PROCEEDINGS OF THE
2011 CENTRAL PLAINS IRRIGATION CONFERENCE

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WATER ISSUES IN COLORADO

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ABSTRACT

I would like to cover two separate areas within Colorado that I thought would be of interest to the Central Plains region.

First, Colorado has been working on the development and implementation of an augmentation plan that was submitted to the Republican River Compact Administration in March 2008. The augmentation plan is required to maintain compliance with the Republican River Compact and the Final Settlement Stipulation reached between Kansas, Nebraska and Colorado in 2002. The presentation will include a discussion of the legal, physical and financial challenges that Colorado has faced in the development of this augmentation plan and the current status of negotiations between the three states regarding the request for approval by Kansas and Nebraska. Additional information regarding our compact compliance efforts can be found at:

http://water.state.co.us/SurfaceWater/Compacts/RepublicanRiver/Pages/RepublicanRiverHome.aspx

Second, I promulgated new rules in the Arkansas River basin titled Irrigation Improvement Rules. The Irrigation Improvement Rules are designed to allow improvements to the efficiency of irrigation systems in the Arkansas River Basin while ensuring compliance with the Arkansas River Compact. I have determined that certain improvements to surface water irrigation systems, such as sprinklers and drip systems that replace flood and furrow irrigation, or canal-lining that reduces seepage, have the potential to materially deplete the usable waters of the Arkansas River in violation of the Compact. The Irrigation Improvement Rules optimize use of the waters of the Arkansas River by allowing such improvements in a manner consistent with the terms of the Compact. I submitted the Rules to the Water Court on September 30, 2009. The Water Court approved the rules on October 25, 2010. The effective date of the rules was January 1, 2011. Additional information regarding the rules can be found at:

http://water.state.co.us/SurfaceWater/RulemakingAndAdvising/ArkRiverAC/Pages/ArkSWIrrigImpRules.aspx

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IRRIGATION CAPACITY IMPACT ON LIMITED IRRIGATION MANAGEMENT AND CROPPING SYSTEMS

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INTRODUCTION

Irrigation capacity is an important issue for irrigation management. Having enough capacity to supplement precipitation and stored soil moisture to meet crop water needs during the growing season to maximize grain yield is important. However, declines in the Ogallala Aquifer have resulted in decreases in well outputs to the point where systems on the fringe of the aquifer can no longer meet crop water needs during average growing seasons and especially during drought years. Changing cropping practices can impact the irrigation management by irrigating crops that have different water timing needs so that fewer acres are irrigated at any one point during the growing season and concentrating the irrigation capacity on fewer acres while still irrigating the majority or all acres during the year.

Many producers have not changed cropping practices with marginal capacity systems due to management increases and the potential for an above-average year. However, the risk of producing lower yields increases. Crop insurance has been used to offset those lower yields. However, the frequency of insurance claims has increased to the point where practices need to be changed on these systems.

Literature Review

System capacities are a function of soil type, crop water use and precipitation. The soil type acts as a bank where moisture reserves can be utilized during times when the irrigation system is not watering between cycles and during time periods when the system capacity is inadequate to meet crop water needs. Soils such as silt loams have a greater water holding capacity compared to sands which decreases the need for larger system capacities. Crop water use determines the total water utilized daily. Greater demand by the crop increases the amount of water needed for the crop over any time period. Precipitation is an important factor in irrigation capacity. A region with a greater probability of precipitation during the growing season will require less capacity to supplement crop growth.

Heermann (1991) determined the net design capacity for Eastern Colorado along with probabilities of meeting the crop water needs for the growing season for full water needs (Figure 1). As capacities decline the probability of meeting crop water needs declines. A 50% probability means that on average, you will meet crop water needs one out of two years and you will not meet crop water needs the other year. The result will be less than desired yields.

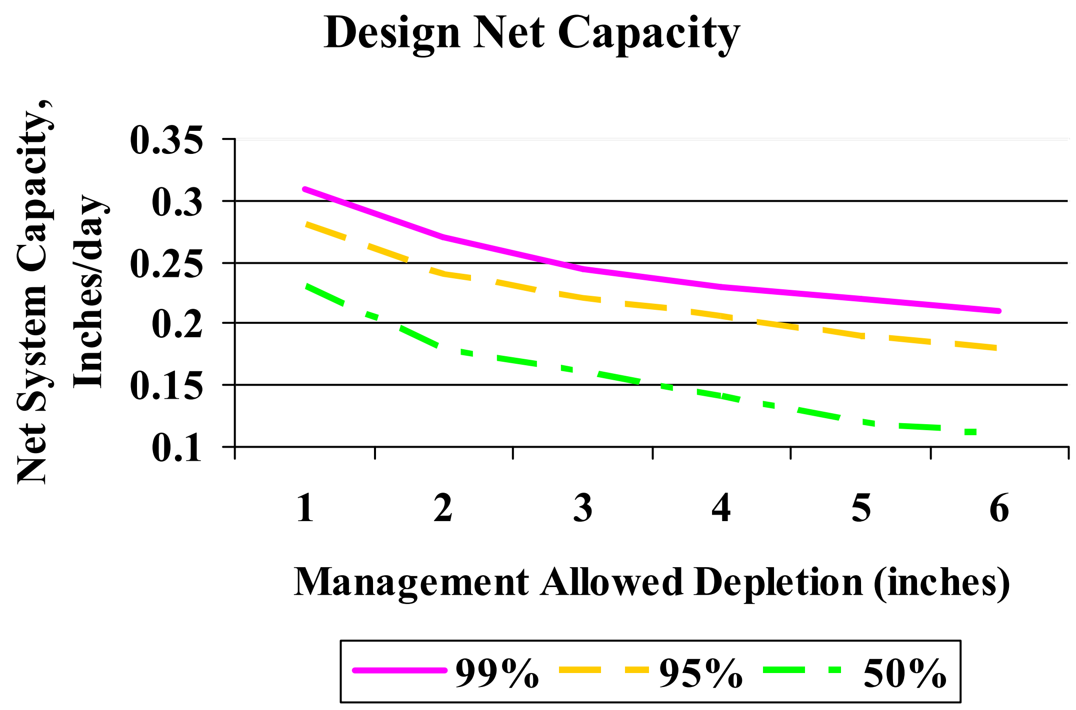

Figure 1. Net irrigation capacities for Eastern Colorado (Heermann).

Lamm (2004) found that irrigation capacities of 50% of needed to meet crop water requirements resulted in approximately 40 bu/acre less corn yields. In above-average precipitation years, the yield difference is less and in drier than average years, the yield difference is greater. The economics of reducing irrigated acres until the irrigation capacity was equivalent to full irrigation capacities showed that irrigating those fewer acres was economically equal or greater than irrigating all of the acres for a single crop.

Lower capacity systems generally are inadequate for meeting crop water needs during the peak water use growth stages. This also coincides with the reproductive growth stages and less average annual precipitation during that time period of a summer crop. Water stress during that time period has more impact upon yield than during the vegetative and late grain-fill growth stages (Sudar et al, 1981; Shaw, 1976). Having water stress earlier or later is more desirable than during the reproductive growth stages of tassel, silking and pollination.

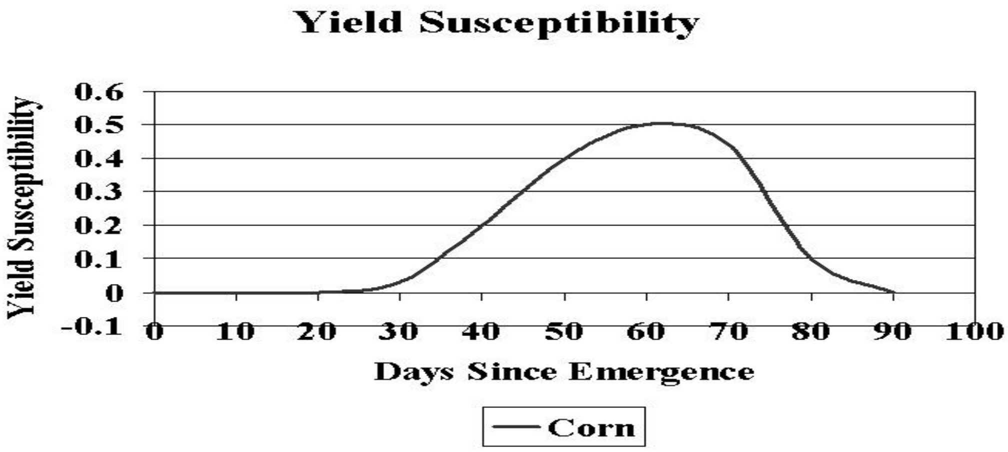

Figure 2. Yield susceptibility to water stress for corn (Sudar et al., 1981).

