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Soil water and temperature regimes in drip and sprinkler irrigation, and implications to soybean emergence

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Abstract

Irrigation has long been used in agriculture as a primary means of water management. It is well known that water distributions in the soil differ depending on the methods of irrigation. However, it is less clear how soil thermal regimes would change over time and space when irrigation methods are different. A field study was conducted to investigate the interactive effect of soil water and temperature regimes in drip and sprinkler irrigation. The effect of different methods of irrigation on soil water and thermal environment was then used to interpret differences in soybean emergence and seedling growth under the two irrigation treatments. Time domain reflectometry wave-guides and thermocouples were installed in field plots to provide soil water content and temperature measurements. Soybean seeds were planted to assess the emergence and seedling development. Consistent with infiltration theory, soil water contents were higher directly under the drip tapes in drip irrigation, but were relatively more uniform across the whole soil surface in sprinkler irrigation. Although five times more water was used in the sprinkler than in the drip plot, the soil water content at the seed zone was similar. Soil temperature was significantly higher in the drip than in the sprinkler plot, which led to a higher emergence rate and enhanced seedling growth. Drip irrigation not only conserved water but also maintained the soil profile at a higher temperature more favorable for plant emergence and seedling development. Published by Elsevier Science B.V.

Keywords: Spatial temporal distribution; Infiltration; Drip; Sprinkler; Soybean

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1. Introduction

Water content and temperature are important soil physical factors for plant growth. Non-optimum levels of water and temperature conditions can strongly deter plant development, especially at the early stages of growth such as seed germination and emergence (Helms et al., 1996). Field management of soil water and temperature conditions to favor plant growth has often been carried out as separate processes, with irrigation as a means of water management and soil surface mulching for temperature control. Because of the large heat capacity of water, different irrigation methods or soil water regimes would very likely lead to different temperature conditions. The interactive effect of different irrigation methods on soil water and temperature regimes should also have a profound effect on plant growth and merits investigation.

Differences in methods of irrigation can directly affect water distribution in the soil profile. The most commonly used irrigation methods in arid and semi-arid agriculture include sprinkler, drip, and furrow irrigation. Sprinkler irrigation is designed to apply water over the entire soil surface in a way similar to rainfall. Infiltration under sprinkler irrigation most closely approximates one-dimensional flow. In drip irrigation, water is applied through evenly spaced point sources or emitters, and the drip lines are placed either on the surface or buried in the soil root zone. Water redistribution from the drip point sources would create a three-dimensional flow regime (Clothier et al., 1995). However, the emitters in many drip irrigated row crops have been replaced with drip tapes which deliver water through closely spaced openings ($2–6\ \mathrm{m}^{-1}$). The drip tapes are often placed on soil surface, and water distribution from the surface drip system can lead to continuously wetted strips centered at the drip line, creating a two-dimensional flow condition. Theoretical principles of heat and water flow are often integrated in mathematical modeling and have been applied to simulate field practices with various initial and boundary conditions (Bristow et al., 1986; Chung and Horton, 1987). Irrigation affects both soil water and temperature and may be considered as a boundary condition in the model simulation (Katterer and Andren, 1995).

Soil water and temperature variations under irrigated conditions are multidimensional and highly dynamic. Field characterization of the two variables is possible only with in-situ instantaneous measurement. Recent development and application of time domain reflectometry (TDR) have provided an accurate, rapid, and in-situ method of measuring the volumetric soil water content (Dalton, 1992). Soil temperature, on the other hand, can be readily measured with thermocouples installed at prescribed locations in the soil profile.

Different irrigation methods will not only determine the distribution patterns of water but will also have a strong influence on the local micro-climatic conditions such as humidity and temperature that are important to plant development. Probably because of the improved soil water and temperature regimes, seedling emergence was significantly higher for maize (*Zea mays* L.) and cowpea (*Vigna unguiculata* (L.) Walp.) under drip than under flooding or furrow irrigation (Fapohunda, 1986). Drip irrigation not only helps to improve soil water and temperature conditions favorable for plant growth but can reduce the total amount of water application since plant roots are capable of extracting water preferentially from regions where soil water is more readily available (Green and Clothier, 1995).

Crop seedling establishment is often very sensitive to soil water and temperature conditions as measured by the mean, the maximum and minimum values, and duration of occurrences. Swan et al. (1996) found that maize seedling establishment may be improved by raising the soil temperature through seed-row residue management. Soybean (*Glycine max* (L.) Merr.) seeds are also very sensitive to the seedbed soil water and temperature conditions and non-optimum water and temperature levels can significantly reduce both emergence rate (Helms et al., 1996) and yield (Hobbs and Obendorf, 1972). The highest soybean emergence rate was achieved when soil temperature was between 25°C and 35°C when no other factors were limiting (Hatfield and Egli, 1974).

It is very likely that soil water and thermal regimes will be different under different methods of irrigation. This study was conducted to determine the spatial and temporal distributions of soil water and temperature under drip and sprinkler irrigation. The irrigation effect on soil water and temperature was further related to soybean emergence and seedling growth.

