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# Subsurface and Surface Microirrigation of Corn —Southern High Plains

T. A. Howell, A. D. Schneider, S. R. Evett

**Abstract.** *Microirrigation has the potential to minimize application losses to evaporation, field runoff, and deep percolation; improve irrigation control with smaller, frequent applications; supply nutrients to the crop as needed; and improve crop yields. This study was conducted to evaluate subsurface and surface microirrigation (SUB and TOP, respectively) application methods on crop performance. The effects of irrigation frequency, amount, and application method on crop yield, yield components, water use, and water use efficiency of corn (Zea* mays *L., cv. PIO 3245) were investigated at Bushland, Texas, on a slowly permeable soil [Pullman clay loam (fine, mixed, thermic* Torrertic Paleustoll*)] in a semi-arid environment in 1993 and 1994. Irrigation frequencies were once a day and once a week; irrigation levels varied from dryland (no post emergence irrigation) to full crop water use replenishment; and application methods were on the soil surface (TOP) and 0.3 m below the surface (SUB) with emitters spaced 0.45 m apart and drip lines spaced 1.5 m apart. Irrigation frequency and application method did not affect crop yields; however, deficit irrigation affected crop yields by reducing the seed mass and the seed number. On the clay loam soil at Bushland, irrigation frequency and application method are less critical than proper irrigation management for microirrigation systems to avoid water deficits that have a larger affect on corn yields.* ***Keywords.*** *Corn, Irrigation management, Microirrigation, Water use, Water use efficiency, Yield, Yield components.*

The Southern High Plains region relies mainly on the Ogallala aquifer for irrigation and the highly variable rainfall to supply the majority of its crop water demands. The groundwater resource is declining in many parts of the region, and irrigation capacity (gross system flow rate per unit irrigated land area) is relatively low (4 to 11 mm $d^{-1}$) considering normal application losses and operational maintenance allowances. Microirrigation (Bucks and Davis, 1986) provides numerous potential advantages over other irrigation methods. Subsurface (SUB) microirrigation has been shown to enhance crop yields and reduce application losses (Phene et al., 1987). Camp et al. (1989) reported reduced corn yields for surface drip lines spaced in alternate rows compared to surface (TOP) and SUB lines placed in the crop rows. However, Camp et al. (1993b) reported successful irrigation of vegetables with SUB lines spaced in alternate rows (1.52 m apart). Camp et al. (1993a) reported higher cotton yields with every row drip line placement compared with alternate row placement. Lamm et al. (1995) used alternate row spacing for drip lines for corn and reported water savings approaching 25% while maintaining yields in excess of 1.25 kg $m^{-2}$. Lamm et al. (1992) reported that 1.5-m drip line spacing performed superior to wider drip line spacings. Caldwell et al. (1994) reported irrigation interval did not affect corn yield or soil water on a silt loam soil in Kansas. Bucks et al. (1973) did not find an important effect from irrigation interval on cotton on a clay loam soil in Arizona. However, irrigation frequency (or interval) has been reported to affect crop performance with microirrigation (Radin et al., 1989; Davis et al., 1985; and Phene et al., 1987).

The objectives of this study were to (1) evaluate SUB and TOP microirrigation methods for corn (*Zea mays* L.) production practices in the Southern High Plains; (2) compare daily and weekly irrigation intervals for a range of water applications varying from highly deficit to fully meeting crop water use; and (3) determine the effects of the deficit irrigation regimes on crop water use and water use efficiency.

## Procedures

The study was conducted during 1993 and 1994 at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (35°N lat, 102°W long, 1170 m elevation), on a Pullman clay loam soil [*Torrertic Paleustoll*] that is characterized as slowly permeable with a 1.0- to 1.5-m clay loam profile overlaying a caliche layer (about 50% calcium carbonate). The field plots had previously been leveled by a laser scraper into 10.7-m wide border strips and fallowed for several years prior to use in these experiments. Each plot was 27.4 m long and diked on

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all sides to prevent storm runoff or runon. The total number of plot borders was 21 and 18 plots were split (for irrigation method treatments). The plots were designed to use 0.76-m wide rows, which is the common row spacing for corn in this region, and conventional six row farm equipment. The plots were cultivated using standard six-row farm machinery.

### Irrigation Treatments

The primary irrigation treatments were (1) irrigation frequency, daily or weekly, and (2) irrigation amount, full (T-100; complete replenishment of soil water use), medium (T-67; 2/3 of full), and low (T-33; 1/3 of full). SUB and TOP irrigation methods were split plot variables. A dryland (no post-emergence irrigation) treatment (T-0) was also included. The design was a complete randomized block with split plots (methods) and three replications. In 1994, the T-0 treatment was not replicated.