The Crop Water Stress Index (CWSI; Idso et al., 1981; Garner et al., 1992) normalizes the canopy-air temperature differential for the drying capacity of the air. It is calculated from measurements of infrared canopy or leaf temperatures, air temperature, and vapor pressure deficit and varies between 0 (no water stress) and 1 (full water stress, no transpirational cooling of the leaf). CWSI has been shown to be highly correlated with other measurements of water stress (Nielsen, 1989; Li et al., 2010) such as leaf and canopy CO_2 exchange rate, leaf and canopy transpiration, leaf water potential, stomatal conductance, and plant available water in the soil profile.

Methods

The system capacity research was conducted at the Central Great Plains Research Station near Akron, CO. Three irrigation capacity strategies and timings were used to determine the response of corn to early season and late season water stress. The experimental field was divided into three sections and irrigated with a solid set irrigation system with an application rate of 0.42 inches per hour. The three capacities and timings were: 5 gallons per minute per acre (gpm/a) with season long irrigation (Full), 2.5 gpm/a with season long irrigation (Inadequate) and 6.7 gpm/a with irrigation delayed until 2 weeks prior to tassel emergence (Growth Stage, GSL). These 3 capacities represent full irrigation capacities, inadequate capacities and growth stage timing with reduced acres for an inadequate capacity. Three varieties were tested with varying relative maturity (99, 101 and 103 day days to maturity).

Irrigation was applied for the full and inadequate capacity if there was allowable storage for the application. During the early growth stages, irrigation applications were 0.5 inch while later applications were 0.75 inch. Irrigation for the growth stage was withheld until 2 weeks prior to tassel emergence. Irrigation applications for growth stage were 1.0 inch per application.

Neutron probe access tubes were installed in the center of each plot (in the row) at the beginning of the experiment. Soil water was measured periodically throughout the growing season with a neutron probe (Model 503 Hydroprobe, Campbell Pacific Nuclear) at depths of 6, 18, 30, 42, 54, and 66 inches. Irrigation water was applied through a solid set irrigation system equipped with impact sprinkler heads and an application rate of 0.42 inches hr^{-1}. Irrigation amounts were estimated from irrigation run times and sprinkler nozzle flow rates. Precipitation was measured at a weather station approximately 1000 feet from the plot area. Water use (evapotranspiration) was calculated by the water balance method from the changes in soil water, applied irrigation, and precipitation. Deep percolation and runoff were assumed to be negligible.

Measurements of infrared leaf temperatures were made on one fully sunlit leaf oriented towards the sun in the upper canopy of the corn crop in the center of each of the 36 plots (three hybrids, three irrigation treatments, four replications). Measurements were made using an Optris LS LaserSight infrared thermometer (IRT) beginning at 1300 MDT (approximately solar noon) after acclimating the IRT to ambient conditions for 60 minutes. Immediately prior to beginning the IRT measurements and following the last reading IRT measurement, the dry and wet bulb air temperatures were taken with an aspirated psychrometer positioned at 1.5 m above the soil surface at the edge of the plot area. Measurements were taken at approximately weekly intervals on days when the sun was not obstructed by cloud passages. IRT measurements were corrected for sensor drift by comparing the IRT output to that of a calibration blackbody reference at the beginning and end of the measurement period and at the end of each replication (9 plots). The entire measurement sequence was completed in approximately 50 minutes.

The CWSI was calculated after the manner described by Gardner et al. (1992) using the non-water-stressed baseline for corn determined by Nielsen and Gardner (1987). The non-water-stressed baseline had a slope of $-2.059^{o}C/kPa$ and an intercept of $2.67^{o}C$. An upper maximum temperature differential of $3^{o}C$ was used in the calculation of CWSI.

Stomatal conductance measurements show the speed at which water vapor transpires from the leaf tissue to the atmosphere. Water stress results in lower conductance as compared to non-stressed vegetation. Stomatal conductance measurements were taken with a Decagon Leaf Porometer model SC-1. Three measurements were taken per plot on the most fully developed leaf in the upper canopy fully exposed to the sun. Measurements were taken between 1300 and 1600 MDT when water stress impacts on transpiration should be the greatest. Atmospheric conditions such as temperature and humidity have a significant impact on stomatal conductance so comparisons within a day are relevant as compared to day to day comparisons within a water treatment.

Results

The different irrigation treatments resulted in differential water stress development (Table 1). Water stress was generally less in 2009 compared with 2010 due to increased rainfall in 2009 (seasonal CWSI for the full irrigation treatment was 0.12 in 2009 and 0.24 in 2010). In both years CWSI values were highest during the vegetative growth stages under the GSL treatment when irrigation was withheld during the vegetative period (CWSI = 0.59 in 2009 and 0.47 in 2010, averaged over hybrids). The water stress was relieved after tasseling for the GSL treatment when irrigation was applied on the same schedule as applied for the full treatment (CWSI = 0.11 in 2009 and 0.24 in 2010, averaged over hybrids during the reproductive stages). Because of the greater rain in 2009 the inadequate capacity treatment did not develop the high levels of water stress seen in 2010 (CWSI = 0.09 during vegetative stages and 0.19

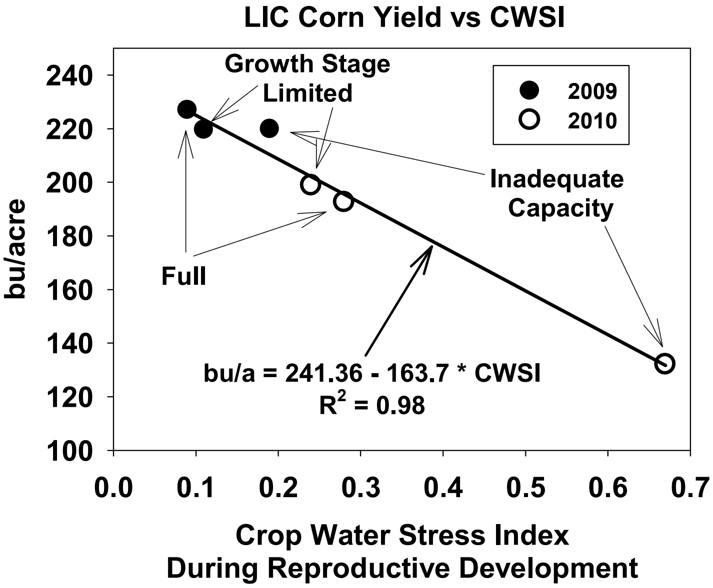

Figure 3. Corn yield vs crop water stress index.

during reproductive stages in 2009 compared with CWSI = 0.32 during vegetative stages and 0.67 during reproductive stages in 2010). There were no differences in CWSI due to hybrid. Yield was highly correlated with CWSI averaged over the reproductive period (Figure 3).

Table 1. Evapotranspiration, yield, and crop water stress index for irrigation capacities and strategies for 2009 and 2010.

Year	Irrigation	Hybrid	ET (in)	Yield (bu/a)	Average CWSI†	Vegetative CWSI‡	Repro-ductive CWSI ζ
2009	Full	ND4903	26.01	251.6	0.10	0.06	0.07
		EXP151	23.62	213.7	0.11	0.14	0.07
		NC5607	26.61	215.3	0.16	0.08	0.14
	Growth Stage	ND4903	22.37	239.5	0.29	0.58	0.11
		EXP151	22.19	202.4	0.40	0.76	0.16
		NC5607	22.40	216.6	0.23	0.43	0.08
	Inadequate Capacity	ND4903	24.25	218.7	0.27	0.09	0.32
		EXP151	24.73	218.0	0.13	0.05	0.14
		NC5607	25.42	222.9	0.14	0.12	0.12
	Avg. by Irrigation	Full	25.41	226.9	0.12	0.09	0.09
		GSL	22.32	219.5	0.31	0.59	0.11
		Inad Cap	24.80	219.8	0.18	0.09	0.19
	Averaged by Hybrid	ND4903	24.21	236.6	0.22	0.24	0.17
		EXP151	23.51	211.3	0.21	0.32	0.12
		NC5607	24.81	218.3	0.18	0.21	0.11
2010	Full	ND4903	22.83	203.8	0.26	0.24	0.30
		TXP151	22.39	209.5	0.24	0.20	0.30
		NE5321	21.98	164.1	0.23	0.22	0.24
	Growth Stage	ND4903	22.6	187.8	0.38	0.48	0.25
		TXP151	22.34	204.9	0.34	0.45	0.22
		NE5321	22.77	203.6	0.39	0.50	0.26
	Inadequate Capacity	ND4903	18.86	140.6	0.51	0.34	0.69
		TXP151	19.02	133.5	0.48	0.33	0.65
		NE5321	19.13	121.9	0.45	0.29	0.65
	Avg. by Irrigation	Full	22.40	192.5	0.24	0.22	0.28
		GSL	22.57	198.8	0.37	0.47	0.24
		Inad Cap	19.00	132.0	0.48	0.32	0.67
	Averaged by Hybrid	ND4903	21.43	177.4	0.38	0.35	0.41
		TXP151	21.25	182.6	0.35	0.33	0.39
		NE5321	21.30	163.2	0.35	0.34	0.38

