THIRTY YEARS OF SDI RESEARCH IN THE CENTRAL GREAT PLAINS

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QUICK FACTS

- *SDI can potentially save water and/or increase water productivity through reducing non-beneficial water losses, improving retention and utilization of natural precipitation, improving irrigation uniformity and improving crop yield and/or quality.*
- *SDI appears to optimize corn yields at irrigation levels in the range of 75 to 85% of full irrigation levels on the deep silt loam soils of western Kansas.*
- *Even small irrigation events (≈ 0.10 inches/day) can be effective with SDI and can greatly increase corn grain yields above rainfed conditions.*
- *Although individual study results vary about whether SDI can increase corn yields over alternative irrigation systems, there is increased evidence that SDI can stabilize yields at a greater level under deficit irrigation.*
- *SDI is well suited to intensive management of inputs, such as nutrients and seeding rates, and the potential exists to further improve corn yields while maintaining high water productivity (crop per drop).*
- *SDI can better manage both nitrogen and phosphorus applications through in-season fertigation.*
- *Design characteristics have been researched on the deep silt loam soils of the Central Great Plains.*
- *Livestock wastewater can be applied through SDI systems for agronomic and environmental benefits.*
- *Although SDI systems are expensive, they can have a long life when properly managed.*

INTRODUCTION

In March 1989, K-State Research and Extension initiated efforts to develop the techniques for successful application of subsurface drip irrigation (SDI) for crop production in the U. S. Great Plains region. Irrigation and nutrient management for field corn has been a major research topic during this 31-year period. The vast majority of the SDI crop research studies have been conducted with field corn (maize) because it is the primary irrigated crop in the Central Great Plains. Other crops that have been researched with SDI at the KSU Northwest Research-Extension Center at Colby, Kansas include grain sorghum, soybeans, sunflower, and alfalfa. Additional research topics have included design issues (i.e., dripline and emitter spacing, dripline depth, system hydraulics and uniformity), irrigation management (i.e., irrigation needs, frequency of events, timing of events within the season), using SDI with livestock wastewater, evaluation of dripline flushing procedures, comparison of SDI with alternative irrigation systems, and SDI system longevity and economics.

CONSERVING WATER AND/OR INCREASING CROP WATER PRODUCTIVITY WITH SDI SYSTEMS

Subsurface drip irrigation (SDI) applies water below the soil surface to the crop root zone through small emission points (emitters) that are in a series of plastic lines typically spaced between alternate pairs of crop rows (Figure 1). This method of irrigation can be used for small, frequent, just-in-time irrigation applications directly to crop root system. Daily irrigation amounts as small as 0.10 inches/day can be of great benefit to corn production when applied with SDI (Lamm and Trooien, 2001).

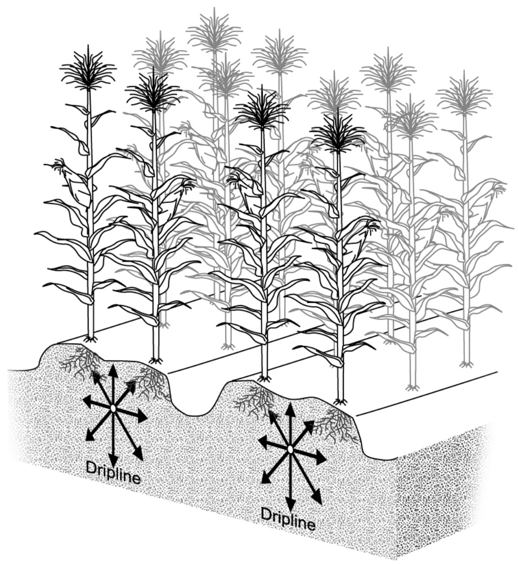

Figure 1. Alternate row/bed 5 ft SDI dripline spacing for corn rows spaced at 2.5 ft. Each plant row is approximately 1.25 ft from the nearest dripline and has equal opportunity to the applied water.

The primary ways that SDI can potentially increase crop water productivity and/or save water are:

- Reduction and/or elimination of deep drainage, irrigation runoff, and water evaporation
- Improved infiltration, storage, and use of precipitation
- Improved in-field uniformity and targeting of water within plant root zone
- Improved crop health, growth, yield, and quality.

The results from four SDI studies on corn water use were summarized by Lamm, 2005. Relative corn yield reached a plateau region at about 80% of full irrigation and continued to remain at that level to about 130% of full irrigation (Figure 2). Yield variation as calculated from the regression equation for this plateau region is less than 5% and would not be considered significantly different. The similarity of results for all four studies is encouraging because the later studies included the effect of the four extreme drought years of 2000 through 2003. An examination of water productivity (WP) for the same four studies indicates that water productivity plateaus for levels of irrigation ranging from 61% to 109% of full irrigation with less than 5% variation in WP (Figure 3). The greatest WP occurs at an irrigation level of approximately 82% of full irrigation. This value agrees with results summarized by Howell, (2001) for multiple types of irrigation systems.

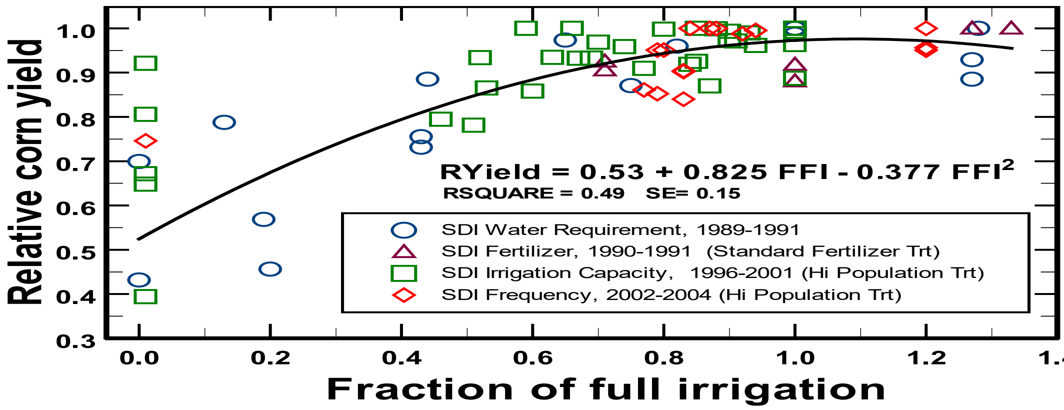

Figure 2. Relative corn grain yield for a given SDI research study and year as related to the fraction of full irrigation, KSU Northwest Research-Extension Center, Colby, Kansas.

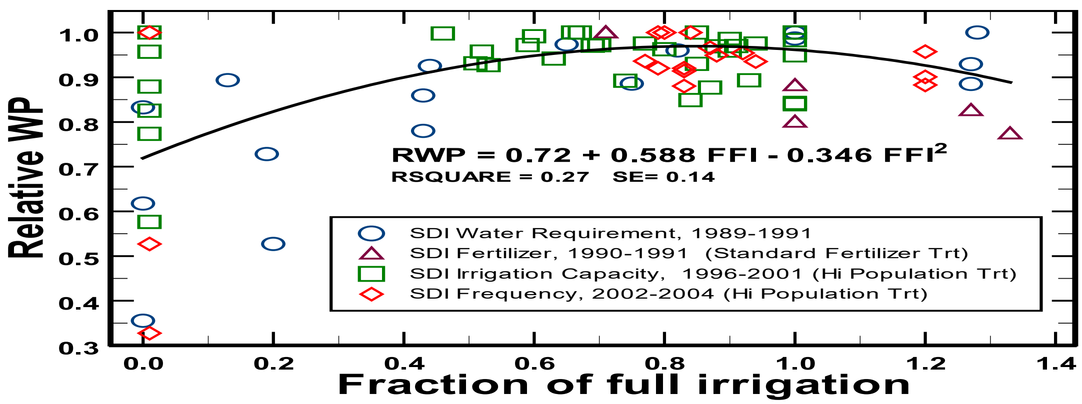

Figure 3. Relative water productivity (WP) of corn for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

The greatest WP (82% of full irrigation) also occurred in the plateau region of greatest corn yield (80 to 130% of full irrigation). This suggests that both water- and economically-efficient production can be obtained with SDI levels of approximately 80% of full irrigation across a wide range of weather conditions on the soils in this region. Some of the stability in corn yield and water productivity across this range of irrigation levels may be explained by how deep percolation is managed and by how soil water is "mined" with SDI on this soil type and in this climatic region.

