AN ECONOMIC ANALYSIS OF POTENTIAL USES
OF GEOTHERMAL ENERGY IN AGRICULTURE

to
Division of Energy Technology
Department of Energy
Washington, DC

by
Bruce W. Cone
Senior Agricultural Economist

February 1978

BATTELLE
Pacific Northwest Laboratories
Richland, WA 99352

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

AN ECONOMIC ANALYSIS OF POTENTIAL USES OF GEOTHERMAL ENERGY IN AGRICULTURE

SUMMARY

The economic feasibility and water quality considerations of the cultural practice of soil warming was evaluated using existing technical, agronomic, and economic data. It was hypothesized that it is technically and economically feasible to use geothermal energy in the cultural practice of soil warming for specific crops. The analysis attempted to reject the hypothesis. Since the hypothesis could not be rejected, the results are presented as a profit equation suitable for inclusion in the GEOCOST computer program.

This determination of economic feasibility utilized heterogeneous crop yield data by comparing the elasticity of response with a normalized product-factor price ratio. Soil warming was determined to be feasible when the elasticity of production was equal to or greater than the normalized product-factor price ratio. A farm enterprise was determined profitable if net returns were positive.

An empirical model in which the energy dissipation rate is a function of the difference between heat source temperature and mean monthly air temperature was transformed to utilize data describing the total heat applied during the growing season. Heat input was then measured as the total number of calories per square centimeter applied during the growing season.

CONTENTS

SUMMARY	iii
LIST OF TABLES	vi
CONCLUSIONS AND RECOMMENDATIONS	1
STATEMENT OF THE PROBLEM	3
CONCEPTUAL FRAMEWORK	6
MEASUREMENT OF UNITS OF GEOTHERMAL ENERGY AS A FACTOR OF AGRICULTURAL PRODUCTION	9
EMPIRICAL AGRONOMIC EVIDENCE	13
The Springfield, Oregon Experiments	13
The North Carolina Experiments	18
The Corvallis, Oregon Experiments	24
Conclusions	41
ECONOMIC ANALYSIS	42
An Estimate of Yield	42
Determination of Product Price	47
Price of Geothermal Heat	47
Quantity of Heat	47
Fixed Costs of Tomato Production	52
An Empirical Profit Equation	53
Conclusions	54
REFERENCES	55
BIBLIOGRAPHY	58

TABLES

1. Yield Response Data from the Springfield, Oregon Experiments ..	15
2. Yield Response Data from the North Carolina Experiments	19
3. Yield Response Data from the Oregon State Experiments	25
4. Crop History Dates and Amount of Water Applied, Bush Beans, 1969	31
5. Recorded Rate of Heat Loss in Calories/CM ² /Min, 1971-72, Hyslop Soil Warming Experiments, Oregon	36
6. Estimated Heat Loss in Calories/CM ² /Month by Month, 1971-72, Hyslop Soil Warming Experiments, Oregon	37
7. Secondary Observations of the Normalized Response of Crops to Heat	44
8. Gross Returns of Ten Commodities, in Dollars Per 100 Pounds, for 1972-74	48
9. Total Initial Investment and Installation Cost of a 125 Acre Open Field Soil Warming System, 1973 Costs	49
10. Average Capital Outlays and Annual Capital Costs Per Acre of a Commercial Scale Soil Warming System, 1973	50
11. Annual Maintenance, Tax, and Insurance Costs Per Acre of a Commercial Scale Soil Warming System, 1973	51

CHAPTER I

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS AND RECOMMENDATIONS

A number of research projects have shown the response of crop yields to heat under specific agronomic and climatic conditions. Heat induced the growth of grass and legumes in Maryland; advanced maturity and made double cropping possible for potatoes in Minnesota; increased yields of tomatoes, sweet corn, asparagus, canteloupe and squash at Springfield, Oregon; improved yields of cabbage, snap beans and sweet corn in North Carolina; and improved the yields of eleven crops tested in Corvallis, Oregon.

In this study, data generated at Corvallis, Oregon, from 116 observations of 11 commodities over 4 years were utilized to estimate an empirical production function. A normalized value of yield was found to be a function of heat, fertilizer and the year in which the data were collected. It was found that the incremental change in yield increased at a decreasing rate as more heat was applied or as heat was applied for a longer period of time. A maximum was reached at a total heat exchange of 5869 cal/cm^2 during a growing season.

Factors of profit were determined to be estimated yield, produce price, price of geothermal heat, quantity of heat, and fixed costs of production. The heat and production functions became a system of equations used to generate secondary data. These data were then utilized to estimate a reduced form quadratic production function in which the change in yield divided by yield was a function of the difference between the atmospheric temperature and the source temperature. Product prices were those of ten relevant commodities averaged over three years. The price of geothermal heat was the annual cost of the heat distribution system. The quantity of heat was defined as 17.5°C temperature differential between the atmospheric and heat source temperature. This value was chosen on the basis of the empirical response function.

Using preliminary criteria, the hypothesis was rejected for all enterprises considered except peppers and tomatoes. Historic cost of production data were used for tomatoes. The return from using geothermal energy in the production of tomatoes was \$2,222.05 per acre. The hypothesis could not be rejected on the basis of available data and the analysis presented. Due to data limitations, this research must be considered as an initial feasibility analysis. This analysis justifies research at a specific site with the measurement of specific resources to produce one or two appropriate products for a defined market.

CHAPTER II

STATEMENT OF THE PROBLEM

2. STATEMENT OF THE PROBLEM

The application of geothermal resource development in agriculture is treated in a peripheral manner in the literature. Koenig mentions the geothermal greenhouse operations in southwestern Iceland which supply much of the fresh vegetables for the Reykjavik market. Greenhouse heating with geothermal waters is common on farms and agricultural experiment stations in Japan. Excess heat from the geothermal heat-exchangers at Paratunka, Soviet Union is used to heat greenhouses and seedbeds. The warm water is used to irrigate crops. However, no reference of yield response to heat from geothermal sources or of the economic feasibility of utilizing geothermal energy in agriculture is cited.⁽¹⁾ Wehlage and Linton describe the potential of using geothermal heat in agriculture and food processing but do not present rigorous analysis suitable for investment decisions.⁽²⁾

A void exists in the literature describing the potential use of geothermal energy in agriculture. To fill this void, it is necessary to generate technical coefficients which describe the response of commodities to heat and relevant prices which reflect the potential profitability of geothermal energy to agriculture.

Barton points out, and it has been verified in the research presented here, that investigations on the agricultural applications of heat have resulted from the concept of utilizing warm water discharge from fossil fuel and nuclear electrical generating stations.⁽³⁾ The literature is rich with applications of warm water to agriculture that results from power plants. Bakken-Arkema et. al. conducted an extensive review of the literature on the use of waste heat from power plants.⁽⁴⁾ The uses which are described in the literature include soil warming, frost protection, fish culture, greenhouse heating, irrigation, grain drying and food processing.⁽⁵⁾ With few exceptions, the primary focus of the investigations reported in the

literature are biology and engineering. Some of the literature includes a discussion of costs. Comprehensive economic analysis has not generally been accomplished as part of the research effort described.

Johns, et. al. present an economic analysis of fish culture, soil warming, irrigation, and greenhouse heating as four alternative uses of warm water. Catfish culture was not recommended in the Mountain and Pacific Coast regions because of poor markets. Chopped carp production as a feed source for shrimp, clam, lobster and oyster production promises greater profits. Potential for soil warming ranked next as an application of heat in agriculture in their economic analysis. No additional revenues were thought to be gained by using warm water as compared with ambient temperature water for irrigation. The potential application of warm water for greenhouse heating was thought to be very limited.⁽⁶⁾

Results obtained by Cone, et. al. substantiate those of Johns with respect to greenhouse heating. Light was found to be the first limiting factor in existing winter greenhouse and hydroponic operations in the Pacific Northwest. On the basis of a techno-economic analysis, it was concluded that it is not profitable to produce off-season produce with artificially lighted hydroponic systems in the Pacific Northwest.⁽⁷⁾

Based on available economic analysis, the two feasible uses of geothermal energy in agriculture were soil warming and fish culture. Soil warming is conducted by flowing hot water through a series of pipes buried under the surface of the ground. The quality of the water has no effect on production. Fish culture with warm water is generally conducted by flowing the water into ponds in which the fish are kept. Water quality could affect production.

Bowen reports that geothermal waters generally carry higher percentages of dissolved solids than do nonthermal waters because their higher temperatures have increased the rate of dissolution of the more volatile chemicals of the host rocks. In many cases the thermal waters are of sufficient purity to be used for agriculture. The geothermal resource at Reykjavik, Iceland, has a mineral content which is remarkably low for geothermal fields (less than 400 ppm). Peterson and Groh are cited as describing the use of geothermal waters for livestock in Klamath Falls, Oregon.⁽⁸⁾ White reports that

most hot-water effluents involve some environmental hazard, since they are generally higher in dissolved salts, B, NH_3 , As and heavy metals than most surface and ground waters.⁽⁹⁾ The geothermal resource at The Geysers, California, has a content of boron and ammonia which preclude disposal to local streams. Other geothermal resources in California are highly saline (260,000 ppm total dissolved solids) brines. Although geothermal energy from some sources is or could be utilized for fish culture, there are sufficient indications of water quality limitations.

The problem at hand is to determine the economic feasibility of utilizing a geothermal facility for agricultural production. The problem is limited to the cultural practice of soil warming on the basis of available economic analysis and water quality considerations. The analysis is limited to the use of existing technical, agronomic and economic data. The hypothesis tested in the subsequent research is that it is technically and economically feasible to utilize geothermal energy in the cultural practice of soil warming for specific crops. If the hypothesis cannot be rejected the results will be presented in the form of a profit equation suitable for inclusion into the GEOCOST computer program.⁽¹⁰⁾

CHAPTER III

CONCEPTUAL FRAMEWORK

3. CONCEPTUAL FRAMEWORK

Agriculture is the process of combining natural agents such as soil and the sun with human effort such as tractors, fertilizer, and physical labor to produce food and fiber. A simple theory of agricultural response is that:

1. There is a continuous smooth casual relationship between the inputs (X's) and food (Y).
2. Dimishing returns prevail with respect to each input factor (X's) so that the additional output from succeeding units of X's becomes less and less. Beyond some peak yield, additional units of X's may have an increasingly deleterious effect on yield.
3. Decreasing returns to scale prevail so that an equal proportionate increase in all inputs results in a less than proportionate increase in output.

There exists for each commodity produced a response function in which input factors, both natural agents and human effort, are variable. Analytically, situations of agricultural production are considered in which only a relatively small number of inputs are variable; the other factors are either held constant or are regarded as having so little influence that they are considered as fixed. The analysis presented here is concerned only with heat. Thus output of a specific food or fiber, as a function of heat, can be written

$$Y = F(X) \quad (1)$$

Given the algebraic form of Equation (1), it is possible to derive the elasticity of response. Elasticity of response with respect to X is

defined as the relative change in Y divided by the relative change in X which caused the given change in Y. Algebraically, in incremental units at a particular point on the response curve, it can be stated as:

$$E = (\partial Y / \partial X)(X/Y) \quad (2)$$

E is a pure number which is most conveniently interpreted as the percentage change in Y resulting from a 1% increase in X.

E must always be less than 1 to be consistent with the theory both in terms of diminishing returns to the factor and in terms of decreasing returns to scale. It must be greater than zero if the input is to contribute to total production.

Any commodity response process involves gains and losses. The losses are the inputs consumed. With gains and losses increased relative to some specified normative goal, best operating considerations occur when net gains are maximized. For this purpose, it is necessary for output gains and input losses to be measured in comparable units. To convert the X's and Y to comparable units, elasticities of response will be used. Elasticities of response are not sufficient to determine whether an enterprise is profitable. It is necessary to also consider price elasticities.