†Averaged over all measurements taken: 7/1 to 9/8/2009 and 6/29 to 8/31/2010
‡Averaged over vegetative development
ζ Averaged over reproductive development

The ET values generally followed the same pattern as CWSI, with greater water use corresponding to lower CWSI. There were no differences in ET due to hybrid. Water use was about three inches less in 2010 than in 2009 for the full irrigation treatment, resulting in about 34 bu/a lower yield in 2010 compared with 2009 for the full irrigation treatment. Under the more favorable growing conditions of 2009, ND4903 produced higher yield than the other two hybrids under full irrigation (252 vs. 214 bu/a) and under the growth stage limited irrigation . But all three hybrids produced the same yield under the inadequate capacity irrigation treatment (220 bu/a). In 2010 NE5321 had much lower yield (164 bu/a) than the other two hybrids (207 bu/a) under full irrigation; ND4903 had lower yield (188 bu/a) than the other two hybrids (204 bu/a) with the growth stage limited treatment. Yields were lowest in 2010 with the inadequate capacity treatment, with ND4903 yielding highest (140 bu/a) and NE5321 yielding lowest (122 bu/a).

Irrigation capacities had a significant impact on stomatal conductance during the growing season in 2010 (Table 2). System capacities less than adequate had lower stomatal conductance as compared to adequate capacities. Early in the growing season, stomatal conductance for inadequate, growth stage and full irrigation were similar on June 29. Since irrigation was not initiated until just prior to tasseling on the growth stage treatment, lower stomatal conductance rates were observed in early July as compared to full irrigation while the inadequate capacity was similar to full. Lack of precipitation during late June and July resulted in reduced stomatal conductance on July 26 for both inadequate and growth stage management as compared to full irrigation. This water stress for inadequate and growth stage treatments was during tassel emergence. Irrigation was initiated on the growth stage treatment at this time with application amounts that would be similar to maximum transpiration rates. Stomatal conductance rates for the growth stage treatment on August 13 were similar to full irrigation while the conductances under the inadequate capacity treatment were less than under both growth stage and full irrigation. The difference in stomatal conductance between full irrigation and inadequate capacity increased later in the growing season (August 20) indicating that water stress levels were increasing in the inadequate capacity management.

Conclusions

Timing and capacity had an impact on grain yield when precipitation was below average. Grain yields with an inadequate capacity resulted in a 32% reduction in grain yields as compared to full irrigation capacities. Timing irrigation towards reproductive growth with a higher capacity resulted in similar grain yields. Reducing irrigation during the vegetative growth stage resulted in higher crop water stress indexes. However, an irrigation capacity which can meet crop water needs reduced the crop water stress index to values similar to full irrigation capacities and resulted in little or no yield loss.

When capacities are limited on the entire system, management strategies and cropping practices that result in fewer acres of an irrigated crop can alleviate the potential for severely reduced yields as compared to irrigating the entire system with inadequate capacities. Variety selection is important as the yield potential can vary by water management.

Table 2. Stomatal conductance for irrigation capacities, strategies and varieties for 2010.

Inadequate Capacity

	ND4903	EXP151	NE5321	Avg
Date	mmol/m^2-sec			
6/29	249	194	212	218
7/12	463	342	446	417
7/26	200	179	298	226
8/13	175	197	203	192
8/20	187	180	214	194
Avg.	255	218	275	249

Growth Stage

	ND4903	EXP151	NE5321	Avg
Date	mmol/m^2-sec			
6/29	249	277	250	259
7/12	305	266	336	302
7/26	165	183	208	185
8/13	264	296	285	282
8/20	316	337	277	310
Avg.	260	272	271	268

Full Irrigation

	ND4903	EXP151	NE5321	Avg
Date	mmol/m^2-sec			
6/29	261	237	322	273
7/12	465	474	480	473
7/26	316	240	328	295
8/13	228	284	245	252
8/20	346	362	369	359
Avg.	323	319	349	330

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PRESEASON IRRIGATION OF CORN WITH DIMINISHED WELL CAPACITIES

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ABSTRACT

Many of the irrigation systems today in the Central Great Plains no longer have the capacity to apply peak irrigation needs during the summer and must rely on soil water reserves to buffer the crop from water stress. Considerable research was conducted on preseason irrigation in the US Great Plains region during the 1980s and 1990s. In general, the conclusions were that in-season irrigation was more beneficial than preseason irrigation and that often preseason irrigation was not warranted. The objective of this study was to determine whether preseason irrigation would be profitable with today's lower capacity wells. A field study was conducted at the KSU-SWREC near Tribune, KS, from 2006 to 2009. The study was a factorial design of preplant irrigation (0 and 3 in), well capacities (0.1, 0.15, and 0.20 in day^{-1} capacity), and seeding rate (22,500, 27,500, and 32,500 seeds a^{-1}). Preseason irrigation increased grain yields an average of 16 bu a^{-1}. Grain yields were 29% greater when well capacity was increased from 0.10 to 0.20 in day^{-1}. Crop productivity was not significantly affected by well capacity or preseason irrigation. Preseason irrigation was profitable at all well capacities. At well capacities of 0.10 and 0.15 in day^{-1}, a seeding rate of 27,500 seeds a^{-1} was generally more profitable than lower or higher seeding rates. A higher seeding rate (32,500 seeds a^{-1}) increased profitability when well capacity was increased to 0.2 in day^{-1}.

INTRODUCTION

Irrigated crop production is a mainstay of agriculture in western Kansas. However, with declining water levels in the Ogallala aquifer and increasing energy costs, optimal utilization of limited irrigation water is required. The most common crop grown under irrigation in western Kansas is corn (about 50% of the irrigated acres). Almost all of the groundwater pumped from the High Plains (Ogallala) Aquifer is used for irrigation (97% of the groundwater pumped in western Kansas in 1995 [Kansas Department of Agriculture, 1997]). In 1995, of 3 billion m^3 of water pumped for irrigation in western Kansas, 1.41 million acre-ft (57%) were applied to corn (Kansas Water Office, 1997). This amount of water withdrawal from the aquifer has reduced saturated thickness (up to 150 ft in some areas) and well capacities.

Considerable research was conducted on preseason irrigation in the US Great Plains region during the 1980s and 1990s (Stone et al., 1983, 1987, and 1994; Lamm and Rogers, 1985; Musick and Lamm, 1990; Rogers and Lamm, 1994). In general, the conclusions were that in-season irrigation was more beneficial than preseason irrigation and that often preseason irrigation was not warranted because overwinter precipitation could replenish a significant portion of the soil water profile. Much of this research was conducted during a generally wetter climatic period in the Great Plains and also under circumstances of ample in-season irrigation capacity. The Great Plains drought that occurred during the early part of the last decade (2000-2009) renewed producer interest and has brought new questions about preseason irrigation. In a more recent study Stone et al. (2008) used simulation modeling to examine the effectiveness of preseason irrigation. They found the differences in storage efficiency between spring and fall irrigation peaked at approximately 37 percentage points (storage efficiency of approximately 70% for spring and 33% for fall irrigation) when the maximum soil water during the preseason period was at approximately 77% of available soil water.

Many of the irrigation systems today in the Central Great Plains no longer have the capacity to apply peak irrigation needs during the summer and must rely on soil water reserves to buffer the crop from water stress. Therefore, this study was conducted to evaluate whether preseason irrigation would be profitable when well capacity is limited and insufficient to fully meet crop requirements.

MATERIALS AND METHODS

A field study was conducted at the KSU-SWREC near Tribune, KS from 2006 to 2009. Normal precipitation for the growing season (April through September) is 13.2 in and normal annual precipitation is 17.4 in. The study was a factorial design of preseason irrigation (0 and 3 in), well capacities (0.10, 0.15, and 0.20 in day^{-1} capacity), and seeding rate (22,500, 27,500 and 32,500 seeds a^{-1}). The irrigation treatments were whole plots and the plant populations were subplots. Each treatment combination was replicated four times and applied to the same plot each year. The irrigation treatments were applied with a lateral-move sprinkler with amounts limited to the assumed well capacities. The preseason irrigations were applied in early April and in-season irrigations were applied from about mid-June to early September. The in-season irrigations were generally applied weekly except when precipitation was sufficient to meet crop needs. Corn was planted in late April or early May each year. The center two rows of each plot were machine harvested with grain yields adjusted to 15.5% moisture (wet basis). Plant and ear populations were determined by counting plants and ears in the center two rows prior to harvest. Seed weights (oven-dried) were determined on 100-count samples from each plot. Kernels per ear were calculated from seed weight, ear population, and grain yield. Soil water measurements (8 ft depth in 1 ft increments) were taken throughout the growing season using neutron attenuation. All water inputs, precipitation and irrigation, were measured.

