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Water Flux Below the Root Zone vs. Irrigation Amount in Drip-Irrigated Corn

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ABSTRACT

With increasing demands on water resources, greater efficiency is needed in irrigated agriculture. Internal drainage from the root zone is a loss that can be reduced or managed to improve irrigation efficiency. Our objective was to determine the relationship between seasonal water flux below the root zone (1.5 m) and irrigation amount with corn (*Zea mays* L.). Subsurface drip irrigation systems near Colby and Holcomb, KS, were used to supply water. Driplines were buried at a soil depth of 0.40 to 0.45 m, with a spacing of 1.5 m. The two soils are deep silt loams that formed in loess. Water flux at the 1.5-m soil depth was determined in four irrigation treatments during 1990 and 1991. Tensiometers were placed at soil depths of 1.4 and 1.7 m and at distances from the dripline of 0, 0.4, and 0.8 m. Water flux was calculated using predetermined hydraulic conductivity vs. matric potential (ψ_m) relationships, ψ_m data from tensiometers within the corn plots, and Darcy's equation of water flow. Irrigation was applied to four treatments such that irrigation plus rain equaled 125, 100, 75, and 50% of calculated corn evapotranspiration (ET). From a regression analysis relating integrated water flux below the root zone (1.5 m) and in-season irrigation, net upward water flux occurred with in-season irrigation $<$ 296 mm (RMSE = 71 mm), whereas net downward water flux occurred with irrigation $>$ 296 mm. Compared with the 100% ET treatment (full irrigation), the 75% ET treatment had 76% of the in-season irrigation, 25% of the in-season water flux (net downward) below the root zone (1.5 m), and 93% of the corn grain yield. Near-maximum corn grain yields can be obtained with significant decreases in irrigation amount and internal drainage from the root zone compared with full irrigation.

The irrigated area of the world expanded from about 94 million ha in 1950 to 220 million ha in 1984 (Jensen et al., 1990). In a similar pattern, the irrigated area of western Kansas increased from about 0.2 million ha in 1960 to 0.8 million ha by 1982 (Buller, 1991), with an accompanying decline in groundwater supply. Though the irrigated area of Kansas remained relatively constant from 1982 through 1992 (NASS, 1996), since 1980 declines in water table elevation of more than 6 m in southwestern Kansas and of 3 to 6 m in northwestern Kansas have been widespread (McGrath and Dugan, 1993). Increased competition for water, declining groundwater supplies, and possible contamination of groundwater by internal drainage of water and dissolved chemicals from the root zone dictate a need for greater irrigation efficiency.

Losses that can be reduced to improve irrigation efficiency are primarily those 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. Despite its importance in water management, internal drainage from the root zone is a component of the field water balance that is seldom measured adequately (Hillel, 1990).

Interest in relationships between crop production and water supply or water use is increasing because of the increasing scarcity and cost of water for irrigation and because of environmental concerns associated with internal drainage from the root zone. Profits and risks inherent in irrigation management decisions depend directly on the underlying crop–water production functions: i.e., the yield of a particular crop associated with level of water application (Ayer and Hoyt, 1981). Irrigation water requirement is defined as the quantity of water, exclusive of effective precipitation, that is required for crop production (SCSA, 1976). Irrigation water requirement values for various crops in western Kansas have been presented by Hanson and Meyer (1953), the Soil Conservation Service (1977), and Lamm et al. (1994).

Against this backdrop of published irrigation water requirements and the need to minimize internal drainage losses from the root zone, our objective was to determine the relationship between seasonal water flux below the root zone (1.5-m soil depth) and irrigation amount in corn production. The 1.5-m soil depth represented the assumed lower boundary of the corn root zone. The study was conducted on deep silt loam soils with subsurface drip irrigation systems.

