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EVAPORATION REDUCTION POTENTIAL IN AN UNDISTURBED SOIL IRRIGATED WITH SURFACE DRIP AND SAND TUBE IRRIGATION

M. Meshkat, R. C. Warner, S. R. Workman

ABSTRACT. *The efficiency of drip irrigation is highly dependent on evaporation losses occurring from the constantly saturated soil beneath emitters. Advent of subsurface drip irrigation is in part an approach to curb this inefficiency. An irrigation method, Sand Tube Irrigation (STI), is proposed to increase the efficiency of "Normal" surface applied drip irrigation (NI method) on permanent tree crops without the need for burying the irrigation tubing. The sand tube consists of removing a soil core beneath the emitter and filling the void with coarse sand. A weighing lysimeter was constructed in the laboratory and instrumented to directly measure temporal evaporation from large, undisturbed soil columns, 0.7 m in diameter and 0.8 m in height. Experiments were performed on six replicated soil monoliths to compare the two methods. The results indicated that, for four consecutive days after irrigation, there was a significant difference at the 95% confidence level between evaporation occurring from the NI and STI methods. After four days of evaporation, comparison of water contents indicated that a higher amount of water existed between the depths of 0.2 to 0.55 m in the STI versus the NI method. Although drainage occurred from the macropore structure of the undisturbed soil monoliths, the STI method showed potential in retaining more water in the micropore structure of the lower depths, that would be available for plant use rather than potential evaporation.*

Keywords. *Evaporation reduction, Drip irrigation, Microirrigation, Efficiency, Soil monolith.*

In irrigation science, the term drip or trickle irrigation has become synonymous with an efficient irrigation system. Drip irrigation has attained popularity due to its ability to convey water from the water source to a plant's root zone without loss of water. Compared to furrow irrigation with its seepage losses in the canals and furrows, and sprinkler irrigation with its direct evaporation from airborne water droplets, drip irrigation has no significant conveyance losses. However, evaporation and deep drainage reduces the amount of water available for plant use. Drip irrigation typically has a decreased wetted volume thus requiring more frequent irrigation. An irrigation regime with an excessively high irrigation frequency can cause the soil surface to remain wet and the first stage of evaporation to persist most of the time, resulting in a maximum rate of water loss. This is one of the disadvantages of trickle/drip irrigation systems. The wetted area beneath each emitter, particularly in semiarid regions, is susceptible to high evaporation; not only due to solar radiation, but also due to the advective forces of hot dry air drifting across the surrounding soil which provides

a steep vapor pressure gradient that promotes evaporation. Estimating bare soil evaporation for seven days following surface trickle irrigation from a point-source emitter, Matthias et al. (1986) concluded that evaporation accounted for about 33 to 40% of the applied water.

Comparisons of furrow irrigation versus drip irrigation in arid regions have indicated that a one-time deep irrigation of flood or sprinkling irrigation may cause a higher initial evaporation. But it will diminish quickly by the second or third day after irrigation and rapidly reach the third stage of the evaporation process. Pruitt et al. (1985) using large weighing lysimeters showed that evaporation losses were similar between drip and furrow irrigation of tomatoes. Dasberg (1995) indicated that the evaporation component of ET was similar when wetting the whole soil surface by sprinkler irrigation or using micro irrigation. On soils experiencing severe restrictions to water infiltration as a result of salt accumulation, surface application of water by drip systems may still result in significant surface wetting areas and ponding during periods of high evaporative demand (Grimes et al., 1990).

Recently, proponents of subsurface drip irrigation have mentioned that there is no difference in seasonal ET of drip irrigation and furrow irrigation when canopy development is similar (Evet et al., 1995). Phene et al. (1987) showed that the yield of crops grown using subsurface drip irrigation out performed surface drip or used less water for the same yield. The yield difference may be related to the difference in plant available water due to evaporation reduction in subsurface drip irrigation in contrast to surface drip irrigation system (Evet et al., 1995).

This article introduces an irrigation method that employs a surface drip system in conjunction with a sand tube (column) for the purpose of significantly reducing evaporation. In soils that display surface ponding around

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the emitter, or areas where evaporation potential is high, a core of soil can be removed and replaced with an equal volume of sand. The sand media transmits water into the profile by way of vertical and horizontal flow from the sand tube's base and circumference (Meshkat et al., 1998, 1999b). Sand tube irrigation is only applicable to permanent tree/vine crops where harvesting and other field processes do not annually alter the soils.