The irrigation control was based on weekly soil water measurements using a Campbell neutron probe (model 503DR, Campbell Pacific Nuclear Corp., Martinez, Calif.). The neutron probe was calibrated to the Pullman soil, and 15-s readings were taken from 0.2 m to 2.4 m deep in 0.2 m increments. One neutron tube was installed in each subplot on 15 June (DOY 166), and the first readings were taken on 16 June (DOY 167) in 1993. Neutron probe access tubes were installed on 27 May (DOY 147) and first read on 31 May (DOY 151) in 1994. The base control soil water level was 500 mm in the 1.5 m depth (0.33 $m^3$ $m^{-3}$) and was held constant throughout the experiment. The daily irrigation frequency, full amount treatment (T-100) for both the SUB and TOP application method subplots were the control plots. The weekly irrigation amount was the difference between the mean soil water content in T-100 and the fixed control level, and the daily irrigation amount was 1/7 of the weekly amount. The daily frequency, T-33 treatment (1/3 of full) set the cycle duration (nearest minute). The T-67 treatment (2/3 of full) was two repeats; the T-100 treatment was three repeats each day of the T-33 treatment. The weekly treatments were then 7 repeats, 14 repeats, and 21 repeats for the T-33, T-67, and T-100 treatments, respectively, applied in one day. If significant rain occurred (>25 mm), the on-going daily irrigation schedule was adjusted as needed in 1993 to maintain similar application amounts. Consequently, the daily treatments received slightly less water than the weekly treatments in 1993.

### Microirrigation Systems

The microirrigation tubing was Netafim Typhoon tubing (T25-0.6-18, Netafim Irrigation Inc., Fresno, Calif.) with 0.45 m emitter spacings, 0.64 μm wall thickness, and 2.3 L $h^{-1}$ (0.6 g/h) nominal flow rate. Microirrigation lines were 1.52 m apart, equally spaced between two corn rows, and each plot was split with one-half irrigated by SUB at a depth of 0.3 m and by TOP. The SUB lines were permanent, and the TOP lines were designed to be removable for field operations. The TOP lines were removed and replaced each year. Figure 1 is a schematic diagram of the microirrigation system. The alternate row configuration was selected as the only feasible microirrigation system for row crops in the southern Great Plains to minimize installation costs.

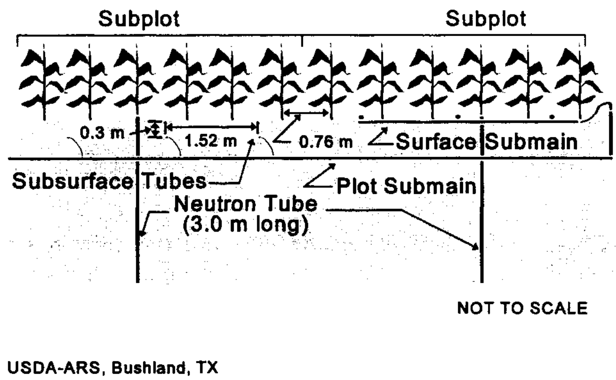


**Figure 1–Schematic diagram of plot microirrigation system.**

The SUB lines were installed using Sundance chisels and reels (Arizona Drip Systems, Coolidge, Ariz.) mounted on a tool bar to plow three lines simultaneously. The TOP plots were also chiseled with the Sundance chisels for tillage treatment similarity (i.e., all plots both surface and subsurface were chiseled the same to remove tillage as a variable). The SUB lines in each plot were connected to a common flush manifold, and the TOP lines could be individually flushed manually. The TOP lines were connected to the plot submain with a flexible PVC hose to an above ground 50 mm PVC submain which delivered water to three laterals. The TOP lines were plugged on the ends with figure-eight loops. Each plot's submain line lead back to the control network where the three lines for a treatment were joined with a single water meter, solenoid valve, and screen filter (150 mesh).

Each plot had an individual 908 L $h^{-1}$ (4 g/m) Dole Flow Control valve (Eaton Corp., Carol Stream, Ill.) to regulate the flow rates (a minimum pressure difference of 140 kPa was maintained across the Dole valves). Pressures at strategic points were observed periodically with dial pressure gauges. A master screen filter (100 mesh) was located before the individual treatment controls. A Rain Bird controller (MC-8, Rain Bird Sales Inc., Glendora, Calif.) was used to set the operating times for each treatment. The controller was set each week to irrigate according to the need established by the soil water levels. Irrigation water was pumped from wells into a lined storage reservoir, and a submersible turbine pump with pressure regulating tanks maintained pressure on the supply pipeline to the plots between 410 kPa and 550 kPa.