Given the response function as stated in Equation (1), for an unconstrained objective function, profit (π) is equal to revenue from output ($P_y Y$) minus cost of input ($P_x X$) minus fixed costs (FC). This is stated:

$$\pi = P_y Y - P_x X - FC \quad (3)$$

Profit is maximized where:

$$\frac{\partial Y}{\partial X} = \frac{P_x}{P_y} \quad (4)$$

In order for Equation (4) to be compatible with the statement described in Equation (2), it is necessary to restate Equation (4) as:

$$\frac{\partial Y}{\partial X} \cdot \frac{X}{Y} = \frac{P_x}{P_y} \cdot \frac{X}{Y} \quad (5)$$

For ease of explanation, the right hand side of the equation is stated as:

$$N = \frac{P_x}{P_y} \cdot \frac{X}{Y} \quad (6)$$

N is a pure number which can be compared with E and is interpreted as a normalized price ratio suitable for comparing with the response elasticity. In those cases where:

$$E \geq N \quad (7)$$

it is profitable to increase the use of X. Where:

$$E_1 < N_1, \quad (8)$$

the situation is not economically feasible. The necessary addition to this theoretical framework is a determination of units in which to measure X which is presented in the next chapter.

CHAPTER IV

MEASUREMENT OF UNITS OF GEOTHERMAL ENERGY AS A FACTOR OF AGRICULTURAL PRODUCTION

4. MEASUREMENT OF UNITS OF GEOTHERMAL ENERGY AS A FACTOR OF AGRICULTURAL PRODUCTION

The agricultural economic literature is rich in empirical analyses of the response of agricultural output to traditional inputs such as labor, capital, land, fertilizer, machinery, and feed. Measurements of these factors of production are well defined and documented.^(11, 12, 13) Such is not the case with the measurement of the units of energy from a geothermal source. The measurement of units of geothermal energy as a factor of agricultural production requires some interpretation.

The use of geothermal energy for soil warming involves a complex relationship of air temperature, soil texture, and soil moisture. These factors determine the rate of energy dissipation. The rate of energy dissipation from a line source at some depth in the soil depends on several parameters specified by Kendrick and Havens and presented in the following equation for steady state conditions:

$$Q = \frac{2\pi k \Delta T}{\ln \frac{(2d-r)}{r} + \sum_{n=1}^N \ln \frac{(n\ell)^2 + (d-r)^2}{(n\ell)^2 + r^2}} \quad (9)$$

where:

- Q = the rate of heat loss per unit length of pipe (cal/cm min),
- r = the pipe diameter (cm),
- ℓ = the spacing (cm),
- d = the depth (cm),
- k = the thermal conductivity of the soil (cal/cm min C), and
- N = the number of parallel pipes on either side of the center pipe. (14)

The importance of thermal conductivity on the energy balance is shown by equation (9). The rate of energy dissipation is proportional to the thermal conductivity. Rates of energy loss may be expected to vary considerably during the growing season.

Thermal conductivity strongly depends on water content; the thermal conductivity of soil increases with increasing water content. De Vries presented measured and computed values of thermal conductivity for sand, clay, and peat soils over a wide range of water contents. ⁽¹⁵⁾ Soil water is continually depleted and replenished during crop production. This can cause thermal conductivities to vary as much as three-fold during short periods of time.

Smith and Byers evaluated the influence of soil texture on thermal conductivity. They showed that for dry soil, coarse texture resulted in the highest thermal conductivity because of less pore space and better particle contact. A linear relationship was observed between increasing pore space and decreasing thermal conductivity. ⁽¹⁶⁾ Similar observations were made by Nakshabandi and Kohnke. ⁽¹⁷⁾

Soil surface temperatures have a wide range on a daily as well as a seasonal basis. ⁽¹⁸⁾ Daily fluctuations at the soil surface may be greater than seasonal changes in the heat source temperature.

Rykbost and Boersma attempted to verify Equation (19) with empirical data collected at the Hyslop Crop Science Field Laboratory near Corvallis, Oregon. The site is on the main floor of the Willamette Valley, a few kilometers east of the Coast Range foothills. The elevation is approximately 70 meters above sea level at a latitude of 44°38' north and longitude 123°12' west. Total annual rainfall is 100 cm with 70% occurring from November through March and 5% 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. The experimental site is on a nearly level terrace. Soil within the one-hectare research plot is classified in the Woodburn Series, an Aquatic Argixeroll in the new Soil Conservation Service classification scheme.

For a continuously energized heat source the seasonal variation in energy dissipation rates was found to be a three-fold increase from a minimum in late summer to a maximum in the winter, coincident with low air temperatures

and high soil water content. A decrease in heat source depth and an increase in source density was found to increase dissipation rates as predicted by the theoretical models. Subsurface irrigation was successful in maintaining high soil water content during periods of high evapotranspiration losses, and therefore maintaining high heat transfer rates.

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

Experimentally determined rates of energy dissipation were quite close to predictions based on theoretical considerations presented by Kendrick and Havens⁽¹⁴⁾ and Schmill.⁽¹⁹⁾ Although simplifying assumptions make it impossible to partition the various heat transfer components active in the soil medium, gross heat loss predictions based on these models were found to be accurate within reasonable limits in most cases.

Mean monthly air temperatures were found to be highly correlated with mean monthly energy dissipation rates for a continuously energized heat source. This suggests that prediction of energy dissipation rates from readily available climatological data is possible. The empirical model as estimated by Rykbost and Boersma⁽²⁰⁾ was found to be:

$$R = .00375 + .000742 (T_s - T_a) \quad (10)$$

where

R is the energy dissipation rate in calories per square centimeter per minute.

Ts is the heat source temperature, and
Ta is the mean monthly air temperature.

Equation 10 is transformed from the measurement of the rate of heat application to the measurement of total heat applied during the growing season by multiplying the coefficients by the number of minutes in a day and the number of days. The equation is restated as:

$$X = 5.4 D + 1.07 D (Ts-Ta) \quad (11)$$

where

X is the total number of calories per square centimeter applied during the growing season, and

D is the number of days heated.

Equation (1) can be rewritten to include equation (11) and is presented as:

$$Y = f \left[5.4 D + 1.07 D (Ts-Ta) \right] \quad (12)$$

Empirical agronomic evidence is necessary to transform equation (11) into an empirical equation of estimation.

CHAPTER V

EMPIRICAL AGRONOMIC EVIDENCE

5. EMPIRICAL AGRONOMIC EVIDENCE

Agronomic evidence is given here to define a response surface of agricultural commodities to heat. Investigation of the effects of soil temperature on plant growth, development and yield have been conducted under conditions which range from the use of growth chambers where climatic factors are rigidly controlled to field studies with no environmental controls.

Decker reviewed the literature and used equipment and facilities to modify soil temperature in the field. The use of these facilities served as a bridge between field studies and use of growth chambers. He concluded that soil temperature had a dramatic effect on the growth of grasses and legumes. Some of the more marked responses were with tiller initiation, seed head emergency, and crown and root growth.⁽²¹⁾

Allred, Read and Gilley conducted soil warming response trials with early (Norlands) and late (Russet-Burbank) variety potatoes on a Hubbard loamy sand located at the Sand Plains Experimental Irrigation Field near Elks River, Minnesota.⁽²²⁾ They concluded that soil warming does not provide significant protection from potatoes against frost at temperatures below 28°F. Soil heating can advance the maturity date for early potato varieties between two and three weeks. Second-crop yields are possible with heated soils in Minnesota, if preplanting immediately follows the first crop harvest.

Three soil warming research efforts generated considerable commodity response data. The Eugene Water and Electric Board and the Environmental Protection Agency sponsored a demonstration project on 170 acres near Springfield, Oregon. Field trials were conducted at the Central Crops Research Station at Clayton, North Carolina. Oregon State University carried out experiments at the Hyslop Crop Service Field Laboratory near Corvallis, Oregon. The results of this research is described in detail in the subsequent sections of this chapter.

THE SPRINGFIELD, OREGON EXPERIMENTS ⁽²³⁾

The Springfield, Oregon project was a cooperative venture among Eugene Water and Electric Board, the Environmental Protection Agency and Vitro Engineering. Weyerhaeuser Company provided the thermal water source. The demonstration took

place on 170 acres under cultivation along the McKenzie River near Springfield. Seven farmers agreed to use thermal water from the Weyerhaeuser mill for irrigation, frost protection, and plant cooling. The focus of the project was the isolation of any harmful aspects related to thermal water application in agriculture. In addition, it was proposed to demonstrate how heat energy in water could be dissipated while moderating an area's naturally occurring conditions of temperature and humidity.

The heated water from the Weyerhaeuser mill was discharged into the project's pumping pit. Water temperature at the pumping pit ranged from about 90 to 120° F. Two 1750-gpm and one 500-gpm pumps were used to deliver water to the project at about 80 to 90 psi. Water was pumped about 2 miles through a 16 in. diameter steel mainline (buried 30 in.) to the edge of the project's farms. Laterals fed individual farms. The mainline continued across the project's farms and was gradually reduced in size to 8 inc. diameter.

Yield Data

Yield data were recorded for two varieties of tomatoes, sweet corn, asparagus, two varieties of cantaloupe and squash. The yield response data are presented in Table 1 and described below. Yield response data were normalized so that the response between crops could be compared. This was done by dividing the difference between the heated plot and the controlled plot (ΔY) by the yield of the heated plot and multiplied by 100.

Tomatoes

The nutrient level of plants from soil heated plots tended to have more N, P, K, CA, Mg, and Zn than plants from non-heated plots. Plants from soil heated plots tended to have less Mn than control plants. Soil heat did not have a positive influence on tomato yields.

Sweet Corn

Sweet corn harvested from heated soil was visually larger than that harvested from nonheated soil on July 20, 1972. Early ear development was stimulated by soil heat; the soil heated plots averaged 72% more ears between 3 and 6 inches than control plots on August 21, 1972. There was no difference in the number of ears less than 3 in. between soil heated and control plots. At harvest, the weight

TABLE 1. Yield Response Data from the
Springfield, Oregon Experiments (3)

<u>Commodity</u>	<u>Variety or Date</u>	<u>$\frac{\partial Y}{Y} \times 100$</u>
Tomatoes	Fireball	-4.87
	Willamette	6.29
Sweet Corn		26.41
Asparagus		49.69
Cantaloupe	Harpers	-98.14
	Supermarket	-71.01
Squash	10/4/72	67.27
	10/9/72	33.33
	10/16/72	28.57
	11/6/72	-20.00
Average		1.75

Based on data generated by:

- (23) Berry, James W. and Herman H. Miller, Jr., A Demonstration of Thermal Water Utilization in Agriculture, 6012 - 74 - 011. Office of Research and Development, U. S. Environmental Protection Agency, Washington, D. C., April, 1974.

of ungraded, graded, and immature ears was increased by 28, 35, and 50% respectively. The number of ungraded, graded, and immature ears were increased by 36, 23, and 129% by heated soil when compared to control plot production. Overall, soil heated plots produced more but slightly smaller ears. There was little difference in average ear weight of graded ears from soil heated and control plots. More immature ears were formed on heated soil than on control plots but the ears did not develop, and there was little difference in weight of immature ears at harvest. Most of the difference in size of corn plants between soil heated and control blocks that was noted in July was not apparent at harvest. There was little difference in average height and weight of plants from heated and control plots on September 20, 1972.

Asparagus

Initial spear emergence and subsequent growth appeared to be more rapid on heated soil than on control blocks. By October 1972, crowns in heated soil appeared to have produced about 50% more fern growth than crowns in control soil. Asparagus fern on control plots was about 2 ft. high while fern on heated soil was at least 3 feet tall on October 4, 1972. The weight of asparagus fern and stalks cut in September from soil heated plots averaged 95% more than from the control blocks. Early spring production of asparagus spears was stimulated by soil heat. The soil heated plots yielded 44 and 98% more asparagus spears than control plots based on number and weight. The greater asparagus fern growth produced during the 1972 growing season on heated soil plots resulted in larger crowns. Heated soil produced crowns that averaged about 40 per cent larger than crowns from control areas. The larger crowns should eventually produce greater yields of asparagus, but only prolonged experiments will determine the effect of heated soil on long-term asparagus yields.