MATERIALS AND METHODS

Field work was conducted in Kansas during 1990 and 1991 near Colby (39°23′ N, 101°03′ W; 967 m above sea level) and Holcomb (37°59′ N, 100°59′ W; 881 m above sea level). The soil near Colby is a Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustolls), and the soil near Holcomb is a Richfield silt loam (fine, smectitic, mesic Aridic Argiustolls). Both are deep, well-drained soils that formed in loess. Similar soils occupy about 2.34 million ha of the central High Plains (Aandahl, 1982). At each location, a corn area was irrigated with a subsurface drip system. Corn areas were 140 by 90 m at Colby and 80 by 100 m at Holcomb.

Subsurface drip irrigation systems were installed at Colby in April 1989 and at Holcomb in April 1990, with driplines buried at a soil depth of 0.40 to 0.45 m and a spacing of 1.5 m between driplines. The dripline tubing was Turbulent Twin

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Abbreviations: DOY, day of year; ET, evapotranspiration; *K*, hydraulic conductivity; RMSE, root mean square error; Trt., treatment; ψ_m, matric potential.

Wall IV (Chapin Watermatics, Watertown, NY) with emitter separation of 0.30 m.[1] Installation of the subsurface drip systems was as described by Lamm et al. (1990). Research plots at each location were in a randomized complete block design with four irrigation treatments and three replications (12 plots) at Colby and four replications (16 plots) at Holcomb. Each plot was 6 by 90 m at Colby and 6 by 43 m at Holcomb. Treatments were irrigation applied such that irrigation plus rain equaled 125% (Trt. 1), 100% (Trt. 2), 75% (Trt. 3), and 50% (Trt. 4) of calculated corn ET (reference ET multiplied by basal crop coefficient). The calculation of reference ET using a modified Penman equation and the use of basal crop coefficient values are described by Lamm et al. (1995). Because irrigation water was applied through buried driplines, no soil water evaporation component was used to modify calculated ET. Irrigation was applied when the cumulative value of calculated ET multiplied by treatment level minus rain was 25 mm.

The area at Colby was fertilized with 290 kg N ha^{-1} and 55 kg P ha^{-1} in October 1989 and 260 kg N ha^{-1} and 45 kg P ha^{-1} in October 1990. At Holcomb, the area was fertilized with 224 kg N ha^{-1} and 67 kg P ha^{-1} in November 1989 and 269 kg N ha^{-1} and 49 kg P ha^{-1} in December 1990. One off-season irrigation of 100 mm was applied through the subsurface drip systems in November of both 1989 and 1990 at Colby and in April and October of 1990 at Holcomb. 'Pioneer 3162' corn was planted at Colby on 30 Apr. 1990 and 7 May 1991 at 70 900 and 72 600 seeds ha^{-1}, respectively. At Holcomb, 'Golden Harvest 2572' corn was planted on 9 May 1990 at 72 500 seeds ha^{-1} and 'Pioneer 3162' corn was planted on 23 Apr. 1991 at 74 300 seeds ha^{-1}. At both locations, corn was planted in rows spaced 0.76 m apart, giving eight rows in each plot. The corn was planted parallel to the driplines, with each dripline centered between two rows. The distance between corn row and dripline was 0.4 m. Corn was harvested by hand, and grain yield is 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 each corn plot. Within each plot, tensiometers were placed at soil depths of 1.4 and 1.7 m and at distances from the middle dripline of 0, 0.4, and 0.8 m (six tensiometers per plot). Tensiometers were read two or three times a week at about 0900 h using a pressure transducer (tensimeter; Soil Measurement Systems, Tucson, AZ). Data at Colby were collected during 11 June to 19 Sept. 1990 and 18 June to 20 Sept. 1991. Data at Holcomb were collected during 28 June to 21 Sept. 1990 and 24 June to 20 Sept. 1991.