The irrigation water was treated with 13 mg $kg^{-1}$ (ppm) of P from phosphoric acid ($H_3PO_4$) continuous injection (the phosphoric acid was diluted as 1:10 before injection) to serve as P nutrient source but mainly to avoid root plugging. Liquid Urea (28-0-0) [$CO(NH_2)_2$] was injected at variable rates from 75 mg $kg^{-1}$ of N to 113 mg $kg^{-1}$ of N from the six leaf stage until silking. The P and N were injected with a proportional chemical injector (Howard E. Hutchings Co., Inc., Penryn, Calif.) so each plot and treatment received N and P in proportion to its irrigation application. These nutrients supplemented the pre-plant applied N fertilizer (next section). Liquid nutrients were applied proportional to water to balance nutrients and water to actual crop needs. These applications were designed to avoid over-fertilizing while insuring more than adequate nutrients for each water level.

### Agronomic Methods

Corn (Pioneer 3245) was planted on 27 May (DOY 147) in 1993 and on 14 April (DOY 104) in 1994 using a six-row planter at about 8 seeds/$m^{-2}$ and 25 to 50 mm deep. The 1993 planting date was about one month later than optimum for this area due to delays in finishing the installation of the irrigation equipment. All the plots had been chiseled (including the surface drip plots) prior to planting in 1993 and fertilized with anhydrous ammonia ($NH_4$) at 15 g(N) $m^{-2}$ in 1993 and 13 g(N) $m^{-2}$ in 1994 prior to planting. Establishment irrigations were necessary due to the dry soil conditions following the tillage operations and the generally "rough" field conditions. Irrigations were applied uniformly to pre-wet the plots and to germinate the crop in both years. These irrigations totaled 131 mm in 1993 from DOY 152 to DOY 154 and 216 mm in 1994 from DOY 110 to DOY 118. These amounts were rather large but less than conventional preplant irrigations normally used with surface irrigation in this region. Nevertheless, we expect some application losses occurred to deep percolation in some plots.

Grain yield was measured by hand harvesting 10 $m^2$ of area from two adjacent center rows in each subplot. The yield samples were harvested on 14-15 October (DOYs 287 and 288) in 1993 and 27-29 September (DOYs 270-272) in 1994. The ears and plants were counted, the ears were dried at 70°C in an oven, and then hand shelled. Seed mass was determined for a 500-kernel subsample. Grain yields were expressed on a dry basis (0 kg $kg^{-1}$). Yield components of kernels per ear and kernel number were computed from the yield samples and the kernel mass subsamples. Harvest index (ratio of grain to biomass yield on a dry basis) was measured on a separate plant sample of eight consecutive plants. The linear distance of the row occupied by the plants was measured and used to compute the area. The ears were counted and the grain yield was determined similar to that described above. The remaining biomass (shucks, leaves, stems, etc.) were oven dried (70°C) and added to the oven dry mass of the ears to determine total biomass.

Water use was determined as the sum of the 2.5-m soil profile soil water extraction plus growing season rainfall and irrigations for the period after neutron tube installation. The plots were diked to prevent runoff, but profile drainage could not be determined and would be included with the total water use values. The soil water content at the 2.5-m depth did not change appreciably, but steady-state flow could still occur. Water use efficiency was computed as the ratio of crop yield to water use.

## Results and Discussion

The corn began emerging on 2 June (DOY 154) and completed emerging by 12 June (DOY 164) in 1993. This variable emergence was mainly due to the shallow planting and poor field conditions following system installation. Emergence occurred on 9 May (DOY 129) in 1994 and was more uniform although slight row differences were noticed due to small drip line and planter misalignments. The corn grew rapidly, tasseled on 3 August (DOY 215) and silked on 10 August (DOY 222) in 1993. Tasseling occurred on 11 July (DOY 192) and silking occurred on 18 July (DOY 199) in 1994. Climatic patterns were typical for the Southern High Plains as shown in table 1. Air temperatures were similar to historical patterns in both years, but July rainfall was 56% and 100% greater than historical mean amounts in 1993 and 1994, respectively. April, May, June, and August rainfall totals in each year were typical of the historical mean amounts. Rainfall totals for the April through October months were 81% of normal in 1993 and 110% of normal in 1994.

All nitrogen fertilizer was turned off on 4 August (DOY 216) at silk emergence in 1993 and on 5 July (DOY 186) in 1994. The 1993 and 1994 crops were normal in all respects, but the 1993 crop was somewhat taller than other corn planted earlier. Southwestern corn borers damaged the plots late in the season in 1993. The plots were aerially sprayed for insect control in both years, but because of timing differences with other nearby corn plots, the corn borers did more damage to these plots. Since the 1993 yield was largely established before major problems developed, the corn borer damage would have been more important for commercial production with mechanical harvesting. The T-33 (33% soil water replenishment) treatment and the dryland check plot (T-0) suffered severe water deficits in 1993. The dryland plots were practically dead following silking, but they produced small yield amounts.

