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Water Flux below the Root Zone vs. Drip-Line Spacing in Drip-Irrigated Corn

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ABSTRACT

Use of microirrigation (drip) is increasing, prompted by factors such as a greater ability to control losses of water and nutrients from the root zone. The cost of drip can be reduced by using wider drip-line spacings. Our objective was to evaluate water flux below the root zone (1.5-m soil depth) with a subsurface drip irrigation system having drip-line spacings of 1.5, 2.3, and 3.1 m near Colby, KS. The soil is a deep silt loam that formed in loess. The crop was corn (*Zea mays* L.), planted in rows spaced 0.76 m apart. Water flux at the 1.5-m soil depth was determined in five treatments (Trt.): 1.5-m spacing, full irrigation; 2.3-m spacing, 67% of full irrigation; 2.3-m spacing, full irrigation; 3.1-m spacing, 50% of full irrigation; and 3.1-m spacing, full irrigation. With full irrigation, irrigation plus effective rain equaled calculated corn evapotranspiration (ET). Tensiometers were placed below the drip line and at increments of 0.4 m from the drip line at soil depths of 1.4 and 1.7 m. Water flux was calculated by using a hydraulic conductivity (*K*) vs. matric potential (ψ_m) relationship, ψ_m data from tensiometers within the corn plots, and Darcy's equation of water flow. In-season water fluxes below the root zone (1.5 m) were 51, 118, and 124 mm at drip-line spacings of 1.5, 2.3, and 3.1 m, respectively. In 1990, corn grain yield was not significantly affected by spacing. In 1991, with drier initial soil–water conditions, corn yielded significantly less grain at spacings of 2.3 m (11.5 Mg ha^{-1}) and 3.1 m (10.7 Mg ha^{-1}) than at a drip-line spacing of 1.5 m (13.1 Mg ha^{-1}). If spacing between drip lines is increased beyond 1.5 m in the silt loam soils of western Kansas, there would be an associated increase in internal drainage from the root zone and decrease in corn yields.

THE IRRIGATED AREA of the world was about 94 million ha in 1950 (Tsutsui, 1992) and 250 million ha in 1992 (Food and Agriculture Organization, 1994). Conflicts for water are increasing in many areas of the world, as demands rise and vital sources of regional water supplies become limited (Bucks, 1995). Hillel (1990) reported that, because of rising costs of energy, scarcity of good land and water, and increasing demand for agricultural products, the need to improve irrigation efficiency has become more urgent than ever.

In management of irrigation, losses that can be reduced to improve irrigation efficiency are primarily losses associated with conveyance of water to the field, internal drainage of water from the root zone within the field, and runoff from the field (Hillel, 1990). Keys to reducing internal drainage through irrigation water management are improving the uniformity of the applied water and decreasing the average depth of water applied (Hanson, 1987). Tanji and Hanson (1990) reported that proper irrigation management can reduce overirrigation, and proper irrigation system selection, design, operation, and maintenance can control the uniformity. Jensen et al. (1990) stated that research is needed to achieve improved on-farm systems that would facilitate the application of lighter and more timely irrigations in order to minimize crop water stress and excess water applications.

In an attempt to conserve water and use water more efficiently, the use of microirrigation systems has increased throughout the world. The area worldwide of microirrigation systems increased from about 0.4 million ha in 1981 to 1.8 million ha in 1991 (Bucks, 1995). Interest in microirrigation (drip) is prompted by factors such as the increasing cost of water, limited water supplies, and a greater capacity for control of internal drainage losses of water and soluble nutrients (Hutmacher et al., 1995). The major disadvantage of drip is the high cost, which can be reduced by reducing the amount of materi-

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Abbreviations: DOY, day of year; ET, evapotranspiration; *K*, hydraulic conductivity; RCB, randomized complete block; Trt., treatment; ψ_m, matric potential; LSD, least significant difference.

als needed, e.g., by using wider spacing between drip lines (Camp et al., 1995b). With drip tape material being one of the largest costs associated with buried drip systems, drip lines on a 1-m spacing increase the system cost by about 40% compared with drip lines on a 2-m spacing (Henggeler, 1995).

