Potential of Drip Irrigation in Row Crops for Agricultural Water Conservation in California

Pruitt, W. O
Henderson, D. W
Fereres, E.
et al.

1982-12-01

POTENTIAL OF DRIP IRRIGATION IN ROW CROPS FOR AGRICULTURAL WATER CONSERVATION IN CALIFORNIA

by

William
W. O. PRUITT, D. W. HENDERSON, E. FERERES and R. M. HAGAN
Principal Investigators

Department of Land, Air and Water Resources
University of California, Davis

Office of the Director
CALIFORNIA WATER RESOURCES CENTER
University of California Davis, California 95616

The research leading to this report was supported in part by the UNITED STATES DEPARTMENT OF THE INTERIOR, under the Annual Cooperative Program of Public Law 95-467, Project No. A-076-CAL, and by the University of California Water Resources Center, Project UCAL-WRC-W-572. Contents of this publication do not necessarily reflect the views and policies of the Office of Water Policy, U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement or recommendation for use by the U.S. Government.

TECHNICAL COMPLETION REPORT

December 1982

ABSTRACT

Results are presented of a two-year study comparing the evapotranspiration (ET), yields and the microclimate under drip and furrow irrigated processing tomatoes. Results from a water conservation standpoint were not encouraging with approximately equal values of evapotranspiration found for the two methods of irrigation. This was true in replicated field-plot studies as well as the lysimeter studies. The latter studies indicate that although ET under furrow irrigation was considerably higher than under drip irrigation for the three days following each furrow irrigation, this advantage is largely cancelled by a reversal in trends thereafter. Apparently the advection of sensible heat in air and soil to the narrow wet strips under the drip-irrigated canopy produces quite significant evaporation losses in spite of a nearly zero under-canopy net radiation.

Yield of ripe fruit in the drip irrigated lysimeter exceeded yields in the furrow lysimeter by 9% and 16% respectively in 1979 and 1980. In the replicated field-plot study yields in 1979 were not significantly different between treatments. In 1980 yield from a plastic mulched drip irrigated treatment was significantly different from the regular drip and furrow irrigated treatment. Yields for the three treatments were respectively 83.8, 66.2 and 58.6 tons/ha.

POTENTIAL OF DRIP IRRIGATION IN ROW CROPS FOR AGRICULTURAL WATER CONSERVATION IN CALIFORNIA

W. O. Pruitt, D. W. Henderson, E. Fereres, R. M. Hagan,
Paul E. Martin, E. Tarantino, Harbir Singh
and Bashir Chandio

SUMMARY

This paper reports on the results of a recent study at Davis, California directed at determination of possible water savings and/or increased production per unit of evapotranspiration (ET) under drip irrigation. Two 6.1 meter diameter, highly sensitive lysimeters provided hourly ET data during two summers for both drip- and furrow-irrigated canning tomatoes planted at a 152-cm row spacing. A replicated field plot study provided for statistical analyses of yield and ET differences for treatments represented by the two lysimeters as well as for a treatment involving drip irrigation under a plastic mulch.

An intensive micromet study was conducted in and above the two lysimeters involving some 80 soil and air temperature sensors and 12 net radiometers, with data collected at 3-minute intervals during many days of the growing season. Wind speed was recorded continuously for many days at both under-canopy and between-row locations at a 1-cm height above the soil surface.

Except for the first four to five days following furrow irrigations, very high soil surface temperatures (around 60°C) were noted in mid-row positions for both methods of irrigation. With the application of water to

the broad-base flat-bottom furrows, three nearly instantaneous to longer-lasting effects were noted: 1) soil surface temperatures ($-\frac{1}{2}$ cm) dropped some 20-30°C; 2) net radiation (over exposed soil surfaces) increased some 0.2 to 0.3 cal cm^{-2} min^{-1}; and 3) very dramatic increases in evapotranspiration resulted, although with increasing plant cover the effect became moderated. In spite of much higher ET losses under furrow irrigation than under drip irrigation for the first two to three days following each furrow irrigation, this advantage for the drip method was cancelled out by a reversal in trend thereafter, apparently due to a continuously rather high daily loss by evaporation from the narrow (20-30 cm) wet strip under the tomato rows. During stages of plant cover of 50%,it is subject to high levels of sensible heat transfer from hot, mid-row zones of soil and air.

The water use efficiency data do indicate some advantage for drip-irrigation treatments where, for example, in the field plots (replicated four times) WUE for drip plots was 20% and 9% higher than for furrow plots in 1979 and 1980, respectively. The larger difference in 1979 may have been the result of a breakage in the furrow delivery system which delayed the first furrow irrigation for some 11 days after drip irrigation was initiated. The drip plots with a plastic cover under the upper 1-2 cm of soil (and with emitters under the plastic) resulted in some water saving in 1979 but not in 1980.

JUSTIFICATION

The need for more precise evaluation of evaporation losses under different methods of irrigation comes from the increased interest in possible savings in overall water requirements in agriculture. With the increasing awareness that improvement of farm irrigation application efficiency may seldom lead to overall basin or district water savings, the one loss (evaporation) which for the most part, does not enhance growth of plants, has become a subject of considerable interest and controversy. Proposals for conversion of much of California's surface irrigated farmland to drip irrigation, have received serious attention. Thus, there is a vital need for developing reliable information on the magnitude of possible savings and/or the increase of production per unit of evapotranspiration (ET).

Water loss from a cropped area to the atmosphere is the result of evaporation from the soil (E) and transpiration (T) from plant surfaces. The combination of both processes, called evapotranspiration (ET), is equivalent to the crop water requirements.

When annual row crop plants are in an early growth stage and have little ground cover from the canopy, the evapotranspiration rate from the field is dominated by the soil evaporation rate. As the crop canopy increases, the evapotranspiration rate becomes more dependent on the leaf area (Penman et al., 1967).

Studies of crop water requirements have been conducted in most countries of the world where irrigated agriculture is involved. Examples illustrative of the extensive nature of such work in some areas, are those in Israel as reported by Shalevet et al. (1981); in Arizona, USA (Erie et al., 1965); in Washington State, USA (Middleton et al., 1967); and in California as reported by the State Department of Water Resources (California, State of, 1975). Many other studies have been aimed at development of models for prediction of evapotranspiration, both potential and actual losses by crops. Examples of some widely used methods are those developed by Thornthwaite (1948), Penman (1948), Blaney and Criddle (1950), Jensen and Haise (1963), Turc (1961) and Christiansen and Hargreaves (1969).

Models have been developed for calculating evaporation (E) and transpiration (T) separately. Examples are methods developed by Ritchie (1972), Hanks (1974) and Tanner and Jury (1976). Such models deal with conventional irrigation methods that essentially wet the entire soil surface. However, because of the smaller area of wet soil surface under drip irrigation and strong thermal gradients between dry and wet zones with microscale advection from the former to the latter area, those measurements and models are not easily applied to drip-irrigated crops.

Because drip irrigation ideally would involve minor losses of water by evaporation, it may be expected to reduce evapotranspiration more than most other methods, especially during the early stage when a large percentage of the soil surface remains unshaded. However for crop-soil-climate conditions where few early-stage surface irrigations are required, drip irrigation, if applied frequently, might produce greater ET losses than for surface methods such as furrow irrigation.

Although many studies have compared drip irrigation with other methods of irrigation, very few involved an accurate determination of actual ET loss for short periods or the detailed microclimate measurements needed for separating the E and T components of ET. This and other considerations led to this project initiated at the University of California at Davis in 1979. A major objective of the project was to investigate possible savings in evapotranspiration by drip-irrigated row crops as compared with furrow-irrigated row crops, and to develop models for predicting expected evapotranspiration losses that might be extended to plant and row spacings not represented.

MATERIALS AND METHODS

The experiment was conducted during the summers of 1979 and 1980 on a Yolo loam soil at the Experimental Farm of the University of California at Davis. Geographic coordinates of the site are latitude 38°32'15" north, longitude 121°46'30" west, and altitude 17 m above mean sea level.

Processing tomatoes (UC82 variety) were direct-seeded in two large lysimeters and surrounding fields (>1 ha) on 15 May 1979 and on 23 April 1980. The rows were spaced 152 cm apart and were oriented east-west. In 1979, practices recommended by Cooperative Extension for fertilizer applications were followed. Liquid fertilizer (10-34-0) was applied at planting at a 7 cm depth and directly under the seed bed. The rate was at 112 liters/ha. On June 18 a side dressing of NH_4NO_3 was applied at the rate of 78 kg N/ha. In 1980 due to the difficulty of using the above procedure in the lysimeters and immediate surroundings, a single broadcast application of NH_4NO_3 (134 kg N/ha) was made on 14 April and sprinkled in.

In 1979 the herbicide Treflan was rototilled in (5-7 cm) on 21 June. On 24 April 1980, 11.2 kg/ha of Enide was sprayed on in a water mixture and sprinkled in.

The plants began emerging on 22 May 1979 and on 2 May 1980. They were thinned to an approximate 22.9 cm (9 in) spacing within each row in mid June 1979 and on 20 May 1980.

The crop was uniformly sprinkler irrigated from planting up to June 26, 1979 and up to May 24 in 1980. Differential irrigation methods were started on July 12 in 1979, although due to a pipeline break the first furrow irrigation was delayed until July 23. Furrow and drip irrigations in 1980 were initiated on June 13.

Evapotranspiration of tomatoes under furrow irrigation was determined from a 6.1 m-diameter, 90-cm deep weighing lysimeter described by Pruitt and Angus (1960), and that of the crop under drip irrigation was determined by a 6.1 m floating drag-plant lysimeter described by Brooks et al. (1966), and Goddard (1970). Both systems are sensitive to within approximately 0.02 mm of evapotranspiration and are, perhaps, the only such highly sensitive lysimeters existing that also are large enough to provide for a sample size of almost a hundred plants even with a row spacing of 152 cm and a plant spacing in the row of 22.9 cm. However, the limiting of rooting to the depth of the lysimeters (90 cm) may be a problem with irrigation intervals greater than seven to ten days in midsummer Davis conditions since up to 50 percent of the so-called available water can be removed in that length of time.

Evapotranspiration was also determined in the field plot areas where yield trials were conducted on three treatments, replicated four times. Individual plots contained 12 rows at the 152-cm row spacing. They were 15.2 meters long. In addition to the drip and furrow irrigation treatments (to be managed similarly to those in the lysimeters) another treatment of drip irrigation was involved using a plastic mulch to minimize evaporation. Strips of black plastic 152 cm wide and 15.2 cm long were placed between the plant rows and covered with approximately 2-3 cm of soil to simulate a normal condition. In all field plots a water balance procedure was used to estimate evapotranspiration. Each individual plot was instrumented with four 3.5-m-long aluminum access tubes spaced uniformly between two rows near the middle of each plot. Neutron probe readings were taken just before each irrigation. Water applied was measured with water meters.

Flow in furrows supplying water to mid-plot zones were also checked volumetrically at the gated pipe outlets.

The drip irrigation system delivered water through microtubing emitters of 0.82 mm inside diameter, placed every 45.7 cm apart on the lateral so that after thinning, each emitter supplied water to two adjacent plants. Operating pressure was such that each emitter delivered 2.65 liters per hour. Several evaluations of the drip system indicated an emission uniformity of 93 to 95 percent.

During periods of differential irrigation the drip lysimeter and its surrounding field along with the drip plots were irrigated daily during the season except for a few times during early stages when the field was irrigated every other day. Frequency of furrow irrigation in the weighing lysimeter and surrounding field was at approximate 10-day intervals. Most farmers in the area use a 10-14 day schedule. At each irrigation, both the furrow- and the drip-irrigated tomatoes (in the lysimeters and in field plots) received an amount of water equal to the total ET lost in the respective lysimeters since the previous irrigation.

For both the furrow- and the drip-irrigated lysimeter sites, micrometeorological data were recorded on most of the days during both growing seasons although only 1980 data are reported herein. The vertical and horizontal variation in soil and air temperature, net radiation, humidity, and windspeed were determined. This report concentrates on detailed micrometeorological data for only three representative days in 1980, July 16 the day of the fourth furrow irrigation, July 17, the following day, and July 24, one day before the fifth furrow irrigation. Some soil and air temperature data are presented graphically for several irrigation cycles. Much of the micrometeorological data collected in 1980 will be presented in a supplemental report now in preparation.

Figure 1 shows two vertical cross-sections, respectively, for furrow and drip methods for the 1980 study. The location of soil and air temperature sensors, and net radiometers are indicated. Soil-temperature sensors were made up of 24-gauge, two-junction copper-Constantan thermopiles to give a mean of temperature at two places on transects parallel to the plant rows, and to provide a sensitivity twice that of single-junction units. They were placed in the soil profile at depths of 0.5, 5, 15, and 30 cm at several locations transversely between the plant rows. The upper two levels had thermopiles located 7.5, 22.5, 40, and 63 cm north of one row in the lysimeter (positions hereafter identified as NS), and at the same distances south of an adjacent row in the north (identified as SN). Thermopiles located 15- and 30-cm deep in the soil were located at every other position. Similarly, two-junction, air-temperature thermopiles (30-gauge Cu-Co) were located 6 cm above the soil surface at 7.5, 22.5, and 40 cm NS, in the middle between rows (-76-), and at 7.5, 22.5, and 40 cm SN. In addition at each of these locations, a thermopile of four equally-spaced 30-gauge junctions were located on a light, 58-cm long framework, oriented parallel to the plant rows. These provided a voltage output directly related to the difference in 6 cm and 1 cm air. Each thermopile set was calibrated in a water bath of known temperature with an ice bath as reference, to obtain the response curve. The photo of Figure 2 shows several of these T_6 and (T_6-T_1) units. The thermocouple junctions were not aspirated, no doubt resulting in some degree of error.