2. Materials and methods

A field experiment was conducted on the University of California Agricultural Experimental Station near the Riverside campus (117° 20′ 30″ W longitude and 33° 58′ 23″ N latitude). The soil at the research site is an Arlington fine sandy loam (coarse-loamy, mixed, thermic, Haplic Durixeralf) and consists of approximately 64% sand, 29% silt and 7% clay. The soil contains a considerable amount of mica, which tends to form a surface crust after drying from a rainfall or sprinkler irrigation event. Soil bulk density averages 1.52 g cm^{-3} for the surface 20 cm and increases to 1.68 g cm^{-3} at 1 m from the soil surface.

Furrow beds were constructed in four field plots each measuring 27.4 m×36.6 m with a bed shaper pulled behind a tractor. Immediately prior to bed construction, the surface 10 cm soil was disced and roto-tilled to a loose and uniform state. The beds, shown in Figs. 1, 2, 4 and 6, were 0.8 m center-to-center, 30 cm wide on the bed top, and 10 cm deep from the bed top to the bottom of the furrow. Seeds of soybean, variety "Manokin", were planted on June 11, 1998 at the center of the furrow beds approximately 4 cm (±1 cm) from the soil surface. The seeds were planted using a soybean planter mounted behind a tractor at 32.8 m^{-1} rate. Volumetric soil water content at the time of planting averaged 0.098 $\text{cm}^3\,\text{cm}^{-3}$ at the 0–5 cm depth range. Soybean emergence rate was measured by counting the number of visible soybean seedlings in three randomly selected 2 m sections from each field plot three weeks after planting. Although some soybean seeds started to emerge only one week after planting, the emergence survey was made at three weeks to ensure that soybean seeds were given sufficient time for emergence. Therefore, the measurement would most likely represent a final total emergence rate. At the time of emergence survey, soybean growth parameters such as seedling height and root length were also recorded from six randomly selected seedlings from every 2 m section of the emergence measurement.

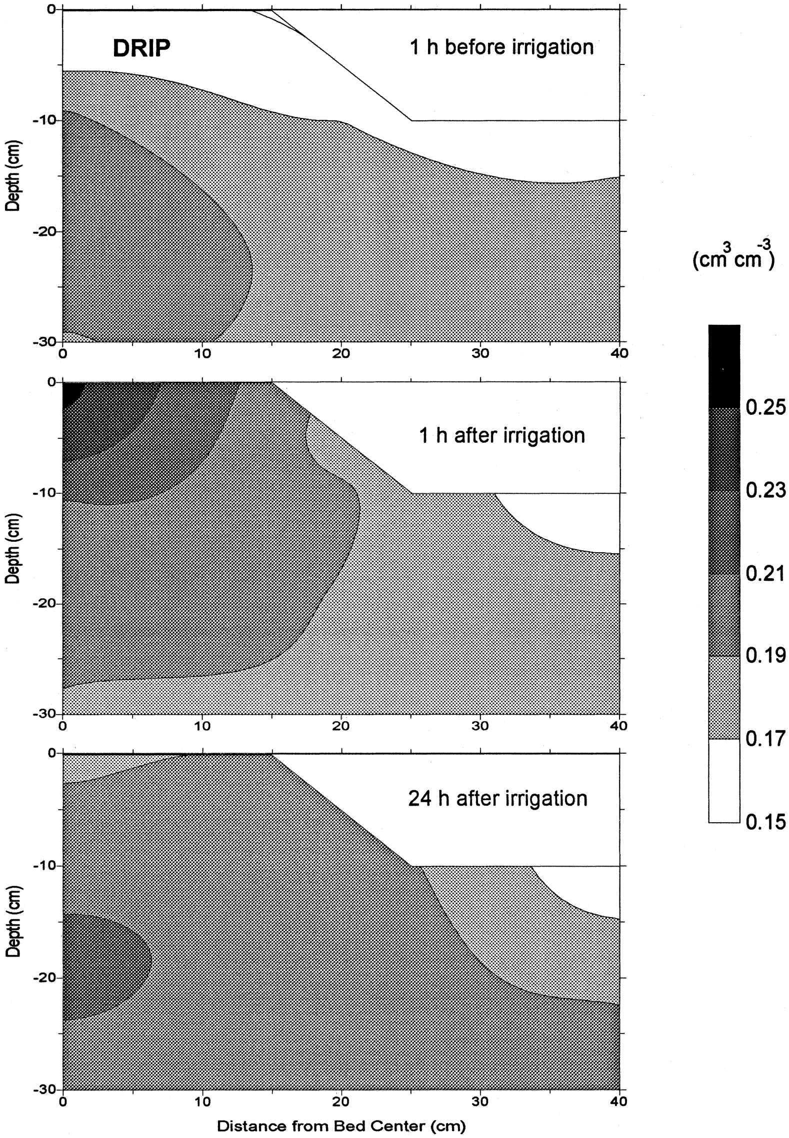

Fig. 1. Spatial distribution of soil water content 1 h before, 1 h after, and 24 h after a drip irrigation event of 3.5 h duration in which an equivalent of 2.7 mm of water was applied to the whole soil surface.