For a more detailed discussion of these and other SDI research topics focused on water, the reader is referred to Lamm, 2018; Darusman et al., 1997 a and b; Lamm and Trooien, 2003; Lamm et al., 1995, and Lamm and Trooien, 2001.

There is growing evidence from our K-State studies (Figure 4, 5, and Table 1) and others in the Great Plains that SDI can stabilize yields at a greater level than alternative irrigation systems when deficit irrigated (Lamm et al., 2012).

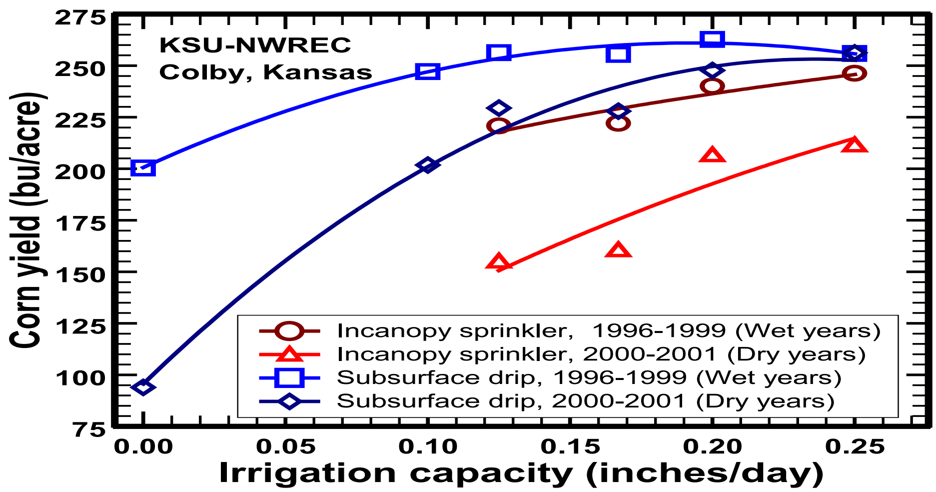

Figure 4. Corn yields for SDI and mid elevation spray application (MESA) sprinkler irrigation in wet years and dry years at Colby, Kansas. Note: Results are from different but similar studies, so these are not statistical differences.

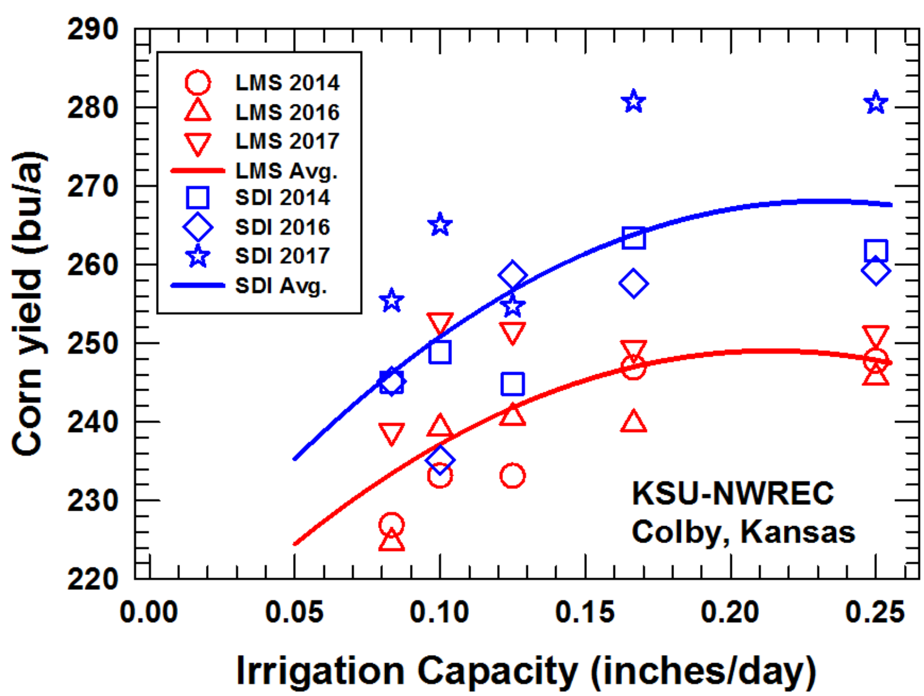

Figure 5. Corn yields for SDI and lateral move sprinkler (LMS) irrigation for 2014, 2016 and 2017 as affected by irrigation capacity at Colby, Kansas. Note: Results are from different but similar studies, so these are not statistical differences.

In two study periods, the first period from 1996 to 2001 and the second period 2014, 2016, and 2017, SDI generally had greater yields than mid-elevation spray application (MESA) with center pivot or lateral move sprinklers (Figure 4 and 5). There was also a greater plateau region of stable yields under SDI in dry years (Figure 4).

In other studies directly comparing SDI to either simulated LEPA (low energy precision application) or simulated MDI (mobile drip irrigation), the results have been more mixed (Table 1). In nearly all years SDI outperformed LEPA in grain filling (i.e. greater kernel mass) as discussed in Lamm (2004). However, in some but not all extreme drought years, LEPA had greater kernel set (i.e., kernels/ear) and as a result had greater yield than SDI in those years. Overall mean yield results for SDI and LEPA were similar with only a slight increase for SDI (Table 1). Similarly, in a study with SDI and MDI, yields have been similar and not statistically different (Table 1 and Figure 6). On average, SDI yields were about 5 bu/acre greater than MDI. However, there was differences in crop water use with SDI using less water.

Table 1. Yield (bu/a) for corn grown with SDI and LEPA center pivot irrigation (1998 to 2014) and for SDI and MDI (2016 to 2019) under full and deficit irrigation at KSU-NWREC, Colby, Kansas. There was no crop harvested in 2011 and 2015.