Net radiation was measured at 25 and 150 cm above the soil surface using Fritschen net radiometers located with respect to rows as shown in

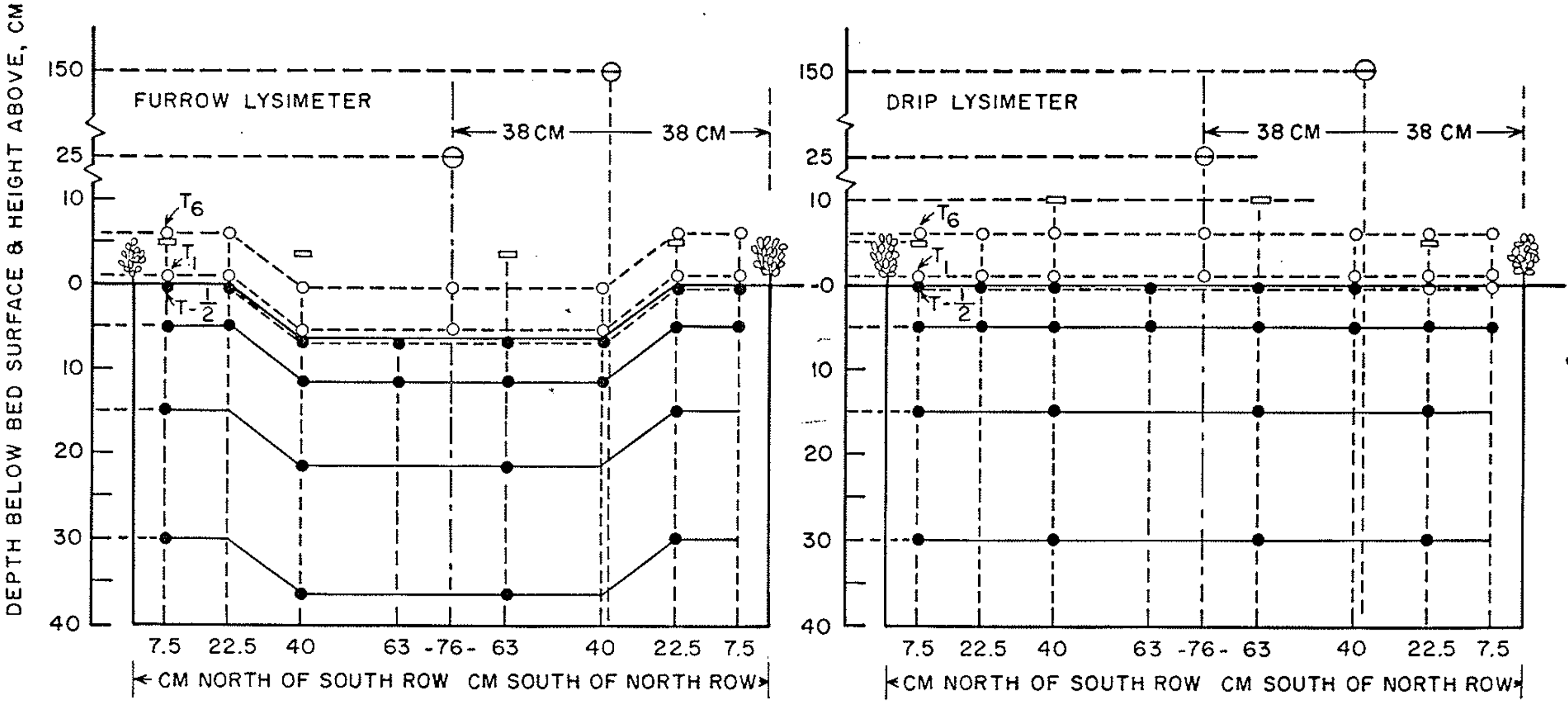

Figure 1. A cross-section view showing most of the positions of various instruments used in the 1980 study at Davis, California. Fritschen hemispheric net radiometers, ⊖; Delta-T tube net radiometers, ▭; air temperatures (and/or T_6-T_1) thermopiles, ○; and soil temperature thermopiles, ●.

Figure 2. A view of the 6.1-meter-diameter weighing lysimeter planted to processing tomatoes. Photo was taken on August 7, 1980, two days after an irrigation using flat-bottom furrows.

Figure 1. Net radiation under the plant canopy and between the rows was measured with 39-cm long tube net radiometers (Delta-T Devices of Cambridge England) placed in each lysimeter at four locations as indicated in Figure 1. The two units closest to tomato rows were placed 5 cm above the soil surface to avoid excessive contact with plant stems and leaves. The other two were placed 10 cm above the soil surface. Two of these units are just discernible in the center of the photograph. The 25-cm Fritschen hemispheric is visible in the upper right corner.

Although not reported on herein, total wind for half hour periods at a 2-meter height was measured with a Casella cup anemometer. On a few select days in 1979 wind readings from an Alinor hot-wire anemometer located at a 1-cm height above the soil surface were observed at 1 to 2 minute intervals. In 1980, the outputs from two hot-wire anemometers (Thermonetics Corporation) located at under-canopy and at mid-row locations at a 1-cm height, were recorded for many days of the summer on a fast-speed strip chart recorder.

Class A pan evaporation and precipitation data were available from an irrigated turf grass weather station located about 150 m south of the lysimeter area.

Soil moisture profiles from 0 to 30 cm were determined for both lysimeters several times before and after each furrow irrigation date. Samples were obtained just under the rows, in the middle between the rows (-76-), and at the 22.5 cm SN and NS locations. These data were needed to determine thermal conductivity and heat capacity values. The percentage moisture in the soil samples was measured gravimetrically.

Percent ground cover during the growing season was calculated by dividing the width of plant canopy by row spacing which was 152 cm. A 150-cm ruler was used to take 30 random measurements of plant row width in each lysimeter. During the early growth stages percent cover data were obtained from careful evaluation of 35 mm slides projected on a screen.

Tomatoes were harvested on 10 October 1979 in both field plots and in the lysimeters. For yield determinations plants were cut at the soil surface and shaken to remove the fruit, with red, green and rotten fruit weighed separately. The 1980 harvest was complicated by the desire to obtain evaporation-only losses from the weighing lysimeter, but with plants cut to stop transpiration, all in an effort to derive a wind functional relationship. This was done on September 6, 1980. Furrow and drip plots were harvested on September 10 and the drip lysimeter plants on the 17th.

EXPERIMENTAL RESULTS

Soil and Air Temperature — Figure 3 provides an example of soil isotemps in the upper 30-cm layer along with air temperature at 6 cm above the soil surface (hourly mean values between 1300 and 1400 on July 17 and 24, 1980. Included are values of ΔT (T_6-T_1) as indicated by the four-junction thermopiles above the soil surface.

From the soil isotherms the marked difference between the microenvironment of drip- and furrow-irrigated tomatoes is evident, especially for the day following a furrow irrigation (July 17). Although under-canopy soil and air temperatures are quite comparable the mid-row soil temperatures at the 0.5-cm depth ran some 20°C hotter in the dry surface soil of the drip-irrigated lysimeter than for the moist surface soil of the furrow-irrigated lysimeter. For July 17 the 6-cm air temperature (T_6) at mid-row was 37°C for drip as compared to 34°C for furrow. T_6-T_1 at mid-row locations ran a -3.5° for the former as compared to -0.8° for the latter.

Although a temperature inversion over the wet soil surface of the furrows might be expected, such was not the case. Apparently the resistance to transfer of water vapor from this rather smooth protected surface precluded the development of a latent heat transfer greater than net radiation minus soil heat flow (Rn-G). On the other hand the net radiation and ET patterns presented by Tarantino et al. (1982),for July 17 (their Figure 4), suggests an average sensible heat transfer from the furrow lysimeter to air and soil (H+G) of 0.1 cal cm^{-2} min^{-1} for the 1300-1400 period. By comparison one could also deduce from their Figure 4 that the value of H+G at mid-row in the drip lysimeter was approximately 0.8 cal cm^{-2} min^{-1} assuming E from the very dry surface soil at mid-row to be

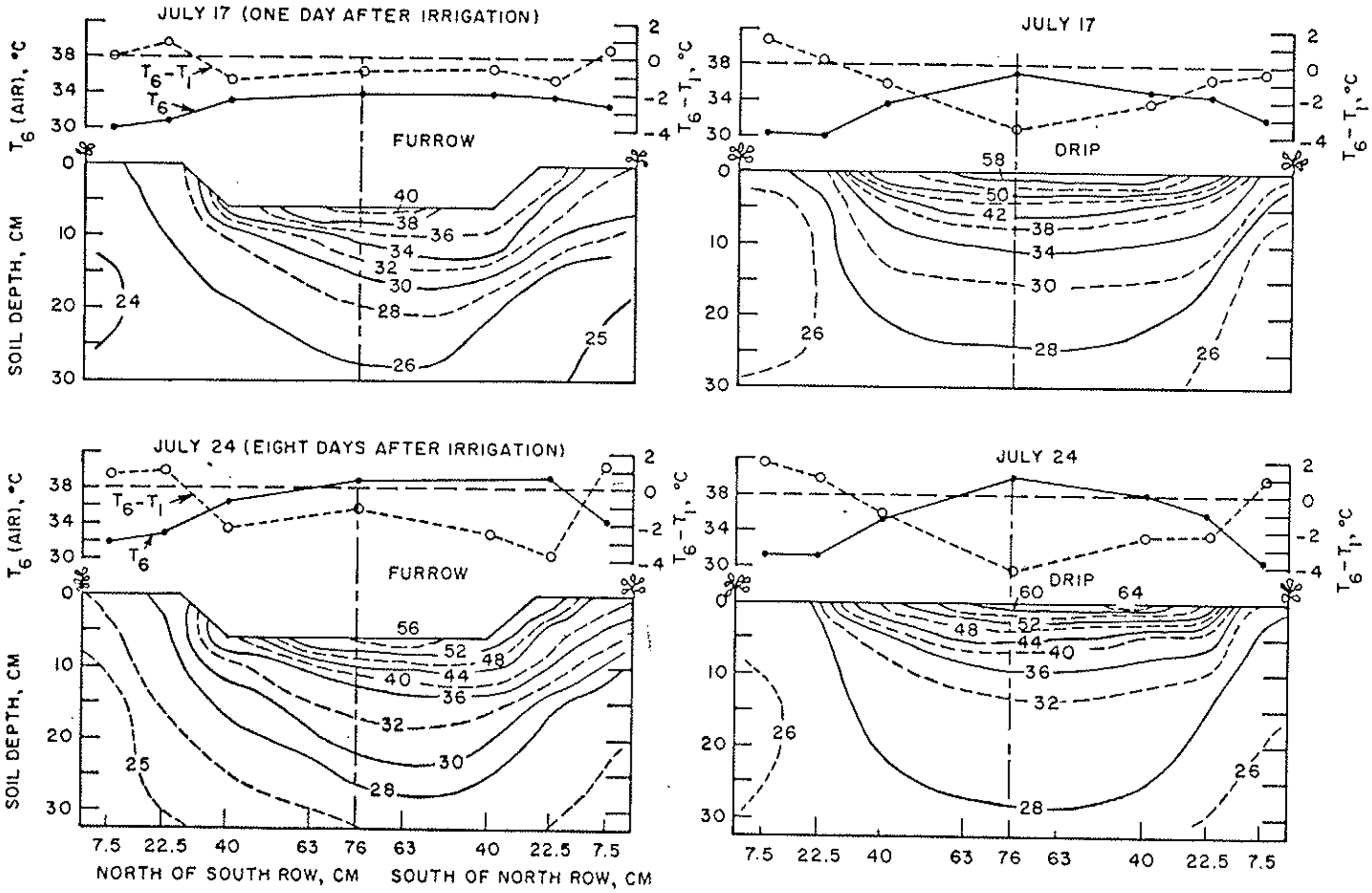

Figure 3. Air temperature at 6 cm above the soil surface, T_6 and (T_6-T_1) at various locations between tomato rows, along the isotherms based on the soil temperature measurements for the period of 1300-1400 hrs. Results are for both lysimeters for July 17, 1980, one day following a 6-cm irrigation of the furrow lysimeter, and July 24, eight days after the July 16 irrigation.

negligible. Although much of this sensible heat must escape as H to the above canopy air, some would end up as transfer of energy to the plant canopy. Hence on days such as July 17 following a furrow irrigation, transpiration losses by drip-irrigated plants must considerably exceed that by furrow-irrigated plants. Even so as will be shown later, the total ET loss on such days is greater for the latter. Transpiration losses may be less but this is more than compensated for by high evaporation losses from the wet soil of the furrows.

The results in Figure 3 show much less difference between soil temperatures of the two lysimeters on July 24, eight days after the furrow irrigation of July 16. However, the 0.5-cm soil temperature near mid-row was still some 4 to 8°C hotter in the drip-irrigated lysimeter.

Rather consistent in Figure 3 (and in review of all mid-day periods of the study) is the indicated inversion profile just above the under-row wet strip of the drip-irrigated tomatoes. Thus, even though these strips are largely shaded by plants, and the net radiation is very low (see Tarantino et al., 1982, Figure 4), the evaporation is likely quite high due to advected heat both in soil and in air. Tarantino et al. (1982) show that ET (furrow)/ET (drip) averaged 0.9 for six days prior to furrow irrigations. A simple calculation assuming; 1) a 25-cm wide strip is affected by the drip emitters, and 2) that evaporation from soil surfaces during such periods is the same in all other areas for both drip and furrow systems, shows that on a day when ET (drip) = 5 mm/day and ET (furrow) = 4.5 mm/day, the 25-cm wet strip under the drip plants would have to lose a depth of water 3 mm more than that under the furrow plants. This does illustrate that quite significant advection to the wet strips is involved since the net radiation of such areas is very low. It would not require, as prior reports on the project have speculated (Pruitt et al., 1981 and Tarantino et al., 1982) that evaporation from the drip irrigated wet strip under a canopy might be as much as 1.5 to 3.0 times the loss expected from a strip the same size in a wet, bare field.

Although much can be deduced from the results reproduced in Figure 3 the soil and air temperature profile data presented in Figure 4 are also helpful for interpretation of results. Tarantino et al. (1982) show a similar figure but without the air temperature data. Also the previously published data for soil temperature are in error on the high side, especially in the 50 to 70° range. A linear calibration equation for the thermocouple had been used for simplification in a preliminary analysis. Although quite adequate in the 20-40°C range, a subsequent careful calibration of the sensors from 5° to 65°C showed the equation used by Tarantino et al. (1980), to overpredict soil temperature at higher ranges, e.g., by approximately 4.5°C at 65°C.

The soil and air temperature profile variation from early morning (0400-0500) to early afternoon (1300-1400) for under canopy location was rather minor as might be expected. This is in contrast to very large changes at the exposed 63SN position. At this location the difference between soil surface temperature and 1-cm air temperature ranges from 16 to 20°C except for July 17 furrow data when high evaporation rates kept surface temperatures from building up.

The lapse or inversion air temperature profiles shown in Figure 4 are in all cases in agreement with underlying soil surface conditions. Also note the inversion profiles for the under-canopy location for the 1300-1400 period for both days and both methods of irrigation. On the other hand lapse conditions prevailed at both locations for the 0400-0500 period.