Studies have examined the relationship between drip-line spacing and crop yield with corn (Powell and Wright, 1993) and cotton (*Gossypium hirsutum* L.) (French et al., 1985; Bucks et al., 1988; Camp et al., 1995a), but did not consider internal drainage from the root zone. Internal drainage is a component of the field water balance that is seldom measured adequately (Hillel, 1990). To maintain a proper salt balance within the root zone, efficient irrigation must provide for adequate but minimum leaching through internal drainage management (Rhoades and Loveday, 1990). Excessive internal drainage is wasteful of water, leaches plant-needed nutrients from the root zone, and moves agricultural chemicals from their intended-use region.

Against this backdrop of the need to reduce costs by increasing the distance between buried drip lines and the need to minimize internal drainage losses from the root zone, our objective was to evaluate water flux below the root zone (1.5-m soil depth) with a subsurface drip irrigation system having three drip-line spacings. The test crop was corn, and the soil was a deep silt loam. The 1.5-m soil depth represented the assumed lower boundary of the corn root zone.

MATERIALS AND METHODS

Field work was conducted during 1990 and 1991 near Colby, KS (39.4° N, 101.1° W; 967 m above sea level). The soil is mapped as Keith silt loam (fine-silty, mixed, mesic Aridic Argiustoll); a deep, well-drained soil that formed in loess (Barker et al., 1980). Similar soils occupy about 2.34 million ha of the central High Plains (Aandahl, 1982).

A corn area (100 by 115 m) was irrigated with a subsurface drip system, installed in July 1989 with drip lines buried at a soil depth of 0.40 to 0.45 m. The drip-line tubing was Turbulent Twin Wall IV (Chapin Watermatics Inc., Watertown, NY)[1] with emitter separation of 0.30 m. Installation of the subsurface drip system was described by Lamm et al. (1990). Irrigation water was obtained from the Ogallala Aquifer and is of excellent quality (Na adsorption ratio, adjusted, of 1.3 and total dissolved solids of 0.3 g L^{-1}).

Research plots were in a randomized complete block (RCB) design with 11 treatments and three replications (33 plots), each plot 9 by 28 m. Spacing between drip lines and water application amount per drip line were treatment variables. Water flux below the root zone (1.5-m soil depth) was determined in five of the 11 treatments, (Trt. 1) 1.5-m spacing, full irrigation; (Trt. 4) 2.3-m spacing, 67% of full irrigation; (Trt. 5) 2.3-m spacing, full irrigation; (Trt. 8) 3.1-m spacing, 50% of full irrigation; and (Trt. 9) 3.1 m spacing, full irrigation. Full irrigation was calculated so irrigation plus effective rain would equal calculated ET. Corn ET was calculated as reference ET (from a modified Penman equation) multiplied by basal crop coefficient values (Lamm et al., 1992). Because irrigation water was applied through buried drip lines, no soil water evaporation component was used to modify calculated ET. Irrigation was applied when the cumulative value of calculated ET for Trt. 1 minus effective rain was ≈30 mm. The amounts of irrigation applied to Trt. 1, 5, and 9 were based on land area, i.e., the three treatments received the same amount of water per plot, but Trt. 5 received 1.5 times more water per drip line than Trt. 1, and Trt. 9 received 2.0 times more water per drip line than Trt. 1. The amounts of irrigation applied to Trt. 1, 4, and 8 were based on application amount per drip line, i.e., drip lines in the three treatments each provided the same amount of water, but the total amount of water applied per plot to Trt. 4 was 67% of that in Trt. 1, and the total amount of water applied per plot to Trt. 8 was 50% of that in Trt. 1. Water application was started at the same time for all treatments at each irrigation event, but ended at different times because of different amounts of water applied per drip line as the result of different drip-line spacings. That is, Trt. 1, 4, and 8 received water for the same amount of time, whereas Trt. 5 received water for 1.5 times as long and Trt. 9 received water for 2.0 times as long as Trt. 1, 4, and 8. An irrigation event to apply 30 mm of water lasted ≈24 h for Trt. 1 and 48 h for Trt. 9.