Crop water use was calculated by summing soil water depletion (soil water at planting less soil water at harvest) plus in-season irrigation and precipitation. In-season irrigations were 9.6, 12.6, and 19.0 inches in 2006; 7.2, 10.1, 15.6 inches in 2007; 8.2, 11.0, 14.8 inches in 2008; and 8.8, 11.8, 17.9 inches in 2009 for the 0.10, 0.15, and 0.20 in day^{-1} well capacity treatments, respectively. In-season precipitation was 6.9 inches in 2006, 8.1 inches in 2007, 9.4 inches in 2008; and 14.4 inches in 2009. Non-growing season soil water accumulation was the increase in soil water from harvest to the amount at planting the following year. Non-growing season precipitation was 15.0 inches in 2007, 4.2 inches in 2008, and 8.6 inches in 2009 with an average of 9.3 in. Precipitation storage efficiency (without preseason irrigation) was calculated as non-growing season soil water accumulation divided by non-growing season precipitation. Crop productivity was calculated by dividing grain yield (lb a^{-1}) by crop water use (in). Local corn prices ($3.39, 4.80, 3.96, and 3.46 bu^{-1} in 2006, 2007, 2008, and 2009, respectively), crop input costs, and custom rates were used to perform an economic analysis to determine net return to land, management, and irrigation equipment for each treatment.

RESULTS AND DISCUSSION

Preseason irrigation increased grain yields an average of 16 bu a^{-1} (Table 1). Although not significant, the effect was greater at lower well capacities. For example, with a seeding rate of 27,500 seeds a^{-1}, preseason irrigation (3 in) increased grain yield by 21 bu a^{-1} with a well capacity of 0.10 in day^{-1} while only 7 bu a^{-1} with a well capacity of 0.20 in day^{-1}. As expected, grain yields increased with increased well capacity. Grain yields (averaged across preseason irrigation and seeding rate) were 29% greater when well capacity was increased from 0.1 to 0.2 in day^{-1}. Preseason irrigation and increased well capacity increased the number of seeds ear^{-1} but had little impact on seed weight.

The optimum seeding rate varied with irrigation level. With the two lowest well capacities and without preseason irrigation, a seeding rate of 22,500 seeds a^{-1} was generally adequate. However, if preseason irrigation was applied, then a higher seeding rate (27,500 seeds a^{-1}) increased yields. With a well capacity of 0.2 in day^{-1}, a seeding rate of 32,500 seeds a^{-1} provided greater yields with or without preseason irrigation.

Crop productivity was not significantly affected by well capacity or preseason irrigation (Table 1), although the trend was for greater crop productivity with increased water supply. Similar to grain yields, the effect of seeding rate varied with irrigation level. With lower irrigation levels, a seeding rate of 27,500 seeds a^{-1} tended to optimize crop productivity. It was only at the highest well capacity that a higher seeding rate improved crop productivity.

Crop water use increased with well capacity and preseason irrigation (Table 2). Soil water at harvest increased with increased well capacity, but this caused less soil water to accumulate during the winter. Non-growing season soil water accumulation averaged 2.7 in (without preseason irrigation). Average non-growing season precipitation was 9.3 in giving an average non-growing season precipitation storage efficiency of 29%. Preseason irrigation (about 3 in) increased available soil water at planting by 1.7 in. Seeding rate had minimal effect on soil water at planting or crop water use but increased seeding rate tended to decrease soil water at harvest and increase over-winter water accumulation.

Preseason irrigation was found to be profitable at all irrigation capacities (Table 3). At the two lower well capacities, a seeding rate of 27,500 seeds a^{-1} was generally the most profitable. However, the highest irrigation capacity benefited from a seeding rate of 32,500 seeds a^{-1}.

CONCLUSIONS

Corn grain yields responded positively to preseason irrigation and increases in well capacity. This yield increase generally resulted from increases in kernels ear^{-1}. Preseason irrigation was profitable at all well capacities. Seeding rate should be adjusted for the amount of irrigation water available from both well capacity and preseason irrigation. At well capacities of 0.10 and 0.15 in day^{-1}, a seeding rate of 27,500 seeds a^{-1} was generally more profitable than lower or higher seeding rates. A higher seeding rate (32,500 seeds a^{-1}) increased profitability when well capacity was increased to 0.20 in day^{-1}.

Acknowledgements

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Table 1. Crop parameters of corn as affected by well capacity, preseason irrigation, and seeding rate, Tribune, KS, 2006 - 2009.

Well capacity	Pre-season irrigation	Seed rate	Grain yield	Crop prod.	Plant pop.	Ear pop.	1000 seed	Kernel
in day^{-1}		10^3 a^{-1}	bu a^{-1}	lb ac-in^{-1}	- 10^3	acre^{-1} -	oz	# head^{-1}
0.10	no	22.5	153	386	22.4	21.5	13.20	476
		27.5	158	397	26.7	24.7	12.75	442
		32.5	155	389	31.2	28.8	12.46	379
	yes	22.5	171	403	21.9	21.5	13.43	531
		27.5	179	416	26.7	25.3	13.15	478
		32.5	183	419	31.5	29.6	12.80	427
0.15	no	22.5	172	389	22.2	21.2	13.24	543
		27.5	173	395	27.0	25.9	12.93	465
		32.5	171	383	31.1	29.2	12.84	406
	yes	22.5	185	405	22.4	21.9	13.36	563
		27.5	197	431	27.0	26.2	13.08	512
		32.5	201	433	31.4	30.2	12.80	466
0.20	no	22.5	200	404	22.3	22.0	13.29	615
		27.5	211	414	27.0	26.8	13.02	544
		32.5	223	440	31.8	31.3	12.74	503
	yes	22.5	204	396	22.1	21.9	13.59	617
		27.5	218	414	27.0	26.8	13.27	551
		32.5	229	436	31.9	31.2	12.74	517
ANOVA (P>F)								
Well Capacity (WC)			0.001	0.411	0.086	0.001	0.687	0.001
Pre-Season			0.002	0.099	0.659	0.107	0.160	0.001
WC*Pre-Season			0.222	0.297	0.452	0.401	0.752	0.138
Seed Rate			0.001	0.001	0.001	0.001	0.001	0.001
Seed Rate*WC			0.001	0.018	0.012	0.001	0.212	0.176
Seed Rate*Pre-Season			0.018	0.126	0.089	0.345	0.186	0.263
Seed Rate*W*Pre-Season			0.402	0.626	0.427	0.373	0.518	0.295
MEANS	Well cap.	0.10	167	402	26.8	25.2	12.97	456
		0.15	183	406	26.9	25.8	13.04	493
		0.20	214	417	27.0	26.6	13.11	558
		$LSD_{0.05}$	11	25	0.2	0.5	0.35	21
	Pre-season	no	180	400	26.9	25.7	12.94	486
		yes	196	417	26.9	26.1	13.14	518
		$LSD_{0.05}$	9	21	0.2	0.4	0.28	17
	Seed rate	22,500	181	397	22.2	21.7	13.35	558
		27,500	189	411	26.9	25.9	13.03	499
		32,500	194	417	31.5	30.1	12.73	450
		$LSD_{0.05}$	3	8	0.2	0.3	0.09	10

Table 2. Available soil water in 8 ft profile, crop water use, and non-growing season water accumulation for corn as affected by well capacity, preseason irrigation, and seeding rate, Tribune, KS, 2006 - 2009.