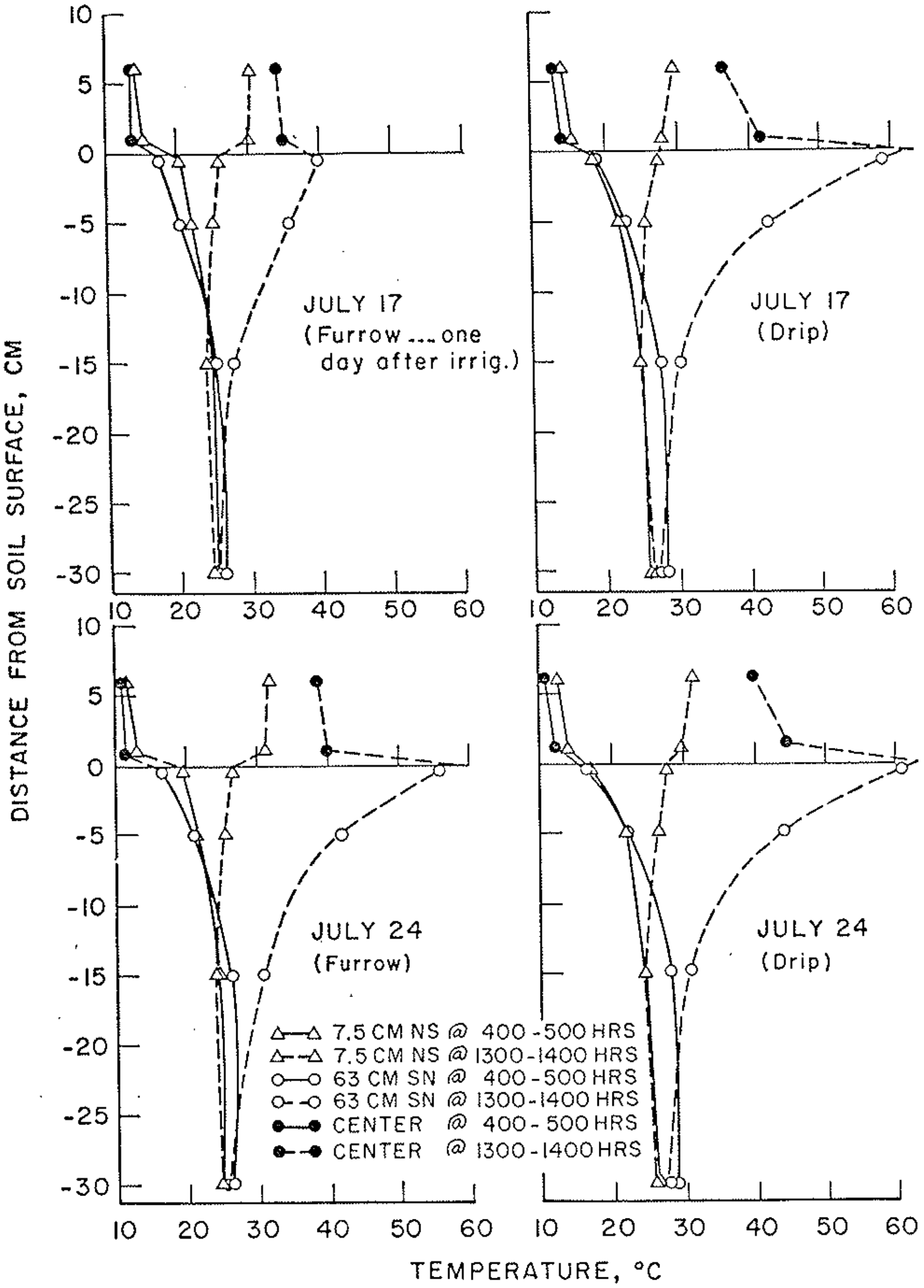

Figure 4. Average soil and air temperature profiles under and within the plant canopy (7.5 NS position) and at (-76-) or near (av. of 63 NS and 63 SN) the mid-row positions for the hours of 0400-0500 and 1300-1400 hours on July 17 and 24, 1980.

The morning to afternoon change in soil temperature profiles at 63 SN for furrow irrigation was much less for July 17 than for July 24 or for either day in the case of drip irrigation. This should not be construed as an indication of a greatly reduced heat transfer since the heat capacity and thermal conductivity of the very moist soil would be much greater than for the dry soil cases.

The differences noted in preceding paragraphs can be more easily understood by referring to Table 1, showing the results of gravimetric determinations of soil moisture on 18 and 24 July. Each value represents the moisture content of a composite of three samples collected along the row. The temperature of a bare soil surface, under a given incident radiation, is affected by the soil reflectivity, emissivity and soil moisture content. Another factor exerting considerable influence is the partitioning of the net radiation of the surface into latent and sensible heat transfers.

Table 1. Soil moisture on 18 and 24 July, two days after and one day before furrow irrigation, respectively, percent by weight.

Depth	Furrow			Drip		
	Distance from the row (cm)			Distance from the row (cm)		
(cm)	0	22.5	76	0	22.5	76
			18 July			
0-5	7.5	18.9	18.2	23.0	12.8	6.7
5-15	19.4	23.0	23.6	25.8	21.5	18.6
15-30	17.3	22.8	25.0	26.6	--	26.3
			24 July			
0-5	14.1	15.0	14.3	23.9	19.6	10.1
5-15	20.4	21.4	20.2	27.9	23.0	20.0
15-30	21.3	20.9	22.6	33.1	26.9	23.2

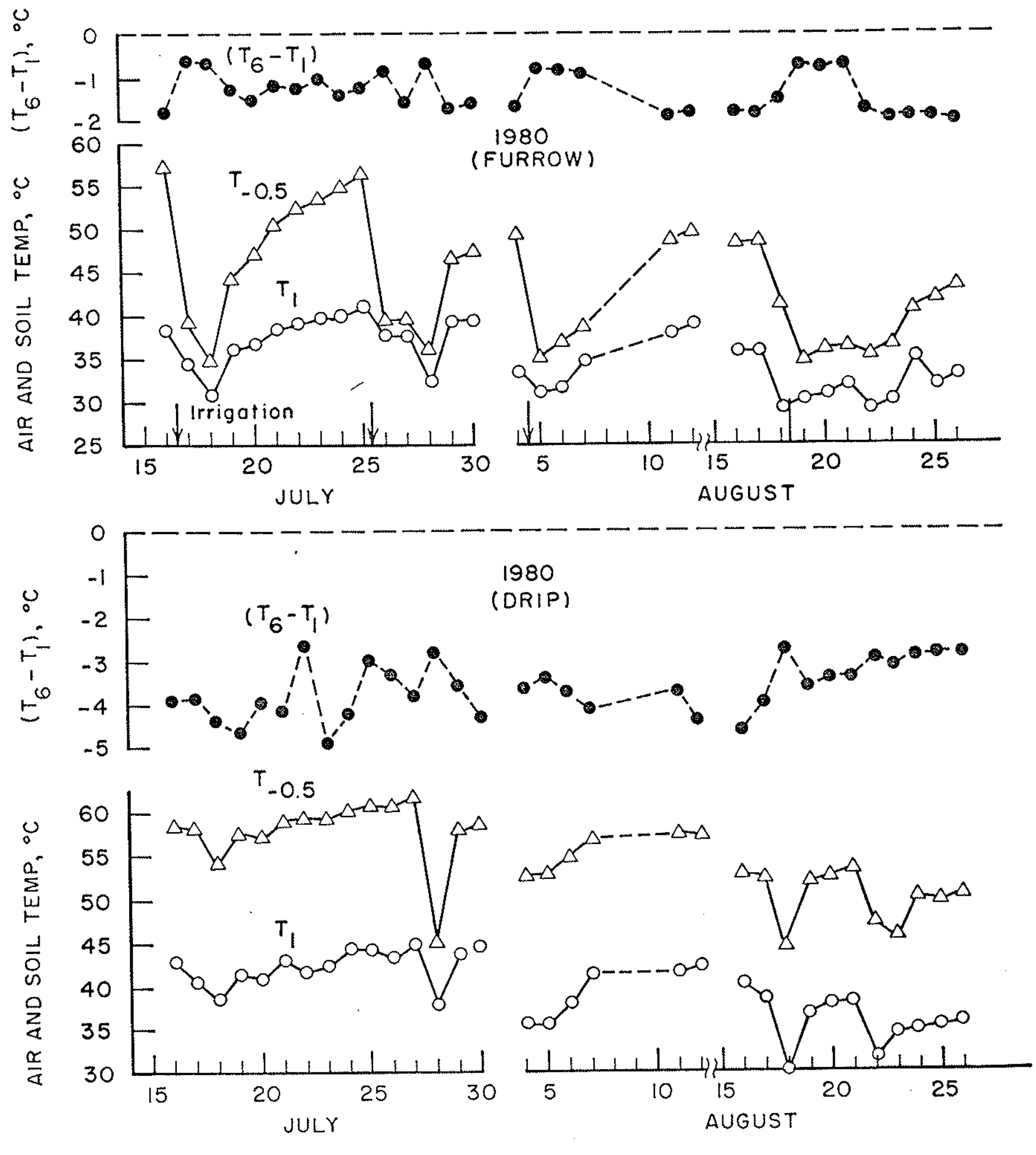

Figure 5. Near surface soil and air temperatures collected at, or near the mid-row positions for the 1300-1400 hour during several irrigation cycles.

Figure 5 presents the day-to-day variation in the 0.5 cm soil temperature (average of 63NS and 63 SN locations) and 1-cm air temperature at mid-row in both lysimeters. Also shown are data for T_6-T_1 for the same hours. The data for the period following the July 16 furrow irrigation illustrate the sharp increase in $T_{-.5}$ by early afternoon of the third day following irrigation. One might consider that the gradual increase each day thereafter until the next irrigation was produced by a decreasing evaporation loss each day. This may be the case for evaporation from mid-row zones but the lysimeter data reflect no further decrease in ET after the fifth day following irrigation. It is also obvious that the effect of irrigation on $T_{-.5}$ is lessened as the season progresses and plant cover increases.

The T_6-T_1 data of Figure 5 suggest that the effect of rewetting by furrow irrigation of mid-row zones every 10 or so days, prevents the forming of lapse rates as great as those in the drip-irrigated lysimeter.

Net Radiation — Tarantino et al. (1982) presented the diurnal patterns of net radiation for July 17 and July 24 for both methods of irrigation. Figure 6 compares on a single graph the patterns of Rn for several radiometers for both July 17 and July 24 for the furrow lysimeter. Data for one radiometer located over the drip-irrigated lysimeter are also shown.

The data for the tube radiometers located out in the open should be considered as somewhat relative, since the directional response of such units is less than ideal (Szeiz, 1975). However a comparison of patterns from the hemispheric Fritschen units with the 63 SN tube units reveals fairly minor problems within the hours of 0800 to 1600. The results also suggest the radiometer calibration factors used[1] are in good agreement.

Results in Figure 6 indicate very low net radiation values on July 17 for the under-canopy location, with only 5-7% of that measured out in the open. Data for the unit located at the 22.5 SN position reflect the increasing canopy cover from July 17 to July 24 although records indicate an increase in average plant cover of the furrow-irrigated lysimeters of only 2% (from 33% to 35%). On July 24 this unit was obviously exposed to some direct sunlight in morning hours but experienced complete shading from 400 on. The negative Rn values reached by 1430 seem unreasonable but the 0.5 SN soil temperature at 1430 was 56.1°C and had dropped only to 46°C by 1630. Assuming a significant area of soil surface viewed by the underside of the radiometer was similarly hot, the negative Rn could occur as soon as all direct solar radiation was blocked out by shading of the plants.

The 15-20% higher Rn on the earlier date for units located at or near mid-row is no doubt due to the lower reflectance and emitted long-wave radiation from the cooler moist soil surface on that date. Figure 7 giving net radiation and soil and air temperature data on the July 16 irrigation date illustrates more clearly the effects of dry and moist soil surfaces (for a 33% plant cover situation). The furrow lysimeter, because of the shape of the furrows (see Figure 1) and lysimeter edges, was essentially basin irrigated. Hence, the very short time period involved in the 6-cm irrigation application. The results indicate a sharp drop in $T_{-.5}$ temperatures in the mid-row zones with some slight increase in surface

---

[1] Factory calibration constants were used for the Delta-T tube radiometers whereas constants developed in calibrations by the USDA Water Conservation Laboratory in Phoenix were used for the Fritschen units.

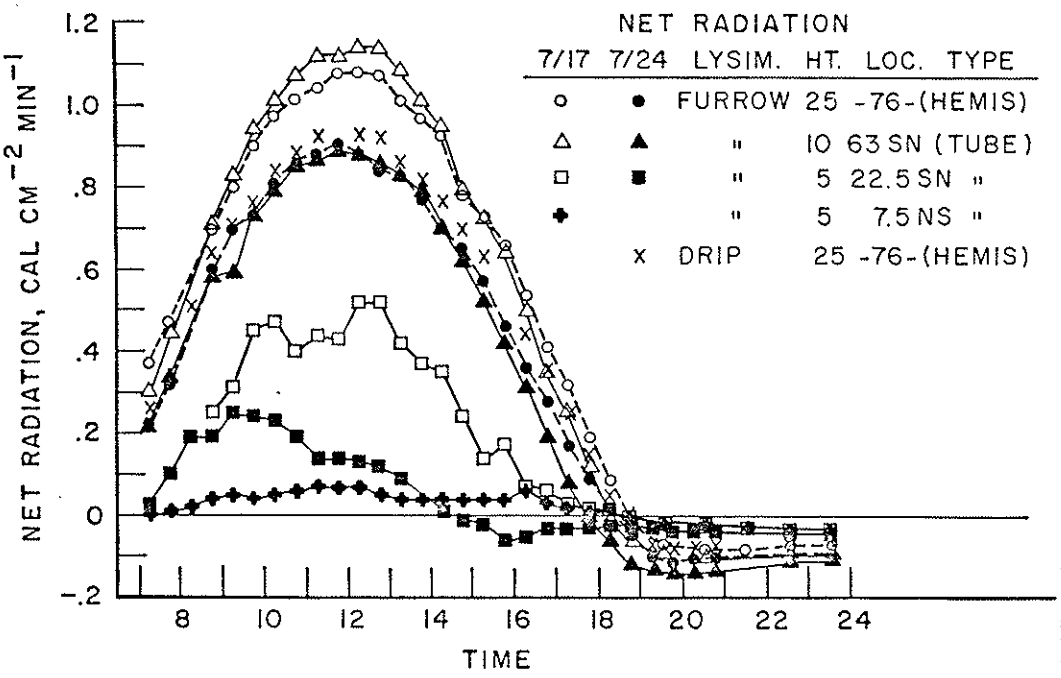

Figure 6. Patterns of net radiation for several positions as indicated by both Fritschen hemispheric and Delta-T tube net radiometers on July 17 and 24, 1980.

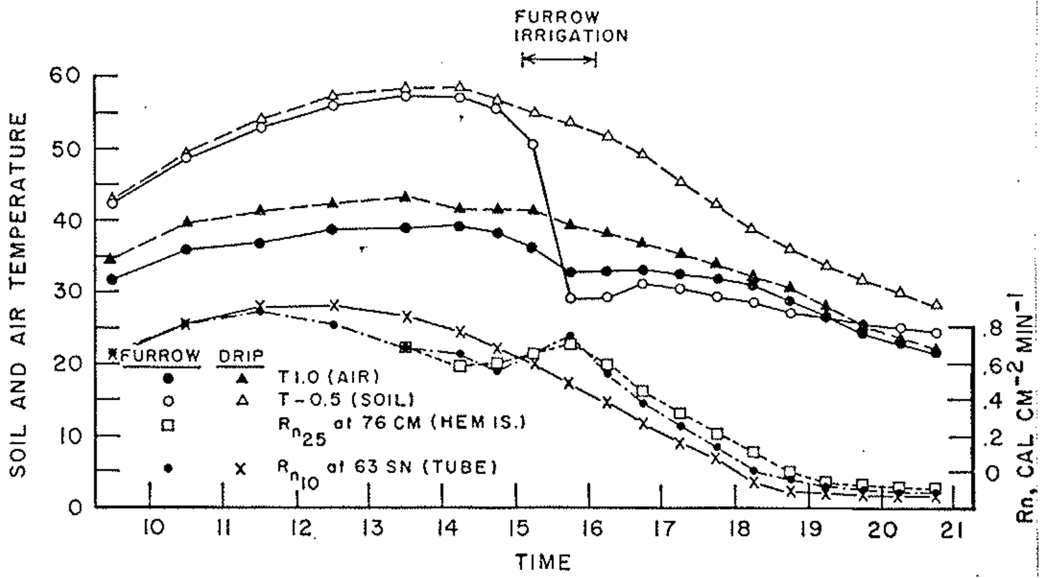

Figure 7. Net radiation and soil and air temperature data before, during, and after the July 16, 1980 irrigation.

temperature after irrigation ceased. Surprisingly, air temperature was effected little. The large drop in $T_{-.5}$ did produce a slight inversion condition.