Immediately after planting, drip tapes (RO-DRIP®, Roberts Irrigation Products, San Marcos, CA)[1] were placed on the soil surface at the center of the field beds directly above the planted soybean seeds in two of the four field plots. The drip tapes consisted of 20 cm spaced turbulent pressure-relief openings and were designed for use in row crops. With a

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[1] Mention of products and company names does not constitute endorsement by the USDA.

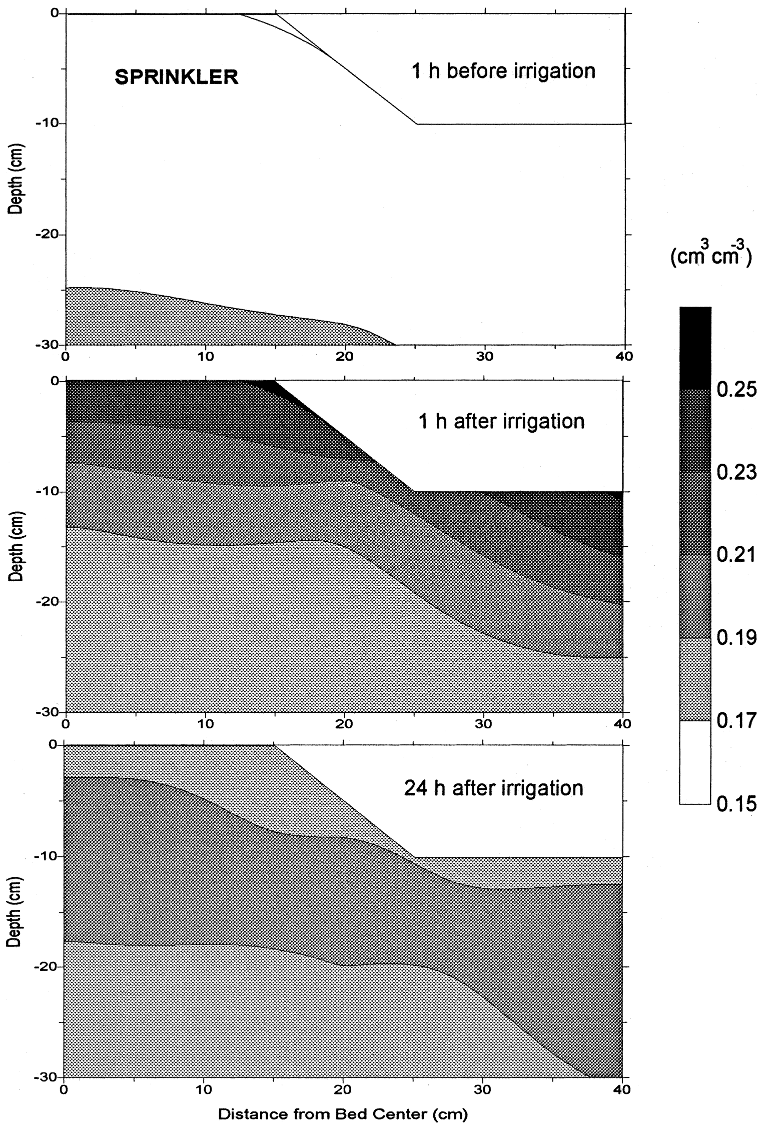

Fig. 2. Spatial distribution of soil water content 1 h before, 1 h after, and 24 h after a sprinkler irrigation event of 3.5 h duration in which an equivalent of 17.8 mm of water was applied to the whole soil surface.

55 kPa water pressure, the drip system supplied water to the field plots at 0.62 l h^{-1} m^{-1} for each row or 0.78 mm h^{-1} for the whole plots. A sprinkler system was installed in the other two field plots immediately after planting. The sprinkler heads (Hunter Industries, San Marcos, CA)[1] were selected for better control of application uniformity and spray angle selection. Application rate for the sprinkler system was 5.08 mm h^{-1} at 275 kPa water pressure. The application rates were selected to be low to prevent surface ponding

Table 1
Irrigation schedule between planting and soybean emergence measurement

Day of Year	Duration		Amount	
	Drip (h)	Sprinkler (h)	Drip[c] (mm)	Sprinkler (mm)
162.4[a]				
163.5	7.0	3.0	5.4	15.2
168.7	2.5	1.5	1.9	7.6
171.3	1.5	1.0	1.2	5.1
174.7	5.5	5.5	4.2	27.9
178.7	3.5	3.5	2.7	17.8
182.5	3.0	3.0	2.3	15.2
183.3[b]				
Total			17.7	88.8

[a] Time of planting.

[b] Soybean emergence and seedling growth parameter measurement.