			Available soil water			Non-growing
Well capacity	Pre-season irrigation	Seed rate	Planting	Harvest	Water use	season accumulation.
in day^{-1}		10^3 a^{-1}	- - in 8 ft. profile^{-1} - -		in	in 8 ft. profile^{-1}
0.10	no	22.5	8.36	5.21	21.28	2.79
		27.5	8.24	4.83	21.55	2.73
		32.5	8.02	4.63	21.52	2.78
	yes	22.5	10.66	5.43	23.36	5.02
		27.5	10.52	4.88	23.78	5.30
		32.5	10.83	4.96	24.00	5.33
0.15	no	22.5	8.78	5.47	24.35	2.71
		27.5	9.17	6.08	24.13	2.56
		32.5	9.06	5.68	24.42	2.98
	yes	22.5	10.51	6.19	25.36	4.05
		27.5	10.46	6.15	25.35	4.77
		32.5	10.71	5.98	25.76	5.05
0.20	no	22.5	10.51	9.07	27.94	2.14
		27.5	9.95	7.86	28.59	3.02
		32.5	10.56	8.53	28.53	2.82
	yes	22.5	13.44	10.82	29.11	3.15
		27.5	13.22	10.13	29.58	3.68
		32.5	12.90	9.85	29.55	3.55
ANOVA (Probability>F)						
Well capacity (WC)			0.010	0.001	0.001	0.001
Pre-season			0.001	0.266	0.001	0.001
WC*Pre-season			0.647	0.587	0.010	0.001
Seed rate			0.779	0.076	0.001	0.002
Seed rate*WC			0.692	0.173	0.059	0.156
Seed rate*Pre-season			0.985	0.820	0.546	0.424
Seed rate*WC*Pre-season			0.389	0.625	0.749	0.303
MEANS	Well capacity	0.10	9.44	4.99	22.58	3.99
		0.15	9.78	5.92	24.89	3.69
		0.20	11.76	9.37	28.88	3.06
		LSD$_{0.05}$	1.49	1.77	0.39	0.38
	Pre- season	no	9.18	6.37	24.70	2.73
		yes	11.47	7.15	26.21	4.43
		LSD$_{0.05}$	1.22	1.44	0.32	0.31
	Seed rate	22.5	10.38	7.03	25.23	3.31
		27.5	10.26	6.65	25.50	3.68
		32.5	10.35	6.61	25.63	3.75
		LSD$_{0.05}$	0.34	0.40	0.18	0.24

Table 3. Net return to land, irrigation equipment, and management from preseason irrigation (0 or 3 in) at three irrigation well capacities and three seeding rates at Tribune, KS 2006-2009.

Well capacity	Preseason Irrigation	Seeding rate (10^3 a^{-1})		
		22.5	27.5	32.5
in day^{-1}		Net return, \$ a^{-1} yr^{-1}		
0.10	No	231	238	214
	Yes	285	300	297
0.15	No	290	283	261
	Yes	321	352	357
0.20	No	415	449	485
	Yes	417	458	492

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CORN PRODUCTION WITH LIMITED WATER SUPPLIES

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INTRODUCTION

Crop yield response to irrigation has been measured since the early years of irrigated agriculture research (Wagner, 1921). Field research on this topic has continued because irrigation systems, management techniques, and crop genetics have improved. Field research from the Great Plains research indicates that as irrigation applications to corn decrease, yields do not decrease at the same rate. Yield response to irrigation can be location specific and can vary by years due to differences in precipitation and stored soil water. Economic studies can use average yield responses over years to find overall trends but year to year variations in yields are needed for risk analysis. Testing and validation of crop production models need robust data sets that may include reference evapotranspiration (ETr), soil water measurements, crop grain yields, dry matter accumulation, harvest index, growth stage dates, maximum leaf area index, plant population, and crop residue coverage of the soil surface. These parameters were measured in this study to find the response of corn to a range of irrigation application amounts. The corn was grown in a no-till environment with best management practices for weed and insect control. Crop productivity (yield/ETc), yield/irrigation ratio, soil water accumulation during the non-growing season, and soil water use during the growing season were also derived from field data. Therefore, the objectives of this study were to: (1) build a robust data set of parameters for testing crop models over a range of irrigation; (2) find the relationships of grain and dry matter yields to ETc and irrigation; and (3) carry out the study over multiple years to find year to year variability in yield responses.

METHODS

The cropping systems project was located at the Kansas State University, Southwest Research-Extension Center near Garden City, Kansas. The soil type was a Ulysses silt loam (fine-silty, mixed, mesic Aridic Haplustoll) with pH of 8.1 and organic matter content of 1.5%. The soil had an available water capacity of 1.92 in/ft between field capacity (volumetric water of content of 33%) and permanent wilting (volumetric water content of 17%). Long-term average climatic data for Garden City are: annual precipitation, 18.7 inches; mean temperature, 54^{o}C; open-pan evaporation (April-September), 71 inches; and frost-free period, 170 days. Corn was grown in a five year rotation of corn-corn-wheat-sorghum-sunflower. Two consecutive years of corn were planted, the first after sunflower and the next after corn. All crops were planted in 2004 and the irrigation treatments were imposed so all crops were in rotation in 2005 and the initial soil water content included the effects of the irrigation variable from the previous 2004 crop. High through low water treatments were maintained on the same individual plots during all years and crops. Each crop was present every year in five cropping blocks, which were replicated over years. Irrigation treatments were randomized and replicated four times within each of the crop blocks in a randomized complete block design. The irrigation plots were 45 feet wide and 18 feet long.

Cultural practices, including hybrids, no-till planting techniques, fertilizer applications, and weed control, were the same across irrigation treatments. Cultural practices followed the requirements of no-till management and fertilizer and weed management were carried out so they would not limit crop production. Seeded plant populations increased across the six irrigation treatments with increasing levels of irrigation (19,500; 22,000; 24,500; 27,000; and 32,000 plants/ac) based on past research to be appropriate for the yield expectations of each irrigation treatment.

Grain yield was measured by hand harvesting two adjacent rows 10 feet long. Biomass was harvested from one row 10 feet long. Leaf area was measured by removing five plants from the field and passing the leaves through an optical scanner (Li-COR Portable leaf area meter). Crop residue coverage from the previous crop was measured shortly after planting using the line-transect method described by Dickey et al., (1986). Growth stages were recorded from field observations during the season.

A commercial four-span (135 ft span width) model 8000 Valley (Valmont Corporation) linear move sprinkler system was modified to deliver water in any combination of irrigation treatments simultaneously to each of the four replications (Klocke et al., 2003). Application depth for every irrigation event was 1 inch. Six irrigation treatments, replicated four times received from 13 inches (treatment 1) to 3 inches (treatment 6) of water during the growing season (table 1). If rainfall was sufficient to fill the soil profile to field capacity in treatment 1, water was not applied. To achieve the irrigation frequency variable, plots were irrigated or skipped during each pass of the irrigation system to achieve the target frequency (table 1). Each plot received no more than 2 inches of water per week to simulate the common commercial system capacity of 0.22 in/day.

Table 1. Average irrigation frequency and irrigation amounts for 2005-2009.

Irrigation Treatment	Irrigation Frequency	Total Irrigation
	(days)	(in)
1	4.8	13.3
2	6.3	10.5
3	7.0	9.2
4	8.8	6.8
5	12.0	5.2
6	15.2	3.2

Volumetric soil water content was measured bi-weekly to a depth of 8 feet in 6 inch increments with neutron attenuation techniques (Evett and Steiner, 1995). Drainage was calculated with a Wilcox-type equation (Miller and Aarstad, 1972) and runoff was observed to be negligible. The change in soil water from the start to the end of the sampling period, rainfall, net irrigation, and estimates of drainage were used in a water balance to calculate crop evapotranspiration (ETc). ETc was calculated for the days between plant emergence and the first soil water measurement with the Kansas Water Budget (KSWB) (Klocke et al., 2010). Reference ET (ETr) was calculated with an alfalfa-referenced Modified Penman model (Kincaid and Heermann, 1984), using weather factors including maximum and minimum air temperature, relative humidity, solar radiation, and wind run from an automatic weather station near the study site.

RESULTS

Above average ETr occurred during the 2005 and 2006 cropping seasons (previous October through current September) as well as the 2005-2006, 2007-2008, and 2008-2009 non-growing seasons (previous October through current April). Above average ETr occurred during the 2005 and 2006 growing seasons (current May through September). During the remaining periods, near average or below average ETr was recorded (table 2).

Cropping season precipitation was above average during the 2006-2007 and 2008-2009 periods and below average during the 2007-2008 periods (table 2). The other two years had nearly average cropping season precipitation and nearly the same precipitation during the growing and non-growing seasons. This year to year variation in precipitation patterns is common in the region.

Table 2. Reference ET (ETr) and precipitation with above average amounts underlined.