Unfortunately the Rn_{25} unit in the weighing lysimeter was inoperative until 1300 and the respective unit in the drip lysimeter was out of order during the entire day. The sharp drop in surface temperature and no doubt the reduced reflectance of the soil surface produced a very appreciable increase in Rn for the bare soil near mid-row. Looking at the data for 1600-1630, Rn appears to run about 0.3 cal cm^{-2} min^{-1} higher than a projected curve would indicate, had the area remained dry. A calculated longwave emitted radiation using a T_s of 304°K indicates a value of 0.70 cal cm^{-2} min^{-1}. This compares with a 0.89 value using a projected surface temperature of 323°K. Presumably decreased reflectance could account for the other 0.1 cal cm^{-2} min^{-1}.

Although not shown in Figure 7, the Rn of the furrow lysimeter as measured at a 150 cm height, was approximately 0.15 cal cm^{-2} min^{-1} higher for the 1600-1630 period than it apparently would have been if the soil had remained dry. The Rn_{150} ran almost identical to Rn_{25} from the end of irrigation on, whereas prior to irrigation, Rn_{150} (furrow lysimeter) was paralleling the drip lysimeter Rn_{10} record, but approximately 0.07 cal cm^{2} min^{-1} higher.

Evapotranspiration — Continuing with a presentation of data for the two days we have concentrated on, a figure given by Tarantino et al. (1982) is reproduced in Figure 8, showing a cumulative record of ET for both lysimeters on July 17 and July 24. ET was 8.21 and 6.15 mm on July 17 for the furrow- and drip-irrigated crops, respectively, and 5.05 and 6.25 mm on July 24. Thus there was less than 2% difference in ET in drip irrigation

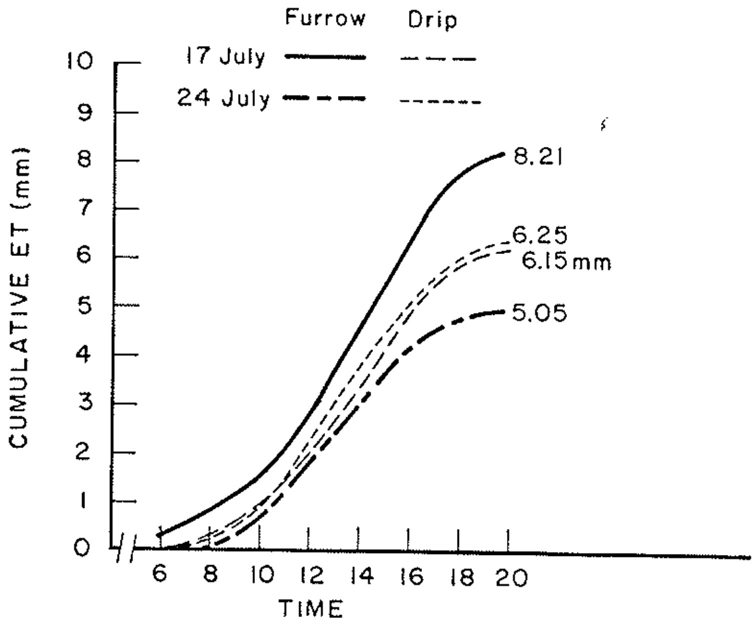

Figure 8. Cumulative hourly evapotranspiration of tomatoes under furrow and drip irrigation as measured by the lysimeters on July 17 and 24, 1980.

for the two days while with furrow irrigation, a 62% higher loss occurred on the first day when all of the soil surface exposed to direct sunlight was moist due to an irrigation late afternoon of the day before.

Figure 9 gives a record for the entire 1980 season of the daily ratios of ET to evaporation from a Class A pan. Although not included herein, the 1979 results were very similar, but with the higher degree of plant cover reached by midsummer (63%), the ET/E_{pan} ratios were averaging around 0.75 rather than 0.7. In earlier Davis studies with a seven to 10 day frequency of irrigation by sprinkling, ratios around 0.9 were common in mid-season but with 85-90% plant cover (Pruitt et al., 1972). The day-to-day values of ET/E_{pan} during the growing season were influenced by the development of the crop canopy and the surface soil moisture status. For both crops in the early stage, as the amount of canopy increased, the ratio increased until maximum values were reached, around the end of July. After that, the ratio began to drop as the plants aged. As a rule, great increases of

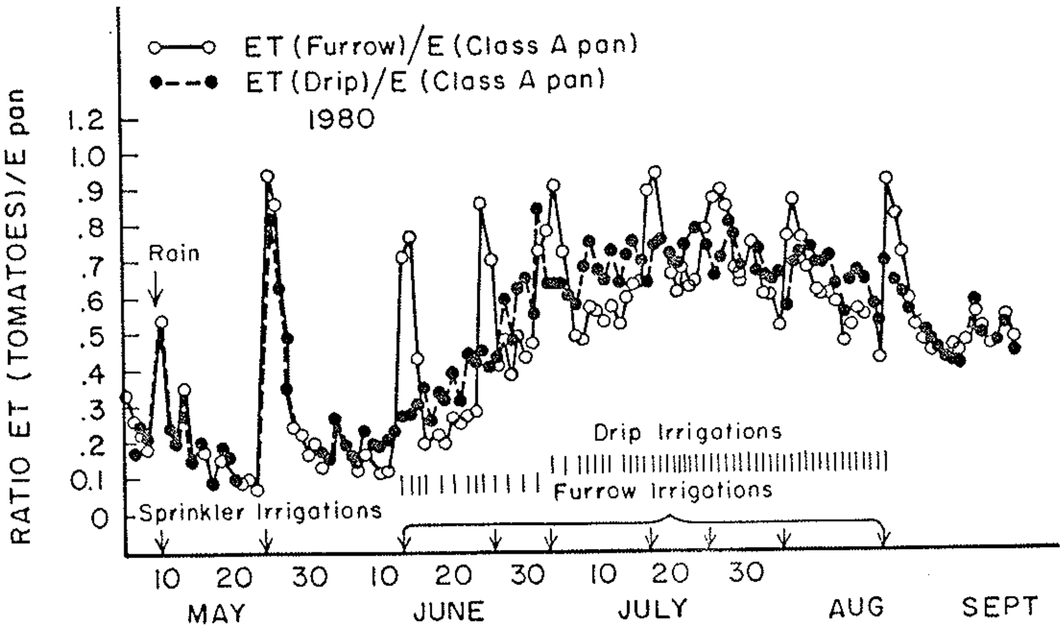

Figure 9. Ratio of daily evapotranspiration (ET) by tomatoes under furrow and drip irrigation to Class A pan evaporation (E) from a date soon after emergence to September 7, Davis, California 1980. Pan was located in a frequently irrigated, frequently mowed grass field (approximately 0.6 ha) near the lysimeters.

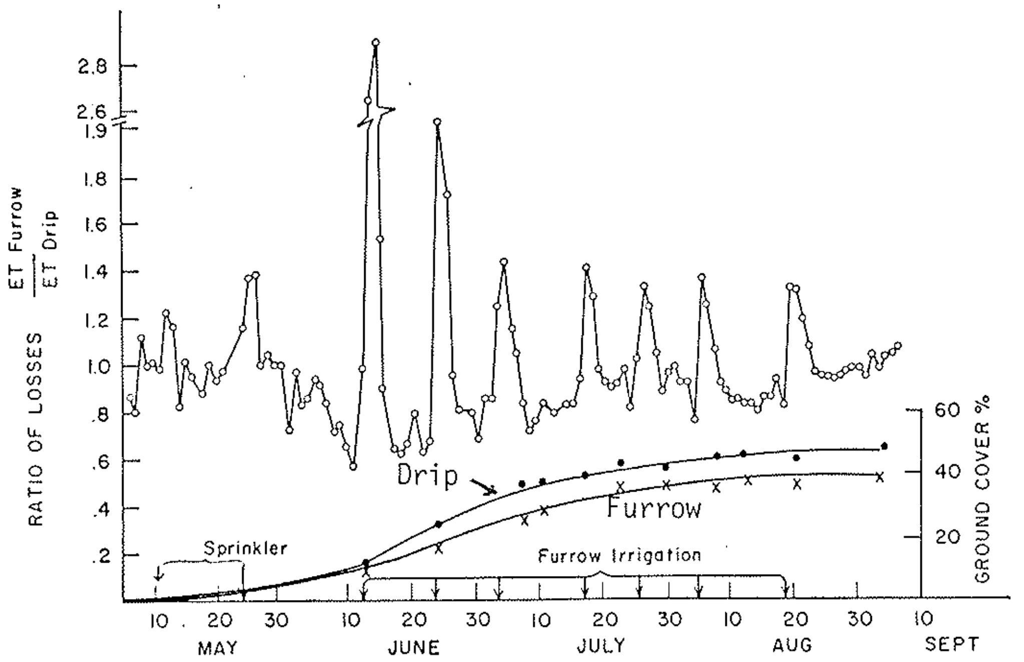

Figure 10. Ratio of daily evapotranspiration by tomatoes under furrow irrigation to those under drip irrigation during the 1980 season. Percent cover data are also shown.

ratios were observed after each watering of the crop under furrow irrigation, especially during early stages of growth.

Figure 10, extracted from Tarantino et al. (1982), shows the variation of the ratio of ET(furrow)/ET(drip) for the 1980 season which somewhat more clearly reveals the effect of rewetting of the soil by each furrow irrigation.

Tarantino et al. (1982) also presented a figure showing the average ratio for the season of ET(furrow)/ET(drip) as a function of days following furrow irrigation. Figure 11 is a similar presentation for 1980 results but with the effects shown for all but the last furrow irrigation. The individual sets of data are identified by the percent cover figures involved from the first full day of wet surface conditions following an irrigation to the last full day preceding the next irrigation.

Figure 12 presents plots based on the same set of data plus some for the 1979 season. Rather than a curve identifying ratios on successive days, Figure 12 curves identify for given days following furrow irrigations (or groups of days) how the ratio of ET(furrow)/ET(drip) varied as a function of percent ground cover. The two sets of data blend very well together, and by inclusion of the 1979 data, the trends in the ratios as affected by increasing percent cover, are more clearly identified. It is obvious that with furrow irrigations of 5-8 cm on Yolo loam soil, that the number of days following an irrigation in which evaporation from the soil surface remains a significant factor, varies with percent cover. For example, note that for the fourth day the ratio is well below 1.0 during early stages of plant cover but by the time 60% cover is reached the ratio exceeds 1.0. Also revealed is the fact that for the first and second day very high ratios are reached at early growth stages with a reduction to around 1.3 by the time cover reaches 30%. Relating this to Figure 9, however, it should be recognized that these very high ratios for low percent cover situations, are largely because the losses of the drip-irrigated lysimeter are still rather minor. It should be noted that the ratios in Figure 11 (all 1980 data), and for the 1980 data in Figure 12, would no doubt have been higher if the percent cover for both drip-irrigated and furrow-irrigated crops had been closer in 1980.

Data on total seasonal evapotranspiration for both years are given in the first column of Table 2. In 1979, a year when plant cover in both lysimeters remained very close throughout the season (see Figure 13(A)), the ET loss by the two lysimeters was very close with only a 1% greater loss for the furrow lysimeter. Although not given in Table 2 the ET for the furrow and drip lysimeters for the period from July 3 to October 8 was 48.3 cm and 47.6 cm respectively or 1.5% different. The ET for the total season for the field plots in 1979 likewise showed a 1.5% greater loss for furrow as compared to drip but with both field treatments running some 7-8% above the lysimeter losses. However, it is evident from Figure 13(A) that the percent cover developed in the field plots was greater than in the lysimeter. In 1979 both drip treatments reached close to 90% ground cover but the plastic mulch treatment had 6% less ET, no doubt due to decreased evaporation losses from the soil.

Total seasonal evapotranspiration for the 1980 tomatoes growing in the furrow-irrigated lysimeter was practically the same as that in the drip-irrigated lysimeter from April 1 to September 10, with values of 55.9 and 56.6 cm, respectively. Losses from June 6 to September 10 which relate to the actual period of differential methods of irrigation were, respectively, 45.4 and 46.1 cm. The somewhat higher ET by the drip-irrigated lysimeter

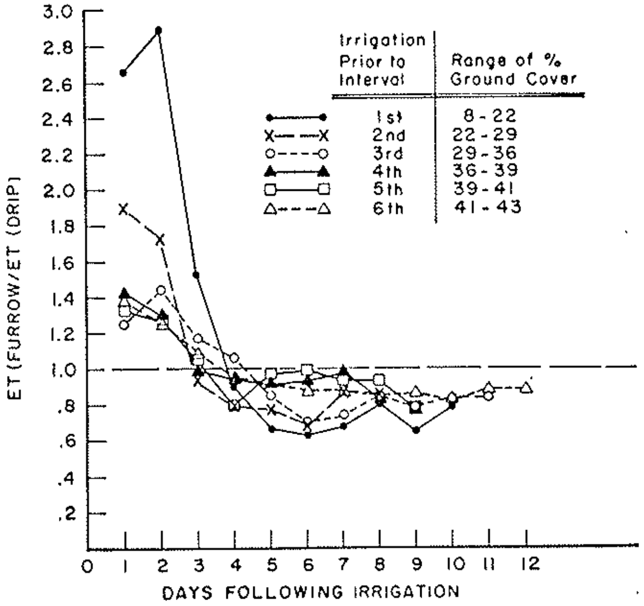

Figure 11. Ratio of daily evapotranspiration by furrow-irrigated to drip-irrigated tomatoes in 1980, plotted against days following irrigation. The percent ground cover (average of data for the two lysimeters) at the beginning and end of each interval between irrigations are also given.

