DRIPLINE DEPTH EFFECTS ON CORN PRODUCTION WHEN CROP ESTABLISHMENT IS NONLIMITING

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ABSTRACT. *A four-year yield study (1999-2002) was conducted to examine the effect of dripline depth on subsurface drip-irrigated field corn grown on the deep silt loam soils of western Kansas. An additional year (2003) was included in the analysis of long-term dripline flow rates and temperatures at the soil/water interface along the dripline. Germination of the field corn with the subsurface drip irrigation system was not examined in this field study. Results indicate that dripline depths ranging from 0.20 to 0.61 m are acceptable for field-corn production on silt loam soils in the region. Averaged over the 4 years of the study, yields were slightly less for the deepest (0.61 m) dripline depth and water use was slightly less for the 0.51- and 0.61-m depth compared to the 0.20-, 0.30-, and 0.41-m depths. There were no apparent effects of dripline depth on long-term flow rates. The results suggest that other factors external to the study might have a larger influence on selection of dripline installation depth. These other factors might include producer preferences, tillage schemes, rodent management, perceived need for surface wetting for germination, and installation draft requirements and costs.*

Keywords. *Microirrigation, Subsurface drip irrigation (SDI), Irrigation design, Dripline depth, Corn production.*

Subsurface drip irrigation (SDI) is a relatively new technology in the central Great Plains but producers are beginning to adopt and adapt the technology to their farms. Most of the SDI research for field corn conducted at Kansas State University has been with driplines at a 0.40- to 0.45-m depth in deep silt loam soils. In general, at this depth the soil surface stays dry. This helps to eliminate evaporative losses, but low flow driplines at this depth, for the typical 1.5-m dripline spacing centered between 0.76-m spaced corn rows, will not adequately wet the corn seed zone for germination. Shallow placement of driplines can assist with seed germination. For example, when tomato seeds were placed directly above driplines in a Yolo clay loam soil, better germination was obtained with dripline depths of 0.15 or 0.23 m, and germination was reduced with a dripline depth of 0.3 m (Schwankl et al., 1990). They also showed, however, that even at a depth of 0.3 m, driplines assisted with germination if enough water was applied (half or greater of estimated ETo). Charlesworth and Muirhead (2003) recommended a dripline depth no greater than 0.2 m on loam soils when germination assistance is an objective of the SDI system. Dripline depths of 0.3 m were too deep for germination assistance in that study.

After the crop is germinated, deeper dripline placement has many advantages. Shallow SDI installation can result in mechanical problems. Driplines at a depth of 0.1 m have been damaged by alfalfa harvesting operations (Bui and Osgood, 1990). In silty clay loam and clay loam soils in California, Ayars et al. (1999) reported that a dripline depth of 0.45 m was successful for row crops. Dripline depth of 0.4 m resulted in greater cotton yields in the southeastern coastal-plains soils of the United States than dripline depths of 0.3 or 0.2 m (Khalilian et al., 2000). This is in agreement with the recommended dripline depth of 0.45 to 0.5 m for cotton obtained in a greenhouse study (Plaut et al., 1996). But driplines must not be so deep that the crop roots are unable to easily reach water early in the growing season, when the plants are small. Faba bean yield and water use efficiency were both reduced at a dripline depth of 0.6 m, compared with those at depths of 0.3 and 0.45 m (Bryla et al., 2003).

In many years, irrigation is not required to establish a summer crop in the central Great Plains because May and June have the highest potential for precipitation during the year in this semi-arid, summer-precipitation pattern climate. Some producers in the region want the capability to use SDI for germination in those isolated dry years and believe that shallower dripline depths may enhance those prospects. But the long term effects of dripline depth on corn production, water use and on system management have not been evaluated fully. Chemical precipitation and biological activity in microirrigation systems are affected by water temperature (Boman et al., 2002; Pitts et al., 1990; Rogers et al., 2003). Driplines on the surface or near the surface can experience wide temperature variations. Temperature increases from 26°C to 42°C were reported for surface driplines on a bright sunny day in British Columbia, Canada (Parchomchuk, 1976). But subsurface placement can buffer temperature extremes, as the peak temperature for driplines at a shallow 15-cm depth was 32°C. In Arizona, surface driplines had water temperatures up to 42°C, whereas empty lines had a peak temperature of 48°C (Nakayama and Bucks, 1985). In

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the Great Plains region of the United States much of the pumped irrigation is from the Ogallala aquifer and has an approximate temperature of 15°C. This cold water when applied through deeper subsurface driplines may reduce some of the chemical and biological clogging hazards typically associated with microirrigation.