Noncropped plots (3.7 by 3.7 m) for determining in situ hydraulic conductivity (K) as a function of matric potential (ψ_m) in the 1.4- to 1.7-m soil depth zone were established in July 1990 (one each at the Colby and Holcomb research areas). Matric potential was measured using tensiometers at the 1.4- and 1.7-m soil depths. Water content was measured 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 then was allowed to drain. At Colby, the drainage times were 84 d in 1990 and 121 d in 1991. At Holcomb, the drainage times were 90 d in 1990 and 124 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 relationships between K of the 1.4- to 1.7-m soil depth zone and ψ_m were determined to be (for the Keith silt loam soil, near Colby)

$$\mathrm{Log}_{10} K = -0.5994 + 3.379 \exp(\psi_m/1.69) \quad [1]$$

or (for the Richfield silt loam soil near Holcomb)

$$\mathrm{Log}_{10} K = -0.9639 + 3.885 \exp(\psi_m/2.37) \quad [2]$$

where K is in mm d^{-1} and ψ_m is in m. Equations [1] and [2] were 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 dripline in the corn plots was calculated using Darcy's equation (K multiplied by hydraulic head gradient). Hydraulic conductivity values were obtained using ψ_m data from the corn plots and the predetermined relationships of K vs. ψ_m (Eq. [1] for Colby and Eq. [2] for Holcomb). 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 the three tensiometer distances from the dripline. With dripline spacing of 1.5 m, the 0- to 0.8-m region represented one-half (one side) of the dripline's influence. Each of the two outside tensiometer positions (0 and 0.8 m) represented one-half as much of the horizontal plane's area as the inside tensiometer position (0.4 m). Therefore, in calculating weighted-mean water flux, flux values at the 0- and 0.8-m distances from the dripline were given a weighting of 0.5 each and flux values at the 0.4-m distance were given a weighting of 1.0. 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 using PROC GLM of SAS (SAS Inst., 1987). Analyses of variance for grain yield and total in-season water flux were calculated using the format for a randomized complete block design (Gomez and Gomez, 1984). Water flux during the corn season at each of the three tensiometer distances from the dripline was analyzed using a pooled analysis of variance. The format of the pooled analysis of variance for measurements with time for a randomized complete block design is that of a split-plot design with treatment as the main plot and time (day of year, 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 for Colby and Holcomb is plotted in Fig. 1. Total rain from 20 April (DOY 110) to 20 September (DOY 263) at Colby was 302 mm in 1990 and 365 mm in 1991 (mean from 1900 to 1992 of 335 mm). At Holcomb, rain was 441 mm in 1990 and 292 mm in 1991 (mean from 1948 to 1990 of 334 mm). At Colby, corn emerged on 15 May and reached physiological maturity on 19 September in both years. At Holcomb, corn emerged on 18 May 1990 and 10 May 1991 and reached physiological maturity on 24 Sept. 1990 and 20 Sept. 1991.

Cumulative irrigation amounts for each treatment and location during the 1990 and 1991 corn seasons are shown in Fig. 2. Irrigation was applied on numerous dates

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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.

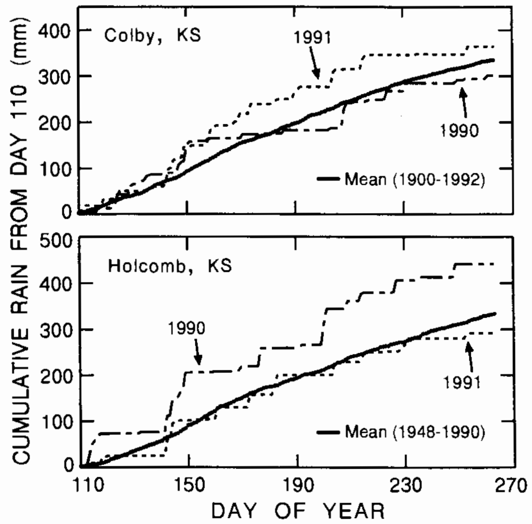

Fig. 1. Cumulative rain from Day 110 vs. day of year, 1990 and 1991, and long-term means (1900–1992 at Colby and 1948–1990 at Holcomb).

from 15 June to 5 Sept. 1990 and 26 June to 9 Sept. 1991 at Colby and from 20 June to 31 Aug. 1990 and 6 June to 5 Sept. 1991 at Holcomb. Total in-season irrigation amounts are presented by treatment in Table 1.