	ETr				Precipitation			
Year	Annual	Oct-Apr[a] In.	May-Sep[b] In.	Oct-Sep[c] In.	Annual In.	Oct-Apr[a] In.	May-Sep[b] In.	Oct-Sep[c] In.
2005	$\underline{64.5}$	19.2	$\underline{42.4}$	$\underline{61.6}$	18.1	5.3	$\underline{12.1}$	17.4
2006	$\underline{69.8}$	$\underline{29.5}$	$\underline{42.2}$	$\underline{71.7}$	$\underline{22.8}$	5.6	$\underline{13.0}$	18.5
2007	56.3	17.0	37.4	54.4	17.6	$\underline{13.2}$	10.1	$\underline{23.3}$
2008	58.4	$\underline{23.1}$	36.5	59.5	17.3	4.4	9.5	13.9
2009	53.6	$\underline{23.9}$	32.4	56.2	$\underline{21.7}$	$\underline{10.7}$	$\underline{12.5}$	$\underline{23.2}$
Avg	60.5	22.5	38.1	60.7	19.5	7.8	11.4	19.3

[a] Non-growing season from previous October through current April

[b] Growing season from the current May through September

[c] Cropping season from the previous October through the current September

Surface residue coverage from the previous crop varied among years and irrigation treatments (table 3). Residue coverage decreased significantly as irrigation amounts decreased, which showed the combined effects of the previous crop and residue decay during the non-growing season.

Year to year differences in leaf area index (table 3) were caused by hail events that occurred every year of the study, except 2007. Leaf area index was a good indicator of the hail's impact on the crop (Currie and Klocke, 2008). Significant leaf stripping was caused by hail events that occurred on July 4, 2005; July 11, 2006; June 20, 2008; and July 18, 2009 prior to tassel emergence. There was a hail event on June 19, 2007, but it was very minor and caused little to no leaf damage as indicated by leaf area measurements. Since effects of hail events and other possible crop stressors varied among years, relative grain yields were calculate for each year, where the relative yields were a ratio of the respective irrigation treatment yields and the yield of treatment 1.

The effects of irrigation treatments averaged over crop sequence and years showed a correlation of irrigation with grain yields, corn dry matter, and relative grain yields. Irrigation amount did not affect dry matter per plant which shows the influence of plant population on yield results.

Differences in year to year crop evapotranspiration (ETc) were not affected by the level of hail injury as much as they were by other crop production factors (table 4). ETc and grain yield decreased significantly as irrigation decreased. Productivity, the ratio of yield and ETc, was the same for the three highest levels of irrigation, but productivity declined as irrigation decreased.

Table 3. Crop yields and characteristics.

	Grain Yield	Relative Grain Yield	Total Dry Matter	Leaf Area Index	Residue Coverage
	bu/ac		tons/ac		%
(a) Year as an independent variable over irrigation treatments					
2005	133 c	0.87 a	11.6 c	N/A	46.9 c
2006	128 c	0.76 b	12.7 cb	3.22 b	52.6 a
2007	190 a	0.84 a	17.3 a	4.08 a	49 bc
2008	90 d	0.65 c	8.1 d	2.47 c	48 bc
2009	155 b	0.81 ab	13.4 B	3.26 b	50.6 ab
LSD0.05	9	0.062	1.2	0.285	3.2
(b) Irrigation treatment as an independent variable over year					
1	178 a	1 a	16.0 a	4.11 a	51.3 ab
2	167 a	0.94 ab	13.4 bc	N/A	52.6 a
3	157 b	0.88 b	14.0 b	N/A	51.2 ab
4	130 c	0.73 c	12.1 c	3.17 b	49.8 ab
5	112 d	0.63 d	10.2 d	N/A	48.5 b
6	91 e	0.5 e	9.8 d	2.49 c	43.2 c
LSD0.05	10	0.07	1.3		3.6

Table 4. Evapotranspiration, productivity, and grain yield/irrigation.

	Etc	Etr	Etc/Etr	Productivity[1]	Yield/Irr
	in	in		bu/ac-in	bu/ac-in
(a) Year as an independent variable over irrigation treatments					
2005	23.3 a	36.9	0.63 c	8.4 c	27.4 b
2006	22.0 bc	36.6	0.6 d	7.8 c	18.6 c
2007	22.1 bc	37.4	0.66 b	11.7 a	40.8 a
2008	17.5 d	30.1	0.58 e	6.8 d	15.0 d
2009	21.7 c	28.1	0.77 a	9.8 b	42.6 a
LSD0.05	0.4		0.012	0.6	2.6
(b) Irrigation treatment as an independent variable over years					
1	24.8 a	32.6	0.76 a	9.9 a	19.9 e
2	23.0 b	32.4	0.71 b	10.0 a	23.8 d
3	22.4 c	33.0	0.68 c	9.6 a	26.1 d
4	20.4 d	32.9	0.62 d	8.8 b	29.5 c
5	19.3 e	32.7	0.59 e	8.0 c	33.1 b
6	17.9 f	33.1	0.54 f	6.9 d	41.0 a
LSD0.05	0.4		0.013	0.7	2.8

[1] Grain yield/ETc

Increases in corn grain and dry matter yields had strong linear relationships to ETc (figure 1). The relationship of dry matter yields to ETc was more variable than grain yields, perhaps due in part to variation in the hail damage over the years. This linear regression of relative grain yield and ETc was much stronger than ETc and grain yield (figure 2). The slopes of Y-ETc for individual years may have been slightly different, but Y-ETc is usually considered to be an average over multiple years as the crop responds to the individual year's environment. Gomez and Gomez (1984) suggested that the treatment means averaged over replications are more appropriate for regressions of independent and dependent variables. When averaged over replications within years and replications among years, the relationship is well defined by the equation:

$$\text{Relative Yield} = 0.009\ (\text{ETc}) - 1.17 \quad \text{with } R^2 = 0.94 \tag{1}$$

where ETc in inches; Relative Yield as a fraction of full irrigation

A quadratic regression was used for the relative grain yield-irrigation data for all irrigation treatments for all years (figure 3).

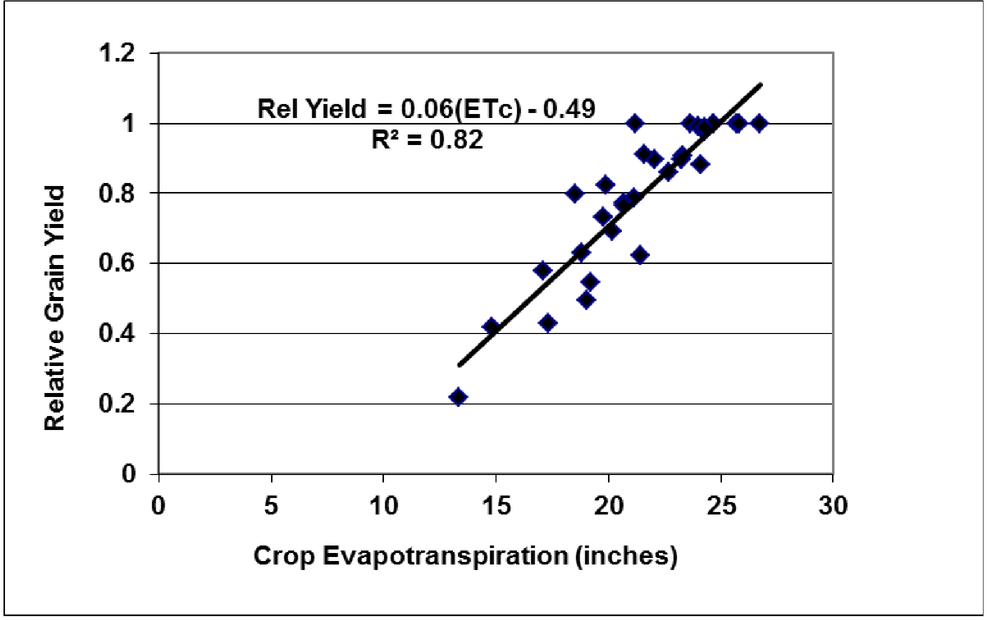

Figure 1. Relationship of relative grain yield with crop evapotranspiration (ETc).

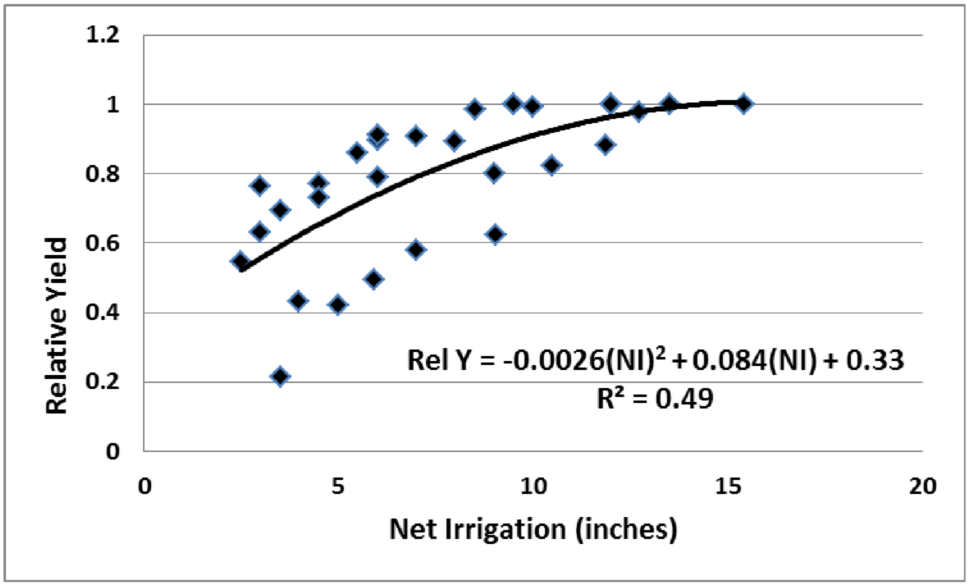

Figure 2. Relative grain yield response to irrigation.