SDI system life is an extremely important factor in the economics of SDI for the lower-value commodity crops such as field corn (O'Brien et al., 1998). Information is needed about how factors such as clogging or mechanical damage are affected by dripline depth and thus how these interrelationships affect overall system life.

In 1999, Kansas State University initiated a field study to evaluate the effect of dripline depth for field corn production. The objectives were to determine whether dripline depth affects corn yield components, water use and water use efficiency, emitter clogging, and SDI system longevity.

PROCEDURES

This experiment was conducted at the Kansas State University Northwest Research-Extension Center at Colby, Kansas, during the period 1999-2003. Cropping system and soil water results will be reported for the years 1999-2002. Long-term flow measurements will be reported for the five seasons (1999 to 2003), and soil temperature measurements will be reported for 2003 only.

The deep silt loam soil can supply about 445 mm of available soil water from a 2.4-m soil profile. The climate can be described as semi-arid, with a summer precipitation pattern and a long-term average annual rainfall of approximately 480 mm. Average precipitation is approximately 300 mm during the 120-day corn growing season.

The treatments were five microirrigation dripline depths (0.20, 0.30, 0.41, 0.51, and 0.61 m) replicated four times in a randomized complete block design. Plot length was 42 m, and plot width was eight corn rows spaced 0.76 m apart (approximately 6 m).

The subsurface drip irrigation (SDI) system was installed in the spring of 1999, before corn planting in May. Low-flow (0.0455 L s^{-1} 100 m^{-1}) Toro Ag dripline (Riverside, Calif.) with a 0.3-m emitter spacing and 22-mm inside diameter (Aquatraxx EA7XX1222) was installed with a 1.5-m dripline spacing using a shank-type injector at the specified treatment depths. The emitter exponent for the dripline is 0.54 and the manufacturer's coefficient of variation is approximately 3%. There were four driplines in each plot. Each plot was instrumented with a municipal-type flowmeter to record accumulated flow. Mainline pressure entering the driplines was first standardized to 138 kPa with a pressure regulator and then further reduced with a throttling valve to the nominal flow rate of 0.088 L s^{-1} for each plot, coinciding with an operating pressure of approximately 69 kPa. Irrigation water was supplied from an unlined surface reservoir to which groundwater was pumped for temporary storage. The surface reservoir adds three major issues to the study, the introduction of silt and clay materials into the dripline, biological activity, and changing water temperature that can affect both chemical precipitation and biological activity. Filtration to the SDI system was provided by an automated disk filter (Netafim 2 x 3 model, Fresno, Calif.) with 75-µm (200-mesh) filtration, which agreed with the dripline manufacturer's recommendation. The filtration system was flushed automatically on a two hour interval or when the differential pressure between the filter inlet and outlet exceeded 48 kPa.

Pioneer hybrid 3162 seed corn was used in 1999 through 2002. This 118-d relative maturity hybrid is a full season hybrid for the region. In 2003, the corn planting was purposely delayed until mid-May to attempt an examination of germination potential of the different depths. Heavy rains after planting negated this study and the results are excluded from discussion. This late planting date resulted in a much later first irrigation for this study than normal. Pest (weeds and insects) control was accomplished with standard practices for the region. Nitrogen fertilizer was applied to the study area, with approximately 140 kg N ha^{-1} early preplant and 84 kg N ha^{-1} through the SDI system in late June each year. A starter fertilizer application at planting banded an additional 34 kg N ha^{-1} and 50 kg P_2O_5 ha^{-1}. These fertilizer rates can be described as non-limiting for high corn yields. The corn rows were planted parallel with the dripline with each corn row approximately 0.38 m from the nearest dripline. A raised bed was used in corn production which allowed centering the corn rows on the dripline and also limited wheel traffic to the furrow (fig. 1). This controlled traffic allowed shallow cultivation procedures.