Fertilizer applications with the post-plant irrigation water are given in table 2. The nitrogen application totals of 32 g(N) $m^{-2}$ in 1993 and 33 g(N) $m^{-2}$ are similar to the yield plateau level reported by Lamm and Manges (1991) [26 g(N) $m^{-2}$] and their nitrogen uptake range [28-31 g(N) $m^{-2}$] and slightly above the nitrogen requirement range reported by Eck (1984) for surface irrigated corn at Bushland [14-30 g(N) $m^{-2}$]. The T-33 treatment received slightly more irrigation than design due to early controller setting errors in 1993, but the differences were usually small. The weekly irrigation (T-100 and T-33) treatments

**Table 1. Mean monthly climatic parameters compared with historical trends**

| Month | Rain (mm) 1993 | Rain (mm) 1994 | Mean Rain (mm) 20-yr | Max. Air Temp. (°C) 1993 | Max. Air Temp. (°C) 1994 | Mean Air Temp. (°C) 20-yr | Min Air Temp. (°C) 1993 | Min Air Temp. (°C) 1994 | Mean Min Temp. (°C) 20-yr |
|---|---|---|---|---|---|---|---|---|---|
| April | 14 | 41 | 24 | 21.1 | 20.9 | 21.1 | 2.3 | 2.8 | 3.9 |
| May | 56 | 56 | 66 | 24.7 | 24.3 | 24.9 | 9.1 | 10.1 | 9.3 |
| June | 65 | 51 | 77 | 30.3 | 34.3 | 30.2 | 14.5 | 16.1 | 14.8 |
| July | 100 | 128 | 64 | 32.6 | 32.3 | 32.1 | 18.2 | 16.7 | 16.9 |
| August | 50 | 74 | 75 | 31.2 | 31.6 | 31.0 | 16.1 | 15.7 | 16.2 |
| September | 14 | 44 | 59 | 31.9 | 28.2 | 27.3 | 9.8 | 11.6 | 11.7 |
| October | 23 | 44 | 32 | 20.8 | 22.2 | 21.7 | 3.2 | 5.7 | 5.0 |

**Table 2. Fertilizer amounts added with irrigation water for each treatment**

| Treatment | Nitrogen | Phosphorus | Irrigation |
|---|---|---|---|
| **1993** | | | |
| T-100 | 17 g(N) $m^{-2}$ | 8 g(P) $m^{-2}$ | 657 mm |
| T-67 | 11 g(N) $m^{-2}$ | 5 g(P) $m^{-2}$ | 445 mm |
| T-33 | 6 g(N) $m^{-2}$ | 3 g(P) $m^{-2}$ | 250 mm |
| T-0 | 0 g(N) $m^{-2}$ | 0 g(P) $m^{-2}$ | 0 mm |
| **1994** | | | |
| T-100 | 20 g(N) $m^{-2}$ | 8 g(P) $m^{-2}$ | 656 mm |
| T-67 | 14 g(N) $m^{-2}$ | 6 g(P) $m^{-2}$ | 445 mm |
| T-33 | 7 g(N) $m^{-2}$ | 3 g(P) $m^{-2}$ | 250 mm |
| T-0 | 0 g(N) $m^{-2}$ | 0 g(P) $m^{-2}$ | 0 mm |

received 80 mm and 39 mm more irrigation than the daily treatments, respectively, again due to incorrect timer settings and rainfall interferences in 1993. In 1994, daily irrigation amounts were applied regardless of rainfall to maintain similar application amounts across the two frequencies. However, the T-100 weekly treatment received about 79 mm more than the daily treatment due to a valve sticking open late in the season.

Irrigation applications were determined for the T-100 treatments to maintain soil water contents near 500 mm (about 90% of field capacity) based on the weekly neutron probe measurements (fig. 2). The timers were set to apply the desired amounts to each treatment at the desired frequency either daily or weekly. Usually, the weekly irrigations were applied on Thursday, and the weekly schedule was Wednesday through Tuesday. TOP irrigations wetted most of the area between the adjacent rows. SUB applications wet a smaller area on the soil surface but did keep the soil surface wet above the drip lines. The alternate rows without drip lines generally remained dry, except for rains. No detectable emitter plugging occurred for the SUB treatments, and all lines maintained nearly equal operating pressures. Generally, the T-100 treatments were maintained within ±20 mm (<0.02 $m^3 m^{-3}$ for the 1.5 m profile) from about 475 mm (0.32 $m^3 m^{-3}$) which is near the practical full profile value for the Pullman soil to avoid profile water movement. High soil water contents which occurred following significant rain events in both years may have resulted in profile losses to deep percolation.