Matric potentials on the first reading dates at Colby (11 June 1990 and 18 June 1991) and at Holcomb (28 June 1990 and 24 June 1991) describe the initial soil water conditions in the 1.4- to 1.7-m region of the soil profile. Initial values of ψ_m at Colby were −1.9 and −2.1 m of water in 1990 and 1991, respectively; at Holcomb, initial ψ_m's were −2.4 and −3.1 m of water in 1990 and 1991, respectively. During the 2-yr study, ψ_m never reached zero during the corn season at either location. Matric potential decreased as irrigation amount decreased. Late in the 1991 corn season at Holcomb, tensiometers in Trt. 4 stopped functioning because potentials decreased below the tensiometer working limit (ψ_m of −7.3 and −7.0 m of water for the 1.4- and 1.7-m tensiometer depths, respectively).

Water fluxes below the root zone (1.5-m soil depth) at three distances from the dripline during the 1990 and 1991 corn seasons at Colby and Holcomb are presented in Fig. 3 through 6. Negative water flux indicates upward water movement, and positive flux indicates downward water movement. Water flux patterns during the corn seasons were associated with irrigation patterns. At both locations, Trt. 1 (125% ET) had the greatest amount of water flux among treatments, and flux decreased as irrigation amount decreased. Upward water flux occurred primarily in Trt. 4 (50% ET), at both locations.

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 presented in Table 1. Integrated water flux values are those plotted on Fig. 3 through 6. In Trt. 4 (50% ET) at Holcomb, tensiometers exceeded the working limit on 27 Aug. 1991. Because of dryness and the water flux pattern of Fig. 6, total water flux from 27 Aug. to 20 Sept. 1991 (DOY 239 to 263) was assumed to be 0 mm.

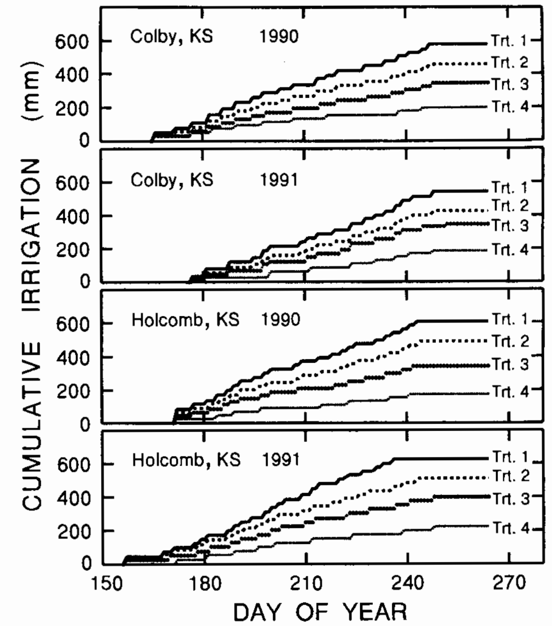

Fig. 2. Cumulative irrigation for the four irrigation treatments vs. day of year, 1990 and 1991.

Total in-season water fluxes (Table 1) of the four treatments at two locations were used to generate the relationship between total in-season water flux below the root zone (1.5-m soil depth) (dependent y-variable) and total in-season irrigation (independent x-variable) (Fig. 7). From the regression equation of Fig. 7, in-season irrigation of 296 mm (applied through buried driplines) resulted in zero net water flux during the corn season, with RMSE of 49 mm.