Irrigation was scheduled using a climatic water budget each year and all dripline treatments received the same amount of water within a given year. Daily or bi-daily irrigations were scheduled whenever the calculated soil water depletion in the profile exceeded approximately 25 mm. Irrigation amounts ranged from approximately 6 to 13 mm for each event, depending on availability of pumping capacity for the given event. The crop was fully irrigated throughout the season. Soil water content was measured weekly or biweekly with a neutron attenuation moisture meter in 0.3-m increments to a depth of 2.4 m at the corn row (approximately 0.38 m horizontally from the dripline).

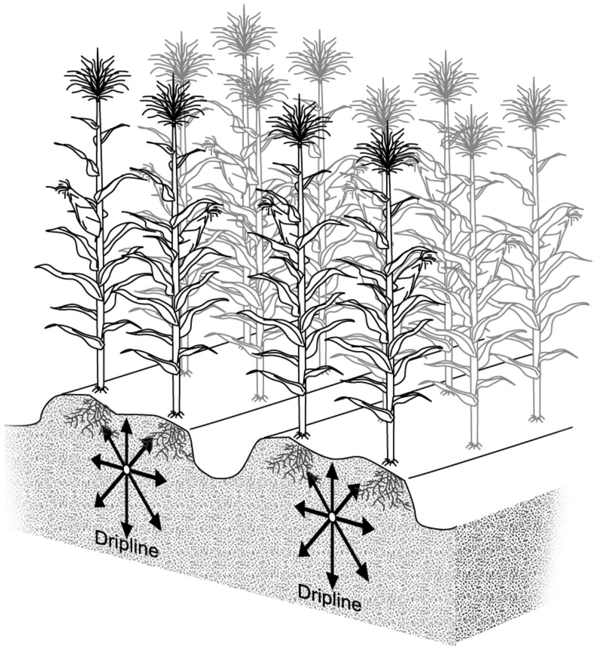

Figure 1. Physical arrangement of the subsurface dripline in relation to the corn rows.

Pressure and flow measurements were made at the beginning of the study and also at the end of each irrigation season using municipal grade flowmeters for approximately 20 min. and recording the pressure at the inlet and tail end of the plots. High quality 0- to 207-kPa (0.1-m diameter face) pressure gauges with approximate full scale accuracy of ±1% were used in 1999 to 2002, and 0- to 207-kPa pressure transducers with ±0.5% of full scale were used in 2003. The measured flow rates were normalized to a standard pressure of 69 kPa using the emitter exponent. This was done to allow direct comparisons between years and to remove the effects of small pressure variations between events.

In 2003, thermocouples were installed in each plot adjacent to one of the center two driplines (closer than 5 mm) at a distance of 30 m from the water inlet for the plot. In addition, three thermocouples were installed in three plots in the soil surface layer (0 to 20 mm). The three near surface thermocouples were installed in plots that had dripline depths of 0.20, 0.41, and 0.61 m. The water inlet temperature was measured for two plots by installing a thermocouple directly in the inlet pipe immediately before entering the plot. During these 2003 temperature tests, large irrigation amounts were used (50 to 100 mm for each event) to examine the duration of temperature effects.

Corn production data collected during the growing season included irrigation and precipitation amounts, weather data, yield components (yield, harvest plant population, ears/plant, kernels/ear, mass/100 kernels), and periodic soil water content. Yield component data were measured by hand-harvesting a 6-m section of row near the center of the plot. Weather data were collected with an automated weather station approximately 500 m from the research site. Values calculated after final data collection included seasonal water use and water use efficiency. Water use efficiency was calculated as corn grain yield at a grain moisture content of 15.5% wet basis divided by total crop water use.

RESULTS AND DISCUSSION

WEATHER CONDITIONS

The weather conditions were wetter than normal in 1999 and excessively dry in 2000 through 2002. Precipitation during the cropping season was 431, 158, 235, and 252 mm for the respective years, 1999 through 2002. Calculated evapotranspiration was slightly less than normal in 1999 (550 mm) and above normal at 698, 668, and 703 mm for the years 2000 through 2002, respectively. This resulted in irrigation requirements of 268, 457, 483, and 499 mm for the four respective years, 1999 through 2002. The SDI system was not used to enhance germination in any year, although some additional residual soil water in the surface layers for the shallower dripline depths may have existed in the spring of 1999 shortly after the late spring installation. Normally irrigation is not needed to establish summer crops, such as corn, in this region. The crop year 2002 was very dry at planting, and it is possible that the shallower depths could have benefited in crop germination if they had been irrigated. This was not part of the experimental protocol, however, so no irrigation was performed at this time.