The field was irrigated through the subsurface drip system in August 1989, soon after system installation. Fertilizer was surface applied as a solution in October of both 1989 and 1990 (245 kg N ha^{-1} and 45 kg P ha^{-1}). On 23 Apr. 1990 and 7 May 1991, corn (Pioneer 3162) was planted in rows spaced 0.76 m apart, giving 12 rows in each plot. The corn was planted parallel to the drip lines at 67 950 seeds ha^{-1} in 1990 and 71 900 seeds ha^{-1} in 1991 with each drip line centered between two rows. The closest distance between any corn row and the nearest drip line was 0.4 m (all treatments), and the widest distance was 1.1 m (Trt. 4, 5, 8, and 9). Corn was harvested by hand, and grain yield reported at 155 g kg^{-1} water content on a wet-mass basis.

Tensiometers were installed in June of 1990 and 1991 in the central area of the 15 study plots and perpendicular to the middle drip line. In Trt. 1 plots, tensiometers were placed at soil depths of 1.4 and 1.7 m and distances from the drip line of 0, 0.4, and 0.8 m (six tensiometers per plot). In Trt. 4 and 5 plots, tensiometers were placed at soil depths of 1.4 and 1.7 m and distances from the drip line of 0, 0.4, 0.8, and 1.1 m (eight tensiometers per plot). In Trt. 8 and 9 plots, tensiometers were placed at soil depths of 1.4 and 1.7 m and distances from the drip line of 0, 0.4, 0.8, 1.1, and 1.5 m (10 tensiometers per plot). Tensiometers were read two or three times weekly at about 0900 h by using a pressure transducer (Tensimeter, Soil Measurement Systems, Tucson, AZ). Data were collected from 18 June through 20 Sept. of 1990 and 1991. Matric potentials (ψ_m) on the first reading dates (18 June of 1990 and 1991) at the 1.4- and 1.7-m soil depths were used to describe initial water conditions in that region of the soil profile.

A noncropped plot (3.7 by 3.7 m) for determining in situ *K* as a function of ψ_m in the 1.4- to 1.7-m soil depth zone was established in July 1990. Matric potential was measured by using tensiometers at the 1.4- and 1.7-m soil depths. Water content was measured by using neutron attenuation to a soil depth of 2.4 m in 0.15-m depth increments. After ponding achieved ψ_m equilibrium, the soil was covered with plastic, to prevent soil water evaporation, and allowed to drain. Drainage times were 84 d in 1990 and 121 d in 1991. Hydraulic conductivity calculations were based on Darcy's equation and use of the unsteady drainage–flux method (Green et al., 1986). The relationship between K of the 1.4- to 1.7-m soil depth zone and ψ_m was determined to be

$$\log_{10} K = -0.5994 + 3.379\exp(\psi_m/1.69) \qquad [1]$$

for the Keith silt loam soil, where *K* is in millimeters per day

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[1] Mention of a commercial or proprietary product does not constitute an endorsement or a recommendation for its use to the exclusion of other suitable products.

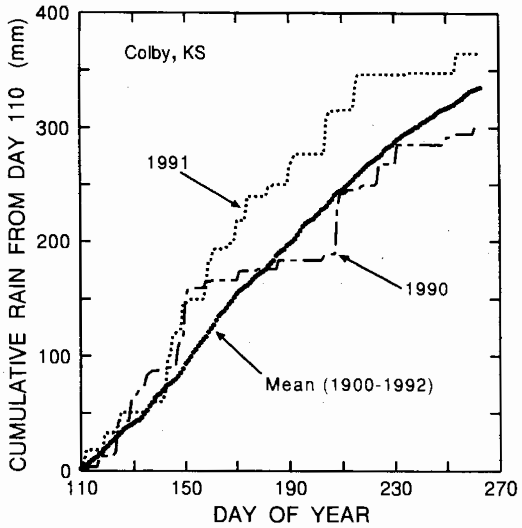

Fig. 1. Cumulative rain from Day 110 vs. day of year of 1990, 1991, and 1900 to 1992 (long-term mean).