Cantaloupe

Soil heat resulted in early vine development of muskmelons. Although early vegetative growth of cantaloupes was stimulated by soil heat, the yield of fruit was not. There was no significant difference in yield of soil heated and control areas of "Harper's Hybrid" and "Supermarket." Soil heat

appeared to delay fruit maturity as indicated by the number of immature fruit at the end of the harvest season. Temperatures of heated soil at 6 and 12 in. depths were generally warmer through June and into July than non-heated soil. This probably accounts for the early stimulation of vegetative growth of cantaloupe plants.

Squash

The soil heated block of squash produced 24% more fruit by number and 13% more fruit by weight than the non-heated control block. In this case, early maturity of squash appeared to be enhanced by the soil heat. At first harvest, the yield from the soil heated block was 10.2 tons. The control yielded 3.5 tons. The 10.2 tons of fruit represented 36.2 per cent of the heated block's production, while the control had only produced 14.1 per cent by October 4, 1972. Production from control and heated block was about the same on October 9 and 16. On the last harvest, November 6, the control block produced 4.6 more tons per acre than the soil heated block.

Input Heat Data

No data were presented that could be utilized to establish a correlation between the quantity of heat applied and crop yield.

Parameter Estimation

Insufficient data were presented for the Springfield, Oregon experiments to estimate the parameters of a heat response function. Table 1 shows that response to heat varies among crops, between varieties and over time. The data collected for squash shows strong positive heat effect which gradually decreases over time until it is negative. In general there was a small positive response of crops to heat.

THE NORTH CAROLINA EXPERIMENTS⁽²⁴⁾

Skaggs, Sanders and Willey conducted soil warming experiments in North Carolina during 1971-73 with cucumber, snap bean, strawberry, sweet corn, cabbage, and sweet potato. Soil warming systems were installed in 18 by 18 ft. field plots located on the Central Crops Research Station at Clayton, N.C. The soil was a Wagram sandy loam which had an A horizon of 18-22 inches deep underlain by a sandy clay subsoil extending to a depth of greater than 4 feet.

Heated water was circulated through eight 1-inch diameter 18 ft. long plastic pipes buried 20 inches deep and spaced 20 inches apart. The pipes were connected end to end by 20-inch long sections to form a serpentine pattern. The temperature drop from the outlet (at 38°C) to the inlet of the water heater was only .5 to 1.6°C.

Crops were planted using conventional cultural practices. The cultivar, depth of seeding, spacing within and between rows, rows per plot and fertilization were according to North Carolina recommended practices and were outlined earlier. Strawberries were grown at closer than normal spacing in an effort to maximize differences between treatments during a shorter than normal period of growth.

Multiple harvests were made on cucumbers, strawberries and sweet corn. Harvests were affected twice weekly during crop bearing season. A single harvest was made on snap beans, cabbage and sweet potatoes. A period of abnormally low temperature in January 1972 caused premature termination of the cabbage study and no yield data were taken. In 1973 cabbage was injured by cold temperatures and the degree of injury was evaluated by weighing and counting heads with slight, moderate and extensive injury.

Yield Data

Yield data were collected for six crops. Agronomic response data are described in detail and presented in Table 2.

Cabbage

Cabbage is normally a cool season crop and is produced during late fall or early spring in the North Carolina Coastal Plain. Cabbage does have some

TABLE 2. Yield Response Data from the North Carolina Experiments⁽²⁴⁾

<u>Commodity</u>	<u>Year</u>	$\frac{\partial y}{\partial Y} \times 100$
Cabbage	1972-73	60.34
Snap Beans	10/18/71	28.57
	5/16/72	78.69
	6/30/72	21.43
	9/25/72	-40.48
	6/25/74	-121.36
Sweet Corn	6/14/73	81.82
	6/18/73	-5.88
	6/21/73	85.71
	6/25/73	-66.67
	7/2/73	-80.00
	7/3/74	56.52
	7/12/74	-45.45
Sweet Potato	1974	-1.55
Strawberry	1972	-79.38
	1973	-77.11
	1974	22.72
Cucumber	1973	-19.30
	1974	1.08
Average		-5.28

Based on data generated by:

- (24) Skaggs, R. W., D. C. Sanders, and C. R. Willey, An Evaluation of the Use of Waste Heat for Soil Warming in the Southeast, Water Resources Research Institute, University of North Carolina, Raleigh, North Carolina, 1975.

frost hardiness and can withstand temperature to -7°C . Thus cabbage was chosen as a crop for the fall and winter season. Cabbage planting was late in 1971 (November 2), thus, plants were not as well established as is normal during the fall. Due to this late planting, plants did not mature. The growth of cabbage in 1972-73 was not affected by soil warming until late November (Fig. 22). At this time cabbage plants which received soil warming continued to grow rapidly while control plants tended to level off. The normalized yield ($\frac{\partial Y}{Y}$) as influenced by soil warming during the 1972-73 season was 60.34.

Snap Beans

Snap beans are considered a warm season crop, but will grow during cooler seasons. Snap bean is sensitive to excessively high soil temperature during germination. Further, excessive evapotranspiration during flowering will cause young pods to drop off and reduce yield. Snap beans were tested during early spring and late summer. This was done to test plant response during a season which is normally too cool for good growth and to determine if the crop could be successfully grown during late summer when high soil temperatures were unfavorable.

Soil warming enhanced the plant stand of snap beans when trials were seeded in early spring. But, when snap beans were seeded in late July or August, stand was reduced or not affected respectively.

The number of days to flowering was decreased by soil warming during the early spring planting of 1972. However, soil warming actually slowed seedling emergence and reduced final stand when snap beans were planted in July, 1972. Soil temperatures resulting from soil warming were above the optimum for germination and seedling growth.

The increased rate of plant growth with soil warming can also be detrimental, as in the instance of spring of 1972 when fiber content of similar sized bean pods was increased by soil warming.

When snap beans were planted in relatively warm soil as in August 1971 or late April 1974, the growth of bean plants was respectively not affected or decreased by soil warming. But when snap beans were seeded into cool soil in late March 1972, plants produced more leaf and stem tissue where soil warming was practiced.

The yield of pods followed a similar pattern to that of plant growth. Soil warming resulted in an increase in pod production in March 1972 plants and a decrease in pod production in April 1974 planting. The normalized yields ranged from -121.36 to 78.36 and are presented in Table 2.

Sweet Corn

Sweet corn is a warm season crop which responds to increased temperature during its seedling growth. But sweet corn can withstand lower soil temperatures than snap beans or cucumbers during early growth periods. Thus sweet corn was tested during very early spring in an effort to produce earlier harvest and obtain a higher market price.

In both 1973 and 1974 plants receiving soil warming matured earlier, yielded more both as number and weight, and were more concentrated at harvest. The weight of sweet corn was increased 67 and 73% in 1973 and 1974, respectively. The number of ears was increased 83 and 49% respectively during the 2 years. During 1973 the quality and market acceptability of corn was much better when plants received soil warming. The mean weight per ear was increased by soil warming in 1974 but was not altered in 1973. This difference in response may be due to different cultivars being used in the respective years.

The weight of ears harvested during the first harvest of 1974 was increased by soil warming when plants were evaporative cooled. No increase in yield with soil warming was noted when plants were not cooled. The mean weight of ears harvested during the whole 1974 season was increased by evaporative cooling. The normalized yield ranged from -80.00 to 85.71 for 5 harvest dates in 1973. The average was -40.34. The normalized yield for 1974 was 42.50.

Sweet Potatoes

Sweet potato is a crop which requires a long warm season and does not grow well in cool temperatures. In fact sweet potatoes require higher temperatures than corn, snap beans or cucumbers and will withstand very high temperatures. Because sweet potatoes respond favorably to high temperature it was chosen for use during the hot summer months, when soil temperatures were too high for good growth of the aforementioned crops.

Sweet potato top growth expressed as fresh weight was increased by almost 200% with soil warming and plant top dry matter was increased 140%. The total production of storage roots was not affected by soil warming. When the soil was warmed there was a trend toward larger roots which command a greater value in the market place. The normalized yield for 1974 was -1.55.

Strawberry

Strawberry is a perennial crop which is usually grown commercially for two years. Flower buds of the strawberry are produced during the fall, thus soil warming did not affect yield potential for the first year. But earliness and final yield could be affected by changes in ambient temperature. The plots that were soil warmed started production sooner. However, these plots also stopped producing sooner. The accumulated yield was greater in soil warmed plots during the first 2 weeks of harvest which would have distinct economic value but after this time non-soil warmed plots produced more berries.

Indication that the first flowers are being lost when soil warming is practiced is seen in yield during 1972 and 1973. Soil warming resulted in a higher percentage of berries in the small size classes. Because the first berries produced are usually the "large" size fruit it was felt many of these berries were lost to frost, thus reducing yield. In 1974 early spring warm temperatures hastened flowering in all plots and equal amounts of berries were lost due to frost. Another reason for smaller berries may be that soil warming reduced soil moisture levels which can reduce berry

size. Part of the reason for reduced yields in 1973 is also found in the fact that soil warming was practiced on these plots year round and resulted in greater plant death. The increase in plant losses was due both to high temperature in mid-summer, nematode population build-up, and reduced winter hardiness of plants grown with soil warming.

The normalized yield ranged from -79.38 to 22.72. The yields for three years are presented in Table 2.

Cucumber

Cucumbers are generally considered to be a warm season crop. However, they do not withstand extremely high soil temperatures during germination. Because they do respond favorably to increased soil temperature, cucumbers were grown during mid and late summer to determine if they could withstand higher temperatures caused by soil warming. Total yields of slicing cucumbers were increased by soil warming during 1973 and 1974. Soil warming did alter the yield of slicing cucumbers expressed as either number or weight regardless of the grade. This is presented in Table 2.

Input Heat Data

Sufficient data were not presented in available sources to establish a correlation between the quantity of heat applied and crop yield.

Parameter Estimation

Insufficient data were presented for the North Carolina experiments to estimate the parameters of a heat response function. Table 2 presents a more complete description of the interrelationship between heat and changes in yield than was presented in Table 1. Some crops were more positively responsive to heat and others more negatively responsive than was demonstrated in the Springfield, Oregon experiment. The response of snap beans to heat in 1972 in North Carolina showed a similar response to squash in 1972 in Springfield. In general, while the yields recorded at Springfield

showed a slight positive response, the yields recorded in North Carolina showed a negative response. However, there were sufficient examples of crops responding positively to inputs of heat to warrant future inquiry.

THE CORVALLIS, OREGON EXPERIMENTS (25)

Rykbost and Boersma conclude that a wide range in yield response to soil heating was observed for different crops and for some crops in different years. 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.

Yield Data

Yield data were collected for 11 crops. Agronomic conditions are described in detail. Quantification of the experiments is presented in Table 3.

Sudangrass

The sudangrass cultivar Trude 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 most of the growing season.

Plots were harvested on July 29 and October 7. Dry matter yields in metric tons per hectare (tons/ha) are shown in Table 3. To obtain dry matter content samples were placed in an oven maintained at 70°C for 48 to 72 hours.