TILLAGE AND RODENT-MANAGEMENT ASPECTS

Although tillage and rodent management were not specifically examined in the study, it should be noted that there were no instances of dripline damage due to tillage or rodents. Shallow cultivation for weeds during the corn season was accomplished even for the 0.2-m depth. This may have been enhanced by the controlled-traffic, bed-management scheme used in this study area (fig. 1). Deep tillage schemes would definitely be affected by dripline depths less than 0.3 m. Deeper SDI depths (45 cm or greater) may avoid some rodent damage (Van der Gulik, 1999). Many of the common burrowing mammals of concern in the United States have a typical depth range of less than 45 cm (Cline et al., 1982).

CORN YIELD AND YIELD COMPONENTS

Corn yields were very high in all four years, ranging from 15.6 to 18.3 Mg ha^{-1} (table 1, fig. 2) which greatly exceeds typical commercial production of approximately 12 to 13 Mg ha^{-1}. In any given year, there were no statistically significant differences in yield attributable to differences in dripline depth. However, when averaged over the 4 years, the 0.61-m depth resulted in significantly lower yields (table 1, fig. 2). In general, there were no statistically significant effects on the yield components with the exception of a greater number of kernels/ear for the 0.2-m depth in 1999 (table 1) and a greater ears/plant for the 0.41-m depth for the 4-year average. The greater kernels/ear for the 0.2-m depth in 1999 may possibly reflect more favorable soil water conditions early in the season caused by greater residual soil water conditions in the surface layers after SDI system installation (data not shown). These results indicate there is little reason to select one dripline depth over another on the basis of grain yield.

WATER USE AND WATER USE EFFICIENCY

Crop water use for individual years was not significantly affected by dripline depth. However, when averaged over the four years, the 0.51- and 0.61-m dripline depths used slightly less water (table 1). There were no significant differences in water use efficiency (WUE, grain yield divided by water use) in any year. Because no appreciable differences exist, all treatments likely received adequate water and dripline depth in the range of 0.20 to 0.61 m is probably not a major design issue in terms of water use and water use efficiency.

SOIL WATER IN THE TOP 0.9 m

Visual observations of the various treatments throughout the irrigation seasons indicated that the 0.2- and 0.3-m dripline depths had more wetting at or near the soil surface. This might be an advantage in germinating crops, but has little or no advantage once the crop is germinated. Damp soil surfaces can result in greater evaporative losses and perhaps more weed growth. Visual observations indicated greater incidence of late-season grasses for the 0.2-m dripline depth, but the small weed pressure increase did not affect corn yields. Soil water measurements in the top 0.9 m are shown for 2002 in figure 3. The graph shows a few instances in which soil water is noticeably greater for the shallower dripline depths in the top 0.3 m of the soil profile, but the deeper dripline depths show slightly greater soil water in succeeding 0.3-m increments (0.6 and 0.9 m) of the soil profile. Under the full-irrigation scheme used in this study, none of the soil water differences would be considered of

Table 1. Yield-component and water-use data from a dripline depth study for corn, 1999-2002.

