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UTILIZATION AND DISSIPATION OF WASTE HEAT BY SOIL WARMING

D. R. DeWalle
Institute for Research on Land and Water Resources
and
School of Forest Resources
The Pennsylvania State University
University Park, PA, 16802, USA

ABSTRACT

Soil warming research at The Pennsylvania State University and other locations in the United States and West Germany is reviewed from both a crop production and heat dissipation viewpoint. Earlier harvests and increased yields for crops grown in heated soil have been reported in the majority of studies. Soil warming systems for dissipation of all the reject heat from a 1000 MWe power plant would require too large a land area to be practical. However, it appears possible to design optimized systems which can be economically competitive with conventional cooling methods.

INTRODUCTION

Many beneficial uses of waste heat in agriculture have been proposed such as: space heating for poultry and swine, convectional greenhouse heating, warm-water irrigation, aquaculture and soil warming in open fields as well as greenhouses. Soil warming is a term being used to describe a technique in which heated water is circulated through a pipe network buried in the soil, thereby warming the soil for potential beneficial use of the heat in agriculture. In addition to utilizing the waste heat for agricultural production via the warmed soil, a soil warming system can also be conceived as a heat dissipation system, e.g., a buried wet-cooling tower. With the proper system design a land area equipped with buried pipe can be used to dissipate all or part of the reject heat from an industrial source such as a steam-electric power plant. The water could be passed through the buried pipe network for cooling and returned in a closed system back to the plant. An integrated system for soil warming to utilize as well as dissipate waste heat must be carefully designed since the optimum system for heat dissipation is not necessarily the optimum for crop production.

At The Pennsylvania State University in 1972, an interdisciplinary study was funded by the National Science Foundation (RANN) to determine the economic and technical feasibility of soil warming as an alternative to commonly used heat dissipation methods such as cooling ponds, run-of-river cooling, and wet- and dry-cooling towers. In this study a computer model was developed to simulate a soil warming system operated for heat dissipation in conjunction with a 1500 MWe nuclear power plant. A 0.09 ha (15 x 60 m) soil warming field prototype was developed to test functions for prediction of heat transfer from buried hot-water parallel

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pipe networks used in the computer model. A unique feature of the prototype was the spray application of treated municipal wastewater on the warmed soil to maintain efficient heat transfer and supply crop nutrients. Details of this investigation were reported in [1] and [2]. More recently with funding from the USDI Office of Water Research and Technology, this research has been continued to study year-round heat dissipation, crop growth and development and wastewater renovation in artificially warmed soil.

Considerable experience has been gained through soil warming research at Penn State and several other locations. In fact, at two locations in West Germany [3] and in Minnesota, demonstration projects have now been initiated using actual power plant effluent. The purpose of this paper is to describe the Penn State research project and to compare and contrast the Penn State research with other known soil warming research projects. The status of soil-warming research and future potential of the soil-warming technique are discussed.

DESCRIPTION OF SOIL WARMING RESEARCH FACILITIES

Penn State Field Prototype

A key feature of the Penn State soil warming research is the field prototype located near the campus. The prototype consists of a buried pipe network, hot-water heating system, a wastewater spray irrigation system and heat-transfer data acquisition system. The pipe network consisted of 26 parallel 5-cm diameter polyethylene plastic pipes buried at about 30-cm depth and 60-cm spacing. The pipes were about 60 m long, giving a plot surface area of 15 x 60 m or 0.09 ha. Each plastic pipe was valved at both ends to permit variable pipe spacing. A manifold constructed from iron pipe was attached to either end of the set of plastic pipes to convey the heated water. Each manifold was equipped with a dry-well drain on the low end and an air-escape valve on the high end to facilitate filling the system with water.

The heating system incorporated an oil-fired hot water furnace which was thermostatically controlled to continuously supply water at 38 to 40°C to the inlet manifold. An insulated mixing tank was used to buffer water temperature variations due to firing of the furnace. Water was pumped continuously through the mixing tank, buried pipe network and back to the furnace in a closed cycle. The average flow velocity in each of the plastic pipes was equivalent to a Reynolds number of 1900.