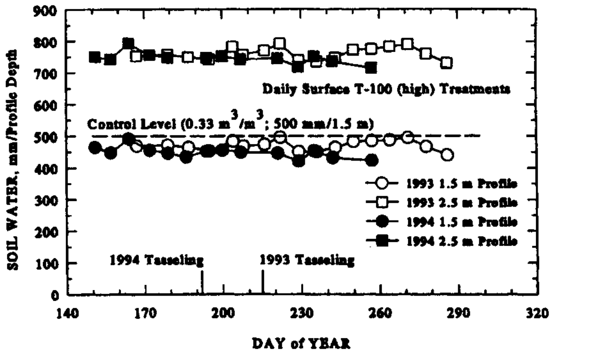


**Figure 2–Soil water contents for 2.5 and 1.5 m profile depths for the T-100 daily irrigated TOP microirrigation treatments in 1993 and 1994. Each point is the mean of three replications.**

Yield and yield components are given in table 3. Grain yields varied from 0.084 kg $m^{-2}$ for the dryland check (T-0) to 1.314 kg $m^{-2}$ for T-100 with the weekly frequency and TOP in 1993, and from 0.188 kg $m^{-2}$ for the dryland

**Table 3. Yield and yield component data**

| Treatment | | | Grain Yield* (kg $m^{-2}$) | Harvest Index† (kg $kg^{-1}$) | Biomass Yield† (kg $m^{-2}$) | Kernel Mass (mg $kernel^{-1}$) | Kernel No. (no. $m^{-2}$) | Kernels per Ear (no. $ear^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| **1993** | | | | | | | | |
| Daily | Top | T-100 | 1.240 ab‡ | 0.513 ab | 2.60 ab | 309 a | 4014 abc | 579 a |
| Daily | Sub | T-100 | 1.169 abc | 0.542 ab | 2.97 a | 317 a | 3698 bcd | 543 abc |
| Weekly | Top | T-100 | 1.314 a | 0.509 ab | 2.70 ab | 315 a | 4174 a | 577 ab |
| Weekly | Sub | T-100 | 1.307 a | 0.542 ab | 2.89 ab | 324 a | 4036 abc | 566 ab |
| Daily | Top | T-67 | 1.100 bc | 0.511 ab | 2.35 bcde | 293 ab | 3763 abcd | 539 abc |
| Daily | Sub | T-67 | 1.088 c | 0.488 b | 2.46 abc | 286 abc | 3815 abc | 569 ab |
| Weekly | Top | T-67 | 1.097 bc | 0.521 ab | 2.36 bcde | 269 bc | 4074 ab | 574 ab |
| Weekly | Sub | T-67 | 1.080 c | 0.565 a | 2.43 abcd | 302 ab | 3586 cd | 516 cd |
| Daily | Top | T-33 | 0.654 d | 0.495 ab | 1.60 f | 228 d | 2867 f | 447 e |
| Daily | Sub | T-33 | 0.666 d | 0.526 ab | 1.79 ef | 247 cd | 2699 f | 439 e |
| Weekly | Top | T-33 | 0.753 d | 0.481 b | 1.97 cdef | 226 d | 3343 de | 528 bcd |
| Weekly | Sub | T-33 | 0.626 d | 0.478 b | 1.87 def | 212 d | 2955 ef | 488 de |
| Dryland | Check | T-0 | 0.084 e | 0.187 c | 0.65 g | 147 e | 577 g | 239 f |
| | | $LSD_{0.05}$ | 0.148 | 0.078 | 0 59 | 39 | 461 | 50 |
| **1994** | | | | | | | | |
| Daily | Top | T-100 | 1.312 ab | 0.568 | 2.91 a | 338 ab | 4188 a | 511 ab |
| Daily | Sub | T-100 | 1.409 a | 0.589 | 2.71 a | 337 ab | 3880 ab | 566 a |
| Weekly | Top | T-100 | 1.294 ab | 0.587 | 2.24 a | 335 ab | 3860 ab | 521 a |
| Weekly | Sub | T-100 | 1.314 ab | 0.576 | 2.62 a | 342 a | 3834 ab | 526 a |
| Daily | Top | T-67 | 1.226 bc | 0.576 | 2.41 a | 315 abc | 3894 ab | 526 a |
| Daily | Sub | T-67 | 1.183 bc | 0.537 | 2.46 a | 340 ab | 3481 bc | 492 ab |
| Weekly | Top | T-67 | 1.075 c | 0.577 | 2.44 a | 333 ab | 3222 cd | 430 bc |
| Weekly | Sub | T-67 | 1.238 b | 0.601 | 2.50 a | 318 abc | 3906 ab | 548 a |
| Daily | Top | T-33 | 0.624 d | 0.553 | 1.43 bc | 289 c | 2164 e | 279 e |
| Daily | Sub | T-33 | 0.628 d | 0.499 | 1.59 b | 308 bc | 2037 e | 302 de |
| Weekly | Top | T-33 | 0.656 d | 0.499 | 1.04 c | 208 d | 3132 cd | 433 bc |
| Weekly | Sub | T-33 | 0.694 d | 0.583 | 1.32 bc | 241 d | 2909 d | 369 cd |
| Dryland§ | Check | T-0 | 0.188 | 0.399 | 0.49 | na | na | na |
| | | $LSD_{0.05}$ | 0.161 | ns | 0.61 | 34 | 536 | 84 |