Yield responses to irrigation among years can be distinguished from one another, where a particular year's data fall above or below the regression equation to reflect year to year differences in the environment, particularly differences in rainfall. When replications within years and replications among years were averaged for each irrigation treatment, the relationship was even more clearly defined by the equation:

$$\text{Relative Yield} = -0.0033(NI)^2 + 0.107(NI) + 0.196 \text{ with } R^2 = 0.99 \qquad (2)$$

where NI is Net Irrigation in inches; Relative Yield as a fraction of full irrigation

Since the same irrigation treatment was in the same plot location throughout all crops and years, soil water content at the end of the previous growing season influenced the next year's starting soil water content. Soil water content measured at the end of the previous growing season decreased as irrigation decreased (table 5). Soil water measurements by soil depth (data not shown) showed that the crop extracted more water from deeper in the profile in the lower irrigation treatments than in the wetter treatments. The deep silt loam soil allowed roots to extend to depths of 6 to 6.5 feet. Soil water accumulation during the non-growing season prior to planting corn was consistent among the deficit irrigation treatments (2 through 6), but the highest level of irrigation stored approximately 0.8 inch less water. Fallow efficiency, the ratio of accumulated soil water and non-grown season precipitation, showed that 60% of the precipitation was lost through soil water evaporation or drainage. Use of more stored soil water during the growing season prevented its loss during the following non-growing season and contributed to increases in water used for ETc. The crops preceding corn were also able to extract more water from deeper in the profile. The corn following corn used slightly more soil water than corn following sunflower. How effectively the crop can utilize stored soil water is one factor contributing to the diminishing return in yield from increased levels of irrigation.

Table 5. Soil water gains during the previous non-growing season and soil water use during the current growing season.

	Beg SW	End SW	SW Gain	Fallow Efficiency	SW Use	Drainage
	in	in	in		in	in
(a) Year as an independent variable over irrigation treatments						
2005	25.3 a	19.0 bc	4.0 c	0.39 b	6.3 a	0.02 bc
2006	19.9 d	19.1 b	2.0 d	0.29 c	0.7 d	0.00 c
2007	25.9 a	20.7 a	7.0 a	0.55 a	5.2 b	0.07 a
2008	20.5 c	18.5 c	1.4 d	0.21 d	2.0 c	0.01 c
2009	24.3 b	19.0 bc	5.1 b	0.51 a	5.3 b	0.04 b
LSD0.05	0.6	0.6	0.6	0.065	0.4	0.02
(b) Irrigation treatment as an independent variable over year			0.0			
1	24.8 a	22.2 a	3.1 b	0.3 b	2.6 d	0.08 a
2	24.2 ab	20.9 b	4.0 a	0.41 a	3.3 c	0.03 b
3	23.8 b	19.9 c	4.1 a	0.41 a	3.9 b	0.03 bc
4	22.7 c	18.6 d	4.3 a	0.43 a	4.1 b	0.01 bc
5	21.9 d	17.3 e	3.9 a	0.39 a	4.6 a	0.00 c
6	21.6 d	16.7 e	3.9 a	0.39 a	4.8 a	0.01 bc
LSD0.05	0.7	0.6	0.6	0.07	0.4	0.02

[1] Total soil water in 8 foot soil profile

[2] Soil water gain/non-growing season precipitation

SUMMARY

A field study of fully irrigated to deficit irrigated corn was conducted during 2005-2009 in southwest Kansas. Corn was grown in a 5-year rotation of corn-corn-wheat-grain sorghum-sunflower and 5 years of data were collected. Irrigation treatments were delineated by the irrigation frequency from 5 to 17 days with the constraint that the wettest irrigation treatment (scheduled on the basis of soil water depletion) could receive no more than two irrigation events per week, and each event delivered 1 inch of water. Grain and dry matter yields from year to year averaged over irrigation treatments and crop sequence were highly correlated to maximum leaf area index, which possibly reflected the severity of hail events that occurred 4 out of five years of the study. However, dry matter accumulation per plant did not vary across irrigation treatments. Surface residue coverage measured from the previous year's crop was 61% for corn following corn. ETc, calculated as the residual in a bi-weekly soil water balance decreased as irrigation decreased. Productivity, the ratio of yield and ETc (also known as water use efficiency) decreased as irrigation decreased and was the same for the two crop sequences. The ratio of yield to irrigation increased as irrigation decreased.

Deficit irrigation treatments were able to utilize more non-growing season precipitation because the previous crop extracted more soil water from deeper in the profile than the fully irrigated treatment leaving more room to store the subsequent precipitation. The deficit irrigated treatments also extracted more soil water during the growing season.

Although regressions of grain and dry matter yields with ETc produced reasonable linear models, regression of grain yields as a fraction of full yields (relative yields) produced better models with less variability. A curvilinear model of relative yield with irrigation had the greatest predictive value, particularly as year to year variability declined with increasing levels of irrigation. Over the five years of the study, variability in yields consistently increased as irrigation decreased, illustrating greater income risk for the producer as irrigation decreased. The yield response to irrigation, over multiple years provides essential information to build economic studies of cropping alternatives, deficit irrigation management, and income risk.

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PERFORMANCE EVALUATION OF SELECTED SOIL MOISTURE SENSORS

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ABSTRACT

Irrigation water management practices could greatly benefit from using soil moisture sensors that accurately measure soil water content or potential. Therefore, an assessment on soil moisture sensor reading accuracy is important. In this study, a performance evaluation of selected sensor calibration was performed considering factory- laboratory- and field-based calibrations. The selected sensors included: the Digitized Time Domain Transmissometry (TDT, Acclima, Inc., Meridian, ID) which is a volumetric soil water content sensor, and a resistance-based soil water potential sensor (Watermark 200, Irrometer Company, Inc., Riverside, CA). Measured soil water content/potential values, on a sandy clay loam soil, were compared with corresponding values derived from gravimetric samples. Under laboratory and field conditions, the factory-based calibrations for the TDT sensor accurately measured volumetric soil water content. Therefore, the use of the TDT sensor for irrigation water management seems very promising. Laboratory tests indicated that a linear calibration for the TDT sensor and a logarithmic calibration for the watermark sensor improved the factory calibration. In the case of the watermark, a longer set of field data is needed to properly establish its accuracy and reliability.

INTRODUCTION

Soil moisture is an important factor used in irrigated agriculture to make decisions regarding irrigation scheduling and for land managers making decisions concerning livestock grazing patterns, crop planting, and soil stability for agricultural machinery operations. Many methods of determining soil moisture have been developed, from simple manual gravimetric sampling to more sophisticated remote sensing and Time Domain Reflectometery (TDR) measurements. One common technique is to measure dielectric constant, that is, the capacitive and conductive parts of a soil's electrical response. Through the use of appropriate calibration curves, the dielectric constant measurement can be directly related to soil moisture (Topp et al. 1980). However, there are several different types of sensors commercially available which present different levels of soil water content/potential readings' accuracy. Hignett and Evett (2008) indicated the following: *"in general, a manufacturer's calibration is commonly performed in a temperature controlled room, with distilled water and in easy to manage homogeneous soil materials (loams or sands) which are uniformly packed around the sensor. This calibration procedure produces a very precise and accurate calibration for the conditions tested. However, in field conditions variations in clay content, temperature, and salinity may affect the manufacturer's calibration."*

Sensor accuracy needs to be assessed in order to do a better job managing water and to realize the reliability of the sensor. In addition, appropriate sensor calibration curves can be developed during the sensor evaluation process.

This study evaluates the performance of a Digitized Time Domain Transmissometry (TDT) soil water content sensor developed by Acclima, Inc. (Meridian, ID), and of a resistance-based (Watermark 200, Irrometer Company, Inc., Riverside, CA) soil water potential sensor on a sandy clay loam soil from an agricultural field near Greeley, CO.