TABLE 3. Yield Response Data from the Oregon State Experiments⁽²⁵⁾

Commodity	Year	Treatment	Yield (tons/ha)	$\frac{\Delta Y}{Y} \times 100$	Total Heat Loss (cal/cm ²)
Sundangrass	1971	Unheated	12.03		
		Heated	16.76	28.22	2682
	1972	Unheated	7.12		
		Heated	12.75	44.16	2287
Sorghum-Sudangrass	1971	Unheated	11.92		
		Heated	17.56	32.19	2682
	1972	Unheated	8.79		
		Heated	13.79	36.26	2287
Ryegrass	1970-71	Unheated	6.90		
		Heated	8.11	14.92	3038
	1971-72	Unheated			
		112 kgN/ha	0.43		
		224 kgN/ha	1.26		
		336 kgN/ha	2.33		
		Heated			
		112 kgN/ha	2.18	80.26	2688
		224 kgN/ha	3.58	60.80	2688
		336 kgN/ha	3.95	41.01	2688
	1971	Unheated	3.00		
		Heated	4.93	39.15	3038
Fescue	1971-72	Unheated	20.61		
		Heated	24.45	15.71	8183
Corn	1969	Unheated	7.2		
		Heated	9.6	25.00	2800
	1970	Unheated			
		92 kgN/ha	11.36		
		186 kgN/ha	11.67		
		280 kgN/ha	12.10		
		Heated			
		92 kgN/ha	13.53	16.04	3271
		186 kgN/ha	13.71	14.88	3271
		280 kgN/ha	12.90	6.20	3271
		Subirrigated			
		Unheated			
		186 kgN/ha	11.24		
		280 kgN/ha	9.41		
		Heated			
		186 kgN/ha	11.45	1.83	4058
		280 kgN/ha	11.49	18.10	4058
	1971	Unheated			
		92 kgN/ha	3.45		
		186 kgN/ha	4.82		
		280 kgN/ha	3.99		
		Heated (OR)			
		92 kgN/ha	7.03	50.92	2682
		186 kgN/ha	7.59	36.50	2682
		280 kgN/ha	8.27	51.75	2682
		Heated (BR)			
		92 kgN/ha	6.90	50.00	2682
		186 kgN/ha	7.57	36.32	2682
		280 kgN/ha	7.93	49.68	2682
	1972	Unheated	7.61		
		Heated	9.25	17.73	2957
		Subirrigated			
		Unheated	6.95		
		Heated	10.27	32.33	3898

TABLE 3. Yield Response Data from the Oregon State Experiments (Continued)

<u>Commodity</u>	<u>Year</u>	<u>Treatment</u>	<u>Yield (tons/ha)</u>	<u>$\frac{\Delta Y}{Y} \times 100$</u>	<u>Total Heat Loss (cal/cm²)</u>
Bushbeans	1969	<u>Unheated</u>			
		D1	13.9		
		D2	15.2		
		D3	10.8		
		D4	7.4		
		<u>Heated (OR)</u>			
		D1	18.2	23.63	1604
		D2	16.8	9.52	1499
		D3	15.9	32.08	1361
		D4	12.8	42.19	1573
		<u>Heated (BR)</u>			
		D1	15.9	12.58	1604
		D2	15.7	3.18	1499
		D3	13.7	21.17	1361
		D4	14.1	47.52	1573
	1970	<u>Unheated</u>			
		<u>May Planting</u>			
		54 kgN/ha	12.6		
		92 kgN/ha	9.0		
		111 kgN/ha	8.1		
		<u>July Planting</u>			
		54 kgN/ha	18.7		
		92 kgN/ha	19.2		
		111 kgN/ha	19.5		
		<u>Heated</u>			
		<u>May Planting</u>			
		54 kgN/ha	16.3	22.70	1396
		92 kgN/ha	19.2	53.13	1396
		111 kgN/ha	18.4	55.98	1396
		<u>July Planting</u>			
		54 kgN/ha	12.1	54.55	1450
		92 kgN/ha	18.4	4.35	1450
		111 kgN/ha	23.5	17.02	1450
Lima Beans	1969	Unheated	4.9		
		Heated (BR)	5.8	15.52	2310
		Heated (OR)	5.4	9.26	2310
	1971	<u>Unheated</u>			
		54 kgN/ha	5.00		
		92 kgN/ha	5.33		
		111 kgN/ha	4.32		
		<u>Heated</u>			
		54 kgN/ha	6.43	22.24	2543
		92 kgN/ha	8.60	38.02	2543
		111 kgN/ha	5.69	24.08	2543
Tomatoes	1969	Unheated	72		
		Heated	108	33.33	2128
	1970	Unheated	79		
		Heated	100	21.00	2364
	1971	Unheated	59		
		Heated	77	23.38	2725

TABLE 3. Yield Response Data from the Oregon State Experiments (Continued)

Broccoli	1971	<u>Unheated</u>			
	Sept. 2		.58		
	Sept. 10		.96		
	Sept. 21		1.52		
	Oct. 5		1.79		
	Oct. 28		2.28		
		<u>Heated</u>			
	Sept. 2		1.77	67.23	1851
	Sept. 10		2.17	55.76	2079
	Sept. 21		3.43	55.69	2392
Peppers	Oct. 5		3.94	54.57	2500
	Oct. 28		4.86	53.09	2997
	1971	<u>Unheated</u>			
	Aug. 30		.22		
	Sept. 2		.34		
	Sept. 10		.45		
	Sept. 14		1.12		
	Sept. 18		1.84		
	Sept. 21		3.09		
	Sept. 26		3.92		
	Sept. 30		4.64		
	Oct. 5		5.08		
	Oct. 10		5.38		
	Oct. 19		6.32		
		<u>Heated</u>			
	Aug. 30		.43	48.84	1766
	Sept. 2		.74	54.05	1823
	Sept. 10		1.59	71.70	2051
	Sept. 14		2.58	56.59	2165
	Sept. 18		3.70	50.27	2279
	Sept. 21		5.31	41.81	2364
	Sept. 26		6.00	34.67	2506
	Sept. 30		6.12	24.18	2620
	Oct. 5		6.68	23.95	2753
	Oct. 10		7.10	24.23	2886
	Oct. 19		8.92	29.15	3126

The same cultivar was planted on June 13, 1972. A broadcast application before planting of 54 kg/ha of actual nitrogen, 67 kg/ha of P_2O_5 and 50 kg/ha of sulfur 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.

Sorghum-Sudangrass

The Mor-Su cultivar of sorghum-sudangrass hybrid was planted on May 28, 1971. Fertilization, irrigation, and heat source temperatures were identical to those discussed for sudangrass. Harvesting was on July 29 and October 7.

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. Final harvest was October 5.

Ryegrass

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, beginning in early February. The 4th cutting was May 12.

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 335 kg/ha of actual N with a sulfur-coated urea compound. The heat source temperature was maintained at 40-55°C during the growing season. Harvest dates were March 27 and April 27.

Crimson Clover

Crimson Clover was planted on September 28, 1970. A broadcast application of 448 kg/ha of ammonium sulfate was harrowed in before 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.

Fescue

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 31, 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. Last cuttings were September 8, 1971 and May 5, 1972.

Corn

The cultivar Northcoast Oregon 350, 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 harvest heat source. Petroleum mulch was applied immediately after planting in 15 cm wide bands over the rows. Grain yields shown in Table 3 are adjusted to 15.5% moisture in the shelled grain. The grain was harvested on September 25.

The field corn cultivar Northcoast Oregon 350 was grown on surface and subsurface irrigated plot. It was planted on April 17. Cultural

practices and crop history dates were the same as the other 1970 crop trials. 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 systems. Heat source temperatures were maintained below 38°C throughout the season on the sub-irrigated plot. The plot was harvested on September 15.

The cultivar Northcoast Oregon 350 was planted on April 30, 1971 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 season. 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.

The cultivar Northcoast Oregon 350 was planted on May 12, 1972 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. The grain was harvested on October 3.

The cultivar Northcoast Oregon 340 was planted on the sub-irrigation plot. During the growing season, heat, 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.

Bushbeans

The cultivar Oregon 58 was planted at a rate of 30 seeds per meter in 91 cm rows. All treatments received 114 kg/ha of 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 4. 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 16 cm band over the rows immediately after planting. Eptam was applied at the rate of 2.8 kg/ha of active material.

TABLE 4. Crop History Dates and Amount of Water Applied,
Bush Beans, 1969

Treatment	D1	Planting Dates		D4
		D2	D3	
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 29
Irrigation water applied (cm)	15.9	19.3	19.3	27.5
Precipitation	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 is presented in Table 1 for all treatments. These values representing the average of three rows, each five meters long, for planting D1 and four rows, each six meters long, for the remaining plantings.

In 1970, 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. Irrigation scheduling was based on gypsum block readings taken in both heated and unheated plots. Heat source temperature was not monitored on this plot. The crop was harvested on August 1 and September 12.

Lima Beans

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 before planting. At planting time 100 kg/ha of P_2O_5 and 35 kg/ha of K_2O were 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 3.

In 1971, the cultivar Early Thoragreen was planted on May 21, at a rate of 39 seeds per meter of row and a row spacing of 91 cm. A broadcast application of 56 Kg/ha of P_2O_5 was made before 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.

Tomatoes

In 1969, the tomato 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 before planting. During the growing season 19.5 cm of irrigation water was applied with full circle sprinklers. All tomatoes were picked on September 25 regardless of size or state of maturity of the fruit.

The cultivar Victor Cross was planted in field plots on June 2, 1970 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% response 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% 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.

The cultivar Willamette was planted on June 16, 1971 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% 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 21°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.

Broccoli

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 cm³ per plant.

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

Five cuttings were made from September 2 to October 28. Harvest areas were 22.3 and 11.2 square meters on the unheated and heated plots, respectively. The yields were 2.28 and 4.86 tons/ha for unheated and heated plots, respectively. Although quality determinations were not made, heated heads were consistently larger.

Peppers

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 cm³ 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. The total yields of 6.32 and 8.92 tons/ha for unheated and heated plots, respectively, represent a 41% response to soil heating.

Input Heat Data

The input heat data generated from the Oregon State Experiments are presented in Table 5.⁽²⁰⁾ The data consists of 59 observations collected during 2 years with 4 treatments. Twenty-three observations were recorded on plots with no cover. Seventeen observations were recorded on plots which were grass covered. The remaining 19 observations were recorded on plots of corn or which were sub-irrigated.

Inspection of the data in Table 5 reveals that the input heat units steadily decreased from February through May. Grass required fewer heat units than bare ground during months prior to July. No clear differences appear in heat units required among uncovered plots and those of grass and corn. The sub-irrigated plots required about .0071 cal/cm² min more heat than the other treatments to maintain the specified soil temperature.

TABLE 5. Recorded Rate of Heat Loss in Calories/CM²/Min, (20)
1971-72, Hyslop Soil Warming Experiments, Oregon

<u>Date</u>	<u>No Cover</u>	<u>Grass</u>	<u>Corn</u>	<u>Sub-Irrigated</u>	<u>Average by Time Period</u>
<u>1971</u>					
2/3 -2/5	.0278				
2/22-2/24	.0252	.0199			
3/19-3/22	.0255	.0183			
4/12-4/14	.0232	.0158			
4/22-4/23	.0218	.0141			
4/28-4/29	.0211	.0128			
5/10-5/11	.0185	.0102			
6/21-6/23	.0178	.0222			
7/8 -7/9	.0172	.0147	.0113	.0264	.0174
7/29-7/30	.0146	.0182		.0229	
8/23-8/25	.0149	.0131	.0136	.0215	.0158
9/1 -9/2	.0157	.0136	.0139	.0218	.0163
9/13-9/15	.0161	.0231	.0155	.0224	.0193
9/22-9/24	.0157				
Average by Plot	<u>.0196</u>	<u>.0163</u>	<u>.0136</u>	<u>.0230</u>	<u>.0172</u>
<u>1972</u>					
2/14-2/17	.0302				
3/8 -3/10	.0257				
6/17-6/19	.0160				
6/26-6/28	.0151				
7/10-7/12	.0133	.0103	.0124	.0242	.0150
7/26-7/28	.0111	.0116	.0120	.0228	.0144
8/9 -8/11	.0105	.0121	.0106	.0224	.0139
8/29-8/30	.0106	.0111	.0108	.0225	.0138
9/5 -9/6	.0111	.0137	.0115	.0218	.0145
Average by Plot	<u>.0160</u>	<u>.0118</u>	<u>.0115</u>	<u>.0227</u>	<u>.0143</u>

(20) Rykbost, K.A., L. Boersma, Soil and Air Temperature Changes Induced by Subsurface Line Heat Sources, Special Report 402, Agricultural Experiment Station, Oregon State University, Corvallis, Oregon, p. 85, 1973.