We also performed a regression analysis where integrated water flux below the root zone (1.5-m depth)

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

Treatment code and description†	Total in-season irrigation‡		Corn grain yield		Total in-season water flux below root zone§	
	1990	1991	1990	1991	1990	1991
	— mm —		— Mg ha^{-1} —		— mm —	
Colby, KS						
Trt. 1: 125% ET	579	542	12.3	14.9	277	163
Trt. 2: 100% ET	456	425	13.9	14.7	231	36
Trt. 3: 75% ET	343	347	12.1	14.3	62	−19
Trt. 4: 50% ET	198	184	10.5	10.9	26	−65
LSD (0.05)			1.1	1.7	77	98
Holcomb, KS						
Trt. 1: 125% ET	605	624	10.9	13.4	331	330
Trt. 2: 100% ET	489	510	11.1	13.7	159	158
Trt. 3: 75% ET	341	398	10.2	13.0	29	−14
Trt. 4: 50% ET	173	223	10.0	11.3	−35	−21
LSD (0.05)			1.0	1.2	65	109

† Irrigation plus rain equaled the listed percentage of calculated corn evapotranspiration (ET).

‡ One off-season irrigation of 100 mm was applied at Colby in November of both 1989 and 1990 and at Holcomb in April and October of 1990.

§ Total water flux during 11 June–19 Sept. 1990 and 18 June–20 Sept. 1991 at Colby and during 28 June–21 Sept. 1990 and 24 June–20 Sept. 1991 at Holcomb. Rainfall amounts for these same intervals were 136 mm at Colby, 1990; 164 mm at Colby, 1991; 182 mm at Holcomb, 1990; and 135 mm at Holcomb, 1991.

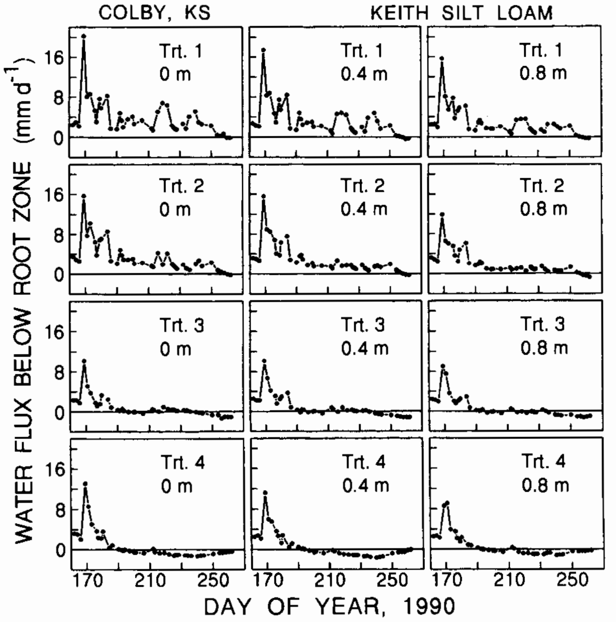

Fig. 3. Water flux below the root zone measured at 1.5-m soil depth vs. day of year, 1990 at Colby. Calculated LSDs (0.05) for comparing treatment means of water flux on any day are 2.2, 1.7, and 1.5 mm d^{-1} for distances from the dripline of 0, 0.4, and 0.8 m, respectively.

was the x-variable and total in-season irrigation amount was the y-variable, in an attempt to estimate the irrigation amount associated with zero net water flux during the corn season. The resulting equation was:

$$y = 296 + 1.419x - 0.00150x^2 \quad [3]$$

where units are in mm and $R^2 = 0.81$. From Eq. [3], zero net water flux during the corn season (x) occurred with estimated in-season irrigation (y) of 296 mm, with RMSE of 71 mm. Net negative (upward) water flux was associated with in-season irrigation < 296 mm. Net positive (downward) water flux was associated with in-season irrigation > 296 mm. The in-season irrigation amount is in addition to off-season irrigation of 100 mm. Therefore, net downward in-season water flux occurred with annual irrigation > 396 mm. With the subsurface drip systems of our study, irrigation application efficiency was essentially 100%. The net irrigation require-