[c] Application amount for drip irrigation was converted from the 0.62 l $h^{-1}m^{-1}$ rate to the whole area of each field plot, including the unirrigated areas.

or runoff. The timing and amount of irrigation, listed in Table 1, were chosen to maintain soil water content near the seeding zone to be above at about 0.15 $cm^3 cm^{-3}$. This is important for seed germination and emergence (Helms et al., 1996). The actual ratio of final amount of water application between the drip and sprinkler irrigation (0.20) was very close to targeted ratio (0.19) computed by assuming only half of the furrow beds be irrigated with the surface drip.

To facilitate field measurement of the highly dynamic soil water content and temperature, time domain reflectometry (TDR) wave guides and thermocouples were installed at preselected locations in both the drip and the sprinkler plots. In each irrigation plot, five 20 cm long 3-rod wave guides (Soilmoisture Equipments, Santa Barbara, CA)Footnote 1 were inserted in the undisturbed soil from a small excavation face at 5, 10, 20, 30, and 50 cm depths below the bed center. Three additional wave guides were also installed on the same cross-section at 10, 20, and 30 cm depth, but at 20 cm off the bed center. The wave guides were inserted horizontally in a direction parallel to the crop rows. Eight thermocouples were installed in each field plot, adjacent to each of the TDR wave guides to provide soil temperature measurement. A 1502 B Tektronix cable tester (Tektronix, Beaverton, OR)[1] with the Campbell SDM1502 communication interface and SDMX50 multiplexers was used to read the TDR wave guides and the readings were recorded hourly with a CR10 datalogger (Campbell Scientific)[1]. The TDR setup was calibrated in the laboratory using the field soil packed to an average bulk density of 1.59 g cm^{-3} under five volumetric water contents determined with the gravimetric method. Because the salinity of the soil was very low (<0.5 dS m^{-1}), a laboratory calibration with deionized water was assumed to represent field conditions. Soil temperature from each location was measured every second then averaged to 10 min output and recorded with the CR10 dataloggers.

During the first three weeks after soybean planting, additional water content and soil temperature measurements were made using the gravimetric method and a YSI meter

(Yellow Springs Instruments, Yellow Springs, OH)[1]. These measurements were made for the surface soil at bed center, 20 cm off center, and 40 cm off the bed center. Measurements for subsurface soil (at 5 and 10 cm) were also made at 40 cm off the bed center. The additional measurements were used as a supplement to the automated TDR and thermocouple measurements to provide a better spatial and temporal representation of soil water content and temperature distribution in the soil profile. As an example, the irrigation on day-of-year (DOY) 178.7 (Table 1) was selected to depict variations in the spatial and temporal distribution of soil water content and temperature from a drip and a sprinkler irrigation event. A weather station was also installed in one of the drip irrigation plots at the time of TDR and soil thermocouple placement. Measured parameters were solar and net radiation, wind speed, air temperature and relative humidity.

3. Results and discussion

Prior to the irrigation on DOY=178.7, soil water content had decreased from the previous irrigation event to less than 0.17 $cm^3\ cm^{-3}$ in the surface 5 cm where soybean seeds were planted (Figs. 1 and 2). The water content was raised to greater than 0.23 $cm^3\ cm^{-3}$ in the seeding zone 1 h after drip irrigation and decreased symmetrically from the source to less than 0.19 $cm^3\ cm^{-3}$ at about 27 cm depth (Fig. 1). This distribution pattern was expected since water was applied from the drip tapes only at the bed center, creating a two- or three-dimensional flow regime. The soil in the furrows did not receive any water from the irrigation event either 1 or 24 h after the irrigation. In fact, the soil surface in the furrows from the two drip plots was never wetted from any of the six irrigation events prior to soybean emergence measurement (Table 1). This was attributed to the low application rate of the drip irrigation and the small sorptivity of the sandy loam soil (3.64 cm $h^{-1/2}$ from Wang et al., 1998). The small soil sorptivity limited the horizontal movement of water to short distances from the drip sources. At 24 h after the drip irrigation event, soil water had redistributed in the field bed to a fairly uniform water content around 0.20 $cm^3\ cm^{-3}$. The wetting center also moved downward to about 20 cm depth due primarily to gravity flow. The distance traveled in 24 h (or 20 cm) was consistent with the saturated hydraulic conductivity values (0.7–3.2 cm h^{-1}) reported for this soil (Wang et al., 1998).

When water was applied by sprinkler irrigation, soil water content in the seeding zone also increased to values greater than about 0.23 $cm^3\ cm^{-3}$ 1 h after the irrigation (Fig. 2). Because water was applied across the whole soil surface, soil water content decreased uniformly following the surface contours to less than 0.19 $cm^3\ cm^{-3}$ at about 15 cm depth. Similar water distribution patterns were predicted for sprinkler irrigation in a simulation study by Wang et al. (1997). Contrary to the drip irrigation, significant wetting was observed in the furrows due to the nature of the irrigation method where water was applied over the whole soil surface. The water in the furrows was inaccessible to the transpiration need of plants, especially during early seedling stage when only limited root growth had occurred. Therefore, sprinkler irrigation was not as efficient as drip irrigation in terms of providing adequate water to meet plant growth needs. Further, the excess amount of soil water in the furrows may increase leaching to greater depths and