* Harvest area 10 $m^2$.
† Harvest sample 8 plants.
‡ Numbers followed by different letters are statistically different (P<0.05) based on the least significant difference (LSD) within each year.
§ This treatment was not replicated in 1994 and not included in the statistical analysis.

check (T-0) to 1.409 kg $m^{-2}$ for the T-100 with the daily frequency and SUB in 1994. SUB yield was not significantly different from the TOP yields in either year or frequency, although the SUB grain yield was a little less and biomass yield a little greater than the TOP in 1993. In 1994, the SUB yields were slightly greater than the TOP yields. Harvest index (ratio of grain yield to biomass yield) declined somewhat with greater irrigation deficits, but the decline was not significant in 1994. Both irrigation methods were effective, but corn yields were not different from an adjoining LEPA irrigated corn study (Howell et al., 1995). The consistent trends in the harvest index indicate that grain yield remained a conservative fraction of the total biomass yield. Grain yield was affected almost equally by kernel mass and by kernel number (number per unit area) in both years. Plant grain yield was linearly correlated with plant biomass yield with the resulting regression equation:

$$G_p\,(\text{g/plant}) = 0.628 \times B_p(\text{g/plant}) - 35.6$$

$$\text{with } S_{y/x} = 12.2 \text{ g/plant } (r^2 = 0.92) \text{ in 1993;}$$

$$\text{and } G_p\,(\text{g/plant}) = 0.606 \times B_p(\text{g/plant}) - 9.9$$

$$\text{with } S_{y/x} = 9.3 \text{ g/plant in 1994 } (r^2 = 0.97).$$

Table 4 shows irrigation, water use, and water use efficiency summary data. Water use varied from 344 mm for the dryland check (T-0) to 956 mm for T-100 for the weekly frequency and TOP irrigation in 1993, and from 309 mm for the dryland check (T-0) to 967 mm for T-100 for the daily frequency and SUB irrigation in 1994. Soil water depletion increased from a mean of 34 mm for T-100 to a mean of 112 mm for T-33 in 1993 and from a mean of 20 mm for T-100 to a mean of 59 mm for T-33 in 1994. Practically all soil water depletion occurred above the caliche layer at about 1.5 m below the surface for the Pullman soil.

Grain yield was related to seasonal irrigation as shown in figure 3 for both seasons. The production function has maximum yield at an irrigation amount (IRR) of 870 mm. Greater marginal crop yields per unit of IRR can be realized at IRR values far less than this optimum, but the risk of yield reductions will be increased. Grain yield was linearly related to water use up to about 820 mm and then leveled (fig. 4). The drip irrigation management and application efficiency were good and resulted in almost 90% of the applied water being consumed in water use (10% not used by the crop and remaining in the soil at harvest). Only small amounts of applied water remained in the soil profile (above initial values), little water was lost to runoff, and both deep percolation and soil water evaporation are included in the water use values. Deep percolation was believed to be minimal because of soil physical characteristics and constant lower soil profile water contents; however, steady-state drainage could have occurred, particularly after large rain events. Figure 4 has two relationships, with one determined without the T-100 treatments and fit with a piece-wise linear equation with a node at a water use of 820 mm. The other relationship is a linear regression using all the data points. The slopes of the regression lines indicate the water use efficiency above the water level required to initially produce yield. Essentially,

**Table 4. Irrigation and water use data**

| Treatment | | | Seasonal Irrigation (mm) | Water Use* (mm) | Water Use Efficiency ($kg\ m^{-3}$) | Soil Water Depletion‡ (mm) |
|---|---|---|---|---|---|---|
| **1993** | | | | | | |
| Daily | Top | T-100 | 617 | 839 b§ | 1.48 a | 23 g |
| Daily | Sub | T-100 | 617 | 832 b | 1.40 ab | 16 g |
| Weekly | Top | T-100 | 696 | 932 a | 1.41 ab | 37 fg |
| Weekly | Sub | T-100 | 696 | 956 a | 1.37 ab | 60 ef |
| Daily | Top | T-67 | 446 | 716 cd | 1.54 a | 71 fg |
| Daily | Sub | T-67 | 446 | 707 cd | 1.48 a | 61 ef |
| Weekly | Top | T-67 | 444 | 727 cd | 1.51 a | 84 cde |
| Weekly | Sub | T-67 | 444 | 738 c | 1.46 a | 95 bcd |
| Daily | Top | T-33 | 231 | 544 f | 1.20 bc | 115 ab |
| Daily | Sub | T-33 | 231 | 549 f | 1.21 bc | 119 ab |
| Weekly | Top | T-33 | 269 | 569 ef | 1.33 ab | 101 bc |
| Weekly | Sub | T-33 | 269 | 581 e | 1.08 c | 113 bc |
| Dryland | Check | T-0 | 0 | 344 g | 0.24 d | 144 a |
| | $LSD_{0.05}$ | | | 30 | 0.22 | 30 |
| **1994** | | | | | | |
| Daily | Top | T-100 | 694 | 967 a | 1.36 abed | 28 bc |
| Daily | Sub | T-100 | 694 | 944 a | 1.49 ab | 5 c |
| Weekly | Top | T-100 | 662 | 939 a | 1.38 abed | 31 abc |
| Weekly | Sub | T-100 | 662 | 925 a | 1.42 abc | 17 c |
| Daily | Top | T-67 | 445 | 756 b | 1.62 a | 66 ab |
| Daily | Sub | T-67 | 445 | 756 b | 1.56 a | 66 ab |
| Weekly | Top | T-67 | 460 | 774 b | 1.39 abed | 69 ab |
| Weekly | Sub | T-67 | 460 | 771 b | 1.61 a | 66 ab |
| Daily | Top | T-33 | 226 | 544 c | 1.14 d | 73 a |
| Daily | Sub | T-33 | 226 | 541 c | 1.16 cd | 70 ab |
| Weekly | Top | T-33 | 245 | 533 c | 1.24 bcd | 63 ab |
| Weekly | Sub | T-33 | 245 | 507 c | 1.38 abed | 31 abc |
| Dryland | Check | T-0 | 0 | 309 | 0.61 | 64 |
| | $LSD_{0.05}$ | | | 42 | 0.24 | 42 |