TABLE 6. Estimated Heat Loss in Calories/CM²/Month
by Month, 1971-72, Hyslop Soil Warming
Experiments, Oregon

	<u>Heat Loss Regular</u>	<u>Heat Loss Sub-Irrigated</u>
February	1008	
March	967	
April	792	
May	699	
June	590	
July	558	875
August	543	860
September	547	854
October	670	

To interpret the data for analytical purposes each observation was plotted. The input of heat resulting in the yields presented in Table 3 was pictorially represented. A trend line was drawn through the observations. The initial point of the curve plotted at $.027 \text{ cal/cm}^2 \text{ min}$, for February 1. The minimum heat input was $.012 \text{ cal/cm}^2 \text{ min}$ on August 15. The curve terminated at $.013 \text{ cal/cm}^2 \text{ min}$ for October 1. Table 6 presents the monthly integral under the curve in $\text{cal/cm}^2/\text{month}$.

Given the sample size and insufficient justification to differentiate between 1971 and 1972, this homogeneous heat input curve was utilized to calculate total input heat units as presented in Table 3. The value presented as total heat loss in Table 3 consists of the integral of the heat input curve from 10 days prior to planting to the date of harvest. Heat input was increased by $.0071 \text{ cal/cm}^2 \text{ min}$ on those plots which were subirrigated.

Parameter Estimates

The purpose of this section is to describe the data presented in Table 3 as a functional relationship. Table 3 consists of 116 observations of 11 commodities with differing fertilizer and irrigation treatment. It was necessary to normalize the yield measurements of each of the 11 commodities and then separate the variation that could be attributed to each year, level of fertilization and irrigation.

Variation in yield as a result in changes of the level of fertilizer applied was measured with the use of index values. Nutrient requirements for each commodity are known apriori. Measuring fertilizer inputs explicitly as kg/ha would disregard this apriori knowledge of specific crop requirements. For this reason the fertilizer input was measured in terms of multiple units of a base value of one. For example, when three equal incremental levels of fertilizers were used, values of 1, 2, and 3 were assigned.

A dummy or 0,1 variable was used to separate variations that resulted from sub-irrigation as compared to sprinkler irrigation. A dummy variable was also used to separate the variations resulting from the natural application of such environmental resources as rainfall, sunlight, and heat for a specific year. The response function is expressed as:

$$\frac{\partial Y}{Y} = a + b_1 X + b_2 X^2 + b_3 F + b_4 (69) + b_5 (70) + b_6 (71) + b_7 (72) + b_8 I \quad (12)$$

where

$\frac{\partial Y}{Y}$ = a normalized value for yield,

X = the total heat loss in 1,000 cal/cm²,

F = level of fertilizer,

69-72 = the years in which the observation was measured, and

I = the use of sub-irrigation.

The equation of estimation was found to be:

$$\begin{aligned} \frac{\partial Y}{Y} = & -0.0000468 - 9.127 X + 0.375X^2 + 4.77F + 28.52(69) + 24.77(70) \\ & (10.27) \quad (8.83) \quad (.964) \quad (3.09) \quad (18.56) \quad (19.15) \\ & + 56.11(71) + 59.53(72) + 6.03I \\ & (20.32) \quad (21.07) \quad (12.97) \end{aligned} \quad (13)$$

The coefficient of determination (R^2) is .44, indicating that 44% of the variation in change in yield could be explained by variation in heat and fertilizer applied, the year and irrigation. The standard deviation of the regression coefficients are presented in parentheses below the coefficients. The linear heat coefficient, the fertilizer coefficient, and the coefficients for each year were larger than the standard deviations which indicates a low level of statistical significance. Only the coefficients representing 1971 and 1972 were significant at the normally acceptable level of 5%. Equation 13 could not be accepted as a functional representation of the data presented in Table 1.

The response function was reformulated as:

$$\frac{\partial Y}{Y} = a + b_1X + b_2X^2 + b_3F + b_4(69) + b_5(70) + b_6(72) \quad (14)$$

where the variables are as previously defined. The values for b_4 , b_5 , and b_6 represent deviations from the base year of 1971. Fifty seven of the 116 observations were collected during the base years.

The second equation of estimation was found to be

$$\begin{aligned} \frac{\partial Y}{Y} = & 20.56 + 7.63X - 1.30X^2 + 6.89F - 20.69(69) - 26.86(70) + 4.57(72) \\ & (10.32) \quad (5.60) \quad (0.71) \quad (3.13) \quad (7.11) \quad (6.48) \quad (7.96) \end{aligned} \quad (15)$$

The coefficient of determination is .35 which is 9% less than that of equation 13. In equation 15 the fertilizer, 1969 and 1970 terms were statistically significant at the 5% level. The 1972 term was the only one that was non-significant at the 20% level. The lack of significance of the 1972 term is explained by the fact that of the eight observations collected during that year, four spanned the growing season of the fall of 1971 through the spring of 1972. For the analysis presented in this report, equation 15 has acceptable properties with respect to statistical significance and shape of the response surface.

In order to determine whether the energy dissipation rate as estimated from equation 10 can be substituted for the total heat loss as presented in equation 15, data sources were compared and a normalized value for yield was calculated. The heat source data used by Rykbost and Boersma to estimate equation 10 ranged from 23°C to 38°C with an annual average of 33.1°C. The average heat source temperature from February through September was 33.15°C. (25) The heat source temperature data collected during the time when the data presented in Table 5 were collected ranged from 23.9°C to 37.6°C. Thus the difference in change is less than 1°C. The average heat source temperature from February through September of 1971-72 was 32.5°C. Again, the difference is less than 1°C. The average heat dissipation rate of the data used to estimate equation 10 was .0007 cal/cm²/min. greater than comparable data used to estimate equation 15. Therefore, it is concluded that while the heat source temperature data related to equation 10 are not identical with those heat source temperature data that resulted in the estimation of equation 15, they were similar enough to continue the analysis.

A comparison of the estimated and observed values for each ΔY of equation 15 showed that the observation representing corn grown in 1971 with heating under the rows and the application of 280 kilograms of nitrogen per hectare had the smallest difference. The heat application began on April 20 and terminated on September 16 for this observation. The heat source temperature varried from 31°C to 38°C. An average heat source temperature of 34.5°C was used. The 1971 mean monthly air temperature ranged from 8.8°C to 19.7°C. The average mean monthly air temperature for the period April 20 to September 16 was 15.5°C. Using equation 10, the estimated dissipation rate was

0.0178 cal/cm²/min. The observed rate was 0.0174 cal/cm²/min. Using a value of 0.0178 to calculate the total heat loss resulted in 3819 cal/cm². Comparing this value with the observed value of 2682 as recorded in Table 1 shows an overestimation of 42%.

Using a value of 3.819 cal/cm² for X and a value of 3 for F in equation 15 results in a calculated value of 51.41. This compares with an observed value of 51.75 as presented in Table 3. It is concluded that equation 15 is an approximate representation of the response function of crops to soil warming in the Willamette Valley of Oregon.

CONCLUSION

The hypothesis could not be rejected on the basis of available agronomic data. A number of research projects have shown the response of crop yields to heat under specific agronomic and climatic conditions. Heat induced the growth of grass and legumes in Maryland. Heat advanced maturity and made double cropping possible for potatoes in Minnesota. Heat increased yields of tomatoes, sweet corn, asparagus, canteloupe and squash at Springfield, Oregon. Heat improved yields of cabbage, snap beans and sweet corn in North Carolina. Heat improved the yields of eleven crops tested in Corvallis, Oregon. In Corvallis, it was found that the incremental change in yield increased at a decreasing rate as more heat was applied or as heat was applied for a longer period of time. A maximum was reached at a total heat exchange of 5869 cal/cm² during a growing season. The economic analysis can be conducted under the premise that an optimum input of heat does exist.

CHAPTER VI
ECONOMIC ANALYSIS

ECONOMIC ANALYSIS

The profit equation presented in Section 3 of this report is restated as:

$$\pi = P_y Y - P_x X - F. C. \quad (3)$$

This Section describes the derivation of values for the terms expressed in equation (3).

AN ESTIMATE OF YIELD (Y)

The result of the analysis presented in Section 4 is equation (11). The result of the analysis presented in Section 5 is equation (15). These two equations are restated as a system of simultaneous equations.

$$X = 0.00540 D + 0.00107 D (T_s - T_a) \quad (11)$$

$$\frac{\partial Y}{Y} = 20.56 + 7.63X - 1.30X^2 + 6.89F - 20.69(69) - 26.85(70) + 4.57(72) \quad (15)$$

The initial task is to estimate the coefficients for the reduced form, which is stated as:

$$\frac{\partial Y}{Y} = f (T_s - T_a) \quad (16)$$

This was done by generating a secondary data series from equations 11 and 15 and estimating the functional form of 16.

Secondary observations of normalized yield were calculated by adjusting the appropriate value presented in column 5 of Table 3 by the coefficient of the appropriate fertilizer and year factors. The normalized yield was increased by 20.69 for 1969, 26.86 for 1970, and decreased by 4.57 for 1970. Estimates representing the lowest level of fertilizer application were decreased by 6.89. Other estimates were decreased by 6.89 times the

relative quantity of fertilizer applied.

The values of the independent variable were calculated on the basis of a transformation of equation 11, which is stated as:

$$T_s - T_a = \frac{X - 5.4 D}{1.07 D} \quad (17)$$

where

T_s is the heat source temperature,

T_a is the mean monthly air temperature,

X is the total number of calories per square centimeter applied during the growing season, and

D is the number of days heated.

The secondary observations are presented in Table 7.

To interpret the data presented in Table 7 as a functional relationship, six functional forms were used. These are presented below. The standard error of the regression coefficient is presented in parentheses below the coefficient. The coefficient of determination (R^2) is presented below the equation.

$$\frac{\partial Y}{Y} = 2.25 (T_s - T_a) \quad (18)$$

(0.15)

$$R^2 = 0$$

$$\frac{\partial Y}{Y} = 21.39 + 0.86 (T_s - T_a) \quad (19)$$

(6.62) (0.45)

$$R^2 = .06$$

$$\frac{\partial Y}{Y} = 4.21 (T_s - T_a) - 0.12 (T_s - T_a)^2 \quad (20)$$

(0.57) (0.03)

$$R^2 = .08$$

$$\frac{\partial Y}{Y} = 1.94 (T_s - T_a)^{.55} \quad (21)$$

(.53) (.20)

$$R^2 = .11$$

TABLE 7 Secondary Observations of the Normalized Response of Crops to Heat

<u>Commodity</u>	<u>Year</u>	<u>Adjusted Normalized Yield</u>	<u>Days</u>	<u>T_s-T_a</u>
Sundangrass	1971	21.33	142	12.6
	1972	32.70	124	12.1
Sorghum-Sudangrass	1971	25.30	142	12.6
	1972	24.80	124	12.1
Ryegrass	1970-71	8.03	238	6.8
	1971-72	68.80	182	7.8
		42.45	182	8.8
		15.77	182	8.8
Crimson Clover	1971	32.36	236	7.0
Fescue	1971-72	4.25	612	7.5
Corn	1969	38.80	146	12.9
	1970	36.01	161	13.9
		34.85	161	13.9
		26.17	161	13.9
		21.80	161	18.5
		38.07	161	18.5
	1971	44.03	149	11.8
		22.72	149	11.8
		44.86	149	11.8
		43.11	149	11.8
		22.54	149	11.8
		29.01	149	11.8
	1972	6.27	154	12.9
		20.87	154	18.6
Bushbeans	1969	37.43	80	13.6
		16.43	77	13.1
		32.10	65	14.5
		35.32	87	11.9
		26.38	80	13.7
		10.09	77	13.1
		21.19	65	14.5
		40.65	87	11.9