In general, all practical methods of evaporation reduction incorporate one or more of the principles of evaporation reduction (Hillel, 1980). The sand tube irrigation method regulates evaporation throughout all three stages of the evaporation process, and prevents resurfacing of irrigation water thus reducing availability for evaporation. The following describes how the three main principles of evaporation reductions are incorporated in the STI method:

1. Controlling energy supply to the site of evaporation by distancing the actual water surface from the ground surface. The amount of energy that reaches the water to change its state from water to vapor is reduced. The drier soil layer above the capillary moistened soil provides a shield against the solar energy accessibility to the moistened soil adjacent to the sand column.
2. Reducing the potential moisture gradient by maintaining a drier surface, the soil surface is kept warmer than the soil profile. Thus, a downward-acting thermal gradient is produced that forces the moisture to migrate from the warmer surface zone to the cooler depths below the surface.
3. Decreasing the conductivity of soil by maintaining a drier and more pulverized surface profile, formation of micropores is prevented, thus decreasing the conductivity of soil.

It has been shown that coarse sand is only slightly more effective than fine sand in evaporation reduction (Modaihsh et al., 1985). However, coarse sand is suggested for the sand tube method, primarily because the capillary rise in the coarse sand is less than fine sand resulting in a lower rise of water in the sand tube. Another advantage of coarse sand is that the flow path will be toward the bottom of the sand tube and channeling to the side of the sand column will not occur.

The objectives of this research were to investigate and quantify the evaporation occurring from a wetted surface area beneath an emitter in a "Normal" surface drip Irrigation system (NI) and the proposed STI method in a permeable soil. Comparisons of the moisture redistribution and wetting front advancement in the soil profile in the two methods are included. The experiments were performed in the laboratory on relatively large undisturbed soil monoliths.

SOIL MONOLITH COLLECTION

Undisturbed soil monoliths were collected from the University of Kentucky, Agricultural Experimentation Station Farm. The undisturbed, Maury silt loam soil monoliths were extracted from an area that was previously under sod and had not been planted or plowed for several years. To estimate the required soil column size, irrigation was applied on a sample area at a rate of 4 L/h. After 12 h

of irrigation, a maximum surface wetted diameter of 0.45 m and an irrigation depth of 0.6 to 0.7 m (determined using an irrigation depth gage) was produced. In reality, irrigation water had channeled down through macropores to much lower depths. A soil column size, 0.7 m in diameter and 0.8 m in depth, was selected to assure that the wetted area created by the drip system could be contained in the large soil column.

A trencher was used to excavate around six soil columns while providing enough clearance so that the soil columns remained undisturbed. Excess soil was removed with a backhoe, leaving a 1.0 × 1.0 m square column. A cylindrical ring, 0.75 m in diameter and 0.15 m wide, was incrementally pressed down on the soil block and the excess soil was hand-trimmed using a chisel. A prefabricated sheet metal cylinder, 0.8 m in diameter and 0.8 m high, was placed over the soil column with a 0.05 m clearance between the soil and the cylinder. This gap was filled with polystyrene expanding foam. Serving two purposes, the foam held the soil column in place for transportation and insulated the soil against thermal conduction.

A cutting device was designed and constructed to detach the soil column at the base (Meshkat et al., 1999a). This device was constructed of a 1.0 m × 0.9 m × 6.4 mm cutting plate with a sharpened edge that was pushed by a 5-ton hydraulic jack within a set of guides on the top of the two side members. The jack assembly was moved seven times, in increments of 0.18 m, to accomplish the cutting of the soil column. After securing the soil column on the cutting plate, a crane lifted the soil monolith out of the pit and onto a truck for transport to the laboratory.

SOIL CHARACTERISTICS

Maury silt loam is typical of the undulating, moderately deep, well-drained soils of upland areas in central Kentucky. A micro-pipette analysis (Miller and Miller, 1987) performed on six cores collected from a 0 to 0.7 m depth (in 0.1 m increments) showed a sand content ranging from 7 to 13%, silt from 55 to 68%, and clay from 25 to 32%. The saturated hydraulic conductivity was determined using a laboratory constant head permeameter. An average saturated hydraulic conductivity of 21.2 mm/h was determined which reflects the flow through the soil matrix without a significant macropore contribution.

LABORATORY PROCEDURE

After the undisturbed soil monoliths were collected and transported to the laboratory, surface vegetation was closely clipped and each soil column was covered with plastic sheeting to preserve the water content. Prior to each experiment, each monolith was equipped with four tensiometers and 12 thermocouples throughout the soil profile (figs. 1 and 2). The small cup tensiometers (10 mm in diameter) were inserted through a horizontally drilled hole into the side wall of the soil column. These tensiometers were constructed with two 2-mm nylon-tubing lines used for purging and tension measurement. A portion of the removed soil was moistened and injected into the end of the drilled hole providing full contact between the tensiometer cup and the soil. Dry bentonite