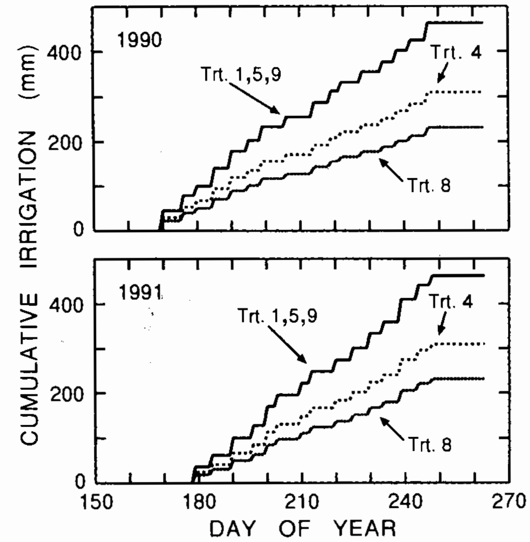

Fig. 2. Cumulative irrigation for drip line spacing treatments vs. day of year, 1990 and 1991.

and ψ_m is in meters of water. Equation [1] was developed and used within a ψ_m range of 0 to -7 m of water. Additional details on determination of K vs. ψ_m are given by Darusman (1994).

Water flux at each horizontal distance of tensiometer from the drip line in the corn plots was calculated by using Darcy's equation (*K* multiplied by hydraulic head gradient). Hydraulic conductivity values were obtained by using ψ_m data from the corn plots and the predetermined relationship of K vs. ψ_m (Eq. [1]). Hydraulic head gradients were calculated as the difference in hydraulic heads between the 1.4- and 1.7-m soil depths divided by the distance between the two depths (0.3 m). Weighted-mean water flux for each plot was calculated from water flux measured at various tensiometer distances from the drip line. Within the tensiometer group for any drip-line spacing treatment, each of the two outside tensiometer positions represented one-half as much of the horizontal plane's area as any inside tensiometer position. Therefore, in calculating weighted-mean water flux, flux values at the two outside tensiometer positions were given a weighting of 0.5 each and flux values at inside tensiometer positions were given a weighting of 1.0 each. Total in-season water flux for each plot was obtained by integrating weighted-mean water flux with time. Integration was by the trapezoidal rule where spacings between abscissa points (times) were unequal.

Analyses of variance were performed by using PROC GLM of SAS (SAS Institute, 1987). Analyses of variance for initial ψ_m at each of five distances from the drip line, grain yield, and total in-season water flux were calculated by using the format for an RCB design (Gomez and Gomez, 1984). Water flux during the corn season at each of the five tensiometer distances from the drip line was analyzed by using a pooled analysis of variance. The format of the pooled analysis of variance for measurements with time for an RCB design is that of a split-plot design with treatment as the main plot and time (DOY) as the subplot (Gomez and Gomez, 1984). The Type III sums of squares were used as the error terms for testing hypotheses in all cases. When an analysis of variance indicated treatment differences at the 0.05 probability level, an LSD (0.05) for comparing treatment means was calculated for the appropriate design (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Rain during the 1990 and 1991 growing seasons is plotted in Fig. 1. Total rain from 20 April (DOY 110) to 20 September (DOY 263) was 302 mm in 1990 and 365 mm in 1991. The long-term (1900–1992) mean rain for 20 April to 20 September is 335 mm. In each year, corn emerged on 15 May and reached physiological maturity on 19 September. The mean minimum temperature from planting until corn emergence was 3.8°C in 1990 and 10.1°C in 1991 (National Oceanic and Atmospheric Administration, 1990 and 1991). Cumulative irrigation amounts during the 1990 and 1991 corn seasons are shown in Fig. 2. Irrigation was applied on many days from 19 June to 4 Sept. 1990 and 28 June to 5 Sept. 1991. Total in-season irrigation amounts are presented by treatment in Table 1.

Matric potentials at the 1.4- and 1.7-m soil depths at five distances from the drip line on 18 June of 1990 and 1991 (DOY 169) were analyzed by treatment (Fig. 3). Analyses of variance for ψ_m on 18 June 1990 showed no significant difference among treatments at any distance from the drip line. The lack of significant difference in ψ_m among treatments in 1990 likely was due to the irrigation of August 1989 and the field being fallow in 1989. From Lamm et al. (1992), water content of the 1.5-m soil profile on 18 June 1990 was at 75% (mean among treatments with standard error = 3.0%) of maxi-

Table 1. Corn grain yield and total in-season water flux below the root zone (1.5-m soil depth) in response to dripline spacing treatment, Colby, KS.