Year	Full irrigation, limited to 0.25 inches/day		Deficit irrigation, limited to 0.17 inches/day	
	SDI	**LEPA**	**SDI**	**LEPA**
1998	278.2	246.2	260.7	250.1
1999	263.5	260.4	263.0	252.5
2000	241.5	238.7	219.4	229.9
2001	247.9	275.0	234.7	248.7
2002	221.6	234.2	198.2	218.8
2003	195.9	220.6	194.1	214.6
2004	274.1	245.9	264.5	238.8
2005	226.4	218.3	206.9	225.4
2006	252.1	261.0	258.7	255.6
2007	273.1	252.9	237.1	262.0
2008	264.6	250.2	275.4	232.2
2009	258.0	254.6	244.3	233.0
2010	232.5	233.4	236.8	205.2
2012	251.0	225.2	208.0	206.0
2013	191.2	186.2	179.4	180.2
2014	247.6	257.9	252.3	263.8
Mean	**244.9**	**241.3**	**233.3**	**232.3**
Year	**SDI**	**MDI**	**SDI**	**MDI**
2016	248.8	246.6	251.1	243.7
2017	272.9	271.6	278.5	271.9
2018	240.9	224.8	234.9	231.8
2019	240.5	237.5	253.5	230.4
Mean	**250.8**	**245.1**	**254.5**	**244.5**

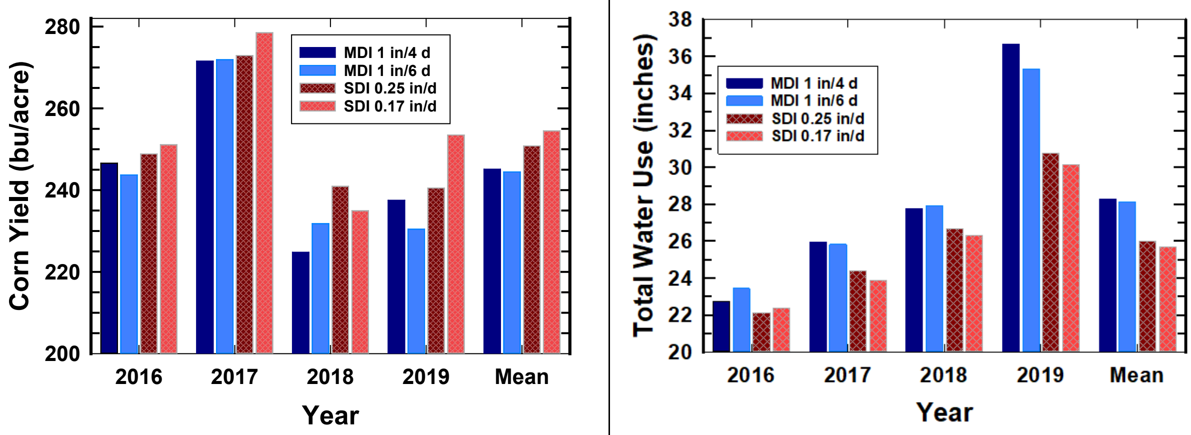

Figure 6. Corn yield and total water use for corn grown with subsurface drip irrigation (SDI) and mobile drip irrigation (MDI) under two equivalent irrigation capacities at KSU-NWREC, Colby, Kansas for 2016 through 2019. Note: Total water used is the sum of the seasonal change in soil water, irrigation and precipitation.

Improving Crop Water Productivity through Intensive Management

A new SDI study was initiated in 2017 and was also conducted in 2019 to evaluate the potential of increasing crop water productivity through intensive management of crop inputs. Fertility management was the same across all treatments but included in-season fertigation of all three macronutrients N, P, and K along with some zinc applied at planting. Study variables were 3 irrigation levels (designed to meet 85, 100 or 115% of the ETc minus precipitation requirements), 2 high-yielding corn hybrids (Pioneer 1151 and Pioneer 1197) and 3 plant densities (34,000, 38,000 or 42,000 plants/acre). Yields were exceptionally high in this study in 2017 (Table 2) and were good in 2019 (Table 3).

Yields were not affected by irrigation level in either year which agrees with earlier discussion that SDI levels matching approximately 75 to 80% of full irrigation will maximize yields. Crop water use was affected by irrigation but this is just reflecting the higher irrigation amounts which probably ended up as increased deep percolation. This is further emphasized by the greatest water productivity at the irrigation level designed to match 85% of ETc minus precipitation. In 2017, there was a strong hybrid effect on yield (Pioneer 1197 exceeded Pioneer 1151 by 24 bu/acre) which emphasizes that hybrid selection remains an important factor in intensively managed corn. In 2019, Pioneer 1197 had the greatest numerical yield but it was not statistically better than Pioneer 1151 (252 vs 247 bu/acre). This yield increase for Pioneer 1197 was primarily caused by greater number of kernels/ear in 2017 but was by greater kernel mass in 2019. Pioneer 1197 also had higher water productivity than Pioneer 1151, but crop water use was slightly greater with Pioneer 1197. Plant density of 38,000 or 42,000 plants/acre resulted in significantly greater yield than 34,000 plants/acre in 2017, but plant density did not affect yield in 2019. Crop water use was not affected by plant density in either year. Although the lower plant density had greater number of kernels/ear, this yield component did not compensate enough for the lower plant density. This reflects a growing understanding that maximizing irrigated corn yields often requires maximizing the intermediate yield component of kernels/area (i.e. plant density x ears/plant x kernels /ear).

Table 2. Corn yield and water use parameters in an SDI study with intensive management at the KSU-NWREC, Colby, Kansas in 2017.							
Main Effect	**Grain yield (bu/a)**	**Plant Density (p/acre)**	**Ears /Plant**	**Kernels /Ear**	**Kernel Mass (mg)**	**Crop Water Use (inches)**	**Water Productivity (lb/a-in)**
Effect of Irrigation Level							
Irr 1, 115% ETc *(16.75 inches)*	293	37679	1.02	587	33.3	**29.19 A**	**563 C**
Irr 2, 100% ETc *(14.50 inches)*	292	37716	1.02	586	33.3	**27.10 B**	**605 B**
Irr 3, 85% ETc *(12.00 inches)*	289	37752	1.01	580	33.6	**25.50 C**	**638 A**
Effect of Hybrid							
Hybrid 1, Pioneer 1151	**280 B**	37873	1.01	**556 B**	33.7	**26.68 B**	**590 B**
Hybrid 2, Pioneer 1197	**304 A**	37558	1.02	**612 A**	33.1	**27.84 A**	**614 A**
Effect of Plant Density							
Plant Density 1, 42K p/a	**296 A**	**41600 A**	0.99	**552 C**	33.0	27.35	607
Plant Density 2, 38K p/a	**295 A**	**37788 B**	1.02	**587 B**	33.3	27.30	608
Plant Density 3, 34K p/a	**285 B**	**33759 C**	1.03	**614 A**	34.0	27.14	591
Data for a main effect within a column followed by different letters are significantly different at P=0.05 level.							

Table 3. Corn yield and water use parameters in an SDI study with intensive management at the KSU-NWREC, Colby, Kansas in 2019.							
Main Effect	**Grain yield (bu/a)**	**Plant Density (p/acre)**	**Ears /Plant**	**Kernels /Ear**	**Kernel Mass (mg)**	**Crop Water Use (inches)**	**Water Productivity (lb/a-in)**
Effect of Irrigation Level							
Irr 1, 115% ETc *(14.30 inches)*	248	36482	0.98	537	332	**28.79 A**	**483 B**
Irr 2, 100% ETc *(12.00 inches)*	252	37026	0.98	541	327	**27.02 B**	**523 AB**
Irr 3, 85% ETc *(10.10 inches)*	248	36300	0.99	542	326	**25.94 C**	**539 A**
Effect of Hybrid							
Hybrid 1, Pioneer 1151	247	36445	0.98	548	**323 B**	26.98	514
Hybrid 2, Pioneer 1197	252	36760	0.99	531	**335 A**	27.52	516
Effect of Plant Density							
Plant Density 1, 42K p/a	253	**40547 A**	0.98	**501 C**	323	27.30	521
Plant Density 2, 38K p/a	247	**36590 B**	0.99	**530 B**	329	27.11	512
Plant Density 3, 34K p/a	248	**32670 C**	0.98	**589 A**	334	27.33	513
Data for a main effect within a column followed by different letters are significantly different at P=0.05 level.							