* Sum of seasonal irrigation, seasonal rainfall, and growing season 2.5-m profile soil water depletion. Assumes deep percolation and runoff were negligible. Plots were diked to minimize field runoff.
† Ratio of grain yield to water use.
‡ Measured soil water depletion over the 2.5-m profile from DOY 167 to DOY 285 in 1993 and from DOY 151 to DOY 257 in 1994 by neutron attenuation.
§ Numbers followed by different letters are statistically different (P< 0.05) based on the least significant difference (LSD) within each year.

1.9 to 2.4 g $m^{-2}$ of grain was produced for each mm of water use above the threshold water use of 186 to 263 mm, respectively. The piece-wise regression fits the lower water use data better and has an intercept more reflective of the soil water evaporation and transpiration used before significant yield is produced. Taking the intercept of the piece-wise fit as soil water evaporation (E; 263 mm) and the maximum water use value ($ET_m$) as 820 mm, we determined the equivalent yield response factor (Ky) from Doorenbos and Kassam (1979) would be 1.47 following methods outlined by Hanks and Rasmussen (1982) ad Howell (1990). This value compares well with other reports of 1.38 to 2.00 at Bushland (Howell et al., 1989; Musick and Dusek, 1980) but larger than the value for corn (1.25) recommended by Doorenbos and Kassam (1979).

Lamm et al. (1995) reported a mean slope for the relationship between grain yield and water use of 0.048 Mg $ha^{-1}$ $mm^{-1}$ (0.041 Mg $ha^{-1}$ $mm^{-1}$ when the grain is expressed on a dry basis) for Northwest Kansas for drip irrigated corn and a mean intercept of 328 mm. Both of