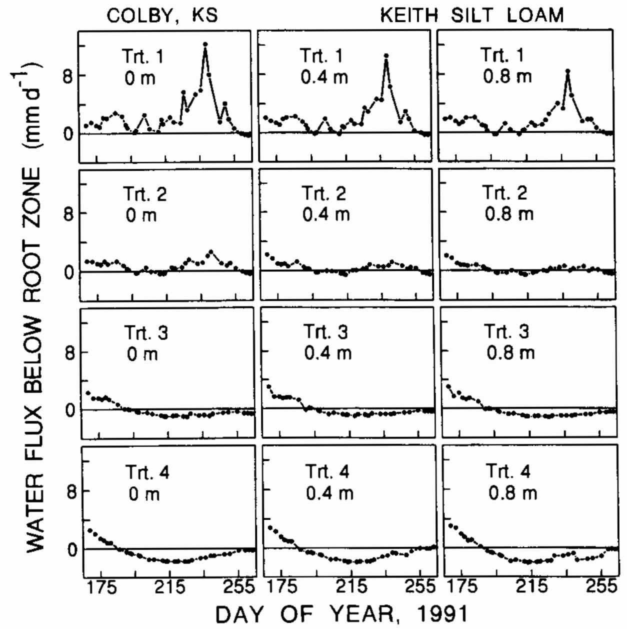

Fig. 4. Water flux below the root zone measured at 1.5-m soil depth vs. day of year, 1991 at Colby. Calculated LSDs (0.05) for comparing treatment means of water flux on any day are 1.5, 1.6, and 1.6 mm d^{-1} for distances from the dripline of 0, 0.4, and 0.8 m, respectively.

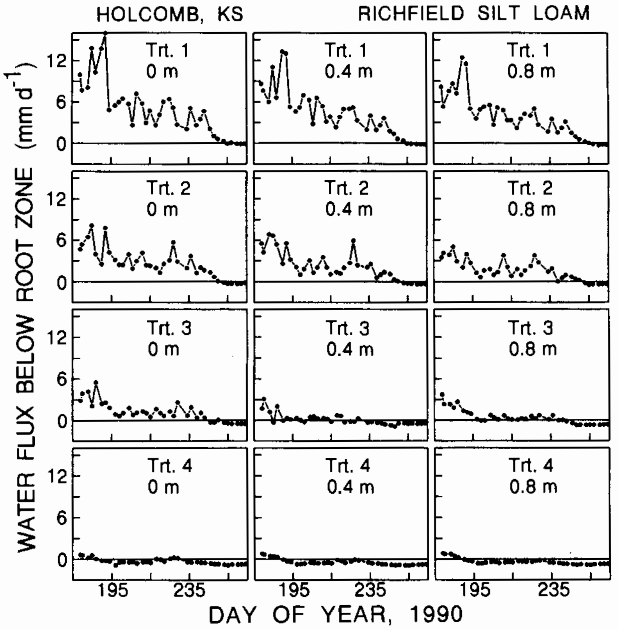

Fig. 5. Water flux below the root zone measured at 1.5-m soil depth vs. day of year, 1990 at Holcomb. Calculated LSDs (0.05) for comparing treatment means of water flux on any day are 2.3, 1.9, and 1.4 mm d^{-1} for distances from the dripline of 0, 0.4, and 0.8 m, respectively.