The spray irrigation system was constructed of aluminum surface irrigation pipe. Laterals running perpendicular to the long axis of the plot were spaced every 13.3 m with offset, 45-cm high risers for sprinklers at 13.3 m intervals. The plot was irrigated with treated municipal wastewater supplied by a buried pipeline running from the University's waste treatment plant. Wastewater was applied at the rate of 1 cm per week in bi-weekly applications year-round.

The heated soil area and an adjacent 15 x 30 m control plot, which received wastewater but no heat, were intensively instrumented. The temperature of the soil at various depths and locations on both plots was measured along with the outer pipe surface temperature and circulating water temperature on the heated plot. Soil thermal conductivity, soil heat flow, net radiation and wet- and dry-bulb temperatures were also measured on each plot. Wind velocity, wind direction, dew-point temperature, downward shortwave radiation and dew-point temperature were also measured. Data were collected primarily with a digital data acquisition system.

The soil warming system was operated continuously from August, 1975 to September, 1976, giving an annual variation of climate conditions. Replicated subplots were planted with various perennial grasses plus winter wheat, winter barley, alfalfa and snap beans on both the heated and control plots.

Other Soil Warming Research Facilities

The widespread interest in soil warming research is evident from the summary given in Table 1 of other known research facilities in the United States and West Germany. Nearly all the research has been initiated since 1970 with a primary focus on crop production. Heat dissipation was also investigated especially in the North Carolina and Oregon State University projects. A discussion of the general conclusions derived from these research projects, the Penn State project and other studies not involving field research follows.

CROP RESPONSE TO SOIL WARMING

Open Field Experiments

Crop response to soil warming has been generally favorable. However, it is already evident that climate and the specific crops grown will interact to produce results unique to a chosen location. Nearly all the studies show that germination, emergence and initial growth rates are greater in warmed soil when planting is in early spring. In most cases this initial growth advantage produces earlier harvests which may result in significantly higher profits. Allred [9] in Minnesota found early varieties of white potatoes grown in heated soil matured from 2 to 3 weeks earlier primarily due to earlier planting possible in frozen soil. Rykbost, et al. (1974) also found earlier maturation for nearly all of the 13 crops tested on heated soil in the Willamette Valley in Oregon. Similar experience has been reported [12] for sweet corn, string beans and squash planted in April at Muscle Shoals, Alabama and for a variety of crops planted during the cooler seasons in North Carolina [13]. In both the Alabama and North Carolina studies, crops planted in summer exhibited reduced germination or no benefits from the heated soil.

Crop yields were generally greater in heated soil. Greatest reported crop yield increases have been with bush beans (up to 85% increase) and cole crops, especially broccoli (yield doubled) in Oregon [4] and cabbage

(300% increase) and cool season snap beans (up to 300% increase) in North Carolina [14]. In general, yield increases ranging from 20 to 40 percent have been reported. Reduced yields have been reported by [8] when varieties of forage crops originating in cool regions were grown in artificially warmed soil. Yield response to soil warming in the Penn State study has been variable for several different perennial forage crops, snap beans, winter wheat and winter barley. Winter kill of switch grass and winter barley has occurred, apparently due to slower development of cold tolerance in the warm soil in these species. Allred [9] also reported the freezing of the above-ground portions of potato plants growing in warm soil in early spring. Increased activity of insects and nematodes and weed growth were found with soil warming in North Carolina [13].

Greenhouse Experiments

Soil warming in greenhouses has also been studied as a method for utilization of waste heat (see Table 1). In Alabama, crops requiring low air temperatures were grown in a greenhouse at two different soil temperatures with heat supplied only by soil warming [12]. Broccoli, cauliflower, bibb lettuce and head lettuce were all successfully grown with greater yields produced by the warmer soil. A soil-heated greenhouse in Oregon [15] was used to grow lettuce, tomatoes and cucumbers. Air temperatures in the winter inside the greenhouse were low, but freezing of a lettuce crop was prevented, even during a disruption in the supply of hot water, by the slow release of stored heat from the soil.

Rybost and Boersma [15] reported significant increases in yields of tomatoes planted in April in a greenhouse with soil heating, but stated that a soil warming system was too inflexible for adequate temperature control within a greenhouse.