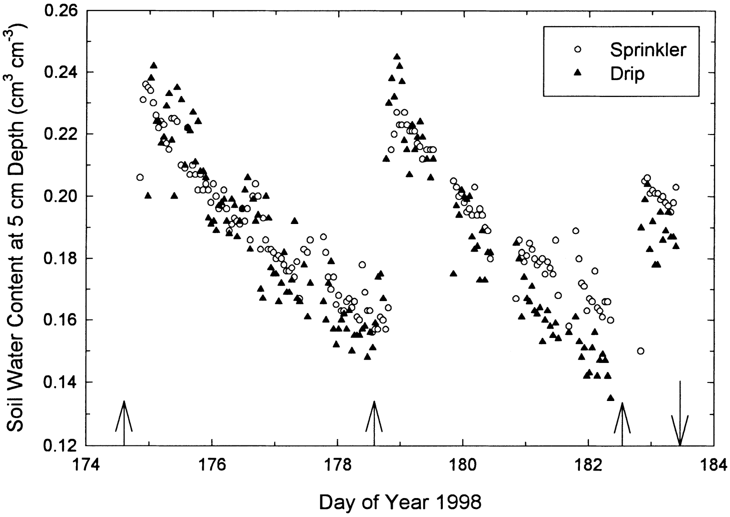

Fig. 3. Time course of soil water content at 5 cm below the bed center under drip and sprinkler irrigation. Upward-facing arrows represent the irrigation events. The downward-facing arrow indicates the time of soybean emergence and seedling growth parameter measurements.

potentially carry environmentally-deleterious contaminant chemicals to the groundwater (Clothier and Green, 1994). Water redistribution measurements also showed that the soil water content was greater directly beneath the furrow than in the bed 24 h after the irrigation. The wetting band, with a water content of about 0.20 cm^3 cm^{-3}, extended from roughly 3 to 17.5 cm below the bed surface, and from roughly 2.5 to 20 cm below the furrow surface. The remainder of the field bed was at a water content value of about 0.18 cm^3 cm^{-3} 24 h after the sprinkler irrigation.

Although the total amount of water applied by drip irrigation was only about 20% of that used in the sprinkler plots (Table 1), soil water content at the seeding zone was not drastically different between the two methods of irrigation (Fig. 3). The TDR measurement showed that in both treatments soil water content cycled between each irrigation from a maximum of about 0.24 cm^3 cm^{-3} to a low of about 0.14 cm^3 cm^{-3}. Water content in the drip irrigation appeared to have a slightly larger fluctuation than in the sprinkler plot. The higher maximum water content in the drip irrigation treatment could be attributed to the direct water application from the drip tapes immediately above the TDR wave guides (at 5 cm). The lower minimum water content in the drip plots, however, was likely caused by the overall smaller amount of water application than in the sprinkler plots. Therefore, the total amount of water stored in the soil would be less, and thus more susceptible to depletion by evapotranspiration. Close examination of Fig. 3 further indicated that soil water content in drip irrigated soils decreased faster after an irrigation event than in soils irrigated with the sprinklers.

The soil profile 1 h prior to irrigation exhibited a large temperature gradient from a high temperature of over 53°C near the surface to lower values at deeper depths (Fig. 4). This may be explained by the timing of the measurement since at 4 p.m. the diurnal solar