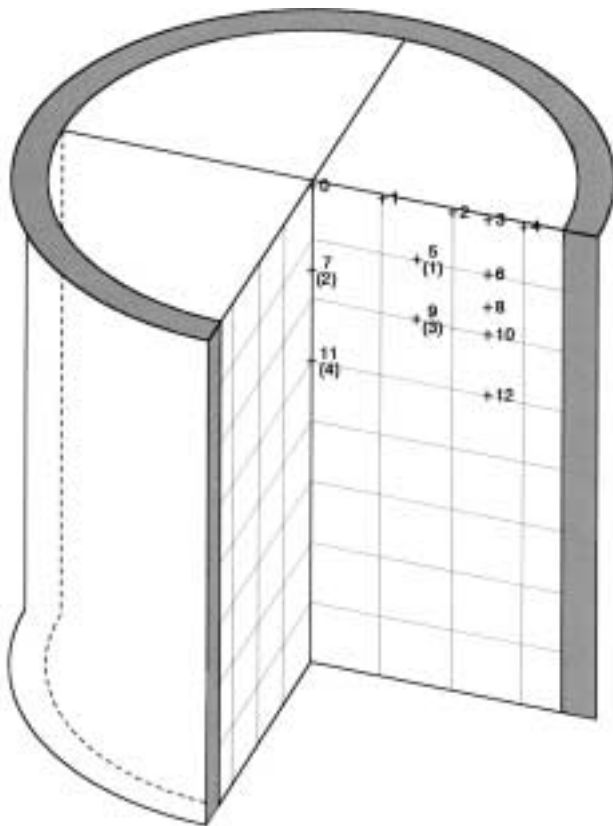


Figure 1—Thermocouples and tensiometers (number in parenthesis are tensiometers) location map for surface-applied irrigation (NI) treatment. Outside ring is the metal cylinder (0.8 m in diameter). Inside ring is the soil core, and the gap is filled with expanding foam (shaded area). Grid is on a 100-mm interval.

was blown into the hole to fill up the void spaces and stop potential leakage of water along the tensiometer lines. Thermocouples were similarly installed. Tensiometers and thermocouples were installed a day before placing the soil monolith on the lysimeter. A mercury manometer was used to measure soil suction. Due to the physical limits of tensiometers, some tensiometers installed close to the soil surface lost suction during the drying cycle prior to irrigation.

The soil monoliths were placed on a large laboratory lysimeter (with a static weighing accuracy of 20 g) designed and constructed for use in measuring (with a 0.025 mm accuracy) evaporation losses in drip irrigation systems (Meshkat, 1997). Irrigation water was stored in a saddle tank with the lysimeter and counter balanced with the soil mass to improve measurement accuracy. An artificial heat source was used to cyclically induce evaporation from the soil surface. The soil surface was heated to between 50 to 60°C.

Twelve hours of heating, in an on/off cycle, was used to simulate day and nighttime conditions. The soil surface was subjected to three days of heating and irrigation was applied on the third day. Evaporation measurements were collected for four days, while temperature changes within the soil profile were monitored. At the termination of the experiment, soil cores were excavated in increments from the entire depth of the soil profile and soil water contents were determined.

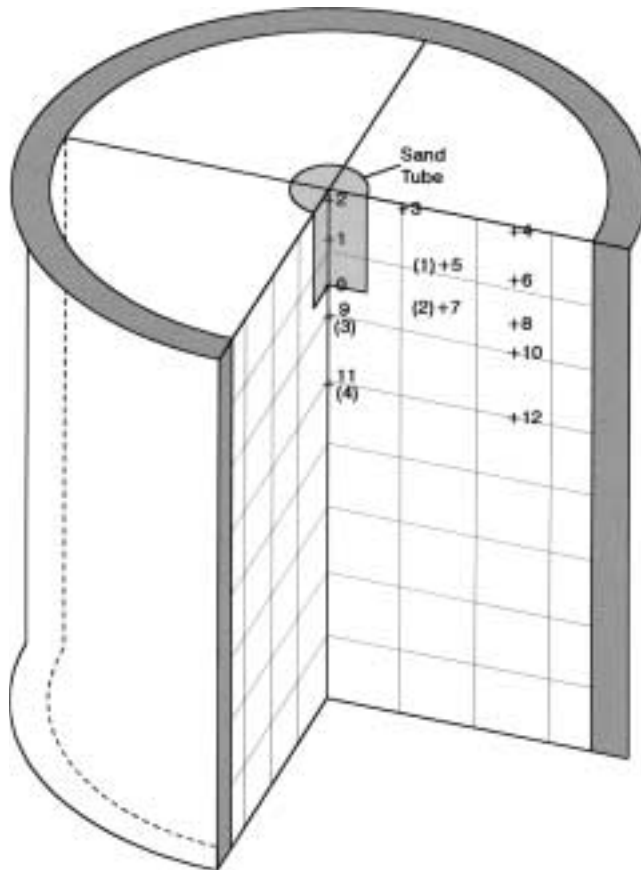


Figure 2—Thermocouples and tensiometers (number in parenthesis are tensiometers) location map for sand tube irrigation (STI) treatment. Outside ring is the metal cylinder (0.8 m in diameter). Inside ring is the soil core and the gap is filled with expanding foam (shaded area). Grid is on a 100-mm interval.