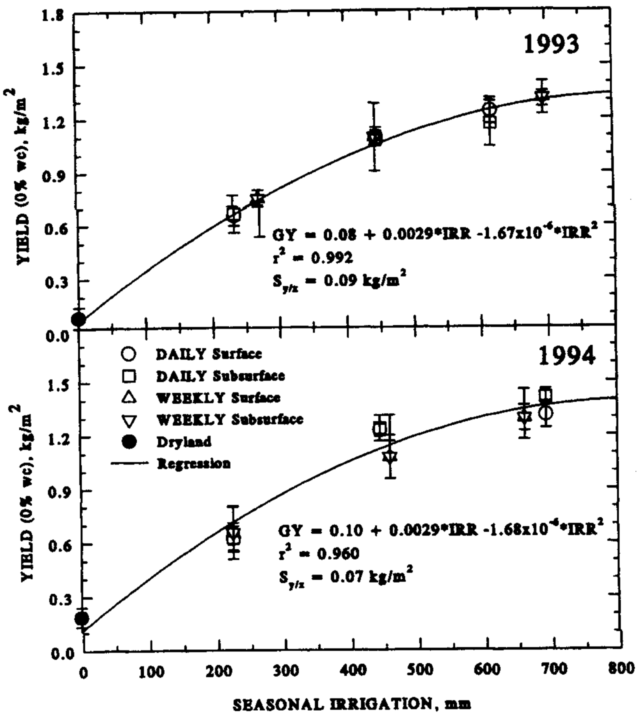


**Figure 3–Corn yield response to microirrigation method, frequency, and amount in 1993 and 1994 at Bushland, Texas.**

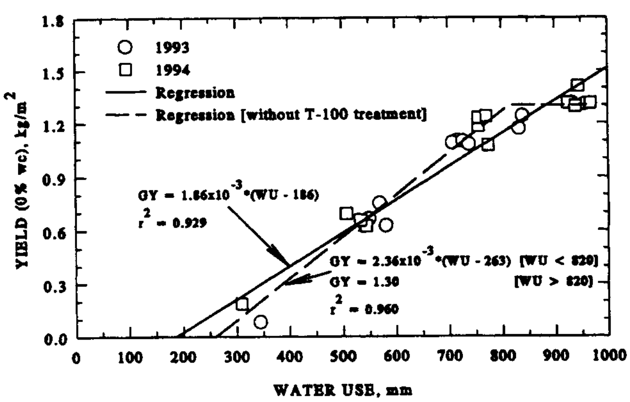


**Figure 4–Relationship between corn grain yield and water use in 1993 and 1994.**

these values are considerably greater than indicated by our data. Part of the difference between our present results and the Kansas data could be attributed to differing climates (vapor pressure deficits and temperatures). Howell et al. (1989) reported a slope of 0.034 Mg $ha^{-1}$ $mm^{-1}$ (0.029 Mg $ha^{-1}$ $mm^{-1}$ for dry grain) and an intercept of 230 mm for sprinkler irrigated corn at Bushland. Howell et al. (1995) reported a slope of 0.017 Mg $ha^{-1}$ $mm^{-1}$ (dry grain) and an intercept of 147 mm for LEPA irrigated corn at Bushland but indicated a steeper slope and larger intercept would better reflect the yield plateau that occurred at about 850 to 900 mm of water use. The relationship between corn grain yield and water use for microirrigation at Bushland in the U.S. southern High Plains remains within the range to be expected based on previous results using other irrigation methods.

Water use efficiency (table 4) was largely unaffected by irrigation application method or frequency for T-100 and T-67 in either year, but the deficit treatments (T-33 and T-0) tended to reduce water use efficiency. However, irrigation water use efficiency (IWUE) [$(Y_t - Y_d)$/IRR; where $Y_t$ is the treatment yield in g $m^{-2}$, $Y_d$ is the dryland yield in g $m^{-2}$, and IRR is the seasonal irrigation amount in mm] increased from 2.2 kg $m^{-3}$ for T-100 to 2.67 kg $m^{-3}$ for T-67 and 2.75 kg $m^{-3}$ for T-33 in 1993. Likewise, ET water use efficiency (EtWUE) [$(Y_t - Y_d)/(ET_t - ET_d)$; where $ET_t$ is the treatment water use in mm and $ET_d$ is the dryland water use in mm] increased from 1.79 kg $m^{-3}$ for T-100 to 2.26 kg $m^{-2}$ for T-67 and 2.38 kg $m^{-3}$ for T-33 in 1993. In 1994, IWUE increased from 1.69 kg $m^{-3}$ for T-100 to 2.19 kg $m^{-3}$ for T-67 and fell to 1.96 kg $m^{-3}$ for T-33 while EtWUE increased from 1.80 kg $m^{-3}$ to 2.18 kg $m^{-3}$ for T-67 and to 2.08 kg $m^{-3}$ for T-33. Deficit irrigation permits greater use of rainfall and soil water thereby increasing the irrigation water use efficiency and ET water use efficiency.

## Conclusions

Microirrigation including SUB methods and alternate row TOP methods can be used to irrigate row crops in the Southern High Plains. A major problem for microirrigation of row crops in the Southern High Plains is crop establishment. In 1993, almost 131 mm of water was necessary to insure germination and emergence of the corn. In 1994, even more water was used to establish the crop due to the inadequacy and undependability of rainfall. In northwest Kansas (Lamm et al., 1995), rainfall for corn establishment is more dependable. Of course, most of this "crop establishment" water was held in the root zone and was available for later use during the growing season. This irrigation amount would be similar to that expected for a preplant irrigation using graded furrow irrigation, but the microirrigation is likely to be more evenly distributed across the field.

Corn yields exceeding 1.4 kg $m^{-2}$ (260 bu/ac at 15.5% wc) were achieved in 1994, and yields exceeding 1.3 kg $m^{-2}$ (245 bu/ac at 15.5% wc) were even achieved with the late planting date and the late insect problems in 1993. Water use and water use efficiency were comparable to other irrigation methods used in the Southern High Plains, although the microirrigation methods minimized application losses and offered advantages for automation and improved nutrient control. In both seasons, the deficit irrigation level of T-67 produced good yields (88% of T-100) while reducing the irrigation amount appreciably (by 33%).

Irrigation frequency on the Pullman soil did not affect corn yields as long as adequate water was applied. If soil water levels were low initially or if the soil had a lower water holding capacity, we would expect irrigation frequency to be more important. Weekly irrigations were just as effective as daily irrigations, although with weekly irrigations storm runoff losses on "normal" fields could be greater than for daily irrigation. The SUB method provides a drier top soil to permit rainfall storage, and even the TOP method still maintains greater than 50% of the soil surface dry for rainfall storage.

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