SOIL AND AIR TEMPERATURE RESPONSE

Crop response to soil warming is closely linked to the increase in soil temperatures within the rooting zone. Air temperature increases occurring from soil heating could also affect crop growth and development.

In the Penn State study, soil temperatures were elevated by soil warming by an average of at least 4°C at all depths year-round. Average temperature increases for each month, at various depths, computed from measurements at 0800 each morning, are presented in Table 2. Increases in soil temperature were greatest at the pipe burial depth of 30 cm, where the average annual increase was 20.8°C. Temperature increases due to soil warming declined with distance above or below the pipes. The decline was more rapid with distance above the pipes and soil temperatures at the surface were raised by only 6.3°C. Temperature increases were greater in winter than in summer at all depths, but especially at the pipe burial depth. In Figure 1, the diurnal variation of soil temperature at the surface, 30-cm and 45-cm depths on the heated plot are compared with surface temperatures on the control on 21 to 22 June, 1976, a clear to partly cloudy day. Surface temperature on this day on the heated plot was about

4 to 6°C higher, and reached 31°C during mid-day.

Soil temperature increases found in other soil warming experiments varied with pipe burial depth. At Springfield, Oregon, where pipes were buried at 60-cm depth, soil temperatures at 15-cm depth were increased 1.4 to 2.5°C in winter and a negligible amount in summer [5]. At the 30-cm depth, soil temperatures were increased 1.7 to 3.9°C in winter and 0 to 3.4°C in summer. In the Oregon State University study [15], with pipes at 51- to 91-cm depths, soil temperatures were increased to 20 to 25°C throughout a large percentage of the profile most of the year. Little horizontal variation in soil temperature was reported near the surface. Allred [9] reported soil temperatures at 20-cm depth were increased by hot-water pipes at 30-cm depth by 7.5 to 10°C in spring, but by negligible amounts in summer. In the North Carolina study [7], with pipes buried at 50-cm depth, soil temperatures for a four-day period in October were increased about 5 to 10°C in the upper 20 cm of soil and up to about 15°C at 40-cm depth. Again negligible horizontal soil temperature variations were found just 10 cm above the pipes.

Prediction of soil temperatures around buried, heated pipe networks is possible using equations developed by Kendrick and Havens [16]. Alpert et al. [2] found generally good agreement between estimated and measured soil temperatures for 34 points around a buried pipe network. The average deviation between estimated and measured soil temperatures was 0.9°C for a day with a soil surface temperature of 11.2°C and 2.1°C for a day with a surface temperature of 20.5°C. The Kendrick and Havens equation consistently overpredicted soil temperatures below the pipe network, especially on days with high surface temperatures, due to an implicit assumption in the equation that the soil temperature at infinite depth below the pipes is equal to the surface temperature.

HEAT DISSIPATION

Several investigators have measured heat loss rates from buried pipe networks. Measurements have been extrapolated to various pipe network configurations using theoretical heat conduction models for buried, hot-water pipe networks. Heat loss rates were then used to estimate the area of land required for dissipation of waste heat rejected by steam-electric power plants.

Measured Heat Losses

Measured heat loss rates from soil warming systems range from about 37.5 to 138 W m^{-2} in North Carolina without irrigation [7], from about 34 to 100 W m^{-2} in Pennsylvania and from 8 to 21 W m^{-2} in Oregon [15]. Average monthly heat loss rates for a soil warming system in Pennsylvania are presented in Table 3. The higher rates in the North Carolina study than in the Pennsylvania study probably are due to higher average pipe surface temperatures even though initial water temperatures were similar. Water had opportunity to cool 5°C in summer and over 20°C in winter while flowing through the pipes in the Penn State study. The low heat loss rates in the

Oregon study can be attributed to the relatively great burial depth (91 cm). A combination of both sub-soil and surface irrigation during a 50 day test period in North Carolina increased heat dissipation rates by an average of 24% from a range of 39 to 98 W m^{-2} to a range of from 45 to 127 W m^{-2}.