NUTRIENT MANAGEMENT WITH SDI SYSTEMS

Properly designed SDI systems have a high degree of uniformity and can apply small frequent irrigation applications, and provide an excellent opportunity to better manage nutrients. Injecting small amounts of nitrogen solution into the irrigation water can spoonfeed the crop just-in-time (i.e., nearer the point of actual crop need), while minimizing the pool of nitrogen in the soil that could be available for leaching into the groundwater. Likewise, utilization of immobile nutrients might be enhanced with SDI by application within the root zone periodically throughout the cropping season. Although traditional recommendations suggest that additional potassium is not typically required on the soils of the region for irrigated corn production, these recommendations may need another look when corn is intensively managed with SDI in high yielding systems.

COMPARISON OF PRE-PLANT BROADCAST APPLIED NITROGEN AND SDI FERTIGATION

In an early study at Colby, 1990-1991, results indicated that nitrogen applied with SDI redistributed differently in the soil profile than surface-applied preplant N (Lamm et al., 2001). Although corn yields were similar between the two fertilization methods, there was greater residual soil-N for the SDI fertigation (Figure 7).

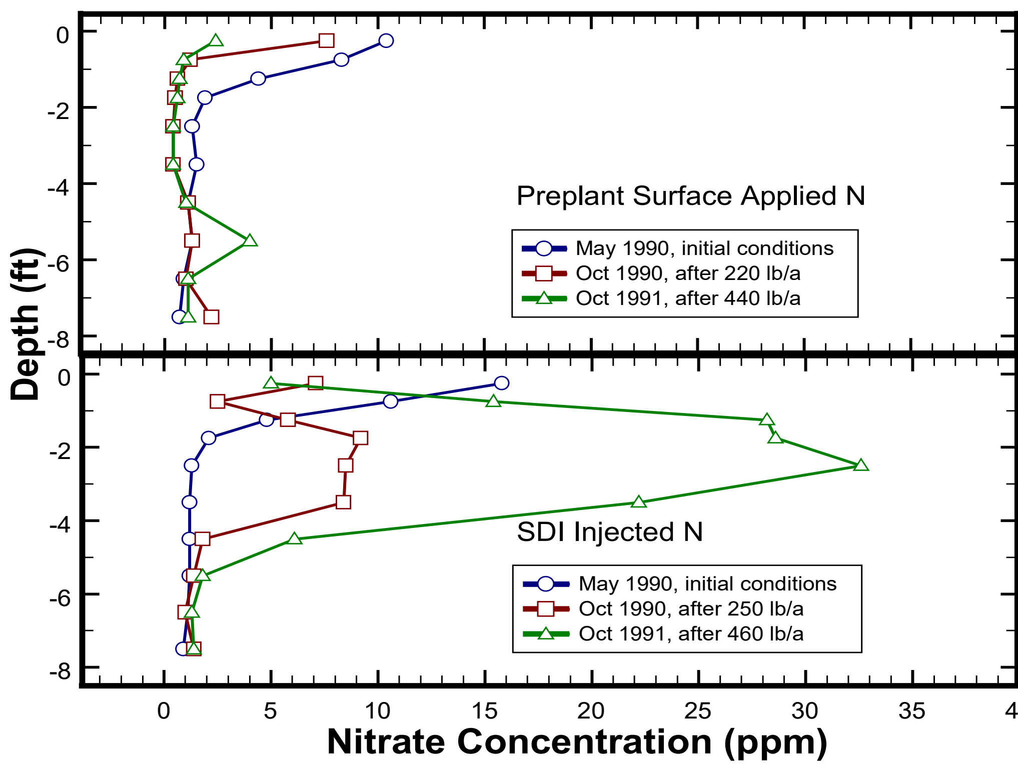

Figure 7. Nitrate concentrations in the soil profile for preplant surface-applied and SDI injected nitrogen treatments, KSU Northwest Research-Extension Center, Colby, Kansas, 1990-91. Data is for selected nitrogen fertilizer rate treatments with full irrigation (100% of ETc-Rain).

The additional in-season fertigation allowed for healthier and more vigorous plants that were better able to utilize soil water. The results suggest that a large portion of the applied N could be delayed until weekly injections begin with the first irrigation provided there is sufficient residual soil N available for early growth. In both years, nearly all of the residual nitrate nitrogen measured after corn harvest was located in the upper 12 inches of the soil profile for the preplant surface-applied nitrogen treatments, regardless of irrigation level. In contrast, nitrate concentrations increased with increasing levels of nitrogen injected with SDI and migrated deeper in the soil profile with increased irrigation (Figure 7). This lead to a study to determine if SDI fertigation N needs could be lowered and still retain excellent yields.

DEVELOPMENT OF BEST MANAGEMENT PRACTICE FOR SDI N FERTIGATION OF CORN

A follow-up four year study was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas on a deep Keith silt loam soil to develop a Best Management Practice (BMP) for nitrogen fertigation for corn using SDI (Lamm et al., 2004). Residual ammonium- and nitrate-nitrogen levels in the soil profile, corn yields, apparent nitrogen uptake (ANU) and water productivity (WP) were utilized as criteria for evaluating six different nitrogen fertigation rates, 0, 80, 120, 160, 200, and 240 lbs N/a. The final BMP was a nitrogen fertigation level of 160 lbs N/a with other non-fertigation applications bringing the total applied nitrogen to approximately 190 lbs N/a (Lamm et. al., 2004). The BMP also states that irrigation is to be scheduled and limited to replace approximately 75% of ET. Corn yield, ANU, and WP all plateaued at the same level of total applied nitrogen which corresponded to the 160 lbs N/a nitrogen fertigation rate (Figure 8). Average yields for the 160 lbs N/a nitrogen fertigation rate was 213 bu/a. Corn yield to ANU ratio for the 160 lbs N/a nitrogen fertigation rate was high at 53:1 (lbs corn grain/lbs N whole plant uptake). The results emphasize that high-yielding corn production also can be environmentally sound and efficient in nutrient and water use.

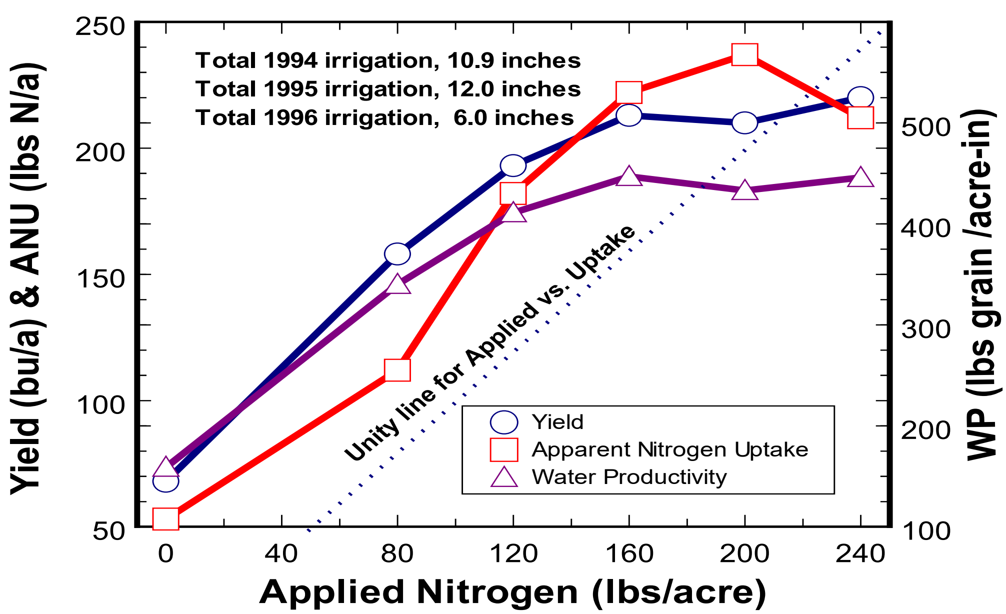

Figure 8. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water productivity as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded fertigation applied nitrogen by 30 lb/acre.