Treatment number	Dripline spacing	In-season irrigation†	Corn grain yield		Total in-season water flux below root zone‡	
			1990	1991	1990	1991
	m	mm	– Mg ha^{-1} –		— mm —	
1	1.5	462	14.1	13.1	78	32
4	2.3	308	13.4	8.3	25	−13
5	2.3	462	14.1	11.5	132	103
8	3.1	231	11.9	6.7	−45	−24
9	3.1	462	13.6	10.7	119	127
LSD (0.05)			0.9	1.4	83	52

† In-season irrigation amounts were the same in both 1990 and 1991.

‡ Total water flux during 18 June–20 September of both 1990 and 1991. Rainfall amounts during these same time intervals were 136 mm in 1990 and 164 mm in 1991.

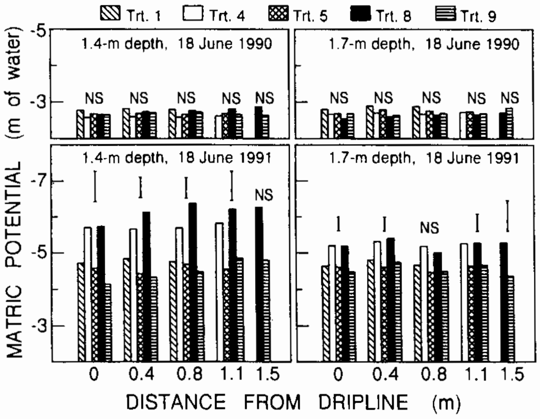

Fig. 3. Matric potential at the 1.4- and 1.7-m soil depths on 18 June of both 1990 and 1991 vs. distance from the drip line, Colby, KS. Vertical line intervals and NS refer to LSD(0.05) values from the analysis of variance for each distance from the drip line.

mum available. Analyses of variance for ψ_m on 18 June 1991 showed a significant difference among treatments at most distances from the drip line. The initial ψ_m values in Trt. 4 and 8 in 1991 (Fig. 3) were lower than those in Trt. 1, 5, and 9 because less water was applied in 1990 to Trt. 4 and 8 (Fig. 2 and Table 1). There was no off-season irrigation between the 1990 and 1991 corn crops. Precipitation between 1 Oct. 1990 and 30 Apr. 1991 was 113 mm (National Oceanic and Atmospheric Administration, 1990, 1991). Water content of the 1.5-m soil profile on 21 June 1991 was at 65, 35, 56, 42, and 55% of maximum available in Trt. 1, 4, 5, 8, and 9, respectively (Lamm et al., 1992). During the 2-yr study, measured ψ_m never reached zero. Treatments receiving full irrigation (Trt. 1, 5, and 9) had greater ψ_m than those receiving reduced irrigation (Trt. 4 and 8).

Water fluxes below the root zone (1.5-m soil depth) at five tensiometer distances from the drip line during the 1990 and 1991 corn seasons are presented in Fig. 4 and 5, respectively. Negative water flux indicates upward water movement, and positive flux indicates downward water movement. In 1990, a pattern of greater downward flux occurred in July, whereas, in 1991, greater downward flux occurred in mid-August to mid-September (Fig. 4 and 5). These water flux patterns were associated with irrigation patterns. Irrigation applied for full irrigation was the difference between rain and estimated ET. With less rain during June and July in 1990 than in 1991 (Fig. 1), more irrigation was applied by late July in 1990 than in 1991 (Fig. 2). Of the irrigation applied during mid-June to early September of each year, 256 mm were applied by 28 July in 1990 compared with 195 mm in 1991.

Treatments receiving full irrigation (Trt. 1, 5, and 9) had more downward water flux than those receiving reduced irrigation (Trt. 4 and 8) (Fig. 4 and 5). Decreasing the number of drip lines in the wider spacing treatments forced the application of more water per drip line where the application amount per plot was kept constant (i.e., Trt. 5 and 9 were kept at the Trt. 1 irrigation level), resulting in considerable downward water flux at the 1.5-m soil depth near the drip-line position in Trt. 5 and 9. Water flux was near zero in Trt. 4 and 8 throughout the 1991 corn season. Treatments 4 and 8 had severe water stress in the 1991 corn season, and about 80 to 90% of plants in corn rows at a distance of 1.1 m from the drip line failed to produce grain.