The diurnal variation in soil heat flow at a 135-cm and 5-cm depth on the heated and control plots are presented in Figure 2 for 21 to 22 June, 1975, along with the heat loss from the pipes buried at a 30-cm depth. Virtually no heat flow was recorded at 135 cm on either plot. Heat flow at the 5-cm depth was downward in the soil during mid-day on both plots. The heat flow at 5-cm depth on the heated plot from about 2200 to 0500 was upward and about equal to the heat loss from the pipes. On the control, heat flow at 5 cm was negligible at night. Obviously considerably more heat was lost from the pipes during the day than was measured at the 5-cm or 135-cm depths on the heated plot. Heat storage in the soil profile and heat transfer by mass flow in the soil, which is not measured by heat flux plates used to measure heat flow, probably account for this difference.

Heat Conduction Models

The basic model used in many studies to describe heat conduction from a buried, parallel pipe network was developed by Kendrick and Havens [16]. Simply stated, their model gives the rate of heat loss from the pipe network (q) in W m^{-1} of pipe length as

$$q = Bk(T_p - T_s)$$

in which k is the soil thermal conductivity in W $m^{-1}s^{-1}{}^{\circ}C^{-1}$, T_p is the pipe outer surface temperature in °C, T_s is the soil surface temperature in °C and B is a constant which is calculated from pipe spacing, pipe burial depth, outside pipe radius and the number of parallel pipes in the system. The Kendrick and Havens model assumes a steady-state system with a soil temperature equal to the soil surface temperature at an infinite depth below the pipe. A model with a more realistic lower temperature boundary condition, developed by Hulbert, et al. [17], has been used at Penn State in which

$$q = B'k\left[(T_p - T_s) - (T_g - T_s)d/L\right]$$

where T_g is the soil temperature below the pipes at some depth from the surface L, d is the pipe burial depth, and B' is another constant for a given pipe network geometry which can be obtained from graphs for many configurations. Using measured pipe and soil surface temperatures and measured soil thermal conductivities obtained with probes developed by Fritton et al. [18], both the buried pipe models were found to give similar results in the Penn State study.

Pipe and soil surface temperatures and soil thermal conductivity must be known to compute heat loss using the foregoing theoretical expressions.

Monthly average pipe surface temperatures were up to 3°C less than the water temperature within the polyethylene plastic pipe in the Penn State study for a Reynolds number for flow within the pipes of 1900 (see Table 3). Soil surface temperatures were also increased by soil warming by an average of 6.3°C. Skaggs, et al. [7] also reported surface temperatures were increased by soil warming in North Carolina. Thus soil surface temperatures cannot be assumed equal to air temperature or natural soil surface temperatures. Van Demark and DeWalle [1] discussed and tested a method for prediction of soil surface temperatures with artificially heated soil which could be used in predictions of heat loss for proposed soil-warming systems.

Soil thermal conductivity can be measured with thermal conductivity probes or an "effective" soil thermal conductivity may be calculated by setting measured heat loss rates equal to heat flow in one of the theoretical models. Conductivity probes may not totally account for the contribution of mass flow to heat conduction along steep temperature gradients in the soil. However, the wide variation of soil thermal conductivity with moisture content makes selection of appropriate values from the literature difficult.

Rykbost and Boersma [15] reported the development of a zone of dry soil around the heating cables used in their experiments due to water vapor migration away from the cables. The dry soil zone reduced the rate of heat conduction away from the cables and was difficult to rewet once it developed. Skaggs, et al. [7] indicated, however, that pipes with a radius greater than the heating cables will produce smaller temperature gradients and less rapid drying of the soil.

Land Area Estimates

Johns, et al., [19] and Rykbost, et al., [4] concluded, based upon results of the Oregon State University study, that the investment for soil-warming systems is probably too great to be offset by agricultural benefits alone unless high value vegetable crops are grown. Thus, it appears that soil-warming over large land areas must be justified, in part, by benefits derived from heat dissipation.