A preliminary test was performed on an auxiliary soil monolith to determine the appropriate irrigation application rate and experimental procedure. An application rate of 4 L/h for 12 h caused excessive drainage. Drainage was due primarily to macropores caused by the fallow condition of the soil in the field and worm activity. Since there was the possibility that drainage caused by water channeling to the side wall and leakage occurring from this area, it was decided to add a dye tracer to the irrigation water.

Three days of heating prior to irrigation was performed to reduce the background evaporation during and after irrigation, because of the relatively high water content of the soil monoliths. Four days of heating followed irrigation. The three days of drying prior to irrigation caused the large columns to shrink and a separation gap developed between the soil and the surrounding insulating foam. The gap was filled with dry bentonite to limit evaporation from the annular space.

Soil water content was determined from 50- to 100-mm length core samples taken at three different times: a sample was taken prior to the start of the heating cycle, before commencing irrigation, and after the termination of the test. Only a single core was taken at each sampling time. The locations of the first two samples were arbitrarily chosen near the edge of the sample, and the third core was taken near at the center of the soil bin.

NORMAL IRRIGATION TREATMENT (NI) TESTS 1, 2, AND 3

Replicated tests were performed on three separate soil monoliths. Water was pumped from the holding tank and applied at the center of the soil column. The irrigation rate was set at 2 L/h, and the duration of application was six hours. Investigation of the soil columns after the tests by cutting the soil monoliths horizontally and vertically indicated that no side wall leakage had occurred. The extent of surface wetting was photographed during the irrigation cycle. There was not a measurable difference between the ponded area and the capillary moistened soil that surrounded it, as it had occurred in the reconstructed soil experiment (Meshkat et al., 1998).

SAND TUBE IRRIGATION TREATMENT (STI) TESTS 4, 5, AND 6

To measure the evaporation change using the sand tube irrigation method, experiments were conducted on three separate soil monoliths. The sand tube dimensions selected for these tests were based on the surface wetness area of the NI tests 1 and 2. The average diameter of the wetted area on the soil surface was approximately 0.26 m. The sand tube dimensions were based on creating a similar water contact area within the sand tube as the measured wetted surface area of the surface applied irrigation (NI treatment):

$$H_s = 1.5 D_s \quad (1)$$

$$A_s = A_{wp} \quad (2)$$

$$D_s^2 + 4 D_s \times H_s = D_{wp}^2 \quad (3)$$

where H_s and D_s are the height and diameter of the sand tube, respectively. A_s represents the combined surface area of the bottom and side wall of the sand tube. D_{wp} and A_{wp} are the average diameter and area of the wetted surface in NI tests 1 and 2. The height of the sand tube was assumed to be 1.5 times the diameter of the sand tube. Applying these criteria a sand tube diameter of 0.1 m and a height of 0.15 m were determined. The depth of water rise in the sand tube was measured during irrigation using an inserted glass tube. Thermocouples were also installed at several depths within the sand tube.

RESULTS AND DISCUSSION WATER CONTENT AND MOVEMENT

The soil cores extracted for water content determination were collected in 50 to 100 mm increments from the soil profile. Ignoring the near surface and the deepest samples, the average initial water content, prior to heating, for the entire depth of the core for test 1 through test 6 was approximately 20.5% with a range of 18 to 23% gravimetric. The similarity in initial soil water content assured that the soil columns represented a similar soil water status prior to heating (fig. 3). The graph of water content after induced evaporation for three days and prior to irrigation (fig. 4) indicates that most of the drying had

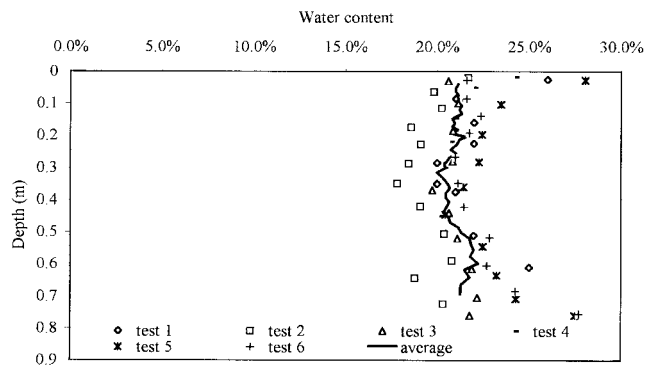


Figure 3—Gravimetric water contents of six soil monoliths prior to induced evaporation.

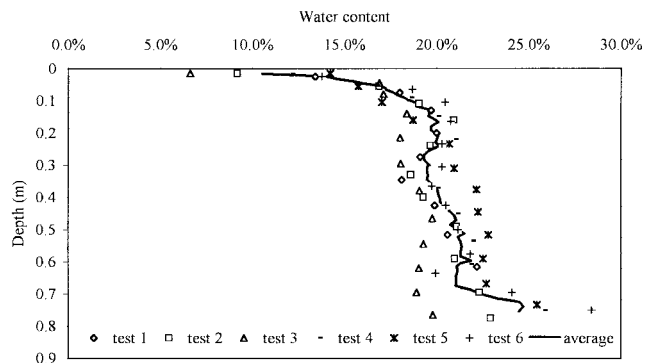


Figure 4—Gravimetric water contents of six soil monoliths after three days of induced evaporation prior to irrigation.