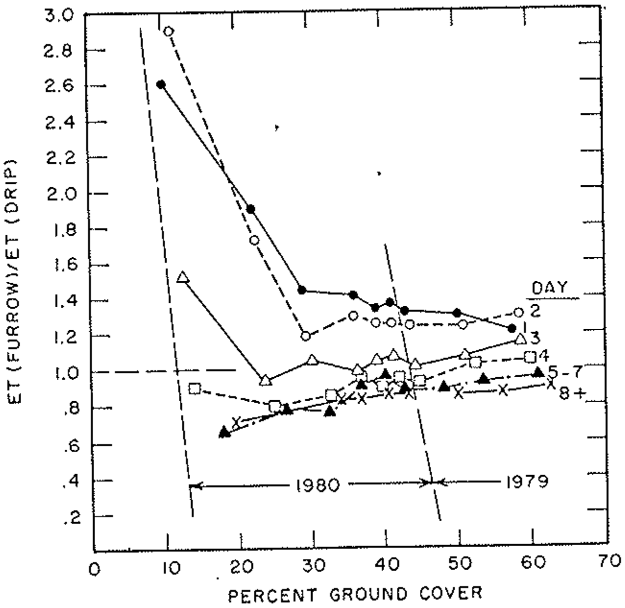

Figure 12. Ratio of daily ET(furrow)/ET(drip) for 1979 and 1980 for first, second, and third, etc., days after irrigation plotted as a function of percent ground cover.

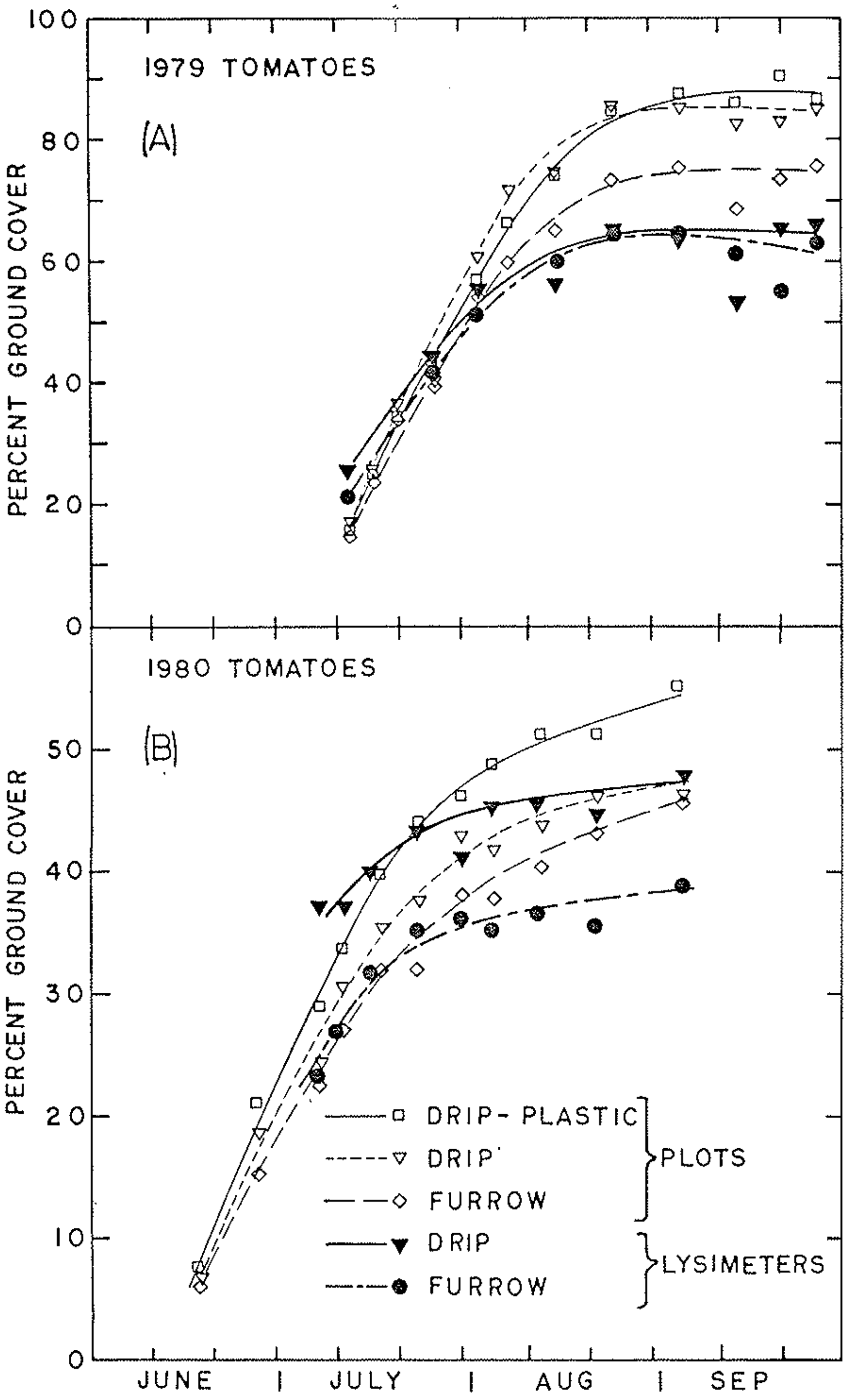

Figure 13. Percent ground cover for processing tomatoes grown in lysimeters and in replicated field-plot treatments in 1979 and 1980, Davis, Ca.

Table 2. Total ET in cm from planting to harvest and yield of processing tomatoes under furrow and drip irrigation. Davis, California, 1979 and 1980.

	ET	Yield Ton/ha				WUE Tha^{-1}cm^{-1}
Irrigation method	cm	Ripe	Green	Rotten	Total	(ripe fruit)
				1979		
Furrow-irrigated lysimeter	61.5	75.1	2.3	2.2	79.6	1.22
Furrow field plots	65.9	86.0 a*	7.2	0.7	93.9 a	1.31
Drip-irrigated lysimeter	60.8	82.1	1.9	4.5	88.5	1.35
Drip field plots	64.9	102.4 a	2.7	1.8	106.9 a	1.58
Drip & plastic plots	60.9	98.8 a	5.8	1.1	105.7 a	1.62
				1980		
Furrow-irrigated[1/] lysimeter	55.9	77.2	3.5	0.0	80.7	1.38
Furrow field plots[2/]	59.6	58.6 b	2.1	-	60.7 b	0.98
Drip-irrigated[3/] lysimeter	56.6	89.4	5.5	4.5	94.9	1.58
Drip field plots[2/]	61.6	66.2 b	1.0	-	67.2 b	1.07
Drip & plastic plots[2/]	61.2	83.8 c	1.5	-	85.8 c	1.37

* Values not followed by the same letter are significantly different at the 5% level.

[1/] Furrow lysimeter plants were cut at ground level on September 6 and left on lysimeter for a special test to determine a wind functional relationship. Fresh weight of fruit as measured on September 17 was corrected back to September 6 based on changes in percent moisture of a subsample of two vines with their fruit allowed to dry in the field.

[2/] Harvest date of September 10.

[3/] As harvested on September 17 seven days after field plots were harvested. Since at this stage of maturity tomato fruits tend to show little if any further assimilation the affect on yield due to the different harvest dates can be ignored.

in 1980 no doubt reflects to some degree the higher percentage of cover achieved in the drip lysimeter (47% maximum) as compared with 38% in the furrow lysimeter (see Figure 10) . Recall however that in 1979, when both lysimeters reached 63% cover, the ET (during the period of differential irrigation treatments) was only 1.5% higher in the furrow lysimeter than in the drip lysimeter.

The ET of field plots in 1980, again was 7-8% higher than for the lysimeters. The plastic mulch treatment did not show a lower ET in 1980 but this could be due to the development of a greater percent ground cover in this treatment (see Figure 13(B)) than for other treatments both within and outside the lysimeters.

Yield and Water Use Efficiency — Table 2 gives yield, ET and water use efficiency data for the 1979 and 1980 seasons. Marketable yield of fruit from the drip lysimeter was 9% and 16% higher than from the furrow lysimeter for 1979 and 1980, respectively. For the field plots the drip outyielded the furrow by 19% and 13% for 1979 and 1980, respectively. It should be noted from Table 2 that the yield differences between treatments in 1979 were not statistically significant at the 5% level. In 1980 the mulched drip treatment showed a significantly higher yield than the other two treatments. It is speculated that with the cool late spring conditions of 1980 the mulched plots had a more favorable thermal condition which enhanced canopy growth in this treatment (see Figure 13(B)) and increased final yields.

Interestingly both lysimeters had somewhat higher yields in 1980 than in 1979 while the reverse was true for the field plots where 1979 yields were some 145 to 155 percent greater than in 1980. The percent ground cover of field plots in 1979 exceeded considerably that achieved in the lysimeters, with furrow plots reaching 75% cover, and both sets of drip plots approaching 90% cover. In 1980 however the percent cover of field plots was similar to that in the lysimeters with values of 45%, 47% and 55% for furrow, drip and drip with plastic, respectively. The 1980 season with a much cooler than normal May and early June was not a good season in the Sacramento Valley for late April plantings of the variety of tomatoes grown. In relation to this study however it did provide a chance for extensive micrometeorological work under limited amounts of plant cover, a condition under which evaporation savings with drip irrigation is most likely.

The water use efficiency data in Table 1 do show some advantage for drip irrigation treatments where, for example, in the field plots (replicated four times) WUE for drip plots was 20% and 9% higher than for furrow plots in 1979 and 1980, respectively. The larger difference in 1979 may have been the result of a breakage in the furrow delivery system which delayed the first furrow irrigation of field plots until July 23, whereas the drip plots were irrigated on July 12, 13, 14, 16 and 17, with a delay then until July 23. (All plots in 1979 were sprinkler irrigated until early in July).

ACKNOWLEDGMENTS

The authors will take this opportunity to recognize important contributions to this work of Dr. Pyare Lal, Dr. Hamid Siadat, Dr. Ali Kamgar, Dr. Saad Ghariani, Mr. Mohammad Rayej, Miss Christina Chauncey and Mr. Okey Onyejekwe.

LITERATURE CITED

Blaney, H. F. and W. D. Criddle. 1950. Determining water requirements in irrigated areas from climatological and irrigation data. USDA(SCS)TP-96. 48 p.

Brooks, F. A., W. O. Pruitt, and others. 1966. Investigation of energy, momentum and mass transfers near the ground. Final Report USAEC Grant No. DA-AMC-28-043-65-G12 (DDC-AD 635-588). University of California, Davis. 259 p.

California, State of. 1975. Vegetative water use in California, 1974. State Dept. of Water Resources Bulletin No. 113-3. 104 p.

Christiansen, J. E. and G. H. Hargreaves. 1969. Irrigation requirements from evaporation. Trans. Intern. Comm. on Irrig. and Drain. III: 23.569-23.596.

Doorenbos, J. and W. O. Pruitt. 1977. Crop water requirements. Irrigation and Drainage Paper No. 24, FAO Rome, Italy (revised 1977). 144 p.

Erie, L. J., Orrin F. French, and Karl Harris. 1965. Consumptive use of water by crops in Arizona. University of Arizona Agr. Exp. Sta. Bull. No. 169. 44 p.

Goddard, Wilson B. 1970. A floating drag-plate lysimeter for atmospheric boundary layer research. J. Appl. Met. 9:373-378.

Hanks, R. J. 1974. Model for predicting plant yield as influenced by water use. Agron. J. 66:660-665.

Jensen, M. E. and H. R. Haise. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. and Drain. Div., ASCE 89:15-41.

Middleton, J. E., W. O. Pruitt, P. C. Crandall and M. C. Jensen. 1967. Central and western Washington consumptive use and evaporation data, 1954-62. Washington Agr. Exp. Sta. Bull. 681. 7 p.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc., London A193:120-145.

Penman, H. L., D. E. Angus, and C. H. M. van Bavel. 1967. Microclimate factors affecting evaporation and transpiration. pp 483-505. In: R. M. Hagan, H. R. Haise, and T. W. Edminister (Eds.), Irrigation of Agricultural Lands, Amer. Soc. Agron. Monograph 11, American Society of Agronomy, Madison, WI.

Pruitt, W. O. and D. E. Angus. 1960. Large weighing lysimeter for measuring evapotranspiration. Trans. ASAE 3(2):13-15, 18.

Pruitt, W. O., F. J. Lourence, and S. von Oettingen. 1972. Water use by crops as affected by climate and plant factors. Calif. Agric. 26(10):-10-14.

Pruitt, W. O., Elias Fereres, D. W. Henderson and R. M. Hagan. 1981. Potential of drip irrigation in row crops for agricultural water conservation in California. 1980-81 Annual Report, Water Resources Center and OWRT Project W-572 (A-076-CAL). University of California, Davis. 4 p.

Ritchie, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8:1204-1213.

Shalevet, J., A. Mantell, H. Bielorai and D. Shimshi. 1981. Irrigation of field and orchard crops under semi-arid conditions. International Irrigation Information Center, Bet Dagan, Israel and Ottawa, Canada. 2nd Revised Edition. 132 p.

Szeicz, G. 1975. Instruments and their exposure. pp. 229-273. In: J. L. Monteith (Ed.), Chapter 7, Vegetation and the Atmosphere, Vol. 1, Principles, Academic Press, London.

Tanner, C. B. and W. A. Jury. 1976. Estimating evaporation and transpiration from a row crop during incomplete cover. Agron. J. 68:239-242.

Tarantino, Emanuele, Harbir Singh and W. O. Pruitt. 1982. The microclimate of processing tomatoes under drip and furrow irrigation. Rivista di Agronomia 1:21-29.

Thornthwaite, C. W. 1948. An approach toward a rational classification of climate. Geograph. Rev. 38:55-94.

Turc, L. 1961. Estimation of irrigation water requirements, potential evapotranspiration: a simple climatic formula evolved up to date. Ann. Agron. 12:13-49.

PUBLICATIONS

Tarantino, Emanuele, Harbir Singh and William O. Pruitt. "The microclimate and evapotranspiration of processing tomatoes under drip and furrow irrigation." *Rivista di Agronomia,* XVI-1:21-29 (1982). (See attachment)

Pruitt, W.O., D.W. Henderson, E. Fereres, R.M. Hagan, Paul E. Martin, E. Tarantino, Harbir Singh and Bashir Chaudio. "Microclimate, evaporation losses, and water use efficiency for drip- and furrow-irrigated tomatoes." Presented to Ninth Technical Conference on Irrigation, Drainage and Flood Control, ICID, Jackson, Mississippi, October 22-24, 1982.

Pruitt, W.O., D.W. Henderson, E. Fereres and R.M. Hagan. "Evapotranspiration and yield of processing tomatoes under furrow and drip irrigation." Presented to California Plant and Soil Conference, Riverside, California, January 26-28, 1983.

Emanuele Tarantino, Harbir Singh, William O. Pruitt

The microclimate and evapotranspiration of processing tomatoes under drip and furrow irrigation

SOCIETÀ ITALIANA DI AGRONOMIA

S. I. A.

Estratto da
« RIVISTA DI AGRONOMIA »
anno XVI - n. 1 - gennaio-marzo 1982

The microclimate and evapotranspiration of processing tomatoes under drip and furrow irrigation (1)

Emanuele Tarantino, Harbir Singh, William O. Pruitt (2)

Introduction

Water losses from a cropped area to the atmosphere is the result of evaporation from the soil (E) and transpiration (T) from plant surfaces. The combination of both processes, called evapotranspiration (ET), is equivalente to the crop water requirements.

When annual row crop plants are in an early growth stage and have little ground cover from the canopy, the evapotranspiration rate from the field is dominated by the soil evaporation rate. As the crop canopy increases, the evapotranspiration rate becomes more dependent on the leaf area (Penman *et al.*, 1967).