TABLE 7 - Continued

<u>Commodity</u>	<u>Year</u>	<u>Adjusted Normalized Yield</u>	<u>Days</u>	<u>T_s-T_a</u>
Bushbeans	1970	42.67	72	13.1
		68.28	72	13.1
		68.65	72	13.1
		74.52	81	11.7
		19.50	81	11.7
		29.69	81	11.7
Lima Beans	1969	29.32	183	6.0
		23.06	183	6.8
	1971	15.35	205	6.5
		26.31	205	6.5
		9.89	205	6.5
		47.13	116	12.1
		40.97	127	12.3
		16.49	144	12.6
Broccoli	1971	60.34	67	18.6
		48.87	75	20.9
		48.88	86	20.9
		48.68	100	18.3
		46.20	123	17.7
Peppers	1971	41.95	64	20.7
		47.16	67	20.3
		64.81	75	20.5
		49.70	79	20.5
		43.38	83	20.6
		34.92	86	20.6
		27.78	91	20.7
		17.29	95	20.7
		17.06	100	20.7
		17.34	105	20.6
		22.26	114	20.6

$$\frac{\partial Y}{Y} = 41.89 - 0.08 D + 0.15 (T_s - T_a) \quad (22)$$

$$(9.87) \quad (0.03) \quad (0.50)$$

$$R^2 = .16$$

$$\frac{\partial Y}{Y} = 34.88 - 0.08 D + 1.12 (T_s - T_a) - 0.03 (T_s - T_a)^2 \quad (23)$$

$$(24.69) \quad (.03) \quad (3.16) \quad (0.10)$$

$$R = .16$$

The first criteria of rejection was the statistical significance of the regression coefficients. Equations were rejected if the coefficients were non-significant at the 5% level. This criteria resulted in the rejection of equations 19, 22, and 23.

The second criteria of rejection was the statistical significance of the coefficient of determination. Equations were rejected if the coefficient of determination was non-significant at the 5% level. This criteria resulted in the rejection of equation (18).

Equation (20) was chosen over (21) to best interpret the response of agricultural commodities to a differential heat source because of the property of describing a maximum. Empirical evidence shown in Table 1 for squash and in Table 2 for snap beans indicates a biological maximum yield with the application of heat. Since this maximum cannot be demonstrated in equation (21), it was rejected. The equation of estimation to best describe the response of crop yield is restated as:

$$\frac{\partial Y}{Y} = 4.21 (T_s - T_a) - 0.12 (T_s - T_a)^2 \quad (20)$$

DETERMINATION OF PRODUCT PRICE (P_y)

Product price varies among commodities and over time. Table 8 presents the average price for 10 commodities over the period 1972-74. The ten commodities were chosen on the basis of positive response to the application of heat as presented in Chapter IV and the availability of statistical price series for the United States. ⁽²⁶⁾

PRICE OF GEOTHERMAL HEAT (P_x)

Schmisser calculated the cost of applying heat to the soil to be \$371.64 per acre per year. The total initial investment and installation cost of a 125 acre open field soil warming system was \$3,325.22, as presented in Table 9. The annual cost is \$343.03 per acre, as presented in Table 10. An additional \$28.61 was included for maintenance, tax, and insurance, as presented in Table 11. ⁽²⁷⁾

There are expected to be additional costs of piping geothermal heat to the field. However, these are expected to be site specific and not available to this research effort.

QUANTITY OF HEAT (X)

If sufficient information were available to determine the cost of heat on the basis of price and quantity used, the quantity of heat applied could be determined from the response function, the product price, and the price of heat. Cost of heat is treated as the fixed cost of applying the heat. Therefore, quantity of heat is determined from the response function.

Referring to equation (20), normalized yield increases as the difference between the atmospheric and source temperature increase to 17.5°C. It then decreases to zero at 35°C. Since normalized yield is the change in yield divided by the yield increase, and the price of heat is assumed to be the cost of the system, if it is feasible to use heat at 17.5°C, it would also be feasible to use heat at 35°C. For purposes of determining economic

TABLE 8: Gross Returns of Ten Commodities, in Dollars
Per 100 Pounds, for 1972-74 (28)

<u>Commodity</u>	<u>Yield in 100 lbs/acre</u>	<u>Price in \$/100 lbs(1)</u>	<u>Gross Return \$/Acre</u>
Potatoes	237.33	4.09	970.68
Tomatoes	145	16.03	2,324.35
Sweet Corn	76	6.95	528.20
Asparagus	23	26.03	598.69
Cabbage	202	4.81	971.62
Snap Beans	35.33	17.03	601.67
Sweet Potatoes	110.67	7.00	774.69
Lima Beans	24.53	12.18	297.55
Broccoli	73	12.30	897.90
Peppers	99.33	13.77	1,367.77
<hr/>			
Average	102.63	12.01	1,232.59

(28) Agricultural Statistics, 1975, U. S. Department of Agriculture,
Washington, D. C., 1975.

TABLE 9 Initial Investment and Installation
Cost of a 125 Acre Open Field Soil Warming
System, 1973 Costs (27, 29)

Item	Quantity	Cost
Schedule-40 PVC pipe, 2 inch diameter <u>a/</u>	907,500 feet	\$371,625.00
Steel pipe, 10 gauge, about 33 inch diameter <u>b/</u>	5,415 feet	75,269.00
Steel pipe, 10 gauge, about 24 inch diameter <u>c/</u>	660 feet	7,557.00
Steel pipe, 10 gauge, about 17 inch diameter <u>d/</u>	660 feet	6,171.00
Outlet connections <u>e/</u>	440	5,280.00
Motors and related pumps, controls, starters and wiring	80 hp	3,750.00
Total Cost		\$415,652.00
Approximate Capital Investment Per Acre		\$ 3,325.22

a/ PVC pipe costs about \$0.250 per foot and it costs \$0.100 per foot to trench, glue, and pull.

b/ Installation costs are about \$4.50 per foot. The pipe costs about \$9.40 per foot.

c/ Installation costs are about \$4.25 per foot. The pipe costs about \$7.20 per foot.

d/ Installation costs are about \$4.35 per foot. The pipe costs about \$5.00 per foot.

e/ Installation and material costs are about \$12.00 per connection.

(27) Schmisser, W.E., et al, A Systems Analysis of the Economic Utilization of Warm Water Discharge from Power Generating Stations, Engineering Experiment Station, Oregon State University, Corvallis, Oregon, 1974. p. 213.

TABLE 10. Average Capital Outlays and Annual Capital Costs
Per Acre of a Commercial Scale Soil Warming System, 1973⁽²⁷⁾ costs

	<u>Expected Life (Years)</u>	<u>Investment and Installation Cost</u>	<u>Annual Capital Cost At 10% Interest</u>
Schedule-40 PVC pipe, 2" diameter	50	\$2,541.00	\$256.39
Steel pipe, 10 gauge, about 33" diameter	25	602.15	66.36
Steel pipe, 10 gauge, about 24" diameter	25	60.46	6.66
Steel pipe, 10 gauge, about 17" diameter	25	49.37	5.44
Outlet connections about 3.5/acre	25	42.24	4.65
Pumps, controls, starters, and wiring, about .64 hp per acre	20	30.00	3.53
TOTAL CAPITAL OUTLAY/ACRE		<u>\$3,325.22</u>	
ANNUAL AMORTIZED COSTS			<u>\$343.03</u>

(27) Schmisser, W. E., et al., A Systems Analysis of the Economic Utilization of Warm Water Discharge from Power Generating Stations, Engineering Experiment Station, Oregon State University, Corvallis, Oregon, 1974, p. 212.

TABLE 11 Annual Maintenance, Tax, and Insurance
Costs Per Acre of a Commercial Scale
Soil Warming System, 1973 (27)

Item	Annual Costs at 10% Material (a)
Maintenance	\$1.73
Taxes and Insurance ^(b)	26.88
Total Annual Costs	<u>\$ 28.61</u>

-
- a. Opportunity cost charges are based on one-half of the average annual maintenance, tax, and insurance cost.
- b. Taxes are based on the average taxable value of the soil warming system times a tax rate of \$22 per \$1,000 taxable value.
-

(27) Schmisser, W.E., et.al., A Systems Analysis of the Economic Utilization of Warm Water Discharge from Power Generating Stations, Engineering Experiment Station, Oregon State University, Corvallis, Oregon, 1974.

feasibility, a value of 17.5°C is used to determine initial economic feasibility.

Assuming a difference between source and atmospheric temperature of 17.5°C, the procedures described in equation 4-8 were applied.

Restating equation (5),

$$\frac{\partial Y}{Y} \frac{X}{\partial X} = \frac{P_X X}{P_Y Y} \quad (5)$$

and presenting it in terms specified in the previous sections,

$$\frac{4.21 (T_s - T_a) - 0.12 (T_s - T_a)^2}{100} \frac{(T_s - T_a)}{1} = \frac{371.64 (T_s - T_a)}{P_Y Y} \quad (24)$$

which can be reduced to

$$P_Y Y = \frac{37,164}{4.21 (T_s - T_a) - 0.12 (T_s - T_a)^2} \quad (25)$$

Using the value of 17.5°C as the difference between the atmospheric and source temperature, the gross return would have to be \$1,006 per acre for an enterprise to feasibly use geothermal heat. Referring to Table 8, the hypothesis is rejected for all enterprises except tomatoes and peppers.

FIXED COSTS OF TOMATO PRODUCTION (FC)

Cost data for tomatoes were collected in Contra Costa, San Joaquin, and Stanislaus Counties of California. The total cost of producing an acre of bin harvested tomatoes in 1974 was \$1,091.37. This value is assumed to be the fixed cost of production. (26)

AN EMPIRICAL PROFIT EQUATION

Equation (3) is transformed into an empirical profit equation with the inclusion of those values previously described. In addition, it is necessary to transform the available equations to specific equations for tomatoes. In chapter V, the data were normalized according to equation (26):

$$\frac{\partial Y}{Y} = \frac{Y_1 - Y_0}{Y_1} 100 \quad (26)$$

where

Y_0 represents yield from unheated plots and

Y_1 represents yield from heated plots.

Equation (20) is restated as:

$$\frac{\partial Y}{Y} = 4.21 (T_s - T_a) - 0.12 (T_s - T_a)^2 \quad (20)$$

thus

$$\frac{Y_1 - Y_0}{Y_1} 100 = 4.21 (T_s - T_a) - 0.12 (T_s - T_a)^2 \quad (27)$$

which is reduced to

$$Y_1 = \frac{100 Y_0}{100 - 4.21 (T_s - T_a) + .12 (T_s - T_a)^2} \quad (28)$$

Drawing on the data in Table 8, the yield equation for tomatoes is:

$$Y_T = \frac{14500}{100 - 4.21 (T_s - T_a) + .12 (T_s - T_a)^2} \quad (29)$$

The empirical profit equation can be written as:

$$\pi = P_{Y_T} \left[\frac{14500}{100 - 4.21 (T_x - T_a) + .12 (T_s - T_a)^2} \right] - \$371.64 - \$1,091.37 \quad (30)$$

where

P_{YT} is \$16.03 and

$T_s - T_a$ is 17.5°C

profit or the return to geothermal energy is \$2,222.05.

CONCLUSIONS

The hypothesis tested in this research is that it is technically and economically feasible to utilize geothermal energy in the cultural practice of soil warming for specific crops. This hypothesis could not be rejected. On the basis of the analysis presented, it is estimated that the value of geothermal energy to the production of tomatoes is \$2,222.05.

The response function was estimated on the basis of eleven crops grown over four years with several cultural practices. This response function was used to generate secondary data for the estimation of a reduced form. The reduced form was then transformed into a response function for tomatoes. Costs and prices for tomatoes were used to estimate the return to geothermal energy. The result is that the economic analysis was conducted on the basis of technical coefficients that were considerably removed from the actual cultural practices. Because of data limitations, this research must be considered as an initial feasibility analysis of the use of geothermal energy in agriculture. Because of the estimated value of geothermal energy resulting from the procedures that have been followed, it is recommended that further research be carried out at a specific site with the measurement of specific resources.