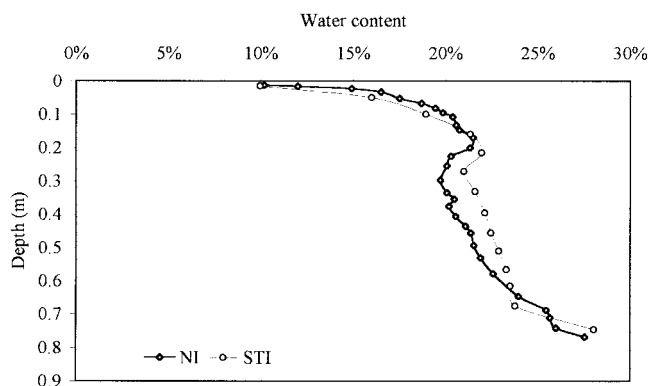


Figure 5—Average gravimetric water content at termination of tests, after four days of induced evaporation.

occurred above the 0.25 m depth. The curves had pivoted about this depth from wet to dry. The water contents measured at the termination of the tests for the NI and STI treatments are illustrated in figure 5. The portions of curves above the 0.15 m depth are similar between the two treatments. The difference between the NI and the STI methods is readily evident in the depth range between 0.2 to 0.55 m. The STI treatment has higher water content at these depths than the NI treatment even after four days of evaporation. These results were consistent with published results on reconstructed soils (Meshkat et al., 1998).

Due to the presence of an extensive macropore network, matrix flow was not the only means of water transport within the soil columns. In some tests, drainage water

appeared at the drainage port prior to registering at tensiometers located 0.1 to 0.3 m beneath the water emission point. Drainage occurred only during the irrigation cycle. The problem of tensiometers losing suction also prohibited use of the graphical results in estimating the wetting front movement in the soil profile. A typical tensiometer reading taken for test 2 is presented in figure 6. For each individual test, the plot of tensions versus time presented an expected trend in variation of tensions before and after irrigation. Prior to irrigation at time 0 h, the profile had slowly dried. After irrigation, the surface layer was saturated as indicated by the zero tension in the tensiometers. Drying proceeded after the irrigation event with those tensiometers nearest to the soil surface drying before the tensiometers installed at greater depths. In such a macropore environment, tensiometer measurements provide inadequate information to accurately interpolate the nonuniform wetting front movement. However, taking into account the considerable amount of irrigation water drained from the soil monoliths, tensiometers were useful in indicating that in all tests the water content of the soil monoliths reached saturation after irrigation. This fact helped in substantiating the results.

TEMPERATURE PROFILE

Twelve thermocouples were used to determine the temperature at specific locations just beneath the surface

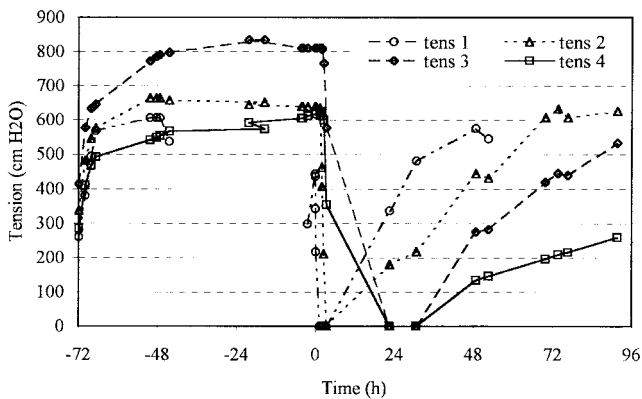


Figure 6—Tensiometer readings taken during test 2, NI treatment. Tensiometer was located at 0.15 m off center and 0.1 m below the surface.

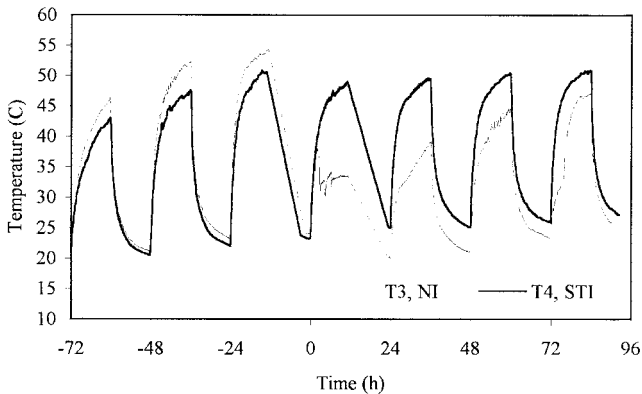


Figure 7—Temperature profiles at thermocouple no. 3, NI treatment, and thermocouple no. 4, STI treatment. See figures 1 and 2 for thermocouple locations.