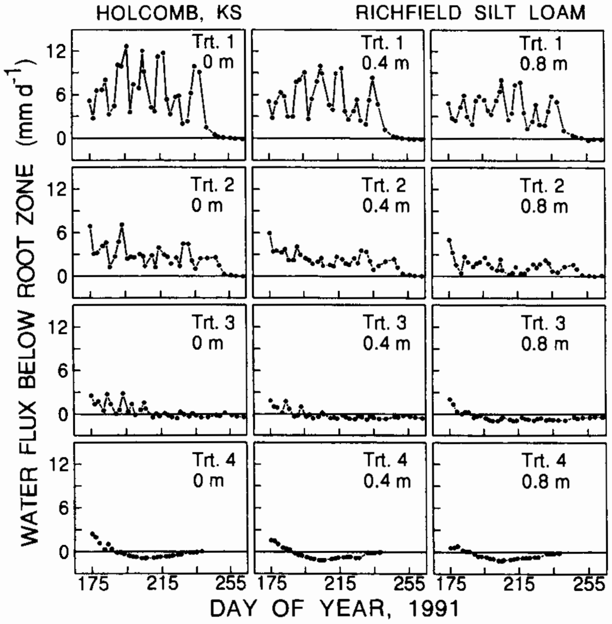

Fig. 6. Water flux below the root zone measured at 1.5-m soil depth vs. day of year, 1991 at Holcomb. Calculated LSDs (0.05) for comparing treatment means of water flux on any day are 2.9, 2.4, and 1.7 mm d^{-1} for distances from the dripline of 0, 0.4, and 0.8 m, respectively.

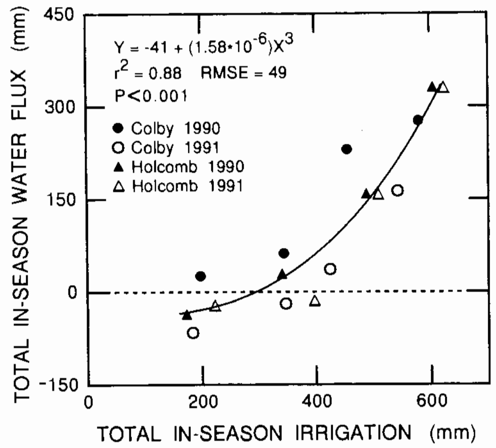

Fig. 7. Total in-season water flux below the root zone measured at 1.5-m soil depth (y) vs. total in-season irrigation (x).

ments (water need for a crop in excess of rain) for corn with an 80% chance rainfall (i.e., rainfall that can be expected to be equaled or exceeded in 8 yr out of 10) are 391 mm at Colby and 414 mm at Holcomb (SCS, 1977). When irrigation schedules for fully irrigated corn were constructed for 22 yr (1972–1993) using weather data from Colby, KS, the mean annual net irrigation requirement was 381 mm (Lamm et al., 1994). Hanson and Meyer (1953) presented net irrigation requirements for corn of 340 mm at Colby and 348 mm at Holcomb. The data of Fig. 7 and Eq. [3] illustrate that, if published net irrigation requirements are not routinely exceeded, in-season water flux losses from the root zone should not be a significant factor in western Kansas.

In-season irrigation, water flux below the root zone, and corn grain yields are presented in Table 1. A hail storm at Holcomb on 19 July 1990 appeared to limit corn yields. Compared with the 100% ET treatment, the 75% ET treatment (averaged across years and locations) had 76% of the in-season irrigation, 25% of the total in-season water flux (net downward) below the root zone (equation of Fig. 7), and 93% of the grain yield (Table 1). In a simulation study, 90% of the corn grain yield response due to irrigation was obtained with about 78% of the irrigation water required for maximum yields (Gilley et al., 1980). On medium-textured soils in North Dakota, about 95% of maximum corn grain yield was achieved with reductions of about 30% in seasonal irrigation relative to full irrigation (i.e., irrigation at 100% ET replacement) (Stegman, 1986). Our results tend to confirm the simulation study (Gilley et al., 1980) and the applicability of the North Dakota work (Stegman, 1986) to our region.

With the subsurface drip systems of our study, essentially 100% of the applied irrigation water was placed in the root zone. With irrigation systems that have application efficiencies < 100%, total irrigation would have to be inflated to achieve treatments similar to those of our study. Therefore, one should keep in mind that the irrigation amounts of Table 1, Fig. 7, and Eq. [3] are with irrigation systems that have application efficiencies of near 100%.

Our treatments illustrate that near-maximum corn grain yields can be obtained in western Kansas with a significant decrease in irrigation amount (75% ET treatment) compared with full irrigation (100% ET treatment). The decrease in in-season irrigation is accompanied by a significant reduction in internal drainage losses from the root zone.

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