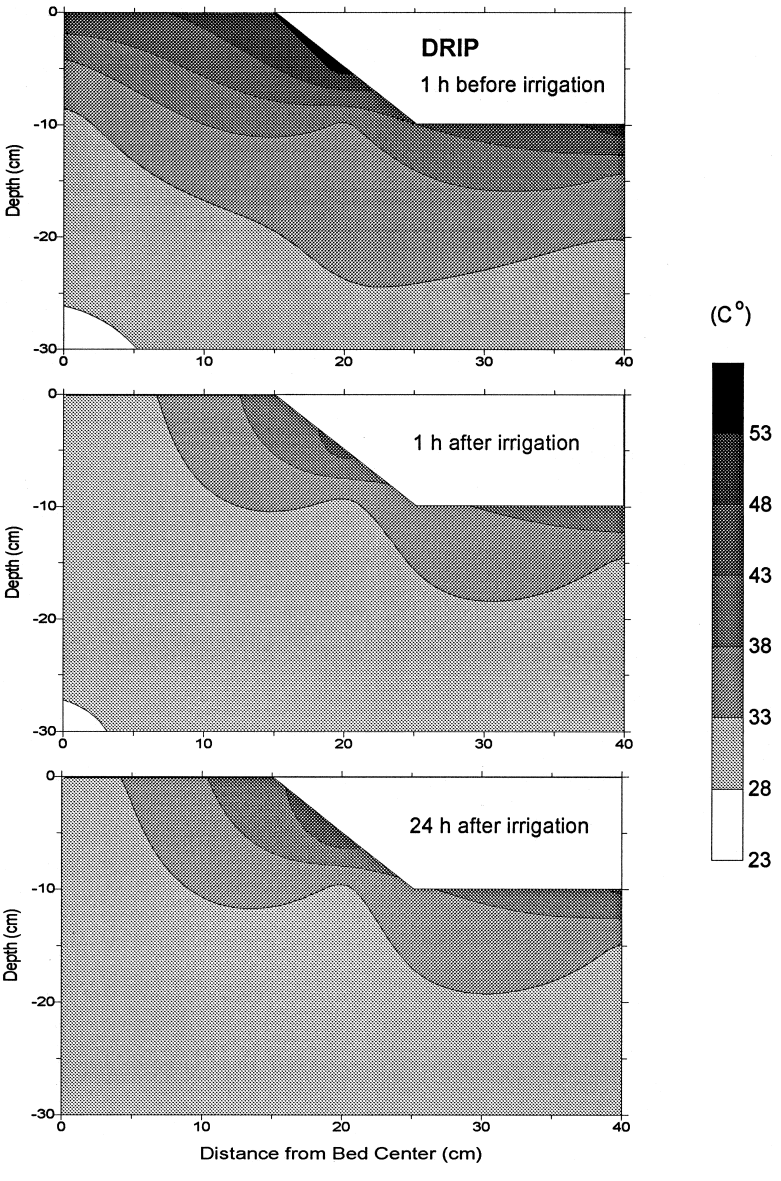

Fig. 4. Spatial distribution of soil temperature 1 h before, 1 h after, and 24 h after a drip irrigation event of 3.5 h duration in which an equivalent of 2.7 mm of water was applied to the whole soil surface.

heating would have raised the surface soil temperature to near or just past the daily maximum. Directly below the drip tape at 5 cm depth where soybean seeds were planted, the soil temperature was at 36.3°C, about 17°C lower than the surface maximum. The difference was attributed to the heat transfer and storage by soil and the amount of reduction should be related to the soil's thermal conductivity and heat capacity. The temperature at 5 cm below the drip tape was reduced to 28.5°C 1 h after irrigation. Soil temperatures at other locations of the profile also decreased significantly from values before the irrigation started (Fig. 4). Since the temperature of the irrigation water was about 23°C, soil cooling was induced primarily by the low temperatures of the added water. This was very likely true since most soil cooling occurred directly below the drip tapes where the soil had received more irrigation water. Other factors contributing to the temperature reduction may include the diurnal cooling effect (past solar noon) and evaporative heat loss from the wetted soil surfaces.

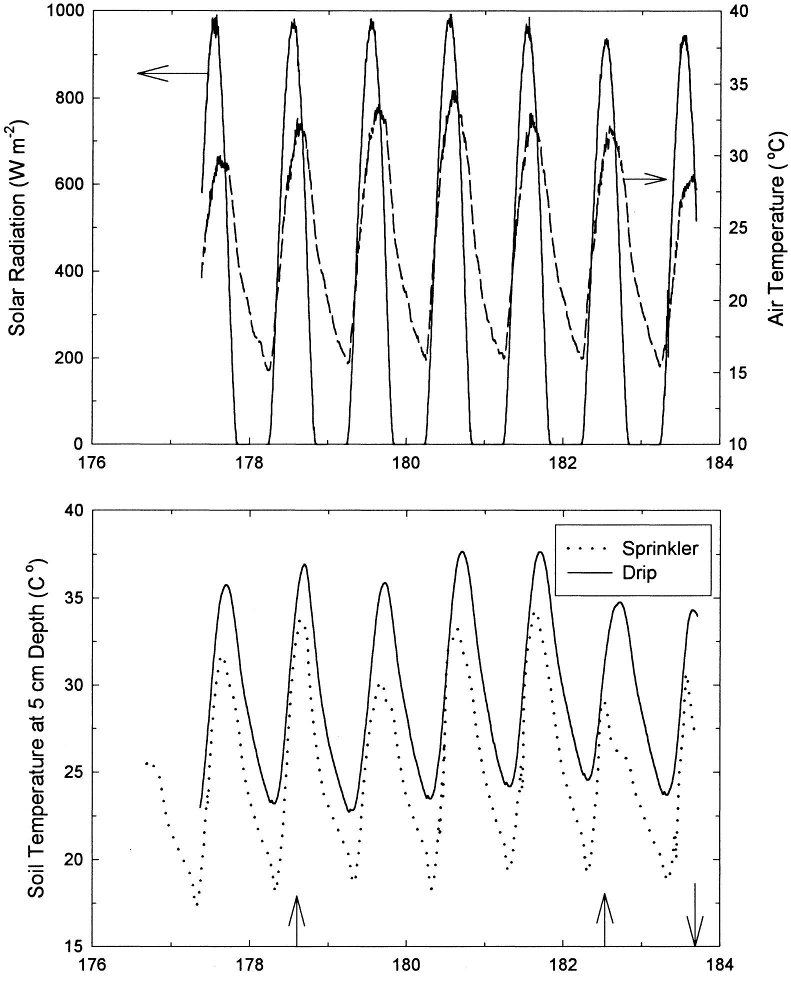

Fig. 5. Solar radiation and air temperature (top); time course of soil temperature at 5 cm below the bed center under drip and sprinkler irrigation (bottom). In the bottom figure, upward-facing arrows represent the irrigation events, and the downward-facing arrow indicates the time of soybean emergence and seedling growth parameter measurements.