Total in-season fluxes (weighted-mean water fluxes integrated with time) below the root zone (1.5-m depth) as a function of treatment for 1990 and 1991 are pre-

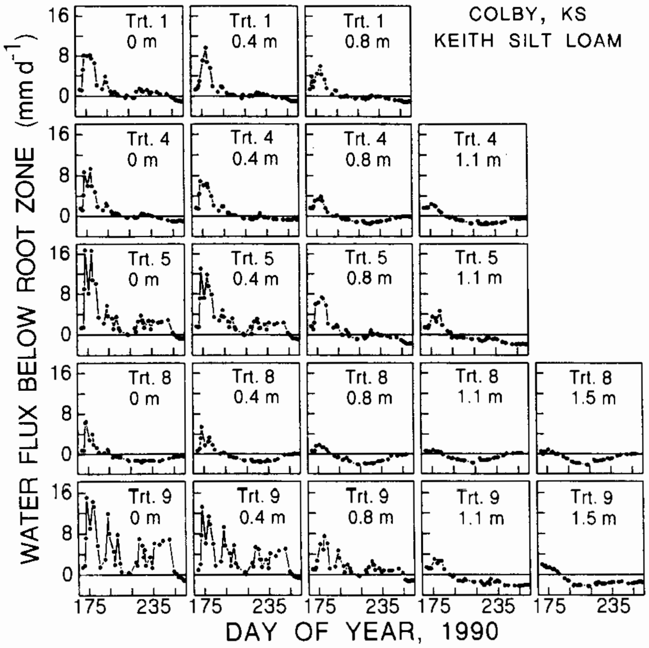

Fig. 4. Water flux below the root zone measured at 1.5-m soil depth vs. day of year, 1990. Calculated LSDs (0.05) for comparing treatment means of water flux on any day are 2.3, 2.8, 2.5, 1.5, and 1.2 mm d^{-1} for distances from the drip line of 0, 0.4, 0.8, 1.1, and 1.5 m, respectively.

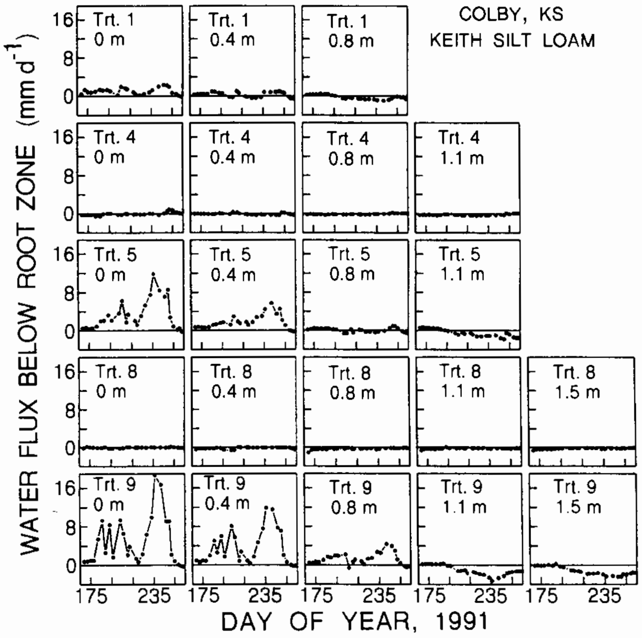

Fig. 5. Water flux below the root zone measured at 1.5-m soil depth vs. day of year, 1991. Calculated LSDs (0.05) for comparing treatment means of water flux on any day are 2.8, 2.1, 1.1, 0.9, and 0.7 mm d^{-1} for distances from the drip line of 0, 0.4, 0.8, 1.1, and 1.5 m, respectively.

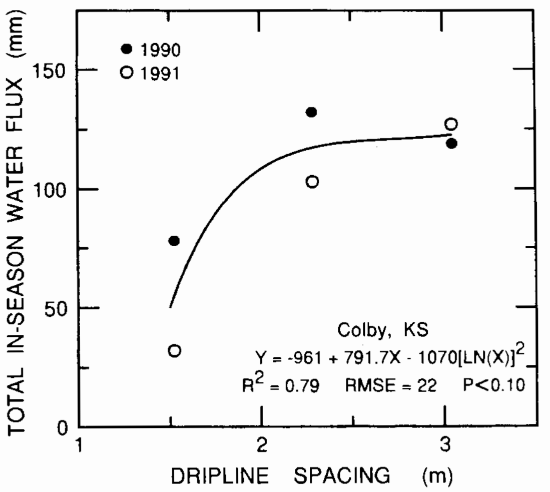

Fig. 6. Total in-season water flux below the root zone measured at 1.5-m soil depth (*Y*) vs. drip-line spacing (*X*).