After 4 years of continuous application of the fertigation treatments (Figure 9), nitrate-N levels in the soil were increasing and moving downward when the fertigation rate exceeded 160 lb N/a (i.e., equivalent to 190 lbs N/a total applications from all sources).

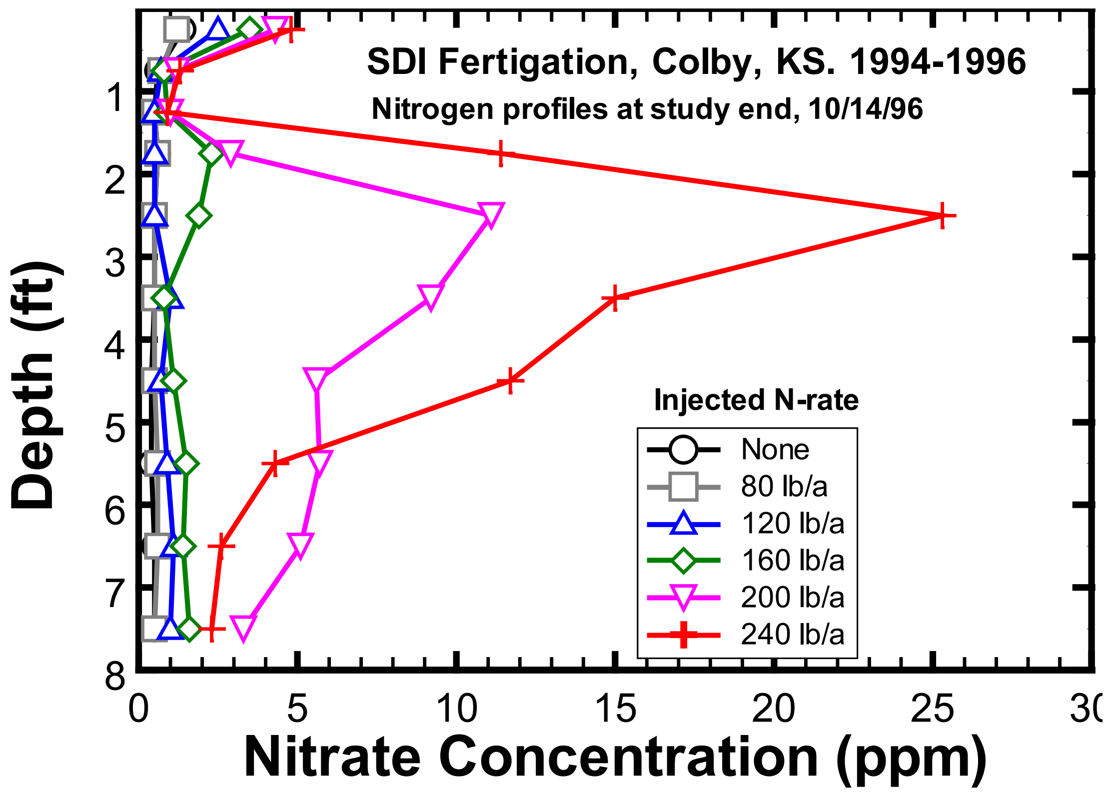

Figure 9. Nitrate concentrations within the 8 ft soil profile as affected by SDI fertigation N rate after four years of continuous application, KSU Northwest Research-Extension Center, Colby Kansas.

Conjunctive management of both irrigation and in-season N fertigation are important for corn production with SDI.

PHOSPHORUS FERTIGATION FOR SDI CORN

A study was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas from 2015 to 2017 to examine timing of in-season phosphorus fertigation for corn production using SDI. The fertilizer treatments, yield and water use results are shown in Table 4.

All treatments received the same amount of nitrogen and phosphorus fertilizer (220 lbs N/acre and 40 lbs P/a, respectively), but Treatments 4 and 5 missed a 25% addition of fertigated Zinc at the 11 leaves to tasseling stage in all three years of the study.

Table 4. Fertilizer treatments, corn yield and water use parameters in a phosphorus fertigation study using SDI at KSU-NWREC, Colby, Kansas from 2015 to 2017. Note: All treatments received a total of 220 lbs N/acre and 40 lbs P/acre in each year.

Fertilizer Treatment	Applied at Planting	In-season Fertigation		
		5 to 10 Leaves	11 Leaves to Tasseling	Tasseling to Blister Kernel
1 No P fertigation	44 lbs N/a, 40 lbs P/a + banded Zinc	66 lbs N/a	66 lbs N/a	44 lbs N/a
2 P Fertigation Trt 1	44 lbs N/a, 24 lbs P/a + banded Zinc	66 lbs N/a, 4 lbs P/a	66 lbs N/a, 8 lbs P/a	44 lbs N/a, 4 lbs P/a
3 P Fertigation Trt 2	44 lbs N/a, 16 lbs P/a + banded Zinc	66 lbs N/a, 8 lbs P/a	66 lbs N/a, 12 lbs P/a	44 lbs N/a, 4 lbs P/a
4 P Fertigation Trt 1	44 lbs N/a, 24 lbs P/a + 50% banded Zinc	66 lbs N/a, 4 lbs P/a + 25% foliar Zinc	66 lbs N/a, 8 lbs P/a	44 lbs N/a, 4 lbs P/a
5 P Fertigation Trt 2	44 lbs N/a, 16 lbs P/a + 50% banded Zinc	66 lbs N/a, 8 lbs P/a + 25% foliar Zinc	66 lbs N/a, 12 lbs P/a	44 lbs N/a, 4 lbs P/a

Fertilizer Treatment No.	Yield (bu/a)	Plant Density (plants/a)	Ears /Plant	Kernels /Ear	Kernel Mass (mg)	Crop Water Use (in)	Water Productivity (lb/acre-in)
Crop Year, 2015							
1	246	34412	0.97	562	332	28.97	476
2	278	33541	1.00	609	346	28.68	544
3	260	33323	0.99	595	336	29.13	501
4	273	33977	0.99	623	332	27.53	555
5	266	33541	0.99	607	337	27.69	539
Crop Year, 2016							
1	258	33323	1.00	536	368	25.16	575
2	276	33323	0.99	591	361	25.26	612
3	284	33106	1.00	600	362	25.44	624
4	274	33759	0.99	590	354	25.52	602
5	272	33541	0.98	568	370	25.60	595
Crop Year, 2017							
1	286	34195	0.99	587	364	27.62	579
2	288	34195	1.01	585	364	27.20	593
3	295	34412	1.01	583	368	28.28	584
4	295	34630	1.01	584	368	27.67	597
5	301	34412	1.00	607	366	28.01	601
Mean of All Years							
1	**263 B**	33977	0.99	561	35.5	27.25	**543 B**
2	**281 A**	33686	1.00	595	35.7	27.05	**583 A**
3	**280 A**	33614	1.00	593	35.6	27.61	**570 AB**
4	**281 A**	34122	0.99	599	35.1	26.91	**585 A**
5	**280 A**	33832	0.99	594	35.7	27.10	**578 A**

Column data followed by different levels are significantly different at P<0.05.

Overall grain yields were excellent (Table 4) and although there were no statistically significant differences ($P<0.05$) in yields in individual years, there was a strong numerical trend for greater yield for in-season phosphorus fertigation. When the data was analyzed over all three years, there was a statistically significant grain yield increase with in-season phosphorus fertigation. There were no significant differences in crop water use, but water productivity was significantly greater for in-season phosphorus fertigation when averaged over the three years. There was no appreciable effect of how the fertigated phosphorus was applied within the three growth stages.