Research in the first Penn State study by Plummer and Rachford [1] indicated that 1,820 ha of land with 5-cm diameter pipe buried at 30-cm depth and 60-cm spacing would be required year-round to dissipate the waste from a 1500 MWe nuclear power plant. The total cost of such a soil-warming system was estimated to be 54% more than heat dissipation using natural draft wet-cooling towers and 40% less expensive than dry-cooling towers. This soil-warming system was an optimum least-cost system where the cost of extra nuclear fuel needed to generate electricity when the water returning to the power plant from the field was not sufficiently cooled was balanced against the cost of using a larger soil-warming land area to dissipate heat. Land area estimates for soil-warming using this optimization approach are well below those from other studies where total power plant heat load is simply divided by heat loss per hectare.

Skaggs, et al. [7] computed that 4900 ha of land with irrigation would be required to dissipate heat from a 1000 MWe power plant if 10-cm diamater pipe at a depth and spacing of 50 cm were used. They concluded that soil warming in North Carolina would not be economically competitive with conventional cooling methods. Sepaskhah, et al. [20] estimated land areas for dissipation of waste heat from a 1000 MWe power plant would range from 75,000 to 3,500 ha depending upon pipe network configuration and soil and climatic conditions. They concluded soil warming appears "...feasible as a part of an integrated waste heat utilization program in conjunction with a conventional cooling system."

CONCLUSIONS AND RECOMMENDATIONS

The crop response to soil-warming varies basically with climatic zones. In the cooler northern climates, crop response to soil-warming is favorable in spring, summer and fall as long as sufficient moisture and nutrients are available. Winter and early spring freezing of crops, including perennials, grown in heated soil may represent the major crop management problem in northern regions. In contrast, fall, winter and spring crop response to soil-warming is promising in warmer, southern climates. Use of greenhouses in winter in the southern regions looks promising, but supplemental heating may be required farther north. Crops for summer cultivation on heated soil in southern climes must be chosen carefully. Further research is needed on the development of cold tolerance in plants grown in heated soil and the effects of soil warming on insect activity, plant diseases and weed growth.

Prediction of average daily heat loss from buried, hot-water pipe networks appears possible using existing steady-state models, if appropriate values for soil thermal conductivity, soil surface temperature and the pipe surface temperature can be obtained. The contribution of mass flow to heat transfer in the soil should be studied further so that an "effective" soil thermal conductivity including the combined effects of mass and heat flow in the soil can be obtained. Soil surface temperatures are increased by soil warming but the magnitude of the increase depends not only on the temperature and configuration of the pipe network, but also on the heat budget at the soil surface. Heat exchange at the soil surface will depend on availability of water and the radiative and convective heat exchange within a crop canopy. Micrometeorological models of the crop canopy which permit forecasts of soil surface temperatures would be needed for routine operation of a soil-warming heat dissipation system.

The outside pipe surface temperature can only be assumed equal to circulating water temperature if turbulent flow exists in the pipe and the pipe wall thermal conductivity is large compared to that in the soil. It appears that polyethylene plastic pipe, which has a thermal conductivity equal to or less than that of most soils (about 0.25 W $m^{-1}{}^{\circ}C^{-1}$), will probably be used in soil-warming systems. Thus, allowance should be made for a temperature drop across the pipe wall in heat loss estimates where polyethylene pipe is used or turbulent flow does not occur.

The application of soil warming for either crop production or heat dissipation, or both, will ultimately depend on economic issues. Soil warming is technically feasible, but will never be employed unless costs compare favorably with alternative methods of crop production or heat dissipation. Costs of installing plastic pipes and the optimum hydraulic pipe network needed to reduce pumping costs are very important to determination of costs for soil warming systems used primarily for heat dissipation. Reduction of consumptive-use of water by using soil warming rather than wet-cooling towers could also become an important economic issue in the future. Mesoscale climatic changes produced by heat dissipation over large areas of warm soil relative to effects of essentially point-source cooling towers needs attention. Integrated systems for heat dissipation and wastewater disposal may also become desirable, since considerable economic advantage can be obtained by having unfrozen soil for wastewater infiltration in winter. A total systems economic analysis of all costs and benefits is needed to properly assess the future potential of soil warming.