REFERENCES

REFERENCES

1. Koenig, J.B., "Worldwide Status of Geothermal Resource Development." Multipurpose Use of Geothermal Energy, Oregon Institute of Technology, Klamath Falls, Oregon, 1974, pp. 35-43.
2. Wehlage, Edward F., "Geothermal Energy's Potential for Heating and Cooling in Food Processing" and Linton, A.M., "Innovative Geothermal Uses in Agriculture," Multipurpose Use of Geothermal Energy, Oregon Institute of Technology, Klamath Falls, Oregon, 1974, pp. 101-120.
3. Barton, C.C., "Agricultural Applications of Geothermal Energy", Present Status and Future Prospects for Nonelectrical Uses of Geothermal Resources, NATO CCMS Report No. 40, UCRL-51926, Lawrence Livermore Laboratory, University of California, Livermore, California, 1975, pp. 58-64.
4. Bakker-Arkema, F.W. et al. Waste Heat Utilization from Power Plants in Agriculture, Agricultural Engineering Department, Michigan State University, East Lansing, Michigan, 1975.
5. See the bibliography for a list of publications which describe these seven uses.
6. Johns, R. W., et. al., Agricultural Alternatives for Utilizing Off-Peak Electrical Energy and Cooling Water, Department of Agricultural Economics, Washington State University, Pullman, WA., 1971.
7. Cone, B. W., et. al., A Techno-Economic Analysis of the Potential Market for Hydroponic Produce in the Pacific Northwest, Battelle, Pacific Northwest Laboratories, Richland, WA. 1974.
8. Bowen, Richard G., "Environmental Impact of Geothermal Development," Multipurpose Use of Geothermal Energy, Oregon Institute of Technology, Klamath Falls, Oregon, 1974, p. 212.
9. White, D.E., "Characteristics of Geothermal Resources," Geothermal Energy - Resources, Production, Stimulation, Stanford University Press, Stanford, California, 1973, p. 88
10. Bloomster, C. H., et. al., Geocost: A Computer Program for Geothermal Cost Analysis, Battelle, Richland, WA., 1975.

11. Heady, E.O. and J.L. Dillon, Agricultural Production Functions. Iowa State University Press, Ames, Iowa, 1972.
12. Dillon, J.L., The Analysis of Response in Crops and Livestock Production. Pergamon Press, Oxford, 1968.
13. Heady, E.O. and L.G. Tweeter, Resource Demand and Structure of the Agricultural Industry, Iowa State University Press, Ames, Iowa, 1963.
14. Kendrick, J. H. and J. A. Havens, "Heat Transfer Models for a Subsurface, Water Pipe, Soil-Warming System", Journal of Environmental Quality, 2:188-197, 1973.
15. De Vries, D. A., "Thermal Properties of Soils", in W. R. Van Wijk (ed.), Physics of Plant Environment, North Holland Publishing Company, Amsterdam, p. 210-235, 1966.
16. Smith, W. O. and H. G. Byers, "The Thermal Conductivity of Dry Soils of Certain of the Great Soil Groups", Soil Science Society of American Proceedings, 3:13-19, 1938.
17. Nakshabandi, G. A. and H. Kohnke, "Thermal Conductivity and Diffusivity of Soils as Related to Moisture Tension and Other Physical Properties", Agricultural Meteorology, 2:271-279, 1965.
18. Van Wijk, W. R. and D. A. De Vries, "Periodic Temperature Variations in a Homogeneous Soil", in W. R. Van Wijk (ed.), Physics of Plant Environment, 2nd edition, North-Holland Publishing Company, Amsterdam, p. 102-143. 1966.
19. Schmill, J. V., "Variable Soil Thermal Resistivity-Steady State Analysis", IEEE Trans., PAS 86(2):215-223. 1967.
20. Rykbost, K. A. and L. Boersma, Soil and Air Temperature Changes Induced by Subsurface Lime Heat Sources, Agricultural Experiment Station, Oregon State University, Corvallis, Oregon, Special Report #402, December 1973.
21. Decker, A.M., Plant Environment Studies with Controlled Soil Temperature Field Plots, Paper No. 4, Department of Agronomy, Maryland Agricultural Experiment Station, College Park, Md.
22. Allred, E. R., P. E. Pead, J. R. Gilley, Use of Waste Heat for Soil Warming and Irrigation in Northern Climates, Proceedings of the ASCE Irrigation and Drainage Division Specialty Conference, Logan, Utah, August, 1975.
23. Berry, James W. and Herman H. Miller, Jr., A Demonstration of Thermal Water Utilization in Agriculture, EPA - 600/2 - 74 - 011, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D. C., April, 1974.
24. Skaggs, R. W., D. C. Sanders, and C. R. Willey, An Evaluation of the Use of Waste Heat for Soil Warming in the Southeast, Water Resources Research Institute, University of North Carolina, Raleigh, North Carolina, 1975.

25. Rykbost, K.A., L. Boersma, H. J. Mack, and W.E. Schmisser, Crop Response to Warming Soils above their Natural Temperature, Agricultural Experiment Station, Oregon State University, Corvallis, Oregon, Special Report #385, pp. 15-72, January 1974.
26. Sandborn, Ross, et. al., Sample Costs of Tomato Production in Contra Costa, San Joaquin and Stanislaus Counties, Agricultural Extension Service, University of California, Davis, California, October, 1974.
27. Schmisser, W. E., et al., A Systems Analysis of the Economic Utilization of Warm Water Discharge from Power Generating Stations, Engineering Experiment Station, Oregon State University, Corvallis, Oregon, 1974, p. 212.
28. Agricultural Statistics, 1975, U.S. Department of Agriculture, Washington, D.C., 1975.
29. Personal communications with Lorin R. Davis and Marvin N. Shearer, Associate Professor of Mechanical & Nuclear Engineering and Extension Irrigation Specialist, respectively, Oregon State University, and de Winter, Francis, "Underground Heating Tubes in Agriculture: Copper versus Polyethylene," a report submitted to Copper Development Association, Inc., New York, New York.

BIBLIOGRAPHY

BIBLIOGRAPHY

Agricultural Statistics, 1975, U.S. Department of Agriculture, Washington, D. C., 1975.

Allred, Evan R., "Use of Waste Heat for Soil Warming and Irrigation," Proceedings of the ASCE Irrigation and Drainage Division Speciality Conference, Logan, Utah, August 13-15, 1975.

Allred, E. R., P. E. Read, and J. R. Gilley, "Use of Waste Heat for Soil Warming and Irrigation in Northern Climates," paper no. 73-2544, Presented at the 1973 Winter Meeting of the American Society of Agricultural Engineers, Conrad Hilton, Chicago, IL, December 11-14, 1973.

Allred, E.R., P. E. Read, and J. R. Gilley, "Use of Waste Heat for Soil Warming and Irrigation in Northern Climates," Proceedings of the ASCE Irrigation and Drainage Division Specialty Conference, Logan, UT, August 1975.

Ashley, G. C., R. V. Stansfield, A. M. Flikke, and L. L. Boyd, "Design and Operating Experience of a Research Greenhouse Heated and Cooled with Warm Water".

Bakker-Arkema, F. W., et. al., "Waste Heat Utilization From Power Plants in Agriculture I - Introduction", for presentation at the 1975 Winter Meeting American Society of Agricultural Engineers, Chicago, Illinois, December 15-18, 1975.

Barton, C.C., "Agricultural Applications of Geothermal Energy", Present Status and Future Prospects for Nonelectrical Uses of Geothermal Resources, NATO CCMS Report No. 40, UCRL-51926, Lawrence Livermore Laboratory, University of California, Livermore, California, 1975, pp. 58-64.

Berry, James W. and Herman H. Miller, "A Demonstration of Thermal Water Utilization in Agriculture", EPA-660/2-74-011, Grant S802032, Project Element 1BB392, Thermal Pollution Branch, Pacific Northwest Environmental Research Laboratory, National Environmental Research Center, Corvallis, Oregon, prepared for the Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., April 1974.

Bloomster, C. H., et. al., Geocost: A Computer Program for Geothermal Cost Analysis, Battelle, Richland, WA., 1975.

BIBLIOGRAPHY (Continued)

Boersma, L., et. al., A Systems Analysis of the Economic Utilization of Warm Water Discharge from Power Generating Stations, Final Report, sponsored by Portland General Electric Company, Pacific Power and Light Co., and the Boeing Company, Bulletin No. 48, Engineering Experiment Station, Oregon State University, Corvallis, Oregon, November 1974.

Bond, B. J., W. K. Furlong, L. D. King, C. E. Madewell, and J. B. Martin, "Progress Report: Using Power Plant Discharge Water in Greenhouse Vegetable Production", sponsored by the TVA's Division of Agricultural Development, Office of Power, and by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

Bond, B. J., C. E. Madewell, J. B. Martin, Jr., and D. A. Mays, "TVA Projects--Beneficial Uses of Waste Heat", paper presented at the National Conference on Complete Wateruse, Washington, D. C., April 23-27, 1973.

Bowen, Richard G., "Environmental Impact of Geothermal Development," Multipurpose Use of Geothermal Energy, Oregon Institute of Technology, Klamath Falls, Oregon, 1974, p. 212.

Bruns, W. A., R. M. Peart, and J. E. Newman, "Simulation of the Field Dry-Down Rate of Corn", for presentation at the 1975 Annual Meeting of American Society of Agricultural Engineers, University of California, Davis, California, June 22-25, 1975.

Cone, B. W., et. al., A Techno-Economic Analysis of the Potential Market for Hydroponic Produce in the Pacific Northwest, Battelle, Richland, WA. 1974.

"Crop Response to Warming Soils above their Natural Temperatures", Special Report 385, Agricultural Experiment Station, Oregon State University, Corvallis, Oregon, January 1974.

Decker, A. Morris, "Plant Responses to Modified Field Soil Temperatures", University of Maryland, College Park, Maryland.

Decker, A.M., Plant Environment Studies with Controlled Soil Temperature Field Plots, Paper No. 4, Department of Agronomy, Maryland Agricultural Experiment Station, College Park, Md.

De Vries, D. A., "Thermal Properties of Soils", in W. R. Van Wijk (ed.), Physics of Plant Environment, North Holland Publishing Company, Amsterdam, p. 210-235, 1966.

Dillon, John L., The Analysis of Response in Crops and Livestock Production, Pergamon Press, Oxford, 1968.

BIBLIOGRAPHY (Continued)

Divine, T. E. and T. F. Demmitt, "Agro-Industrial Utilization of Reject Heat and Water", Paper No. 74-6520, for presentation at the 1974 winter meeting of American Society of Agricultural Engineers, Chicago, Illinois December 10-13, 1974.

Falkenberry, H. L., "Beneficial Uses of Waste Heat - General", USTVA Knoxville, TN, June 1974.

Fazzolare, R. A., and R. A. Sierka, "Feasibility Study of a Nuclear Power-Sewage Treatment System for the Conservation and Reclamation of Water Resources", University of Arizona, Tucson, Arizona, (for the U.S. Department of the Interior, Office of Water Resources Res.), June 1974.

Fields, M., "Waste Heat Utilization in Wastewater Treatment", for U.S. Environmental Protection Agency, Office of Research and Development, URS Systems Corporation, San Mateo, CA., June 1974.

Furlong, W. K. and L. D. King, "Beneficial Uses of Waste Heat - Status of Research and Development in the USA", for presentation at a joint US/USSR meeting on Heat Rejection Systems, Washington, D.C., June 17-19, 1974.

Gaucher, T. A., "Potential for Aquiculture", (Chapter 4) reprint from EBdiv report U413-68-016 to Connecticut Research Commission, Contract RSA-66-8, entitled "Study of Means to Revitalize the Connecticut Fisheries Industry", January 1968.