SDI DESIGN RESEARCH

Overall, SDI systems have been successful in the Great Plains region despite minor technical difficulties during the adoption process. In a 2005 survey of SDI users, nearly 80% of Kansas producers indicated they were at least satisfied with the performance of their SDI system, and less than 4% indicated they were unsatisfied (Alam & Rogers, 2005). A few systems had failed or been abandoned after limited use due to inadequate design. The information discussed below focuses on specific design information developed for local conditions at the KSU Northwest Research-Extension Center at Colby, Kansas and is excerpted from a longer publication that discusses basic SDI design issues in more detail (Lamm et al., 2018)

DRIPLINE SPACING AND ORIENTATION

Crop row, or bed spacing, is usually set by cultural practices for a given crop in a given region and by planting and harvesting equipment specifications. As a general rule, SDI dripline spacing is a multiple of the crop row spacing, whereas emitter spacing is usually related to the plant spacing along the row. Providing the crop with equal or nearly equal opportunity to the applied water should be the goal of all SDI designs. This presents a conflicting set of constraints when crops with different row spacing are grown with SDI. Mismatched crop row/bed and dripline spacing may not only result in inadequate irrigation and salinity problems, but also in increased mechanical damage to the SDI system. Adoption of similar row/bed spacing for crops on a farming enterprise may be advantageous, provided that the crops produce adequate yields under that spacing.

Dripline spacing in the Great Plains region is typically one dripline per row/bed or an alternate row/bed middle pattern (Figure 1) with one dripline per bed or between two rows. The soil and crop rooting characteristics affect the required lateral spacing, but general agreement exists that the alternate row/bed dripline spacing (about 5 ft) is adequate for most of the deeper-rooted agronomic crops on medium- to heavy-textured soils. Closer dripline spacing may be used for high-valued crops, on sandy soils, for small seeded crops where germination is problematic, and in arid areas to ensure adequate salinity management and consistent crop yield and quality. However, closer dripline spacing will probably result in smaller zone sizes because of the limitation on choosing smaller emitter discharge rates.

The orientation of driplines with respect to crop rows has not been a critical issue with SDI systems used for corn production on deep-silt loam soils of the U.S. Great Plains. Traditionally, driplines are installed parallel to crop rows. This may be advantageous in planning long-term tillage, water, nutrient, and salinity management. However, K-State research has shown either parallel or perpendicular orientations are acceptable for the 5-foot dripline spacing on deep silt loam soils (Lamm et al., 1998).

EMITTER SPACING

Emitter spacings ranging from 4 to 30 inches are readily available from the manufacturers, and other spacings can be made to meet a specific application. Increasing the emitter spacing can be used as a technique to allow larger emitter passageways less subject to clogging, to allow for economical use of emitters that are more expensive to manufacture, or to allow for longer length of run or increased zone size by decreasing the dripline nominal flowrate per unit length. The rationale for increased emitter spacing must be weighed against the need to maintain adequate water distribution within the root zone. An excellent conceptual discussion of the need to consider the extent of crop rooting in irrigation design is presented by Seginer (1979). Although the effective uniformity of microirrigation experienced by the crop is high, the actual detailed uniformity within the soil may be quite low. Emitter spacing ranging from 1 to 4 ft had little effect on corn production and soil water redistribution in a three-year study at the KSU Northwest Research-Extension Center at Colby, Kansas (Arbat et al., 2010). It should be noted that using the widest possible emitter spacing consistent with good water redistribution can cause significant problems when emitters become clogged or under drought conditions. As a result, some plants will be inadequately watered. Generally, emitter spacing of 1 to 2 ft are used for SDI systems in the Great Plains.

DRIPLINE DEPTH

The choice of an appropriate dripline depth is influenced by crop, soil, and climate characteristics, anticipated cultural practices, grower experiences and preferences, the water source, and prevalence of pests. In an extensive review of SDI, Camp (1998) reported that the placement depth of driplines ranged from less than an inch to as much as 28 inches. In most cases, dripline depth was probably optimized for the local site by using knowledge and experiences about the crop for the soils of the region. For example, driplines for alfalfa are sometimes installed at deeper depths so that irrigation can continue during harvest. When irrigation is often required for seed germination and seedling establishment, shallower dripline depths are often used. Deeply placed driplines may require an excessive amount of irrigation for germination and can result in excessive leaching and off-site environmental effects.

Soil hydraulic properties and the emitter flowrate affect the amount of upward and downward water movement in the soil and thus are factors in the choice of dripline depth. When surface wetting by the SDI system is not needed for germination or for salinity management, deeper systems can reduce soil water evaporation and weed growth. Deeper dripline placement minimizes soil water evaporation losses, but this must be balanced with the potential for increased percolation losses while considering the crop root-zone depth and rooting intensity. Soil layering or changes in texture and density within the soil profile affect the choice of dripline depth. Driplines should be installed within a coarse-textured surface soil overlaying fine-textured subsoil so that there is greater lateral movement perpendicular to the driplines. Conversely, when a fine-textured soil overlays a coarse-textured subsoil, the dripline should be installed within the fine-textured soil to prevent excessive deep percolation losses. An excellent discussion of how soil texture and density affect soil water redistribution is provided by Gardner (1979).

For lesser-valued commodity crops (fiber, grains, forages, and oilseeds), SDI systems are usually set up exclusively for multiple-year use with driplines installed in the 12 to 18 inch depth range. Most of these crops have extensive root systems that function properly at these greater depths. Corn, soybean, sunflower, and grain sorghum yields were not affected greatly by dripline depths ranging from 8 to 24 inches on a deep Keith silt loam soil at Colby, Kansas (Lamm and Trooien, 2005; Lamm et al., 2010). Their results suggest that, in regions that typically receive precipitation during the growing season, dripline depth will not be the overriding factor in crop development and soil water redistribution. The dripline should be deep enough that the anticipated cultural practices can be accommodated without untimely delays, soil compaction, or damage to the SDI system. Pests such as rodents and insects are often more troublesome at the shallow dripline depths.

APPLICATION OF LIVESTOCK WASTEWATER WITH SDI

Using subsurface drip irrigation (SDI) with lagoon wastewater has many potential advantages. The challenge is to design and manage the SDI system to prevent emitter clogging. Some of the advantages were listed by Lamm et al., 2002:

- Saves fresh water for other uses
- Reduces groundwater withdrawals in areas of low recharge
- Rich in nutrients, such as N, P, and K, for crop growth
- Reduced human contact with wastewater
- Less odors and no sprinkler aerial pathogen drift
- No runoff of wastewater into surface waters
- Subsurface placement of phosphorus-rich water reduces hazards of P movement into streams by surface runoff

and soil erosion

- Greater water application uniformity resulting in better control of the water, nutrients, and salts
- Reduced irrigation system corrosion
- Reduced weather-related water application constraints (especially high winds and freezing temperatures)
- Increased flexibility in matching field and irrigation system sizes
- Better environmental aesthetics

A study was initiated in 1998 on a commercial Kansas feedlot to test the performance of five types of driplines (with emitter flow rates of 0.15, 0.24, 0.40, 0.60, and 0.92 gal/hr-emitter) with beef lagoon wastewater (Lamm et al., 2002). A disk filter (200 mesh, with openings of 0.003 inches) was used and shock treatments of chlorine and acid were injected periodically. Over the course of four seasons (1998-2001) a total of approximately 66 inches of irrigation water was applied through the SDI system. It is estimated that approximately 9300 lbs/acre of total suspended solids have passed through the driplines. The flow rates of the two smallest emitter sizes, 0.15 and 0.24 gal/hr-emitter decreased approximately 40% and 30%, respectively, during the four seasons, indicating considerable emitter clogging (Figure 10). The three driplines with the highest flow rate emitters (0.40, 0.60, and 0.92 gal/hr-emitters) have had approximately 7, 8, and 13% reductions in flow rate, respectively. Following an aggressive freshwater flushing, acid and chlorine injections in April of 2002, the flowrates of the lowest two emitter sizes (0.15 and 0.24 gal/hr-emitter) were restored to nearly 80 and 97% of their initial flowrates, respectively. Further laboratory tests on individual emitters from excavated driplines showed the lowest flow dripline experiencing partial clogging of most emitters with full clogging of about 4% of the emitters. These results indicate SDI can be used to successfully apply beef lagoon wastewater. However, the smaller emitter sizes normally used with groundwater sources in western Kansas may be risky for use with lagoon wastewater.