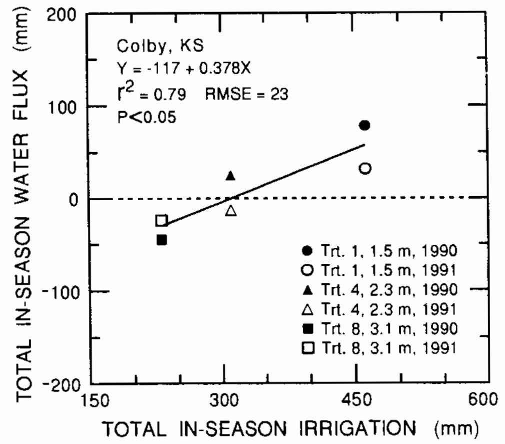

Fig. 7. Total in-season water flux below the root zone measured at 1.5-m soil depth (*Y*) vs. total in-season irrigation (*X*).

sented in Table 1. Integrated water flux values are those plotted on Fig. 4 and 5. Total in-season water fluxes of Trt. 1, 5, and 9 (receiving the same amount of water on a land-area basis) for 1990 and 1991 (Table 1) are expressed vs. drip-line spacing in Fig. 6. From the regression equation of Fig. 6, total in-season water fluxes below the root zone (1.5-m soil depth) were 51, 118, and 124 mm at drip-line spacings of 1.5, 2.3, and 3.1 m, respectively. Irrigation amounts on a land-area basis were 67% of Trt. 1 for Trt. 4, and 50% of Trt. 1 for Trt. 8. Total in-season water fluxes of Trt. 1, 4, and 8 for 1990 and 1991 (Table 1) are expressed vs. total in-season irrigation in Fig. 7. With in-season irrigations at 100, 67, and 50% of full irrigation (Table 1), total in-season water fluxes below the root zone (1.5-m soil depth) were 58, −1, and −30 mm, respectively (equation of Fig. 7).

Corn grain yields are reported in Table 1. In 1990, no significant difference in corn grain yields occurred among Trt. 1, 5, and 9. In 1991, with drier initial soil conditions than in 1990 (Fig. 3), corn in Trt. 5 and 9 yielded significantly less than corn in Trt. 1 (Table 1). The greater initial soil water contents in 1990 compared with 1991 (Fig. 3) allowed for relatively high corn yields regardless of drip-line spacing (Table 1).

Powell and Wright (1993) found significantly lower corn grain yields with 1.8- and 2.7-m drip-line spacings than with 0.9-m spacings in the driest year of a 5-yr study and no significant difference in grain yields in the other 4 yr. On the basis of their study, they recommended 1.8- or 2.7-m spacings between drip lines. They concluded that the lowered yields or increased irrigation water requirements with wider line spacings would be better than the additional installation costs for narrower spacings. The soil in their study was a Uchee loamy sand (loamy, siliceous, thermic Arenic Hapludult) with inclusions of Emporia loamy sand (fine-loamy, siliceous, thermic Typic Hapludult). The Uchee and Emporia soils have sandy clay loam subsoils with moderately slow to slow permeability (Kitchel et al., 1986). Therefore, downward-moving water probably would spread horizontally after it reached the sandy clay loam subsoil. This horizontal spreading of water would help maintain corn yields even with wider spacings.

From a study in Arizona, French et al. (1985) found little difference in lint yield of cotton with drip-line spacings of 1.0 and 2.0 m, whereas a significant reduction in lint yield occurred when drip-line spacing was increased to 3.0 m. Bucks et al. (1988) found that lint yield of cotton was significantly less (by as much as 33%) with a surface drip-line spacing of 3.0 m (one drip line per three crop rows) than with a spacing of 2.0 m (one drip line per two crop rows). Based on observations of farmer-installed buried tubing in Colorado, Kruse and Israeli (1987) selected a drip-line spacing of 1.5 m. Our results indicate that, if spacing between drip lines is increased beyond 1.5 m in the silt loam soils of western Kansas, an associated increase in internal drainage losses from the root zone and decrease in corn grain yields will occur (with the yield decrease more evident in drier years).

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