Heady, Earl O. and John L. Dillon, Agricultural Production Functions, Iowa State University Press, Ames, Iowa, 1972.

Heady, Earl O. and Luther G. Tweeter, Resource Demand and Structure of the Agricultural Industry, Iowa State University Press, Ames, Iowa, 1963.

Johns, R. W., et. al., Agricultural Alternatives for Utilizing Off-Peak Electrical Energy and Cooling Water, Department of Agricultural Economics, Washington State University, Pullman, WA., 1971.

Kendrick, J. H. and J. A. Havens, "Heat Transfer Models for a Subsurface, Water Pipe, Soil-Warming System", Journal of Environmental Quality, 2:188-197, 1973.

Koenig, James B., "Worldwide Status of Geothermal Resource Development," Multipurpose Use of Geothermal Energy, Oregon Institute of Technology, Klamath Falls, Oregon, 1974, pp. 35-43.

BIBLIOGRAPHY (Continued)

Leerskov, R. E. and W. E. McCune, "Greenhouse Heating with Power Plant Condenser Water", Paper No. 73-3528, for presentation at the 1973 winter meeting of the American Society of Agricultural Engineers, Conrad Hilton, Chicago, Illinois, December 11-14, 1973.

McKinney, B. G., "Beneficial Uses of Waste Heat - General", USTVA, Chattanooga, TN. June 1974.

McKinney, B. G., and L. B. Goss, "Beneficial Uses of Waste Heat - Muscle Shoals Greenhouse", USTVA, Office of Power, Knoxville, TN, June 1975.

Meekhof, R. L., and L. J. Connor, "Economics of Waste Heat Utilization from Power Plants in Agriculture and Aquaculture", Department of Agricultural Economics, Michigan State University, presented at the 1975 Winter Meeting of American Society of Agricultural Engineers, Chicago, Illinois, December 15-18, 1975.

Morey, R. Vance, Robert M. Peart, and Douglas L. Deason, "A Corn-Growth Harvesting and Handling Simulator", Transactions of the ASAE, Vol. 14, No. 2, pp. 326-238, St. Joseph, Michigan, 1971.

Nakshabandi, G. A. and H. Kohnke, "Thermal Conductivity and Diffusivity of Soils as Related to Moisture Tension and Other Physical Properties", Agricultural Meteorology, 2:271-279, 1965.

Peart, Robert M. and Ray M. Lien, "Grain Dryer Energy Requirements", Number 75-3019, presented at the 1975 Annual Meeting of American Society of Agricultural Engineers, University of California, Davis, CA, June 22-25, 1975.

Peart, R. M. "Simulation of Crop-Environment Interactions", Agricultural Experiment Station, Purdue University, W. Lafayette, IN.

"'Power Plant' Fish Production: From the United States to New Zealand - The Use of Waste Heat Shows Promise", The Commercial Fish Farmer, Vol. 1, No. 1, pp. 10-13, Little Rock, AR, September/October, 1974.

Price, D. R., "Utilization of Electric Energy in Agriculture", State University of New York, School of Agriculture, Ithaca, New York.

Price, D. R. "Waste Heat Utilization in Agriculture", 32nd Annual Progress Report, Submitted to the Executive Committee New York Farm Electrification Council, State University of New York, Ithaca, New York, pp. 20-25, May 22, 1975.

Price, D. R., W. W. Gunke. and G. L. Casler, "Accounting of Energy Inputs for Agricultural Production in New York State", 32nd Annual Progress Report, Submitted to the Executive Committee New York Farm Electrification Council, State University of New York, Ithaca, New York, pp. 26-40, May 22, 1975.

Price, D. R. and R. M. Peart, "Simulation Model to Study the Utilization of Waste Heat Using a Combination Multiple Reservoir and Greenhouse Complex", Journal of Environmental Quality, Vol. 2, No. 2, Madison, WI, pp. 216-224, April-June, 1973.

BIBLIOGRAPHY (Continued)

Raney, F. C. and Yoshiaki Mihara, "Water and Soil Temperature". Irrigation Management, pp. 1024-1036.

Rochow, J. J. and R. Hall, "Waste Heat Utilization from Power Plants in Agriculture - Industrial Viewpoint", No. 75-3527, presented at the 1975 Winter Meeting of American Society of Agricultural Engineers, Chicago, IL, December 15-18, 1975.

Rykbost, K. A. and L. Boersma, Soil and Air Temperature Changes Induced by Subsurface Line Heat Sources, Agricultural Experiment Station, Oregon State University, Corvallis. Oregon, Special Report #402, December 1973.

Rykbost, K. A., L. Boersma, and G. D. Jarman, "Soil Temperature Increases Induced by Subsurface Line Heat Sources", Agronomy Journal, Vol. 68, January-February, 1976.

Rykbost, K. A., L. Boersma, H. J. Mack, and W. E. Schmisser, Crop Response to Warming Soils above their Natural Temperature, Agricultural Experiment Station, Oregon State University, Corvallis, Oregon, Special Report #385, pp. 15-72, January 1974.

Rykbost, K. A., L. Boersma, H. J. Mack, and W. E. Schmisser, "Yield Response to Soil Warming: Agronomic Crops", Oregon Agricultural Experiment Station, Corvallis, Oregon.

Rykbost, K. A., L. Boersma, H. J. Mack, and W. E. Schmisser, "Yield Response to Soil Warming: Vegetable Crops", Oregon Agricultural Experiment Station, Corvallis, Oregon.

Sandborn, Ross, et. al., Sample Costs of Tomato Production in Contra Costa, San Joaquin and Stanislaus Counties, Agricultural Extension Service, University of California, Davis, California, October, 1974.

Sanders, D. C., and R. W. Skaggs, "Crop and Soil Temperature Response to Soil Warming in the Southeast", No. 75-3541, presented at the 1975 Winter Meeting of the American Society of Agricultural Engineers, Chicago, IL, December 15-18, 1975.

Schisler, I. P. and F. W. Bakker-Arkema, "Waste Heat Utilization from Power Plants in Agriculture I - Soil Warming and Crop Growth", presented at the 1975 Winter Meeting of the American Society of Agricultural Engineers, Chicago, IL, December 15-18, 1975.

Schmill, J. V., "Variable Soil Thermal Resistivity-Steady State Analysis", IEEE Trans., PAS 86(2):215-223. 1967.

BIBLIOGRAPHY (Continued)

Schmisser, W. E., et al., A Systems Analysis of the Economic Utilization of Warm Water Discharge from Power Generating Stations, Engineering Experiment Station, Oregon State University, Corvallis, Oregon, 1974, p. 212.

Schmisser, W. E., L. Boersma, and K. A. Rykbost, "Yield Response to Soil Warming: Economic Feasibility", Oregon Agricultural Experiment Station, Oregon State University, Corvallis, Oregon.

Schultink, V. M. and G. Merva, "Waste Heat Utilization from Power Plants in Agriculture VII - Water Transport", No. 75-3532, presented at the 1975 Winter Meeting of the American Society of Agricultural Engineers, Chicago, IL, December 15-18, 1975.

Sierka, Raymond A. and Rocco A. Fazzolare, "The Use of Power Plant Heat in a Physical-Chemical Domestic Wastewater Renovation System", presented at the National Conference on Complete Water Reuse, Washington, D. C., April 23-27, 1973.

Skaggs, R. W., D. C. Sanders, and C. R. Willey, "An Evaluation of the Use of Waste Heat for Soil Warming in the Southeast", Water Resources Research Institute of the University of North Carolina, March 1975.

Smith, W. O. and H. G. Byers, "The Thermal Conductivity of Dry Soils of Certain of the Great Soil Groups", Soil Science Society of American Proceedings, 3:13-19, 1938.

"Soil and Air Temperature Changes Induced by Subsurface Line Heat Sources", Special Report 402, Agricultural Experiment Station, Oregon State University, Corvallis, OR, December 1973.

"Utilization of Waste Heat from Power Plants for Aquaculture: Gallatin Catfish Project - 1973 Annual Report", Tennessee Valley Authority Power Research Staff.

Valliant, James and T. C. Longnecker, "Micro-Climate Evaluation of Heating Irrigation Water on Cotton and the Resulting Effect on Cotton Yield and Quality", Report No. 284, Proceedings of Sixth Annual Symposium, NGPA-NLPGA, pp. 40-41, January 1969.

VanKuiken, Jack C. and Ramamohan L. Tummala, "Utilization of Waste Heat from Power Plants in Agriculture: IV, Systems Analysis", paper no. 75-3529, presented at the 1975 Winter Meeting of the American Society of Agricultural Engineers, Chicago, IL, December 15-18, 1975.

Van Wijk, W. R. and D. A. De Vries, "Periodic Temperature Variations in a Homogeneous Soil", in W. R. Van Wijk (ed.), Physics of Plant Environment, 2nd edition, North-Holland Publishing Company, Amsterdam, p. 102-143. 1966.

BIBLIOGRAPHY (Continued)

Walker, L. P. and F. W. Bakker-Arkema, "Pond Warming and Fish Culture", paper no. 75-3531, presented at the 1975 Annual Meeting of the American Society of Agricultural Engineers, Chicago, IL, December 15-18, 1975.

Wehlage, Edward F., "Geothermal Energy's Potential for Heating and Cooling in Food Processing" and Linton, A. M., "Innovative Geothermal Uses in Agriculture, Multipurpose Use of Geothermal Energy, Oregon Institute of Technology, Klamath Falls, Oregon, 1974, pp. 101-120.

Whittlesey, Norman K. and George Pfeiffer, "Energy Used for Food Processing in Washington", College of Agriculture Research Center, Washington State University, Circular 575, Pullman, WA, August 1974.

Wierenga, P. J. and Robert M. Hagan, "Effects of Irrigation on Soil and Crop", California Agriculture, Vol. 20, No. 9, pp. 14-16, September 1966.

D I S T R I B U T I O N

PNL-2568
UC-66i

No. of
Copies

No. of
Copies

OFFSITE

1 DOE Chicago Patent Group
Department of Energy
Argonne, IL. 60439
A. A. Churm

15 Division of Energy Technology
Department of Energy
Washington, D.C. 20545
Inja Paik

27 DOE Technical Information Center

2 Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304
Phil LaMori
Vasel Roberts

3 EG&G Idaho, Inc.
Idaho National Laboratory
Idaho Falls, ID 83401
W. P. Jensen
R. C. Schmitt
S. G. Spenser

1 Japan Geothermal Energy Association
Yurakucho Denki Bldg.
1-7-1 Yuraku-Cho Chiyoda-Ku
Tokyo, Japan

3 Oregon State University
Corvallis, OR 97331
L. Boersma
W. E. Schmissuer
K. A. Rykbost

1 Office of Research and Development
U.S. Environmental Protection Agency
Washington, D.C. 20545

3 Water Resource Research Institute
University of North Carolina
Raleigh, NC
R. W. Skaggs
D. C. Sanders
C. R. Willey

1 Department of Agronomy
Maryland Agricultural Experiment
Station
College Park, MD
A. M. Decker

3 Department of Agronomy
University of Minnesota
Minneapolis, MN
E. R. Allred
P. E. Pead
J. R. Gilley

2 Thermal Pollution Branch
Pacific Northwest Environmental
Research Laboratory
National Environmental Research
Center
Corvallis, OR
J. W. Berry
H. H. Miller

ONSITE

1 DOE Richland Operations Office
Programs Division
H. E. Ransom

84 Battelle-Northwest
C. H. Bloomster (20)
A. T. Brix
J. B. Burnham
N. E. Carter
B. W. Cone (40)
T. F. Demmitt
D. E. Deonigi
T. E. Divine
J. C. Fox
E. L. Owzarski
H. D. Huber
J. W. Litchfield
C. L. McDonald
W. H. Swift
R. A. Walter
K. D. Wells
Economics Library (3)
Technical Information (5)
Technical Publications (2)