On the day following irrigation, soil temperature did not reach previous day's values due to the increased evaporative cooling effect and higher soil heat capacity. Soil temperature at the 5 cm depth remained low (30.0°C) 24 h after the irrigation (Fig. 4). The daily maximum soil temperature at the 5 cm depth (35.9°C) was also lower than the previous day's maximum temperature (36.9°C, Fig. 5). This was primarily caused by the increased soil heat capacity due to the increase in soil water content. The total solar radiation did not differ significantly between the two successive days (981 and 982 W m^{-2} maximum for before and after irrigation), and the maximum air temperature was even higher the day after irrigation (33.6°C) than on the previous day (32.7°C) (Fig. 5).

In the sprinkler irrigated plot, the soil temperature started at lower values than in the drip plot (Fig. 6). Soil temperature at 5 cm depth was 32.5°C 1 h before the irrigation, which was 3.8°C less than that in the drip plot. One hour after the sprinkler irrigation, soil temperature at 5 cm depth had decreased to 24.0°C, very close to the temperature of the irrigation water. Soil temperature below the furrow was very low due to the enhanced infiltration of irrigation water. The distribution of soil temperature was also significantly changed due to the strong temperature reduction directly below the bed and the furrow. The maximum soil temperature was less than 27°C, 1 or 24 h after the irrigation. Soil temperature at 5 cm depth remained low (25.1°C) 24 h after the irrigation. Differences in daily maximum soil temperature between the two irrigation plots appeared to be greater after an irrigation than before the irrigation (Fig. 5). For example, the differences before and after the irrigation on DOY 178 were 3.1°C and 5.7°C, respectively. The lower temperatures in the sprinkler than in the drip plots were primarily attributed to the overall increased amount of irrigation water during each irrigation event (Table 1). Sprinkler irrigation may also temporarily lower the air temperature near the soil surface, delaying soil heating by sensible heat transfer. Further, because the drip tapes were black, they may increase heat absorption from solar radiation and transfer additional heat to the soil. No systematic differences in soil temperature were found between the sprinkler and the drip irrigation plots at the end of the experiment or 21 days after last irrigation (Fig. 7). Therefore, the observed low soil temperatures at 5 cm in the sprinkler than in the drip irrigation were primarily attributed to the irrigation treatment, rather than biases in experimental setup or system differences other than the intended irrigation treatment.

Soybean emergence rate appeared to be higher in drip than in sprinkler irrigated field plots (Table 2). Because probably of the small sample size, however, the difference was not statistically significant at $P=0.05$ level. Seedling growth was also more rapid in drip than in sprinkler plots. The enhanced soybean seed emergence and seedling development were directly related to the irrigation methods through the improved soil thermal regimes in drip irrigation. Whereas the mean soil water content at 5 cm depth averaged over time was very similar between the two irrigation methods, the mean soil temperature was significantly higher (at $P=0.05$) in the drip (29.5°C) than in the sprinkler plot (25.1°C). In fact, the soil temperature in the drip plot was at the optimum emergence temperature reported for soybean (Hatfield and Egli, 1974). Other means of relating the emergence to temperature may include the cumulative thermal time if the critical maximum and minimum temperatures for stress to occur were known for this particular variety of soybean (Bristow and Abrecht, 1991). In addition to temperature, the preservation of soil