and throughout the soil profile (figs. 1 and 2). Recorded temperatures from chosen thermocouples at approximately the same physical location are presented in figure 7 for test 3 of the NI treatment and test 4 from the STI treatment. A comparison of the recorded temperatures after irrigation indicates that the drier surface resulting from the STI treatment exhibits a much higher surface temperature than the NI treatment. This phenomenon was also observed in experiments with a reconstructed soil (Meshkat et al., 1998). Thermocouples 5, 8, and 10 in tests 3 and 4 revealed the same temperature profile pattern with dampened effects corresponding to the lower depths. The established thermal gradient is viewed as one of the main advantages of the sand tube irrigation method. The warmer surface and cooler depths in the STI method sets up a downward heat gradient that is a deterrent to upward moisture migration.

EVAPORATION AND STATISTICAL ANALYSIS

The reason for researching the sand tube method was to gain a better understanding of the potential reductions in evaporation from the soil surface. In this experiment, evaporation occurring from the soil surface was measured by monitoring the recorded weight change of the load cell. The measurements were taken for three days before irrigation during the 12-h on/off cycle heating period and for four days post irrigation. The cumulative evaporation and drainage are summarized in table 1 and figure 8.

On the third day of heating prior to irrigation for all six monoliths, the average evaporation was 0.85 L with a standard deviation of 0.11 L. This indicates that the antecedent water content of the soil monoliths prior to irrigation was quite similar. Table 1 shows that, after irrigation, an average of 3.66 and 2.2 L H₂O evaporated from the NI and STI treatments, respectively. Therefore a

Table 1. Total evaporation and drainage (L) from the NI and STI treatments

12 h Time Cycle	Heat Cycle	Normal Irrigation			Sand Tube Irrigation		
		Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
-72 - -60	On	1.33	1.45	1.74	1.77	1.89	1.45
-60 - -48	Off	0.23	0.32	0.43	0.36	0.47	0.27
-48 - -36	On	1.09	0.97	1.14	1.12	1.30	0.91
-36 - -24	Off	0.26	0.28	0.32	0.38	0.42	0.23
-24 - -12	On	0.94	0.75	0.79	0.91	1.00	0.72
-12 - 0	Off	0.21	0.24	0.38	0.36	0.47	0.22
0 - 12*	On	1.16	1.40	1.05	-	1.00	0.91
12 - 24	Off	0.38	0.40	0.38	0.24	0.15	0.07
24 - 36	On	0.91	1.07	1.40	0.62	0.54	0.45
36 - 48	Off	0.21	0.27	0.38	0.19	0.21	0.17
48 - 60	On	0.84	0.66	0.85	0.48	0.50	0.43
60 - 72	Off	0.24	0.22	0.27	0.18	0.21	0.18
72 - 84	On	0.72	0.64	0.59	0.62	0.48	0.37
84 - 96	Off	0.19	0.20	0.16	0.19	0.21	0.11
Total evaporation†		8.70	8.87	9.88	7.42	8.86	6.48
Avg		9.15			7.59		
Total evaporation after irrigation‡		3.49	3.47	4.03	2.51	2.31	1.78
Avg		3.66			2.20		
Drainage		0.54	0.81	0.61	1.46	6.94	7.96
Avg		0.65			5.45		

* Irrigation occurred during 0 to 12 h.
 † Algebraic sum of values.
 ‡ Sum of all positive values since irrigation.

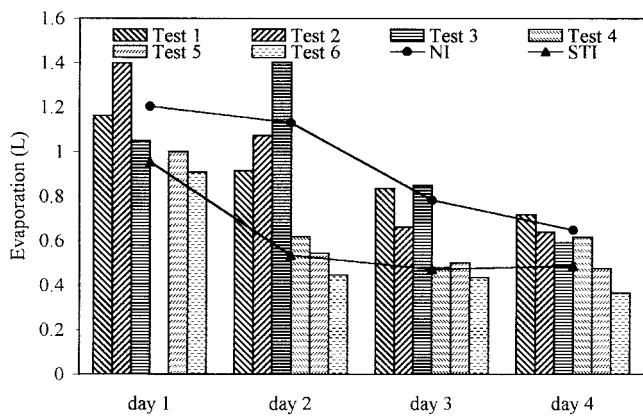


Figure 8—Total daytime evaporation since commencement of irrigation.

1.46 L or 39.8% reduction in evaporation resulted from implementing the STI method.

Average daily evaporation is presented in figure 8. The general trend of the evaporation process is shown for both the NI and STI treatments. After the first day, the STI treatment displayed an exponential reduction of evaporation. The higher evaporation value for the first day was primarily due to the rise of water (95, 150, and 55 mm for tests 4, 5, and 6, respectively) in the sand tube. The mean evaporation of the NI treatment was always greater than the STI treatment. The largest difference between means occurred on day 2 when the soil surface for the NI treatment was at a higher water content due to the wetted area surrounding the emitter. A dry surface layer existed in the STI treatment, accounting for reduced evaporation losses.