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TABLE 1
DESCRIPTION OF SOIL-WARMING RESEARCH FACILITIES

Location	Heating System	Depth x Spacing cm	Heat Source Temperature °C	Soil	Irrigation	Research Emphasis	Source
Oregon (Oregon St. University)	heating cables	92 x 183 51 x 122 55 x 122	30-36	loam	sub-soil	Crops, open field and greenhouse, heat dissipation	[4]
Oregon (Springfield)	6.25-cm diam. pipe	60 x 150	21-49, varied seasonally	sandy loam	spray	crops, open fields and greenhouses	[5]
Alabama	heating cables	(25-30)x30	up to 32	--	sub-soil	crops, open fields and greenhouses	[6]
North Carolina	2.5-cm diam. pipe	50 x 50	38	sandy loam	spray and sub-soil	crops, heat dissipation	[7]
Maryland	pipe	9 x 17	10-30, varied on plots	silt loam	spray	crops	[8]
Minnesota	1.25-cm diam. pipe	30 x 91	35-40	loamy sand	sub-soil	crops	[9]
Minnesota	2.5-cm diam. pipe	30 x 60	power plant condensor water, about 32°C	sandy loam	--	crop production in greenhouses with soil and air heating	[11]
West Germany	5-cm diam. pipe	75 x 100	power plant condenser water	--	--	crops, heat dissipation	[10]
Pennsylvania	5-cm diam. pipe	30 x 60	38-40	sandy loam	wastewater spray	crops, heat dissipation	[1]

TABLE 2
AVERAGE MONTHLY INCREASE IN SOIL TEMPERATURE (°C) DUE TO
BURIED HOT-WATER PIPES AT A 30-CM DEPTH IN PENNSYLVANIA

	Soil Depth (cm)					
Month	Surface	15	30	45	90	180
January	6.7	14.6	28.9	22.7	16.9	14.9
February	7.7	15.3	28.6	22.3	18.3	15.5
March	8.0	13.5	24.4	20.4	16.7	14.8
April	7.5	13.1	21.6	17.6	15.4	13.7
May	8.2	12.8	20.7	16.7	14.7	12.8
June	5.9	10.4	15.5	14.9	12.8	11.9
July	4.8	8.8	13.7	12.6	12.1	13.1
August	5.1	13.1	14.0	11.6	11.6	12.3
September	5.7	13.8	15.9	—	11.9	10.2
October	6.1	11.1	18.5	18.3	11.7	8.5
November	4.6	12.4	21.0	19.2	13.3	9.8
December	5.2	14.4	26.2	21.3	15.3	12.5
Mean	6.3	12.8	20.8	16.5	14.2	12.5

TABLE 3
AVERAGE MONTHLY HEAT LOSS RATES AND TEMPERATURE DROP
ACROSS POLYETHYLENE PLASTIC PIPE FOR
A SOIL WARMING SYSTEM IN PENNSYLVANIA

Month	Heat Loss ($W\ m^{-2}$)	Temperature Drop (°C)
January	91.4	1.8
February	79.6	1.4
March	79.4	2.7
April	66.0	2.2
May	54.0	2.0
June	50.0	1.9
July	56.9	1.2
August	48.4	1.3
September	—*	—*
October	63.4	2.1
November	67.3	2.9
December	83.3	2.9