Many studies have been conducted to predict the ET requirement of varius crops (Pruitt *et al.*, 1972; Doorenbos and Pruitt, 1977), and models for calculating E and T separately have been studied (Ritchie, 1972; Tanner and Jury, 1976) for use with conventional irrigation methods that essentially wet the entire soil surface. However, because of the smaller area of wet soil surface under drip irrigation and strong thermal gradient between dry and wet zones with microscale advection from the former to the latter area, those measurements and models are not applicable to drip-irrigated crops.

Because drip irrigation ideally involves minor losses of water by evaporation, it may be expected to reduce evapotranspiration more than most other methods, especially during the early stage when a large percentage of the soil surface remains unshaded.

Although many studies have compared drip irrigation with other methods of irrigation, very few involved an accurate determination of actual ET loss for short periods or the detailed microclimate measurements needed for separating the E and T components of ET. Therefore, in 1979 a new project was initiated at the University of California at Davis. A major objective of the project was to investigate possible savings in evapotranspiration by drip-irrigated row crops as compared with furrow-irrigated row crops and to develop models for predicting expected evapotranspiration losses that might be extended to plant and row spacings not represented.

The present communication is limited to specific findings from the 1980 growing season. In particular, it deals with some micrometeorological observations on representative days of the growing season and comparisons of ET and yield of processing tomatoes under furrow irrigation with ET and yield under drip irrigation.

Materials and Methods

The experiment was conducted during the summer of 1980 on a Yolo loam soil at the experimental farm of the University of California at Davis. Geographic coordinates of the site are latitude 38°32′15″ North, longitude 121°46′30″ West, and altitude 17 m above mean sea level.

Processing tomatoes (« UC 82 » variety) were direct-seeded in two large lysimeters and surrounding fields (~ 1 ha) on 23 April, the eastwest rows were spaced 152 cm apart. Fertilizer (N 134 kg/ha, P 100 kg/ha) was broadcast by mechanical spreader evenly over the entire area ten days before planting. On May 2 the plants began emerging, and on May

---

(1) Ricevuto l'11.5.1981. The research leading to this report was supported by the Office of Water Research and Technology, USDI, under the Annual Cooperative Program of Public Law 95-467, and by the University of California Water Resources Center as part of the Office of Water Research and Technology Project No. A-076-CAL and the Water Resources Center Project UCAL-WRC-W-572. Contents of this publication do not necessarily reflect the views and policies of the Office of Water Research and Technology, U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement or recommendation for use by the U.S. Government. Principal Investigators: W. O. Pruitt, Elias Fereres-Castiel, Delbert W. Henderson, and Robert M. Hagan.

(2) Researcher, Consiglio Nazionale Delle Ricerche, Centro di Studio sull'Orticoltura Industriale, Bari, Italy; Assistant Professor, Dept. of Agronomy, Haryana Agricultural University, Hissar, India; Irrigation Engineer, Dept. of Land, Air and Water Resources, University of California, Davis, respectively.

The authors gratefully acknowledge the efforts of Paul E. Martin, Hamid Siadat, Saad Ghariani, and Mohammad Rayej. Project Principal Investigators also recognized are Drs. E. Fereres, D. W. Henderson, and R. M. Hagan.

20 they were cultivated and thinned to an appropriate spacing of 22.9 cm within each row.

The crop was uniformly sprinkler irrigated from planting up to May 24. Differential irigation methods (furrow and drip) were started on June 13.

Evapotranspiration of tomatoes under furrow irrigation was determined from a 6.1 m-diameter, 90-cm deep weighing lysimeter described by Pruitt and Angus (1960), and that of the crop under drip irrigation was determined by a 6.1 m floating drag-plate lysimeter described by Brooks (1966) and Goddard (1970). Both systems are sensitive to within aproximately 0.02 mm of evapotranspiration; they are, perhaps, the only such highly sensitive lysimeters existing that also are large enough to provide for a sample size of almost a hundred plants, even when crops are in widely-spaced rows (152-cm row spacing). However, the limiting of rooting to the depth of the lysimeters (90 cm) may be a problem with irrigation intervals>seven days in midsummer Davis conditions.

The drip irrigated lysimeter was irrigated by microtubing emitters (0.82 mm inside diameter) placed 45.8 cm apart on the lateral so that after thinning, each emitter irrigated two adjacent plants, one on each side.

The drip-irrigated lysimeter and the surrounding field were irrigated daily during the season except for a few times during early stages when the field was irrigated every other day. Frequency of furrow irrigation in the weighing lysimeter and surrouding field was at approximate ten-day intervals. Most farmers in the area use a 10-14 day schedule. At each irrigation, both the furrow- and the drip-irrigated tomatoes received an amount of water equal to the total ET lost since the previous irrigation.

For both the furrow- and the drip-irrigation lysimeter sites, micrometeorological data were gathered on a number of representative days during the growing season. The vertical and horizontal variation in soil and air temperature, net radiation, humidity, and wind speed were determined. This report includes data for soil and air temperature and net radiation on July 17 and 24, one day after the fourth furrow irrigation and one day before the fifth furrow irrigation.

Figure 1 shows two vertical cross-sections, respectively, for furrow and drip methods, the location of soil and air temperature sensors, and net radiometers. Soil-temperature sensors were made up of 24-gauge, two-junction copper-Constantan thermopiles to give a mean of temperature at two places and provide a sensitivity twice that of single-junction units. They were placed along the soil profile (0.5-, 5-, 15-, and 30-cm depth) at several locations transversely between the plant rows. The upper two levels had thermopiles located 7.5, 22.5, 40, and 63 cm north of one row in the lysimeter and at the same distances south of an adjacent row to the north. Thermopiles located 15- and 30-cm deep in the soil were located at every other position. Similarly, two-junction, air-temperature thermopiles (30-gauge Cu-Co) were located 6 cm above the soil surface at 7.5, 22.5, and 40 cm from the south row and in the middle between rows, and at 7.5, 22.5, and 40 cm from the north row. In addition at each of these locations, four-junction thermopiles averaged the differences of temperature (△T)between 1 and 6 cm above the soil surface.

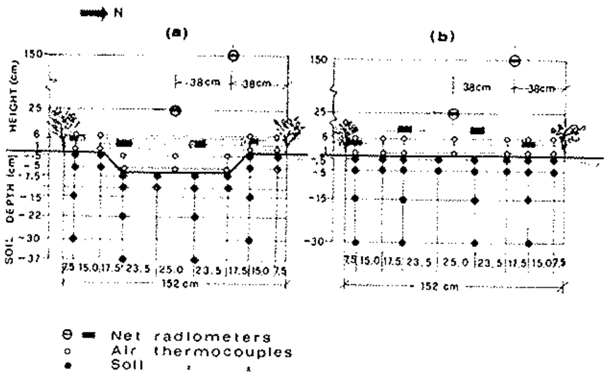

Fig. 1 - Location of the net radiometer (⊖, ▬) and thermocouples along the air (○) and soil (●) profile in tomatoes furrow-irrigated (a) and drip-irrigated (b) lysimeters planted to tomatoes. Davis California, 1980.

Fig. 1 - Posizione dei radiometri netti e delle termocoppie lungo il profilo dell'aria e del suolo in file di pomodoro irrigato a solchi (a) e a goccia (b).

Each thermopile set was calibrated in a water bath of known temperature to obtain the response curve.

Net radiation was measured at 25 and 150 cm above the soil surface using Fritschen net radiometers. Net radiation under the plant canopy and between the rows was measured with 39-cm long tube net radiometers (Delta-T Devices of Cambridge) placed in each lysimeter at four locations 7.5 and 40 cm north of the south row and 22.5 and 63 cm south of the adjacent north row. The two units closest to tomato rows were placed 5 cm above the soil surface, and the other two were placed 10 cm above the soil surface.

Class A pan evaporation and precipitation data were available from an irrigated turf grass weather station located about 150 m south of the lysimeter area.

Soil moisture profiles for both lysimeters were determined several times after each furrow watering and one day before each furrow watering, up to 30 cm deep on the row and in the middle between the rows, at 22.5 cm from the south row, and at 22.5 cm from the north row.
These data were needed to determine thermal conductivity values. The percentage moisture in the soil samples was measured gravimetrically.

Percent ground cover during the growing season was calculated by dividing the width of plant canopy by row spacing which was 152 cm. A 150-cm ruler was used to take 30 random measurements of plant row width in each lysimeter. During the early growth stages data were taken from pictures.

The tomatoes were harvested on September 17. For yield determination, plants were cut at the soil surface and shaken to remove fruit; red, green, and rotten fruit were weighed separately.

Experimental Results

Soil Temperature — Figure 2 shows an example of soil and air temperature profiles (hourly mean values between 14.30 and 15.30) in tomatoes under furrow and drip irrigation on July 17 and 24, respectively (one day after and one day before furrow irrigation). In each situation near the surface, the soil temperature gradient (as indicated by the distances between two isotherms) increased. In addition, average soil temperatures at the time of reading showed an asymmetric distribution along the sections with lower values at southernmost sites between the tomato rows. This reflects the greater degree of shading compared with more exposed northerly zones between the rows. Below 25 cm, the temperature was generally less than 30°C. As shown, maximum soil temperatures under the drip system were higher than under the furrow system.

On July 17, maximum temperatures were 58° or more under the drip method at the 0.5-cm depth in the dry area near the midpoint between rows; whereas the temperature was about 38° in the furrow irrigation crop at the same area (but wet). On July 24, similar trends were found, although differences between the two irrigation methods were much less pronounced.

Those differences between the two methods can be attributed primarily to the difference in soil moisture (Table 1). The temperature of a bare soil surface under a given incident radiation is affected by soil reflectivity, emissivity, and moisture content. The third factor exerts considerable influence on the partitioning of absorbed energy into latent heat and sensible heat transfer (in soil below and air above the surface). In addition, penetration of the heat into the soil is determined by the heat capacity and thermal conductivity, of soil, both of which vary with moisture content. Since each cubic centimeter of soil has a certain heat capacity, the total daytime rise in temperature is a function of the total heat flow into the ground.

Figure 3 shows changes in soil temperature profiles between 7.00 and 14.00 for under-canopy and between-row locations. Profile variations during the day for under-canopy locations were rather minor.

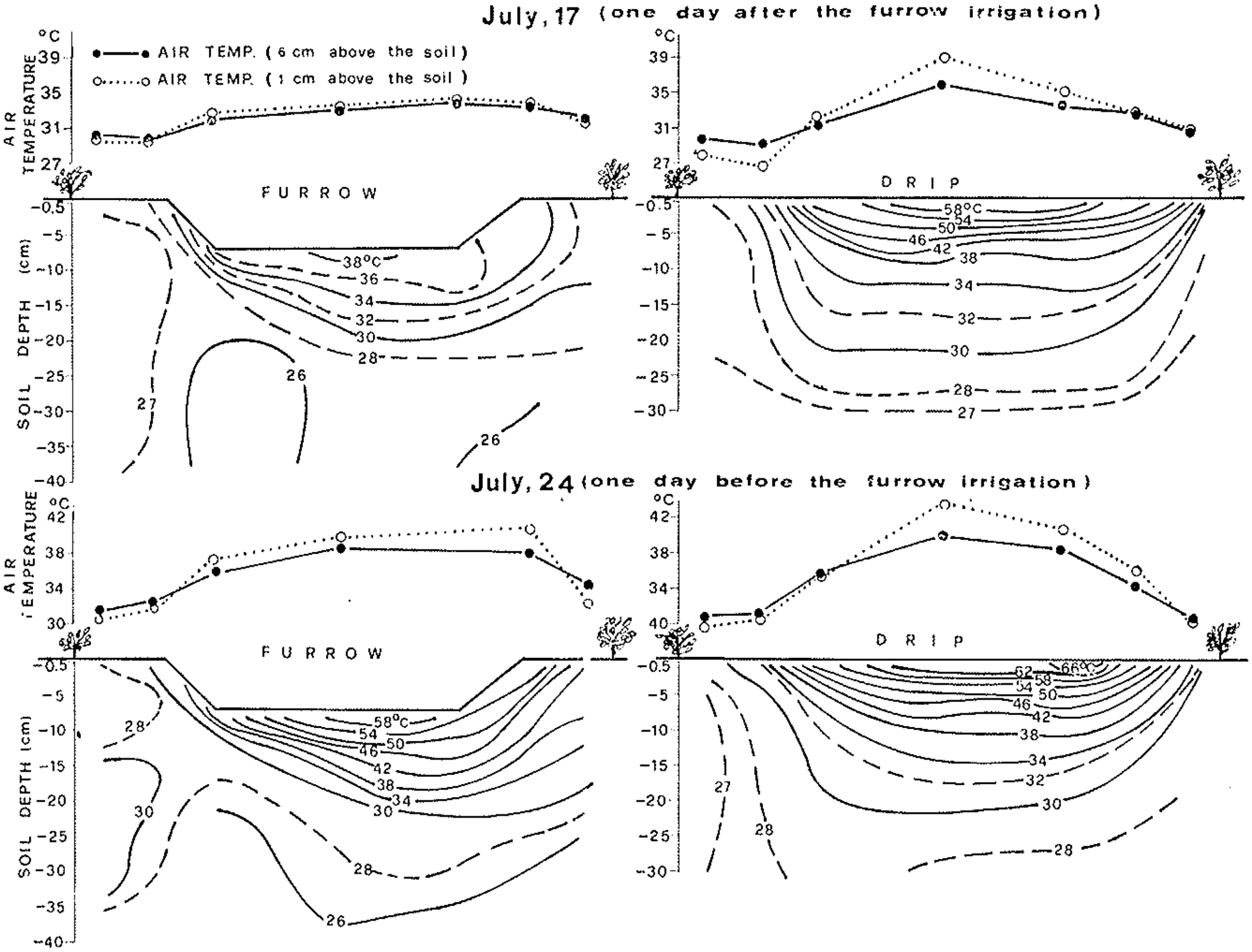

Fig. 2 - Typical distribution patterns of the daily maximum air and soil temperatures in tomatoes furrow- and drip- irrigated (one hour-mean between 14.30 and 15.30) on July 17 and 24, one day after furrow irrigation and one day before the following furrow irrigation. (Data were taken from locations as indicated in Fig. 1).

Fig. 2 - Andamento tipico delle temperature massime giornaliere dell'aria e del terreno in colture di pomodoro irrigate a solchi e a goccia (medie orarie tra le 14,30 e le 17,30 del 17 e del 24 luglio). Il rilevamento dei dati è stato fatto nelle posizioni indicate nella figura 1.

15,30

TABLE 1. - *Percent soil moisture (by weight) on july 18 and 24, two days after furrow irrigation and one day before the The following furrow irrigation.*

TABELLA 1. - Umidità del terreno il 18 e il 24 luglio, due giorni dopo e un giorno prima dell'irrigazione per infiltrazione laterale da solchi, rispettivamente.