Although the experiment had a completely randomized design, the data were analyzed as a split-split plot design. Comparison was made among treatments between the means of the cumulative evaporation since the beginning of irrigation. As a completely randomized split-split plot design, each treatment was separated into four dates representing the 24-h cycles since irrigation. Each treatment was further segmented into four dates with each date analyzed by day and night evaporation (corresponding to the heat on/off cycle). A further comparison was conducted between the day and night evaporation viewed in the temporal context as the experiment progressed beyond the initial application of irrigation.

The ANOVA results (table 2) indicated a highly significant difference was shown to exist between the two treatments at the 95% confidence level regardless of the error term used for evaluation. Tests of the hypothesis of

Table 2. ANOVA table from analysis of variance

Source	DF	S.S.	M.S.	F value	Pr > F
TRT	1	0.4595346	0.4595346	73.65	0.0001*
Error = REP*DATE*TIME(TRT)	11†	0.0686632	0.0062393		
TRT	1	0.4595346	0.4595346	27.47	0.0063*
Error = REP(TRT)	4	0.0669152	0.0167288		
TRT*DATE	3	0.1008390	0.0336130	2.26	0.1337 ^{NS}
Error = REP*DATE(TRT)	12	0.1784451	0.0148704		
TRT*TIME	1	0.1209949	0.1209949	38.13	0.0035‡
Error = REP*TIME(TRT)	4	0.0126923	0.0031731		

* The difference between treatments is highly significant.
 † Because of the missing value, Degrees of Freedom is calculated as [(3 - 1)(4 - 1)(2 - 1) × 2] - 1.
 ‡ Significantly different at 95% confidence level.
^{NS} The difference is not significant.

TRT*DATE interaction using the means square for REP*DATE(TRT) as an error term resulted in a F value of 2.26, which was nonsignificant. This indicated that the cumulative evaporation values of each date (day and night evaporation of all reps of each date averaged) of each treatment were not different. Tests of the hypothesis concerning a difference in evaporation between the day and night periods using REP*TIME(TRT) as an error term indicated a F value of 38.13 for TRT*TIME interactions which was highly significant.

To further investigate and compare the two treatments, a test of the null hypothesis was made between the Least Square Means (LSMEANS) of each event (table 3). Similar to the ANOVA test, the TRT*DATE interaction was nonsignificant at the 0.01 level. In table 3, where day and night evaporation were summed, a highly significant difference among the overall evaporation value of date 2 was shown and a significant difference at the 95% confidence level for date 3 and date 1 existed. Difference in evaporation during date 4, after irrigation, was nonsignificant. The nonsignificant difference of date 4 was during the night period; whereas, the day period was still significant at the 95% confidence level (table 4).

Evaporation was significantly different between the daytime evaporation for the STI and NI methods with the greatest difference existing for the second day following irrigation (table 4). The level of significance, as expected, decreased over time. The difference in nighttime evaporation was highly significant for the first night after irrigation and thereafter was not significant. The daily evaporation differences between the two methods remained significant even into the fourth day. It must be noted that during the irrigation cycle for one of the STI tests, a malfunction of the instrumentation caused evaporation to not be properly recorded. The level of significance shown

Table 3. Probability values and significance level between mean of sum of day and night evaporation

		Sand Tube Irrigation			
		Date 1	Date 2	Date 3	Date 4
Normal Irrigation	Date 1	0.0291*†			
	Date 2		0.0004‡		
	Date 3			0.0231*	
	Date 4				0.2419 ^{NS}

* Significantly different at 95% confidence level.
 † Possibly due to the missing value for date 1. Not enough significance is shown.
 ‡ The difference between treatments is highly significant.
^{NS} The difference is not significant.

Table 4. Probability values and significance level between mean values of day and night evaporation

		Sand Tube Irrigation							
		Date 1		Date 2		Date 3		Date 4	
		Day	Night	Day	Night	Day	Night	Day	Night
Normal Irrigation	Date 1	Day	0.066*						
		Night		0.004†					
	Date 2	Day			0.0001†				
		Night				0.162 ^{NS}			
	Date 3	Day				0.0005†			
		Night					0.425 ^{NS}		
	Date 4	Day						0.0305†	
		Night							0.840 ^{NS}

* Possibly due to the missing value for date 1. Not enough significance is shown.
 † The difference between treatments is highly significant.
^{NS} The difference is not significant.

during (date 1/daytime) was based on only two replications, which biased the level of significance.