Dripline Depth (m)	Yield (Mg ha^{-1})	Plants/ha	Ears/Plant	Kernels/Ear	100 Kernel Wt. (g)	Water Use (mm)	WUE ($\text{Mg ha}^{-1}\ \text{mm}^{-1}$)
Year 1999							
0.20	18.3	75884	1.00	691 a[a]	34.79	862	0.02128
0.30	17.0	73193	1.02	647 b	35.17	858	0.0198
0.41	17.5	75884	1.00	628 b	36.76	849	0.0206
0.51	17.3	77498	1.00	624 b	35.81	856	0.0202
0.61	17.1	74807	1.01	642 b	35.39	839	0.0204
Mean	17.4	75454	1.01	646 b	35.58	853	0.0204
LSD ($p < 0.05$)	NS	NS	NS	44	NS	NS	NS
Year 2000							
0.20	15.9	65121	1.00	642	37.92	751	0.0211
0.30	16.1	67273	1.00	629	38.02	725	0.0222
0.41	16.7	65121	1.05	635	38.45	725	0.0230
0.51	15.6	66196	1.01	622	37.61	704	0.0222
0.61	15.9	67812	1.00	619	38.02	711	0.0224
Mean	16.0	66304	1.01	629	38.00	723	0.0222
LSD ($p < 0.05$)	NS	NS	NS	NS	NS	NS	NS
Year 2001							
0.20	16.9	87187	0.96	585	34.58	826	0.0205
0.30	16.9	83957	1.01	594	33.76	825	0.0206
0.41	17.2	88262	1.00	572	34.40	812	0.0212
0.51	17.4	85032	1.00	570	36.05	802	0.0218
0.61	16.9	86109	0.98	582	34.61	803	0.0211
Mean	17.1	86109	0.99	580	34.68	814	0.0210
LSD ($p < 0.05$)	NS	NS	NS	NS	NS	NS	NS
Year 2002							
0.20	17.4	85035	0.99	519	39.96	811	0.0215
0.30	16.6	81805	0.99	529	39.11	800	0.0207
0.41	18.0	84493	0.99	547	39.21	814	0.0221
0.51	16.5	84496	0.99	485	41.22	777	0.0213
0.61	16.0	82344	0.98	507	39.39	782	0.0204
Mean	16.9	83633	0.99	518	39.78	797	0.0212
LSD ($p < 0.05$)	NS	NS	NS	NS	NS	NS	NS
All Years							
0.20	17.1 ab	78306	0.99b	609	36.81	812 a	0.0211
0.30	16.6 bc	76557	1.00ab	600	36.51	802 a	0.0208
0.41	17.3 a	78439	1.01a	595	37.21	800 ab	0.0217
0.51	16.7 bc	78306	1.00ab	575	37.67	785 b	0.0214
0.61	16.5 c	77767	0.99b	587	36.85	784 b	0.0211
Mean	16.9	77876	1.00ab	593	37.01	797	0.0212
LSD ($p < 0.05$)	0.6	NS	0.02	NS	NS	17	NS

[a] Values followed by the same letter are not significantly different at the 0.05 probability level.

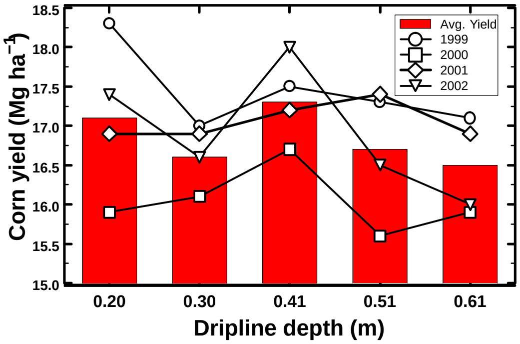

Figure 2. Corn grain yields as affected by dripline depth, Colby, Kansas, 1999 to 2002.

critical importance, with the exception of the possible germination enhancement by shallower dripline depths that was previously discussed.

Long-Term Flow Measurements and Soil/Water Interface Temperatures

As previously discussed, the water source for this SDI system was an unlined surface reservoir. It was hypothesized that there might be an interaction between dripline depth and emitter clogging because of differences in water temperature at the dripline depth. Both biological and chemical clogging hazards are temperature dependent and there may be greater hazards with warmer temperatures (Boman et al., 2002; Pitts et al., 1990; Rogers et al., 2003). Diurnal temperature swings could also affect the growth and decay of bacteria and thus affect emitter clogging. The deeper driplines used in this study may also buffer some of the wide swings in temperatures that have been reported for surface driplines (Parchomchuk, 1976; Nakayama and Bucks, 1985).