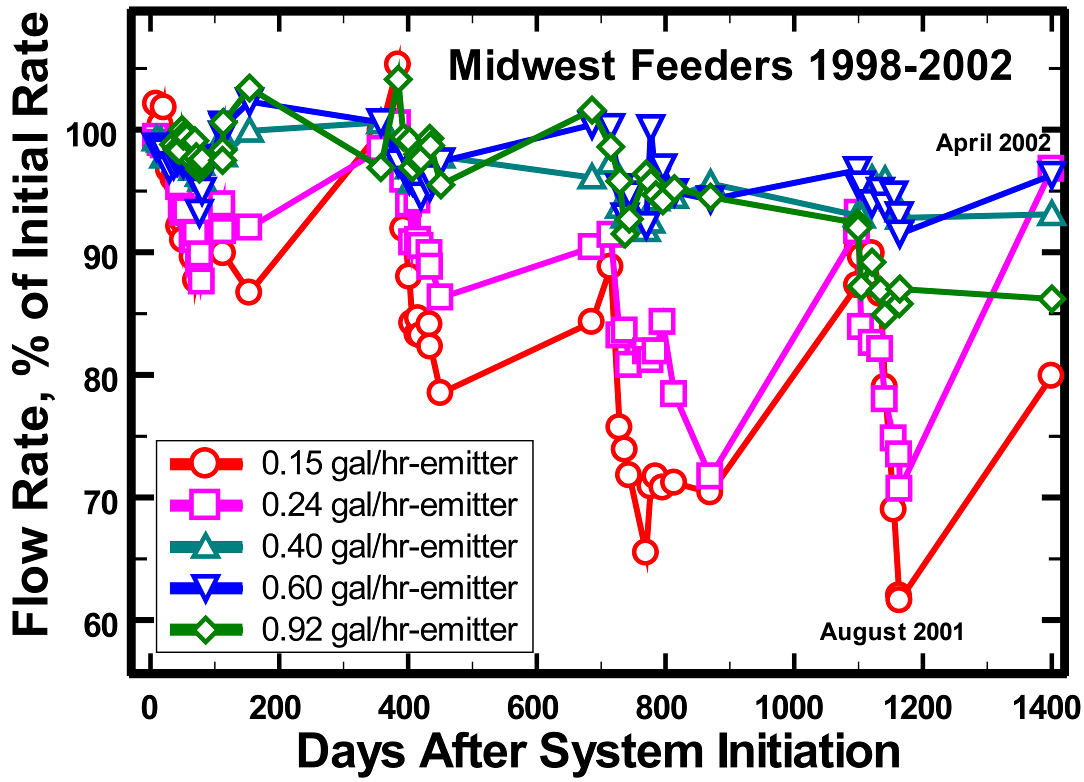

Figure 10. Measured flow rates for five dripline types with different emitter flow rates using lagoon wastewater, Midwest Feeders, KS, 1998-2002.

Another two-year study (2000-2001) conducted at the KSU Northwest Research-Extension Center at Colby, Kansas compared corn production using agronomic levels of swine wastewater to augment irrigation for two irrigation methods (simulated low energy precision application (LEPA) sprinkler or SDI).

Water use was significantly higher (P=0.05) for the LEPA sprinkler irrigation plots as compared to the SDI plots in 2000 averaging approximately 3 additional inches of use (Table 5). Since irrigation was only 0.5 additional inches for the LEPA sprinkler irrigation plots, this extra water use came by decreasing soil water storage. This extra water use was visually evident near the end of the cropping season because there was increased early senescence for the LEPA sprinkler irrigation plots due to decreased soil water reserves. It is not clear why the LEPA sprinkler irrigation treatments had higher total water use in 2000, but a partial reason may be increased water losses from evaporation from the soil surface or deep drainage. Drier soil surfaces with SDI can reduce soil evaporation while smaller SDI applications can also decrease deep drainage. In 2001, there were no statistically significant differences in water use between irrigation systems but LEPA treatments tended to have slightly higher water use. When averaged over the two years, water use for LEPA treatments had approximately 2 inches greater water use than SDI which was statistically significant (P-0.05).

Table 5. Yield component and water use data for corn in a biological effluent study, Colby, Kansas, 2000-2001.

Irrigation System & Effluent Amount	Irrigation inches	Applied N[1] lb/a	Grain yield bu/a	Plant Pop. plants/a	Ears /plant	Kernels /ear	Kernel Mass mg	Biomass ton/a	Water use[2] inches	WUE[3] lb/acre-in
Year 2000										
SDI, Control	19.5	245	253	26136	1.04	570	414	10.6	30.1	472
SDI, 1.0 inch effluent	19.5	229	252	27297	0.97	595	406	11.4	30.4	464
SDI, 2.0 inches effluent	19.5	388	260	26717	1.04	573	414	10.9	29.5	492
LEPA, 0.6 inches effluent	20.0	155	237	26717	0.98	595	386	10.9	33.2	399
LEPA, 1.0 inches effluent	20.0	229	250	26717	0.99	603	400	11.1	32.8	427
LEPA, 2.0 inches effluent	20.0	388	246	27007	0.98	600	394	10.7	33.2	415
LSD P=0.05			NS	NS	NS	NS	16	NS	1.5	51
Year 2001										
SDI, Control	18.0	244	262	32960	0.97	561	371	11.5	28.5	517
SDI, 1.0 inch effluent	18.0	209	270	32525	0.94	598	374	12.4	27.4	553
SDI, 2.0 inches effluent	18.0	356	267	32525	0.94	597	372	11.5	28.1	531
LEPA, 0.6 inches effluent	18.0	143	214	33251	0.95	525	329	8.9	28.2	427
LEPA, 1.0 inches effluent	18.0	209	251	32815	0.95	557	369	10.2	28.7	493
LEPA, 2.0 inches effluent	18.0	356	237	33225	0.97	494	379	10.0	30.3	439
LSD P=0.05			22	NS	NS	63	26	NS	NS	53
Mean of both years 2000 - 2001										
SDI, Control			258	29548	1.01	565	393	11.1	29.3	495
SDI, 1.0 inch effluent			261	29911	0.96	596	390	11.9	28.9	509
SDI, 2.0 inches effluent			263	29621	1.00	585	393	11.2	28.8	512
LEPA, 0.6 inches effluent			225	29984	0.96	559	357	9.9	30.7	413
LEPA, 1.0 inches effluent			251	29766	0.97	580	384	10.6	30.8	460
LEPA, 2.0 inches effluent			241	30116	0.97	547	387	10.4	31.7	427
LSD P=0.05			20	NS	NS	NS	14	NS	1.0	35

There were no significant differences in corn yields due to irrigation method or effluent application in 2000, though SDI yields tended to have slightly higher yields (Table 5). Grain yields were similar with commercial fertilizer or effluent for the SDI treatments at approximately 255 bu/acre. The smaller 0.6 inch effluent amount applied with LEPA had an appreciably lower grain yield (237 bu/acre), perhaps indicating some crop nutrient stress. There were no significant differences in kernels/ear, but LEPA treatments tended to have greater numbers than SDI treatments in 2000. This may be related to the extreme drought conditions which have reduced kernels/ear for SDI in some years (Lamm, 2004). Kernel mass at harvest was significantly affected (P=0.05) with the LEPA plots generally having lower kernel mass. This reduction in kernel mass may be reflecting the previously mentioned crop water stress that was apparent on the LEPA plots near physiological maturity. Final kernel mass for corn is usually set just prior to physiological maturity in mid to late September in this region (Northwest Kansas).