The average drainage for the STI treatment was 5.45 L, which was an order of magnitude higher than the 0.65 L of water drained from the NI treatment. Direct access of water to macropores at the bottom and sides of the sand tube was the reason for the fast drainage in tests 5 and 6, which had 6.94 and 7.96 L of drainage, respectively. The observed water levels for test 4 (fig. 9) were typical of water levels observed in reconstructed soil columns (Meshkat et al., 1998). In test 5, the sand tube became saturated after about 75 min of irrigation and then the water level dropped to a moderate level until the end of the irrigation cycle. We believe that the water pressure in the saturated sand tube reopened a clogged macropore and allowed the sand tube to drain. In test 6 where approximately 66% of the irrigation water was lost to drainage, macropore flow from the sand tube occurred throughout the irrigation cycle. One might argue that due to the excessive drainage of the STI treatment, there was not enough water available in the profile causing less evaporation to occur from the STI method. Although the drainage water was unavailable for evaporation, the tensiometer readings indicated that at least for the first 0.4 m of the profile (which is the primary evaporating region), soil suction declined for both treatments indicating an increase in water content during the irrigation cycle.

The rapid movement of water in the sand tube/macropore system was not expected prior to the experiments but helps to illustrate the advantages and disadvantages of the sand tube methodology. When first proposed, the sand tube method was thought to be ideally suited to very slowly permeable soils that develop a crust at the surface. Under these conditions, water tends to pond on the surface and is lost to evaporation. Soils that do not exhibit these characteristics were thought to be best served by a traditional drip irrigation system. Results of this research effort indicate higher permeability soils can also benefit from the sand tube method if a temperature gradient can be developed at the soil surface. The primary benefit of the STI method is that a combination of a dry surface crust and a thermal gradient impedes evaporation.

In general, macropore development similar to that observed in the Maury soil columns is unlikely in an arid climate. If significant macropore development does occur in the STI system then two possible scenarios are possible.

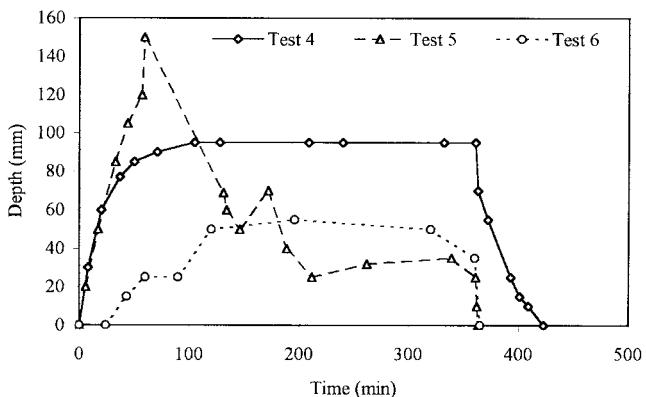


Figure 9—Depth of water inside the sand tube during irrigation. Depth of sand tube was 150 mm.

If the macropores extend beyond the root zone of the crop, water transported through the macropore system would be unavailable to the crop. If the macropores extend into the root zone, a better crop rooting system would likely develop from the wider distribution of water throughout the profile in the STI system.

SUMMARY

Undisturbed soil monoliths from a permeable soil where macropore flow represented the primary flow path were used in experiments to measure and compare evaporation from surface-applied drip irrigation (NI treatment) and the STI method. Six similar soil monoliths were subjected to three and four days of pre and post irrigation evaporation. The STI method was evaluated and shown to significantly reduce evaporation for the undisturbed soil monoliths over the four days after irrigation in contrast to NI treatment. Also, the water content at depths 0.2 to 0.55 m were higher for the STI method than for the NI method. The evaporation measured on the second day after irrigation provided the most significant difference between the two irrigation methods.

As result of macropore flow, tensiometers failed to predict the advancement of the wetting front. However, they proved that prior to evaporation the water content of soil monoliths had reached saturation regardless of the excessive drainage during irrigation. Surface temperatures in the STI method were 5 to 10°C higher in contrast to the NI treatment. Consequently, the temperature gradient caused a downward heat gradient that was considered to be a deterrent to upward moisture flow.

Potential water saving capability of the STI method, consistent with the evaporation reduction principles, in contrast to the NI method can be summarized as follows:

1. Indirect application of water at a lower depth (bottom of sand tube) in the STI method resulted in a gradually drier surface. This reduced the hydraulic conductivity of the soil surface layer thereby repressing the movement of water upward.
2. The thermal gradient induced by the STI method was one of the main advantages of the method. The dryer, warmer surface and cooler depths set up a downward heat gradient as a deterrent to upward moisture migration.
3. With STI a lesser chance for addition of salt accumulation in the root zone exists since the STI method applies less water, equivalent to less evaporation.

The STI method is particularly applicable to permanent tree crops, less permeable soils, and the dry-climate farming environment where achieving higher water usage is especially critical. Although the accelerated sand tube construction procedure requires further investigation, a simple tractor-mounted small auger can facilitate field-scale implementation of this method. As always, initial construction costs must be balanced with annual water saving and potential yield increase.

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