Flow rates did differ appreciably over the course of the five seasons, reflecting decreases caused by the silt and biological loads experienced by the driplines (fig. 4). During

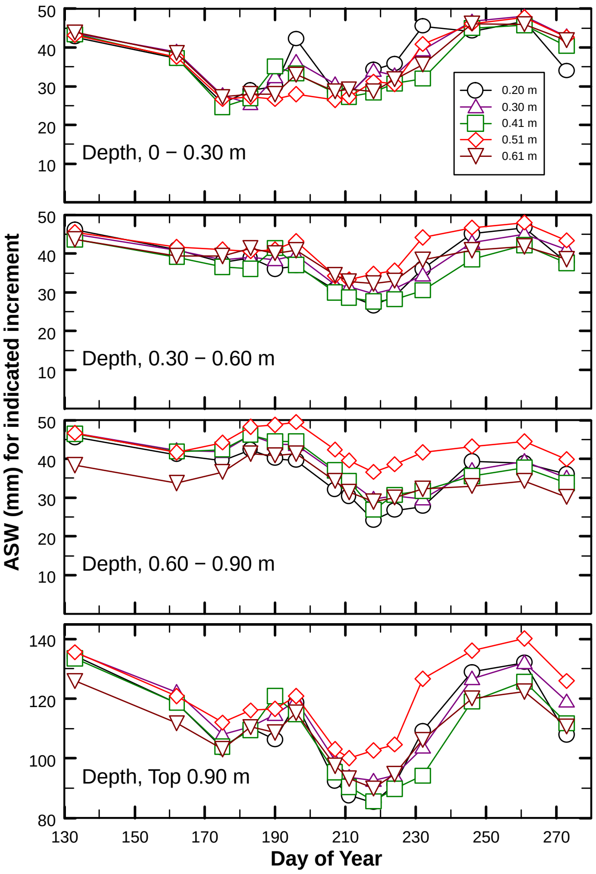

Figure 3. Soil water conditions in the top 0.9 m as affected by dripline depth in the dry year of 2002.

the course of each season, dripline flow rates would decrease. Acid and chlorine were injected every 2 to 3 weeks for a period of 1 h (approximately 50 mg chlorine/L of water and acid to adjust to pH of 4), but dripline flushing during 1999 through 2001 was restricted to the spring and fall. During 2002, it became obvious that clogging was becoming more difficult to manage with just acid and chlorine, so one additional flushing was added mid-season. By the end of 2002, dripline flow rates were 10% to 25% less than the initial flow rate. There was no clear pattern in terms of flow rate decreases as affected by dripline depth (fig. 4). Some of the differences that did exist were more related to the random nature of a particular plot being affected by clogging rather than to a specific dripline depth treatment. In 2003, additional flushing events were added (approximately monthly), along with more aggressive acid and chlorine treatments (about 2 h for each event followed by leaving the system off overnight and then flushing again). This stricter maintenance regimen helped recover much of the flow that had been lost during the previous seasons, and the treatment average (four plots) flow rates were within approximately 8% of the initial flow rates at the close of the season.

In 2003, temperatures were measured at the soil/water interface at the dripline at a point 30 m from the water inlet. The first measurements were made in early July, just before the first irrigation. The corn was approximately 0.45 m tall and did not fully shade the soil surface. Soil temperatures near the surface, and also at the different dripline depths, were greater at this point in time than they were during the rest of the season. This is because the solar radiation load to

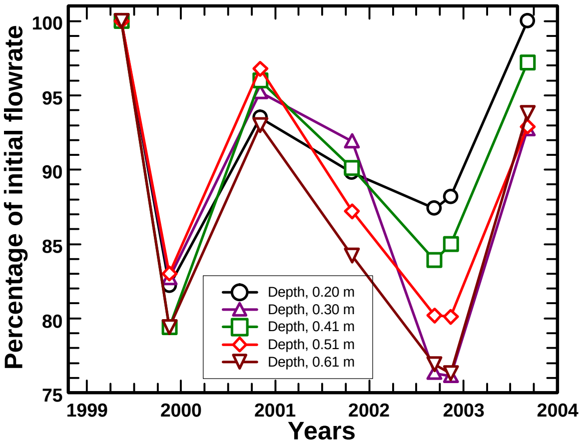

Figure 4. Dripline flow rate as percentage of initial flow rate for the five different depths, 1999-2003.

the soil surface was high and no large increment of water had been added through the dripline. Temperatures before the first irrigation were changing diurnally for the 0.2-m depth from about 24°C to 27°C and were less variable at the deeper depths, with mean values of about 24°C (fig. 5). This contrasted with soil surface temperatures that changed diurnally from 24°C to 41°C. During the first irrigation event, the temperature varied with the water inlet temperature. The temperature at the dripline initially decreased about 3° during the initial portion of the event while the water temperature fell approximately 6°C. Then the temperature at the dripline increased slowly back to about 23°C as the water temperature at the inlet increased to about 23°C. Much of the diurnal variance for the 0.2-m dripline depth disappeared after this irrigation event, suggesting the large temperature-buffering capacity of the wetted soil.