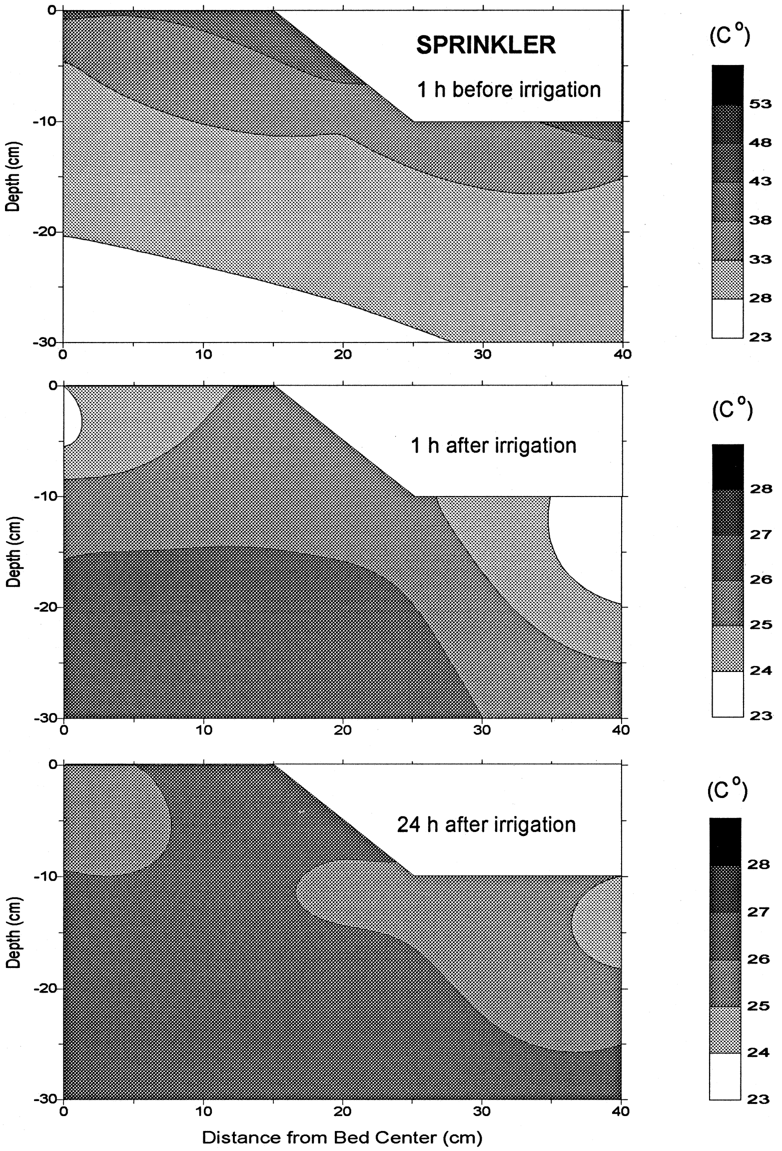

Fig. 6. Spatial distribution of soil temperature 1 h before, 1 h after, and 24 h after a sprinkler irrigation event of 3.5 h duration in which an equivalent of 17.8 mm of water was applied to the whole soil surface.

surface structure in drip irrigation also contributed to the enhanced soybean emergence. Significantly less soil crusting was observed in the drip than in the sprinkler plots. Further studies are needed to better understand the biophysical processes that relate the spatial and temporal variations of soil water and temperature to seed emergence and seedling growth.

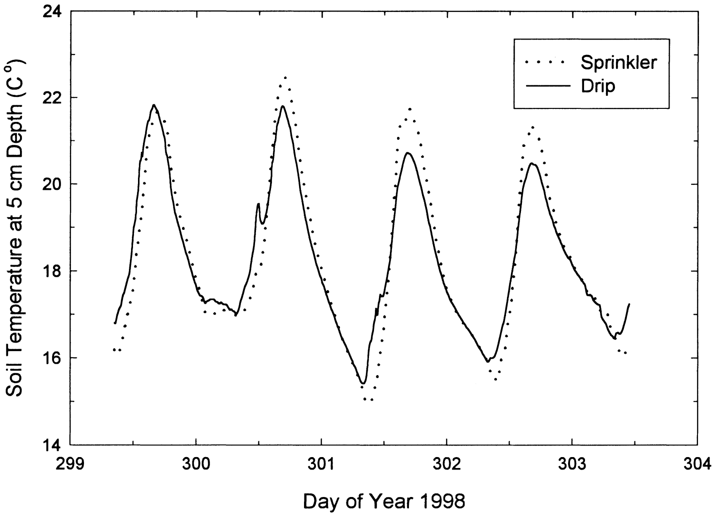

Fig. 7. Soil temperature at 5 cm below the bed center in the drip and sprinkler plots long after the last irrigation event.

Table 2
Soil water content, temperature, soybean emergence ratio and early growth parameters under drip and sprinkler irrigation regimes[a]

Soil water content ($cm^3\ cm^{-3}$)	Soil temperature (°C)	Emergence ratio		Shoot height (cm)	Root length (cm)
		(no. m^{-1})	(%)		
Drip					
0.185 (0.002)	29.5 (0.2)	25.5 (1.7)	77.7 (5.2)	13.6 (1.7)	7.0 (0.9)
Sprinkler					
0.191 (0.002)	25.1 (0.1)	22.3 (2.5)	68.0 (7.6)	10.2 (2.3)	6.4 (1.4)

[a] Numbers are means of hourly soil water content and 10 min interval temperature readings at 5 cm depth averaged over time, and three replicates of emergence counts, shoot height, and root length (SE). A 2 m section was measured for each replicate in the emergence count, and six soybean seedlings were randomly selected from each replicate for the shot height and root length measurement.</tbl

4. Conclusions

Observations from this field study clearly indicate that water and temperature distributions in the soil can be very different depending on the methods of irrigation. Drip irrigation can maintain sufficient soil water content for seed germination and seedling development, but more importantly can keep the soil at a higher temperature which is more favorable for emergence and seedling growth. The observed water and temperature regimes are specific to the irrigation methods used for the study. The effects of irrigation methods on soil water and thermal regimes should be considered, among other management strategies, in optimizing the environmental conditions for plant growth.

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