In 2001, grain yield, kernels/ear and kernel mass tended to be higher with SDI than with LEPA (Table 5). Grain yield averaged approximately 268 bu/acre for the two SDI effluent treatments (1 and 2 inch effluent applications) and approximately 244 bu/acre for similar LEPA treatments. Although extreme drought conditions continued in 2001, the number of kernels/ear tended greater with SDI than with LEPA. The LEPA treatment with the smaller 0.6 inch effluent application had significantly lower yields, which was further indication of the apparent combination of increased nutrient and water stress for the LEPA treatments compared to SDI.

There were no statistically significant differences in biomass at physiological maturity as affected by irrigation method or effluent application in either year although SDI tended to have greater biomass in 2001. Dry above-ground biomass was approximately 11 tons/acre at physiological maturity (Table 5).

As discussed earlier SDI yields tended higher and LEPA water use tended higher, so it was not surprising that water productivity was higher with SDI in both years (Table 5). Averaged over the two years of the study, SDI produced approximately 65 lbs more grain for each inch of total water use for similar effluent treatments. This is probably a combination of better nutrient utilization and less crop water stress for the SDI treatments.

SDI SYSTEM LONGEVITY AND ECONOMICS

Subsurface drip irrigation systems are expensive and their economic competitiveness against alternative irrigation systems greatly depends on SDI system longevity.

In the spring of 2002, K-State Research and Extension introduced a software spreadsheet for making economic comparisons of center pivot sprinkler irrigation (CP) and subsurface drip irrigation (SDI) for corn production (Lamm et al., 2020). Over the years, sensitivity analyses provided by the software indicate that SDI system longevity is a key factor in the economic competitiveness of SDI systems with CP systems (Lamm et al., 2015). Since that time, the spreadsheet has been periodically updated to reflect changes in input data, particularly system and corn production costs. When growing the lesser-value commodity crops, an SDI system that can be amortized over many years is an economic necessity to compete with less expensive CP systems. The competitiveness of SDI increases when a larger proportion of the field is irrigated with SDI than possible with CP systems (i.e., as much as 25% greater land area for SDI as compared to full circle CPs within square fields).

Research with SDI systems at the Kansas State University Northwest Research-Extension Center at Colby, Kansas began in 1989 and the first system installed in 1989 was successfully operated for 26.5 years before being abandoned in the fall of 2015 (Lamm et al., 2016). Layflat thin-walled collapsible driplines (also known as drip tapes) were starting to randomly fail in the crease. Although, a few more years might have been acceptable with a small proportion of leaks on a producer's field, the leaks were unacceptable for the research field. Another study field at the Center failed for similar reasons after 22 years of usage. Industry evaluation of driplines from that earlier field concluded the bonds in the plastic were beginning to break down after the many years of usage. Pressure and flow tests were conducted annually on the 1989 system. Results indicate that plot flowrates could be maintained within +/- 5% of their initial first annual value (Figure 11).

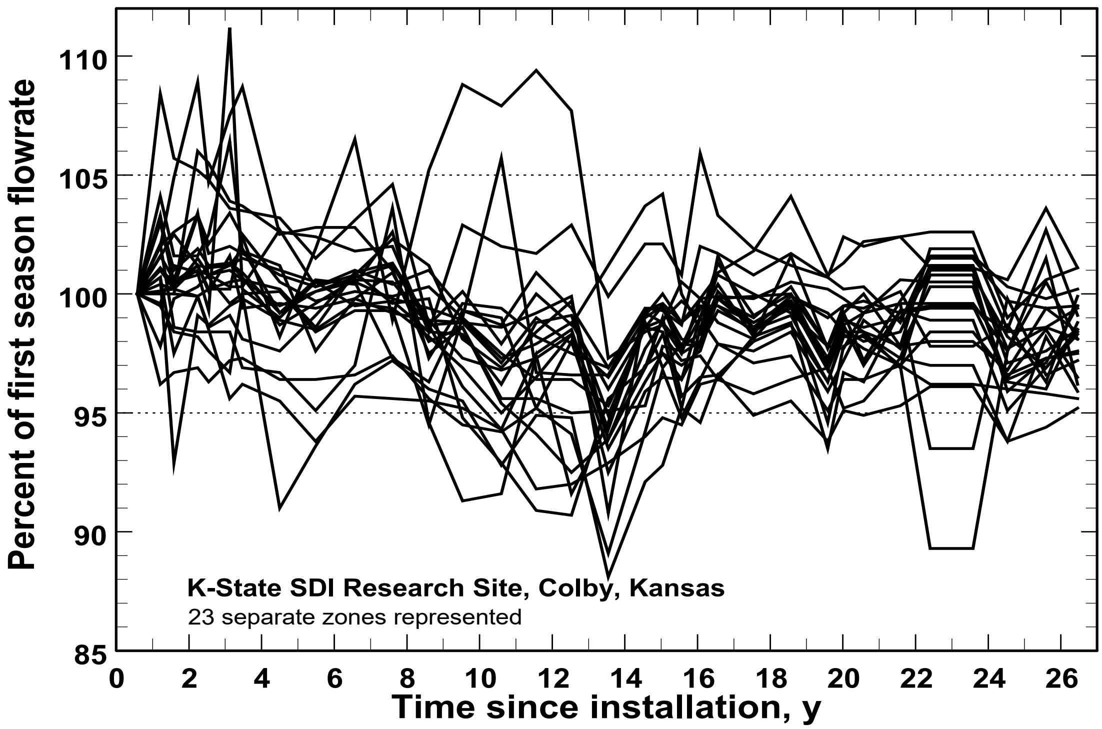

Figure 11. Plot flowrates as affected by years of operation for a 23-zone research SDI system at the KSU Northwest Research-Extension Center, Colby Kansas (1989-2015).

Similarly, corn production was excellent on the SDI system installed in 1989, averaging 232 bushels/acre with the exclusion of the year 2011, when the crop was destroyed by a hail event. These flowrate and corn yield results indicate that with a good design, installation and maintenance protocol, an SDI system can have a long life in the Central Great Plains. There are a few SDI systems in the USA that have been operated for over 25 years without replacement (Lamm and Camp, 2007). There are other SDI systems on commercial farms in Kansas that are approximately 20 years old without replacement and it will be interesting to see how long they will remain operational.

CONCLUDING STATEMENTS

Research progress has been steady since 1989. Much of K-State's SDI research is summarized at the website, SDI in the Great Plains at http://www.ksre.ksu.edu/sdi/. Irrigators are watching the results of K-State closely. Some irrigators have begun to experiment with the technology and most appear happy with the results they are obtaining. SDI can be a viable irrigation system option for corn production, enhancing the opportunities for wise use of limited water resources and also in protecting water quality.

ACKNOWLEDGEMENTS

This paper is also part of SDI technology transfer effort beginning in 2009 involving Kansas State University, Texas A&M University and the USDA-ARS and is funded by the Ogallala Aquifer Program. To follow other activities of this educational effort, point your web browser to http://www.ksre.ksu.edu/sdi/.

This paper was first presented at the Central Plains Irrigation Conference, Feb. 18-19, 2019, Burlington, Colorado.

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