Later in the season (August), temperatures at all of the dripline depths ranged from approximately 22°C to 23°C, with even cold irrigation water (approximately 17°C) only decreasing the dripline temperature 0.5° to 1.0° (fig. 6). No appreciable temperature differences were attributable to dripline depth. This suggests that dripline depths of 0.20 to 0.61 m would greatly moderate temperature variations that would occur for driplines placed on the soil surface. These stable and relatively low temperatures may be helpful in reducing biological, and particularly chemical, clogging hazards.

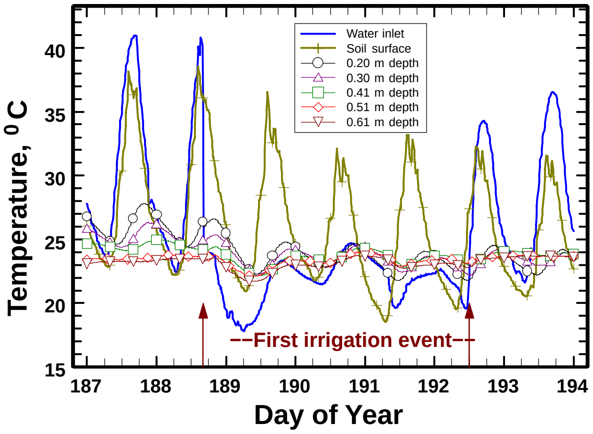

Figure 5. Temperatures at the water inlet, near the soil surface, and near the dripline for the five dripline depths before corn canopy closure and the first irrigation in 2003.

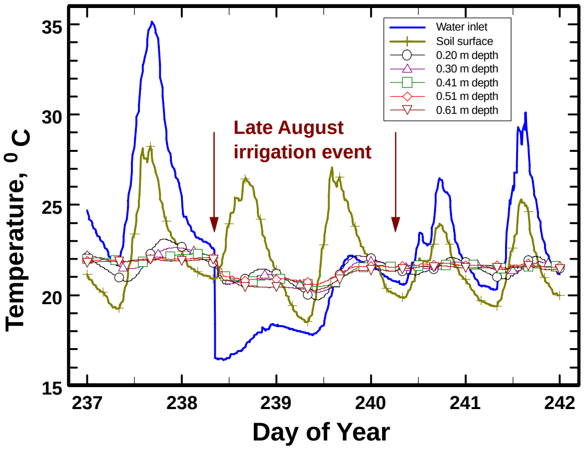

Figure 6. Temperatures at the water inlet, near the soil surface, and near the dripline for the five dripline depths near the end of the corn irrigation season in 2003.

Summary and Conclusions

Corn production was not strongly affected by dripline depths ranging from 0.20 to 0.61 m in this study in which crop germination was not a factor. A slight tendency existed for corn yields to be reduced for the deepest dripline depth (0.61 m), which might be related to early-season growth or water and nutrient availability. The deep, well drained silt loam soil with good water-holding capacity is conducive to deep rooting of field corn, and this may be part of the reason there was no strong effect of dripline depth on corn production. Water use and water use efficiency for the 2.4-m soil profile also were not strongly affected.

The shallower, 0.20- and 0.30-m dripline depths resulted in slightly greater amounts of soil water at the row location in the top foot of the soil profile. This may be advantageous in years in which irrigation is needed for germination, but may also cause greater soil evaporation losses during the cropping season.

Flow rates varied throughout the 5 seasons, indicating some clogging problems that were occurring due to the pumping of water from a reservoir. More aggressive maintenance during the 2003 season remediated much of the clogging problems. However, there was no observable effect of dripline depth on clogging in this study.