*Data limited due to instrument malfunction

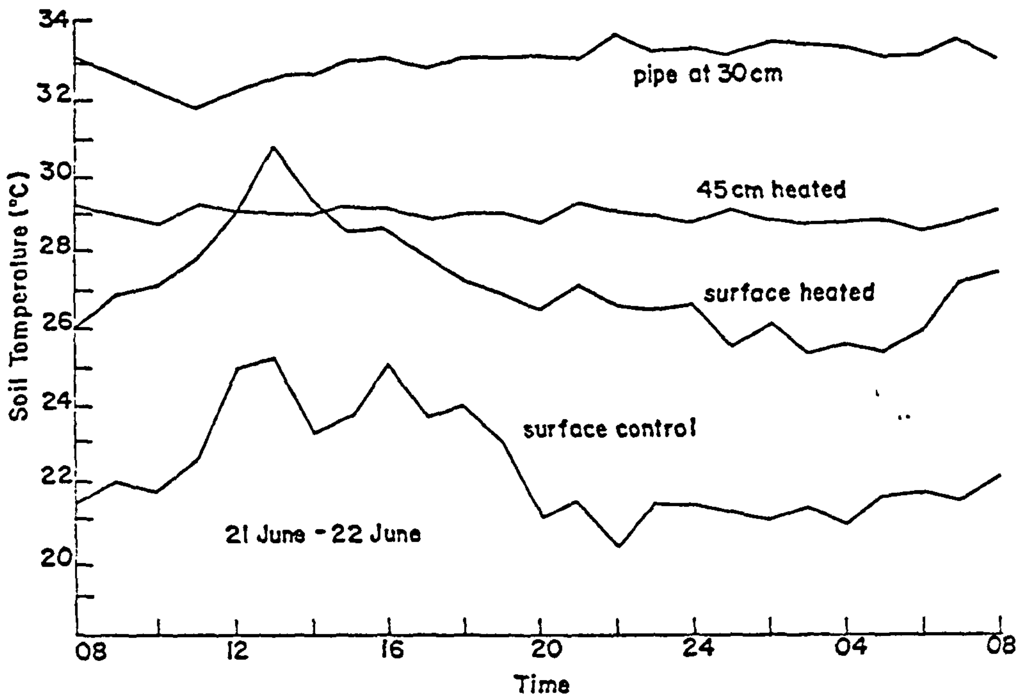

Fig. 1 - Soil temperatures on heated and control plots on 21-22 June, 1976 in Pennsylvania.

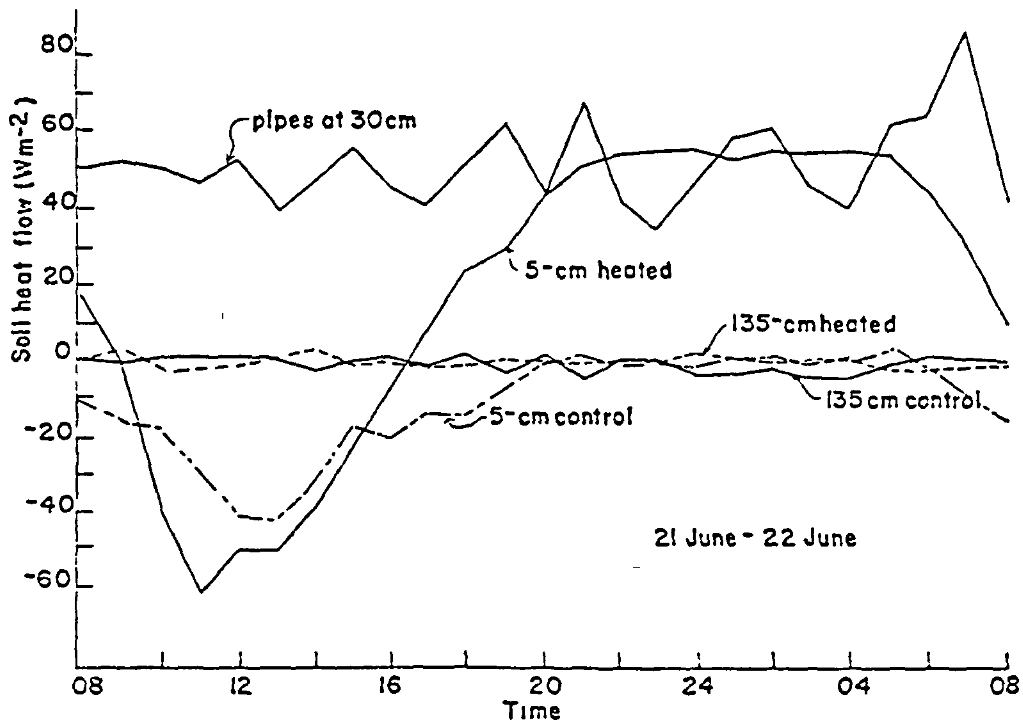

Fig. 2 - Soil heat flow on the heated and control plots on 21-22 June, 1976 in Pennsylvania.

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