Depth	Furrow			Drip		
	Distance from row (cm)			Distance from row (cm)		
(cm)	0	22.5	76	0	22.5	76
18 July						
0-5	7.5	18.9	18.2	23.0	12.8	6.7
5-15	19.4	23.0	23.6	25.8	21.5	18.6
15-30	17.3	22.8	25.0	26.6	—	26.3
24 July						
0-5	14.1	15.0	14.3	23.9	19.6	10.1
5-15	20.4	21.4	20.2	27.9	23.0	20.0
15-30	21.3	20.9	22.6	33.1	26.9	23.2

The variation in temperature from morning to afternoon was about the same for the furrow-irrigated crop, one day before irrigation as for the drip-irrigated crop. The daytime change in the temperature profiles of the furrow lysimeter was much less for the day following irrigation. This does not necessarily mean that a great deal less heat transfer into the soil took place because with the very high soil moisture conditions the heat capacity would have been much greater than for dry soil. A qualitative analysis of soil heat transfer remains to be done.

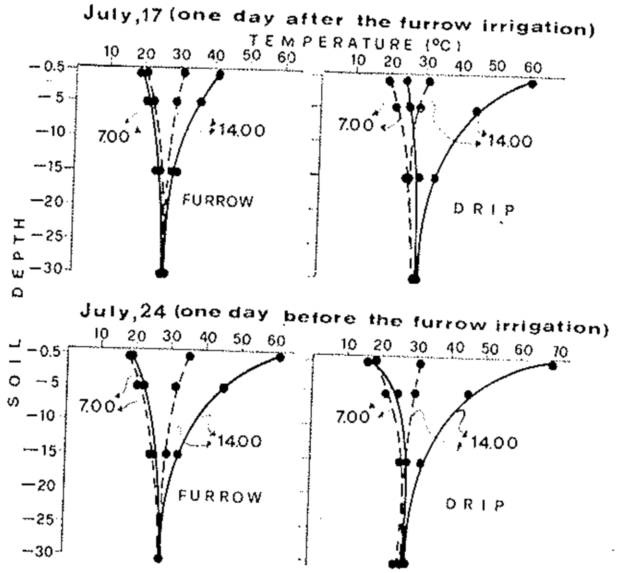

Fig. 3 - Soil temperature profiles in furrow- and drip-irrigated tomatoes as observed at 7.00 and 14.00 on July 17 and 24. Dashed lines indicate profiles under canopy while profile data for between-row sites are indicated by solid lines.

Fig. 3 - Profili delle temperature del terreno osservati in colture di pomodoro irrigate a solchi e a goccia alle 7 e alle 14 del 17 e del 24 luglio. Le linee tratteggiate indicano i profili sotto la copertura vegetale, le linee intere indicano i profili tra le file di pomodo.

Air Temperature — Figure 2 shows air temperatures obtained 1 and 6 cm above the soil surface at several locations across the tomato rows. In areas exposed to direct sunlight, a very strong gradient between soil surface and air was evident in midafternoon with soil temperature (at 0.5 cm) exceeding 1 cm air temperature by as much as 20°C, although in the furrow case, this difference was only 4°C the day after irrigation. In shaded zones, the 0.5-cm soil temperature was within 1-3°C of 1-cm air temperature. As expected in sunlit areas, a strong lapse rate (3-4°C) was evident for the 1 cm to 6 cm level in the air above the dry soil surface, especially in the drip-irrigated case. In the furrow case in sunlit areas, the lapse rate was 2-3°C the day before irrigation, but only 0.2-0.3°C the day following irrigation. In all cases in shaded zones, there was an inversion profile. For the drip plot with the considerably hotter soil surface out in the open (58-63°C), this hot air was obviously being advected into zones under the canopy, creating an inversion of some 1-2°C between the 1 cm and 6 cm levels. This was true only on the north side of the row, suggesting that wind direction at the time was from the north. On the south side of the row, but in shaded zones, there was little if any air temperature gradient.

Net Radiation — As indicated in Materials and Methods, net radiation was measured at 150, 25, 10, and 5 cm above the soil surface. However, on 17 July no values were collected from 10-cm height at 40 cm from the south row in the furrow method, or from the 25-cm height in the drip-irrigation method because of malfunctioning of the instruments.

Figure 4 shows hourly net radiation values (converted to equivalent evaporation in mm/h) and mean hourly values of evapotranspiration, as measured by the large lysimeters on July 17 and 24 for crops under furrow and drip irrigation. The R_n data for the 5- and 10-cm heights should be considered somewhat relative, since the directional response of tube radiometers is less than perfect (Szeicz, 1975). The 5-cm units located well under the canopy should have been providing good absolute values, however.

Overall, on July 17 (one day after furrow watering) the net radiation measured in the furrow method at 150 cm above the ground and at 10 cm at the unshaded location 63 cm from the north row (essentially above the completely moistened soil surface) was higher than that measured at the same locations (practically above the dry soil surface) in the drip-irrigated soil. These differences can be re-

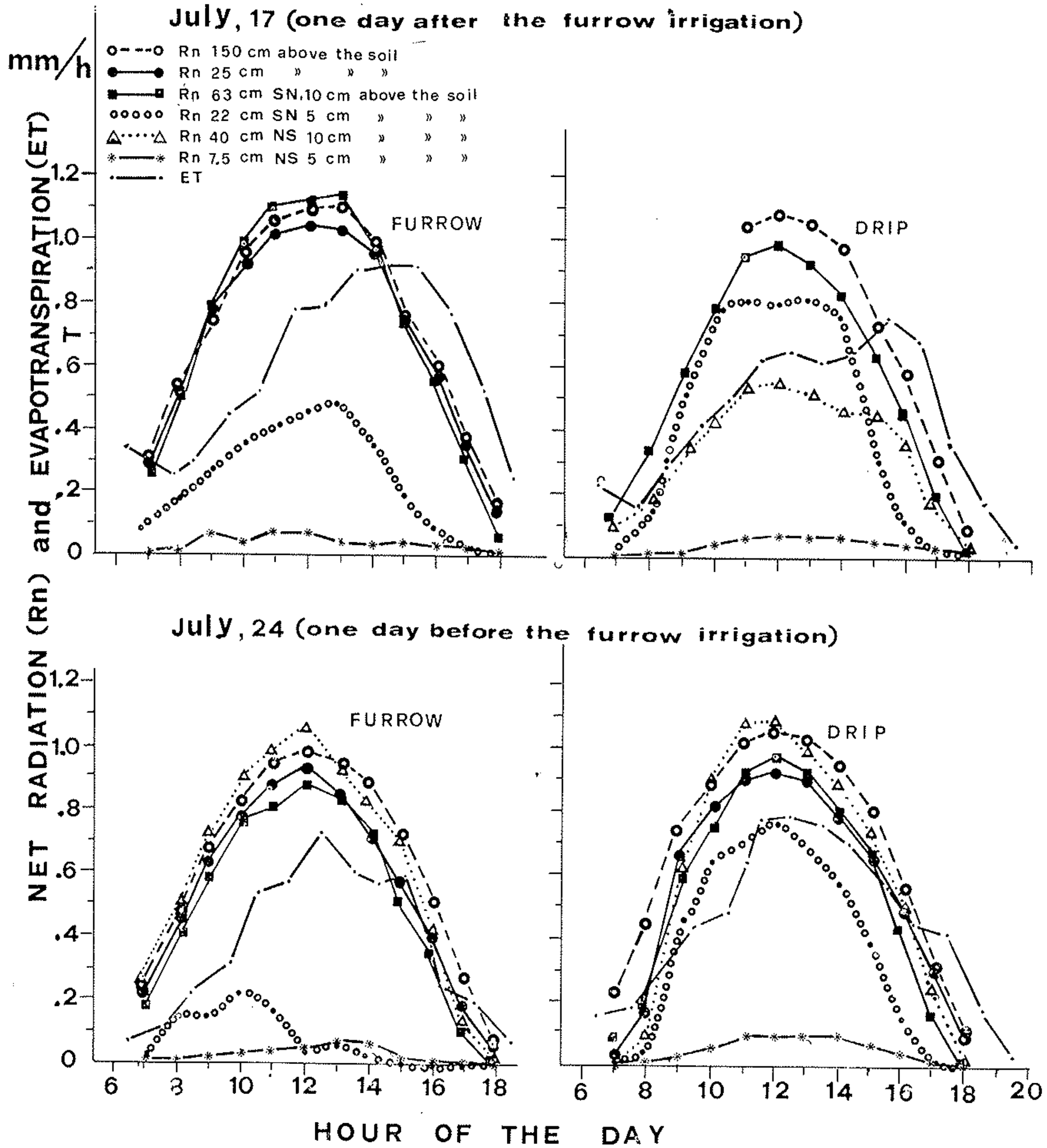

Fig. 4 - Mean hourly evapotranspiration (ET) and net radiation (Rn) (expressed in mm/h) measured above the canopy (150- and 25-cm height), under canopy (5-cm height), and between the rows (10-cm height). Rn under plant canopy was measured at 7.5 and 40 cm north of the south row (NS) and 22.5 and 63 cm south of the adjacente north row (SN).

Fig. 4 - Evapotraspirazione (ET) oraria media e radiazione netta (Rn) espresse in mm/h misurate sopra la copertura vegetale (a 150 e 25 cm di altezza); sotto la vegetazione (5 cm di altezza) e tra le file (10 cm) Rn sotto la vegetazione è stata misurata 7,5 e 40 cm a Nord della fila a Sud (NS) e 22,5 e 63 cm a Sud della fila adiacente (SN).

lated to differences in albedo and thermal properties of the two soil surfaces. Low soil-surface-moisture content between the row plants under drip irrigation produces a high soil surface temperature, greater outgoing longwave radiation, and hence, lower R_n. The energy balance would involve low evaporation and high sensible heat transfer to the air above.

Trends of the net radiation differed between the two methods at 22 cm from the north-row plants (5-cm height). At this location, in fact, the net radiation measured in the drip method was greater than that in the furrow method, probably influenced by differences in shading of the radiometer by the canopies. At the other locations, the net radiation differed little between the two methods on the same day.

On July 24 (one day before furrow irrigation) the net radiation measured at all locations in drip-irrigated tomatoes was greater (although in different measure) than that in the furrow method.

Evapotranspiration (*ET*) — On July 17 (one day after the furrow watering) ET measured from the furrow-irrigated crop was greater than that from the drip-irrigated crop, whereas on July 24 (one day before the furrow irrigation) ET was greater in the drip-irrigated crop (Fig. 4).

In Figure 5, cumulative evapotranspiration curves are presented for the hours from 6.00 to 20.00 hrs for both July 17 and 24. ET was 8.21 and 6.15 mm on July 17 for the furrow- and drip-irrigated crops, respectively, and 5.05 and 6.25 mm on July 24. Thus, there was less than 2% difference in ET in drip irrigation for the two days while with furrow irrigation, a 62% higher loss occurred on the first day when 80-90% of the soil surface was moist all day.

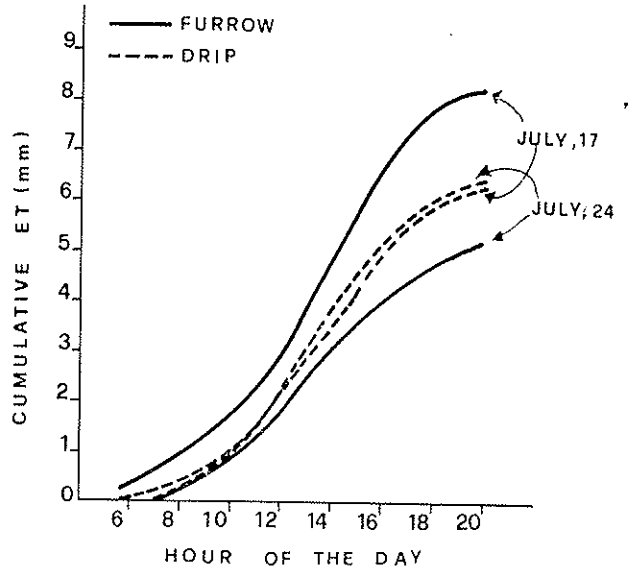

Fig. 5 - Cumulative hourly evapotranspiration of tomatoes under furrow and drip irrigation measured on July and 24, one day after furrow irrigation and one day before the following furrow irrigation.

Fig. 5 - Evapotraspirazione oraria cumulata.

April 23

Total seasonal evapotranspiration for the tomatoes growing in the furrow-irrigated lysimeter was practically the same as that in the drip-irrigated lysimeter from April ~~22~~ to September 10, with values of 55.9 and 56.6 cm, respectively. Losses from June 6 to Septembre 10 which relate to the actual period of differential methods of irrigation were, respectively, 45.4 and 46.1 cm. The somewhat higher ET by the drip-irrigated plots no doubt reflects to some degree the higher percentage of cover achieved in the drip lysimeter (maximum of 47% as compared with 38% in the furrow lysimeter). However, in 1979 when both lysimeters reached 63% cover, the ET during the period of differential irrigation treatments (July 3-October 8) was 48.3 and 47.6 cm, respectively, for furrow- and drip-irrigated lysimeters.

Figure 6 shows the daily water loss by evapotranspiration from each lysimeter compared with Class A pan evaporation, and the results were plotted as the ratio of the former to the latter and as a function of the day of the year. The day-to-day values of ET/E_{pan} during the growing season were influenced by the development of the crop canopy and the soil moisture status. For both crops in the early stage, as the amount of canopy increased, the ratio increased until maximum values were reached, around the end of July. After that, the ratio began to drop as the plants aged. As a rule, great increases of ratios were observed after each watering of the crop under furrow irrigation, especially during the early stage of growth, the effect lasting for several days.

Figure 7 shows ratios of daily evapotranspiration by furrow-irrigated tomatoes to those under drip, together with values of percentage of ground cover during the growing season. Drip-irrigated tomatoes had more ground cover during most of the growing season: maximum values were about 10% more than those of the furrow-irrigated crop. The difference in plant growth response under the drip method can be attributed primarily to the greater availability of water provided by the system except during a few days after each furrow irrigation, although for the lysimeters in the 1979 season, similar irrigation scheduling did not produce growth differences.

After the start of the differential irrigation treatments, the daily ratios of ET (furrow)/ET (drip) were always less than unity, except for a period of three to four days following each furrow irrigation. In particular, under our experimental condition, the ratio ET (furrow)/ET(drip) for each day included between two successive furrow irrigations, as indicated in Figure 8, was as high as 1.35, 1.30, and 1.08 for one, two, and three days after furrow irrigation, respectively, and between 0.97 and 0.87 for each remaining day.