Dripline depths of 0.20 to 0.61 m resulted in temperatures at the soil/dripline interface in the 22°C to 25°C range for the whole irrigation season. The greatest amount of temperature variation occurred for the 0.20-m depth, but it was only 2° to 3° during the period preceding canopy closure and the first irrigation. After canopy closure and the start of the irrigation season, temperatures at the dripline were generally about 22°C to 23°C. These stable and relatively low temperatures may have helped reduce biological and chemical clogging hazards.

The results indicate that there is little effect of dripline depths ranging from 0.20 to 0.61 m for corn production on the deep silt loams of western Kansas, provided there is adequate water for establishment of the crop. Other factors not specifically examined in the study, such as producer preferences, tillage schemes, rodent management, need for surface wetting for germination, and installation draft requirements and cost might be better criteria for the dripline-depth decision.

References

Ayars, J. E., C. J. Phene, R. B. Hutmacher, K. R. Davis, R. A. Schoneman, S. S. Vail, and R. M. Mead. 1999. Subsurface drip irrigation of row crops: A review of 15 years of research at the Water Management Research Laboratory. *Agric. Water Management* 42: 1-27.

Boman, B. J., P. C. Wilson, and E. A. Ontermaa. 2002. Understanding water quality parameters for citrus irrigation and drainage systems. Univ. of Florida IFAS Extension, Circ. 1406. Gainesville, Fla.

Bryla, D. R., G. S. Banuelos, and J. P. Mitchell. 2003. Water requirements of subsurface drip-irrigated faba bean in California. *Irrig. Sci.* 22: 31-37.

Bui, W., and R. V. Osgood. 1990. Subsurface irrigation trial for alfalfa in Hawaii. In *Proc. of the Third Nat'l. Irrigation Symp.,* 658-660. St. Joseph, Mich.: ASAE.

Charlesworth, P. B., and W. A. Muirhead. 2003. Crop establishment using subsurface drip irrigation: a comparison of point and area sources. *Irrig. Sci.* 22: 171-176.

Cline, J. F., F. G. Burton, D. A. Cataldo, W. E. Skiens, and K. A. Gano. 1982. Long-term biobarriers to plant and animal intrusions of uranium tailings. DOE/UMT-0209, PNL-4340, UC-70. U.S. Dept. of Energy Rep. under contract DE-AC06-76RLO 1830. Pacific Northwest Nat'l. Lab., Richland, Wash.

Khalilian, A., M. J. Sullivan, and W. B. Smith. 2000. Lateral depth placement and deep tillage effects in a subsurface drip irrigation system for cotton. In *Proc. Fourth Decennial Nat'l Irrigation Symp.,* 641-646. St. Joseph, Mich.: ASAE.

Nakayama, F. S., and D. A. Bucks. 1985. Temperature effect on calcium carbonate precipitate clogging of trickle emitters. In *Proc. Third Int'l. Drip/Trickle Irrigation Congress,* 45-49. St. Joseph, Mich.: ASAE.

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1998. An economic comparison of subsurface drip and center pivot sprinkler irrigation systems. *Applied Engineering in Agriculture* 14(4): 391-398.

Parchomchuk, P. 1976. Temperature effects on emitter discharge rates. *Transactions of the ASAE* 19(4): 690-692.

Pitts, D. J., D. Z. Haman, and A. G. Smajstrla. 1990. Causes and prevention of emitter plugging in microirrigation systems. Univ. of Florida IFAS Extension, Bul. 258. Gainesville, Fla.

Plaut, Z., A. Carmi, and A. Grava. 1996. Cotton root and shoot responses to subsurface drip irrigation and partial wetting of the upper soil profile. *Irrig. Sci.* 16: 107-113.

Rogers, D. H., F. R. Lamm, and M. Alam. 2003. Subsurface drip irrigation systems (SDI) water quality assessment guidelines. KSU Cooperative Ext. Irrigation Mgmt. Series, MF-2575. Manhattan, Kans.

Schwankl, L. J., S. R. Grattan, and E. M. Miyao. 1990. Drip irrigation burial depth and seed planting depth effects on tomato germination. In *Proc. Third Nat'l. Irrigation Symp.,* 682-687. St. Joseph, Mich.: ASAE.

Van der Gulik, T. W. 1999. B.C. trickle irrigation manual. B.C. Ministry Agric. and Food Res. Manage. Branch and Irrig. Industry Assoc. of British Columbia, Abbotsford, B.C., Canada.