 11 in order to facilitate this examination. The summary shows the fixed costs of the soil warming system and the values of the increased yields resulting from soil warming. The costs of operating the soil warming system are assumed to be $60 for all crops and the assumption was made that no additional cultural costs are associated with producing the additional plant material. The latter cost category would increase the cost of the soil warming practice but it would probably be small in comparison to the fixed costs. The percentage yield increase is also shown.

Figure 11 indicates that the three major determinants in the outcome of the economic analyses are the installation and ownership costs of the soil warming system, the magnitude of the yield increase achieved, and the value of the crop. The effect of each of these factors on the economic feasibility is discussed below.

5.2.2 Installation and ownership costs

Installation and ownership costs can be reduced by using less expensive materials and/or a less dense network of pipes. Only the pipe density will be further considered here. The installation and ownership costs are nearly proportional to the spacing of the parallel pipes. A spacing of 1.8 meters was used in the economic analyses and the corresponding costs are shown in Figure 11. Also shown are the costs for spacing of 3.6 and 5.0 meters.

The feasibility of using wider spacings depends on the relationship between yield and spacing. Unfortunately, this relationship could not be studied satisfactorily in this project. A spacing of 1.8 meters was used except on one plot where a spacing of 1.2 meters was used during the last two years of the study. Plants growing directly over the heat sources and plants growing over the centerline between the heat sources were harvested separately. No statistically significant differences between yields obtained at the two locations were found. Small differences observed during the first growing season were attributed to soil

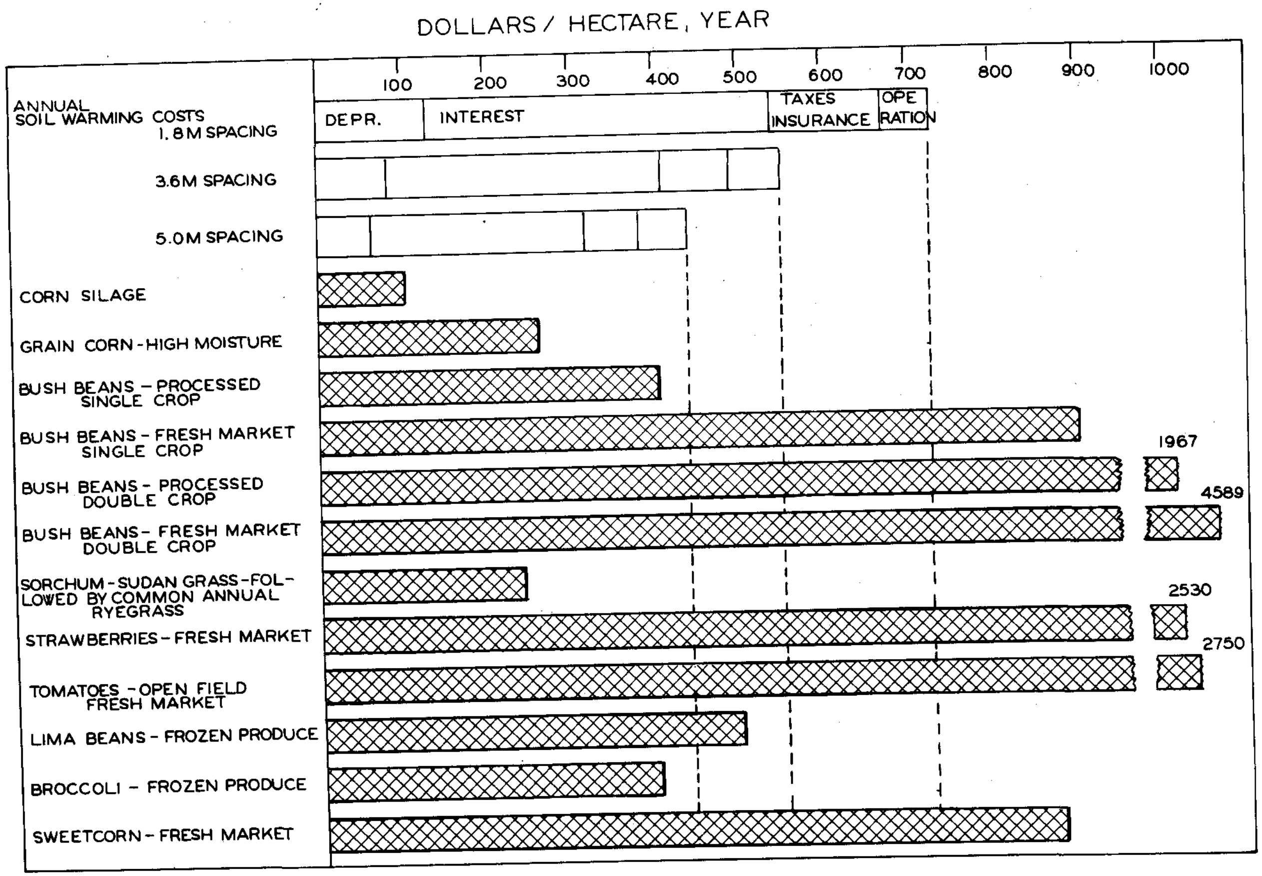

Figure 11. Comparison of the costs of soil warming and values of increased yields achieved with various crops in dollars per hectare per year. Costs are shown for heat source spacings of 1.8, 3.6 and 5.0 meters. The yield increases shown were measured in the project.

disturbance resulting from trenching operations necessary to install the heat sources. On several occasions yields were measured at several distances from the outside heat source of a plot. The yield response was found to extend from 3 to 4 meters beyond this heat source. However, sufficient information to develop the yield response versus spacing relationship was not obtained. The distance to which the spacing between the pipes can be extended before the benefits significantly decrease remains a matter of conjecture.

Figure 11 indicates that extension of the heat source spacing to 5.0 meters substantially improves the economic constraints to the use of a soil warming system if the yield response remains unchanged.

5.2.2 Yield increase achieved

The crop varieties used in the experiments were those recommended for current practices. Efforts to identify crop varieties better able to profit from the increased soil temperatures were not possible in the context of the project. Higher yield increases are desired goals but do not imply achievable goals. They could only be achieved with faster growing varieties, higher plant densities, or more favorable climatic conditions. They might for example be achieved in different geographic regions or in the Willamette Valley by growing crop species more responsive to soil warming. Figure 11 does indicate that the potential for an economically feasible system substantially improves at the higher yield responses.

5.2.3 Value of the yield increase

The benefits derived from soil warming depend on the unit values of the yield increase achieved. These can not be expected to change dramatically over a short period of time. Any increase that might be projected would probably be accompanied by an increase in the installation costs. Different unit values were not shown.

5.2.4 Summary

The economic feasibility of producing crops with soil warming depends on the installation and ownership costs, the yield increase, and the value of the increased production. Economic feasibility can only be realized by decreasing installation costs and increasing the yield response. The potential of achieving either of these goals has not been fully investigated.

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