Yield — Table 2 gives the yields of red and green fruit for each lysimeter, along with average yield from replicated field plots. Total seasonal ET is also given. Although different harvest dates were involved, this need not be of concern because tomato fruits show little if any further assimilation after turning pink (Dr. Allen Stevens, personal communica-

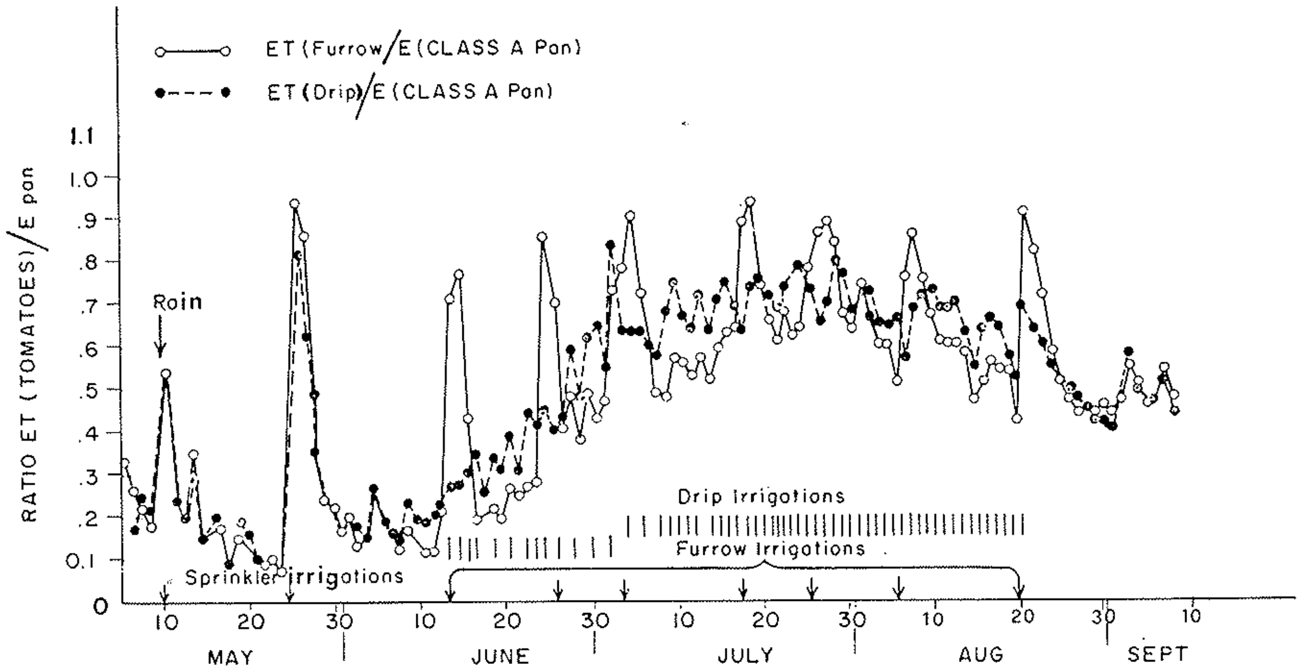

Fig. 6 - Ratio of daily evapotraspiration (ET) by tomatoes under furrow and drip irrigation to Class A pan evaporation (E), from a date soon after emergence to September 7 (ten days before harvest), Davis, California 1980. Pan was located in a frequently irrigated, frequently mowed grass field (approximately 0.6 ha) near the lysimeters.

Fig. 6 - Rapporto tra ET giornaliera delle colture di pomodoro irrigate a solchi e a goccia ed evaporazione da vasca di Classe A per il periodo da poco dopo l'emergenza a 10 giorni prima della raccolta.

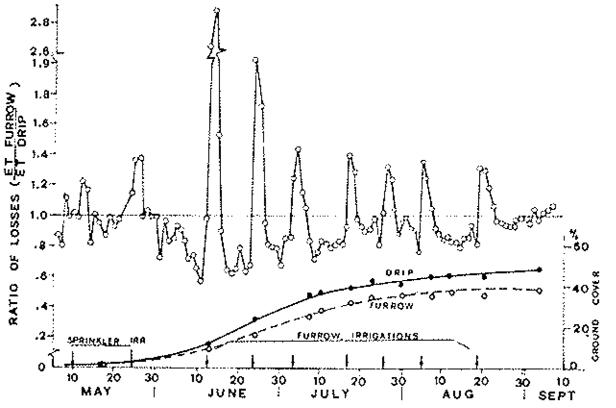

Fig. 7 - Ratio of daily evapotranspiration by tomatoes under furrow irrigation to those under drip irrigation, and ground cover percentage during the growing season. Davis, California, 1980.

Fig. 7 - Rapporto tra ET giornaliera della coltura di pomodoro irrigata a solchi e quella di pomodoro irrigata a goccia, e grado di copertura del terreno (in percentuale) durante la stagione di crescita. Davis, California, 1980.

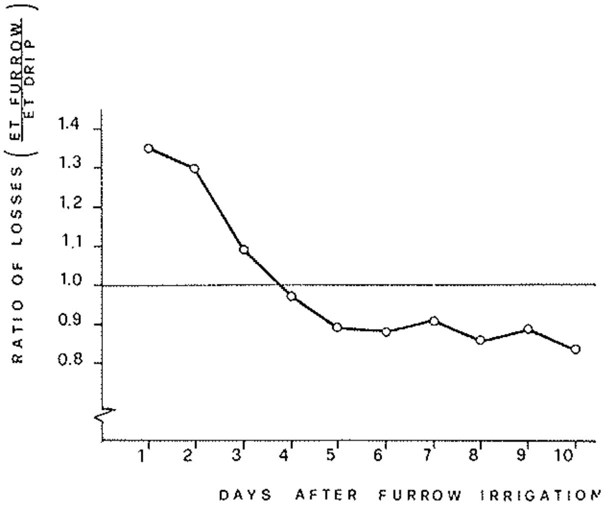

Fig. 8 - Mean ratio of daily evapotranspiration by tomatoes furrow-irrigated to those drip-irrigated (average among each chronological day of ten-day furrow irrigation schedule during the growing season).

Fig. 8 - Rapporto medio dell'ET giornaliera tra le colture di pomodoro irrigate a solchi e a goccia (medie di ogni giorno del turno di 10 giorni).

tion, October 24, 1981, Davis, California). Yield of red fruit in the drip-irrigated lysimeter was 16% higher than that in the furrow lysimeter, although some uncertainty exists, owing to application of drying rates of only two plants to that of the furrow lysimeter fruits. The tomato crop in both lysimeters outyielded by 32-35% the drip- and furrow-irrigated field plots, although similar trends in yield between the two irrigation methods is evident (13% higher for drip-irrigated plots than for furrow-irrigated plots).

Since ET was almost the same for the two lysimeters, water-use efficiency (tons ha^{-1} cm^{-1} for red fruit) was about 15% higher for drip than for furrow with values of 1.58 and 1.38, respectively. This

TABLE 2. - *Total ET in cm from planting to harvest (4/22-9/10) and yield of processing tomatoes under furrow and drip irrigation. Davis, California, 1980.*

TABELLA 2. - ET Totale in cm e produzione di bacche mature, verdi, marcite e totali in pomodoro da industra irrigato a solchi o a goccia.

Irrigation method	ET cm	Yield (ton/ha)			
		Ripe	Green	Rotten	Total
Furrow (weighing lysimeter) (¹)	55.9	77.2	3.5	0.0	80.7
Furrow field plots (²)	59.6	58.6	2.1	—	60.7
Drip (shear lysimeter) (³)	56.6	89.4	5.5	4.5	94.9
Drip field plots (²)	61.6	66.2	1.0	—	67.2

(¹) Furrow lysimeter plants were cut at ground level on September 6 and left on lysimeter for a special test to determine a wind functional relationship. Fresh weight of fruit as measured on September 17 was corrected back to September 6 based on changes in percent moisture of a subsample of two vines with their fruit allowed to dry in the field.

(²) Harvest date of September 10.

(³) As harvested on September 17 seven days after field plots were harvested. Since at this stage of maturity tomato fruits tend to show little if any further assimilation the affect on yield due to the different harvest dates can be ignored.

compares fairly closely with 1979 results where water use efficiencies of 1.35 and 1.22 were realized for drip- and furrow-irrigated lysimeters, respectively, with yields of 82.1 and 75.1 T/ha and total seasonal ET values of 60.8 and 61.5 cm.

Conclusions

For purposes of irrigation scheduling, insufficient data are available for predicting evapotranspiration for drip irrigation with the accuracy currently possible under conventional methods. Studies were initiated in 1979 to verify the evapotranspiration expected under both drip- and furrow-irrigation methods for at least one row crop with a typical row and plant spacing. Additionally the collection of very detailed measurements of the microclimate just above the soil surface as well as within upper layers of the soil is expected to yield the necessary information for significant improvement over present models of predicting the evaporation losses from the soil surface under a wide range of row and plant spacing, irrigation frequency, and crop-canopy conditions.

The reported measurement of the soil and air temperature, net radiation, and soil moisture at various positions in tomatoes under furrow and drip irrigation, on representative days of the 1980 growing season, gives some examples of the different microclimate associated with the two methods. The ET loss under daily drip irrigation actually exceeded that for furrow irrigation by values included between 3 and 13%, except for a period of three days following each furrow irrigation, when the losses for the furrow-irrigated crop were much greater than for the drip-irrigated crop. However, under our experimental conditions (152-cm row spacing, ten-day furrow irrigation intervals, and daily drip irrigation), the seasonal ET loss by the two crops irrigated differently was almost the same (56 cm).

A significant savings of ET under drip irrigation as compared with furrow irrigation would obviously result in situations where more frequent applications by furrow might be required to achieve similar yields for both methods. On the other hand, if top yields could be achieved by a 15- to 20-day schedule, the furrow method would obviously produce less ET loss than the drip method, with the high evaporation losses for three days following each irrigation more than made up for by the steady, everyday evaporation loss from the areas kept moist by the daily drip irrigation. Although these wet areas may represent less than 10-15% of the surface area, our data reveal that they are subjected to advection of sensible heat from mid-row hot areas both above and below the soil surface. Evaporation losses from the wet areas may well efficeed by 1.5-3.0 times the loss from an equivalent wet area in a field where all surface areas are continuously moist.

In 1980, marketable yields of tomato under drip irrigation were 16% higher than that under furrow irrigation, somewhat in line with a similar response in development of plant cover. The results in 1979 were similar, although with about equal development of plant cover (60%), the drip lysimeter outyielded the furrow lysimeter by only 9%. In 1980 plant cover for the furrow- and drip-irrigated lysimeters, respectively was only 38 and 47%, yet the 1980 yields exceeded those of 1979 when the percent cover reached ~~6%~~. A greater water-use efficiency for the drip-irrigated lysimeter is inferred

60%

for both years. However, in ~~le~~ the replicated plot study, water-use efficiency was only 9% greater for drip- than for furrow-irrigated plots, and the drip plots had a 3% higher total seasonal ET.

Riassunto

MICROCLIMA ED EVAPOTRASPIRAZIONE DEL POMODORO DA INDUSTRIA IRRIGATO CON IL METODO IRRIGUO A GOCCIA E PER INFILTRAZIONE LATERALE DA SOLCHI. E. TARANTINO, H. SINGH, W. O. PRUITT.

Si riportano i risultati di una prova condotta a Davis in California, nel 1980, su coltura di pomodoro (« U.C. 82 ») seminato a file distanti 152 cm ed irrigata con due differenti metodi irrigui: infiltrazione laterale da solchi e goccia. I turni irrigui medi sono stati, rispettivamente, di 10 giorni e di un giorno.

Per entrambi i metodi irrigui sono stati misurati anche i valori della temperatura dell'aria e del suolo e della radiazione netta, a diverse postazioni e in particolari giorni del ciclo colturale.

La coltura del pomodoro irrigato a goccia ha fornito valori medi giornalieri di ET superiori ai valori ottenuti con il metodo per infiltrazione laterale da solchi di circa 8-9%, tranne che nei primi tre giorni dopo ogni intervento irriguo per infiltrazione laterale da solchi.

I valori stagionali di ET relativi ai due metodi, misurata con due lisimetri ciascuno del diametro di 6,1 m, sono stati pressocché gli stessi (55,9 cm nel metodo irriguo per infiltrazione laterale del solco e 56,6 cm nel metodo irriguo a goccia), mentre nelle parcelle circostanti tenute nelle stesse condizioni di regime irriguo sono stati riscontrati valori stagionali di ET pari a 59,6 e 61,6 cm rispettivamente nel metodo irriguo per infiltrazione laterale da solco ed in quello a goccia.

Infine, la coltura di pomodoro con il metodo a goccia, in entrambi i casi, ha fatto registrare una produzione di bacche commerciabili più alta di circa 13-15% rispetto a quella irrigata per infiltrazione laterale da solchi.

Summary

The results presented pertain to the 1980 cropping season at Davis, California, for processing tomatoes (UC 82 variety) growing in rows spaced 152 cm apart under an ten-day schedule of furrow irrigation and a daily scheduled drip irrigation.

Results for both irrigated crops include micrometeorological measurement of the soil and air temperature and net radiation at various locations on particular days during the growing season.

The mean ET loss under daily drip irrigation actually exceeded that for furrow irrigation by about 8-9%, except for a period of three days following each furrow irrigation.

Seasonal ET losses by tomatoes irrigated by furrow and drip irrigation, as measured by two 6.1 m-diameter lysimeters, were almost identical (55.9 cm for furrow and 56.6 cm for drip). Field plots with equivalent irrigation schedules had ET values of 59.6 and 61.6 cm for furrow and drip, respectively.

Marketable yield of processing tomatoes in both the drip lysimeter and drip field plots were around 13-15% greater than yield of those under furrow irrigation.

Bibliografia

BROOKS, F. A., PRUITT, W. O. and OTHERS, 1966. *Investigation of energy, momentum and mass transfers near the ground.* Final Report USAEC Grant No. DA-AMC-28-043-65-G12 (DDC-AD 635-588). University of California, Davis, CA 259 p.

DOORENBOS, J. and PRUITT, W. O., 1977. *Crop water requirements.* Irrigation and Drainage Paper No. 24, F.A.O. Rome, Italy. (Revised 1977). 144 p.

GODDARD, WILSON, B., 1970. *A floating drag-plate lysimeter for atmospheric boundary layer research.* J. Appl. Met. 9: 373-378.

PENMAN, H. L., ANGUS, D. E. and VAN BAVEL, C. H. M., 1967. *Microclimate factors affecting evaporation and transpiration. In: Irrigation of Agricultural Lands*, Amer. Soc. Agron. Monogr. 11, edited by R. M. Hagan, H. R. Haise, and T. W. Edminster, American Society of Agronomy, Madison, Wisc., pp. 483-505.

PRUITT, W. O. and ANGUS, D. E., 1960. *Large weighing lysimeter for measuring evapotranspiration.* Trans. ASAE 3(2): 13-15, 18.

PRUITT, W. O., LOURENCE, F. J., and VON OETTINGEN, S., 1972. *Water use by crops as affected by climate and plant factors.* Calif. Agric. 26(10): 10-14.

RITCHIE, J. T., 1972. *Model for predicting evaporation from a row crop with incomplete cover.* Water Resour. Res. 8: 1204-1213.

SZEICZ, G., 1975. *Instruments and their exposure.* Chapt. 7 *In*: *Vegetation and the Atmosphere*, Vol. 1, Principles, (J. L. Montheith, ed.), Academic Press, London. pp. 229-273.

TANNER, C. B. and JURY, W. A., 1976. *Estimating evaporation and transpiration from a row crop during incomplete cover.* Agron. J. 68: 239-242.