MATERIALS AND METHODS

This study took place during the 2010 corn growing season in eastern Colorado. The field was an experimental field cooperatively operated by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) and Colorado State University (CSU) near the City of Greeley, CO. Corn was grown at this location and was irrigated using furrows. Geographic coordinates, dry bulk density, porosity and soil texture of the soil can be found in Table 1. Bulk density was obtained using a Madera Probe (Precision Machine, Inc., Lincoln, NE). The porosity was estimated using the sampled bulk density from each field and an assumed particle density of 2.65 g/cm^3. Soil textures were determined in the Laboratory by a particle size analysis (Hydrometer Method; Gavlak, et al., 2003).

Table 1. Site Name, Geographic Coordinates, Dry Soil Bulk Density (ρ_b), Porosity (φ), and Soil Texture in the 10 - 30 cm soil layer.

Site	Lat. (N)	Long. (W)	ρ_b (g/cm^3)	φ (%)	Sand (%)	Silt (%)	Clay (%)	Class
Greeley, CO	40°26'	104°38'	1.46	45	65	10	25	Sandy clay loam

Factory Calibrations

The TDT soil water content sensor is provided with a calibration by the sensor manufacturer, which enables the sensor to give a direct reading of volumetric soil water content (θ_v), soil temperature (°C), and electrical conductivity (EC, dS/m). According to the Cut Sheet TDT soil moisture sensor (2010), the volumetric water content accuracy of the sensor is ±1% (full scale) under temperature conditions of 0.5 to 50 °C and EC of 0 to 3 dS/m. Laboratory and field tests were conducted to test this claim of accuracy.

The Watermark sensor directly measures voltage excitation (in mV) which is converted to electrical resistance (in kOhms) through the datalogger's internal program (Campbell Scientific, 2009). Soil water potential (SWP, kPa) is then estimated using the electrical resistance through another internal correction. The equations used in the dataloggers are shown as Equations 1 and 2.

$$R_s = V_r / (1 + V_r) \qquad 1$$

$$SWP = 7.407 * R_s / (1 - 0.018 * (T - 21)) - 3.704 \qquad 2$$

where V_r (mV) is the ratio of the measured voltage divided by the excitation voltage, R_s (kOhms) is the measured resistance, T (°C) is the soil temperature measured by the TDT sensor, and SWP (kPa) is the soil water potential. SWP is directly related to θ_v through water retention (or release) curves, which vary by soil type. The manufacturer of the Watermark sensor recommended relating the SWP to volumetric water content through curves for general soil types published by Ley et al. (2004). This curve was generalized using equation 3.

$$\theta_v = \alpha X^{\beta} \qquad 3$$

where α and β are coefficients and X is the sensor-based soil water potential (millibars, mb). The α and β coefficients for the soil in this study are 104.63 and -0.19, respectively.

Laboratory Calibrations

Laboratory calibrations were performed using soil samples collected from the upper 0-30 cm layer.

The laboratory calibration for the TDT sensor was based on the procedure proposed by Starr and Paltineanu (2002) and Cobos (2009). Soil collected from each field was air-dried until it could pass through a 2-mm sieve. It was then packed in a 19 L container to approximate field bulk density. The sensor was then inserted vertically into the soil, and several soil water content readings were taken every 20 minutes. After each sensor reading, soil gravimetric samples were taken from the container and were oven-dried at 105 °C for 24 hours. The volumetric water content was then computed by multiplying the gravimetric water content by the soil bulk density obtained from field core soil samples (undisturbed soil structure). The soil from the container was then wetted with 500 mL of water and was mixed thoroughly. The above procedure was repeated several times, each time repacking the container, taking multiple readings and adding another 500 mL of water.

A total of sixty data points (n=60) were used in the analysis of the soil moisture. The volumetric water contents of the soil moisture samples ranged from 10.7 to 35.9%. Fangmeier et al. (2006) reported values of permanent wilting point (PWP) and field capacity (FC) for the same type of soil as the one used in this study as being 16 to 26% (by volume). Therefore, the range of soil water content sampled in the laboratory covered the PWP to FC range.

A linear calibration equation was developed by plotting the sensor probes' readings (θ_v_s) versus the volumetric water content derived from the gravimetric method (θ_v_g). The linear regression equations were developed using Microsoft Excel® Regression Analysis. The equations take the form of equation 4, below.

$$\theta_v\_g = \alpha_0 \, \theta_v\_s + \alpha_1 \qquad 4$$

where α_o is the slope of the of the curve while α_1 is the intercept of the curve with the Y-axis. θ_v_s is the sensor-based θ_v (dimensionless). During these tests, the average EC recorded by the TDT sensor was 0.69 dS/m. The soil temperature was nearly constant (~21 °C) throughout the entire study.

The laboratory calibration procedure using the Watermark sensor was different from that of the TDT because water tension in the Watermark sensor must equilibrate with that of the surrounding soil before an accurate reading can be taken. Therefore the sieved soils from the previous tests were separated into multiple smaller buckets of different water contents. One Watermark sensor was placed in each bucket and left for three days to equilibrate with the soil. Gravimetric samples were then taken from each bucket, oven-dried and converted into θ_v using the dry soil bulk density obtained from field samples. A total of seven samples (n=7) were used in the analysis.

Two types of calibration equations were developed by plotting θ_v_g versus the SWP sensor output. The logarithmic equation is shown in equation 5 below.

$$\theta_v\_g = \alpha \ln|X| + \delta \qquad 5$$

where α and δ are coefficients and X is the sensor-based soil water tension (millibars, mb).

To assess the accuracy of the developed calibration equation obtained from the laboratory procedure, the 'laboratory equations' were applied to the field sensors' readings and results were compared with the field-sampled θ_v.

Field Calibration

During July of 2010 TDT and Watermark sensors were installed at the study site. This site had three differing irrigation treatments and each treatment contained one TDT sensor and one Watermark sensor. In each irrigation treatment the sensors were installed under the crop row/bed, roughly 0.25 m apart from each other, at a depth of 10-12 cm below the average level of the corn beds. These sensors were installed by digging a shallow trench and inserting the sensors horizontally into the wall, then backfilling the trench. Data collection for each TDT sensor began in the mid July. Data collection for the Watermark sensor in treatment 1 also began in mid-July, while the sensors in treatments 2 and 3 began operating in the middle of September.

From the time of installation until the first week of October, 2010, automated sensor readings were recorded every five minutes. Readings were compared with periodic gravimetric measurements, totaling eleven from each irrigation treatment. Since the Watermark sensors in treatments 2 and 3 did not begin operating until September, only two gravimetric samples were collected for each treatment for these sensors.

The gravimetric samples were taken using a soil auger approximately 1-2 meters away from each sensor location. These samples were immediately placed in sealed containers inside a cooler and taken directly to a laboratory to be weighed (wet), oven-dried, and weighed again (dry). The gravimetric samples were then converted into θ_v using the dry soil bulk density field value. During the times of gravimetric field sampling, soil temperatures ranged from 15 - 22 °C in irrigation treatment 1, 15 - 24 °C in treatment 2, and 16 - 30 °C in treatment 3. EC ranged from 0 - 1.23 dS/m in treatment 1, 0 - 1.31 dS/m in treatment 2, and 0 - 2.12 dS/m in treatment 3.

Sensor-specific linear calibration equations were developed for the TDT sensors based on the θ_v read by the sensor. This equation is shown in equation 4, above. For the Watermark sensors, the logarithmic equation (equation 5) was derived. Generalized equations were developed to incorporate the readings from all of the Watermark sensors in that field.

Statistical Analysis

Four statistical measures were computed to compare and evaluate each model-predicted (*P*) equation with the observed (*O*) gravimetric samples taken from the field and laboratory soils. These include the coefficient of determination (R^2), mean bias error (*MBE*; Equation 6), root mean square error (RMSE; Equation 7), and index of agreement (κ; Equation 8) as defined by Willmott (1982).

$$\mathrm{MBE} = \mathrm{n}^{-1}\sum_{i=1}^{n}(\mathrm{P}_i - \mathrm{O}_i) \qquad 6$$

$$\mathrm{RSME} = [\mathrm{n}^{-1}\sum_{i=1}^{n}(P_i - O_i)^2]^{0.5} \qquad 7$$

$$\kappa = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)}{\sum_{i=1}^{n} (|P'_i| - |O'_i|)^2} \right] \qquad 8$$

where *n* is the sample size, $P'_i = P_i - \bar{O}$, and $O'_i = O_i - \bar{O}$. The units for MBE and RMSE are volumetric water content (%), and κ is dimensionless. Hignett and Evett (2008) point out that in most agricultural and research applications the measurement accuracy needs to be within 0.01 to 0.02 $m^3\ m^{-3}$. Therefore MBE under 2.5% and RMSE less than 5% fit this criterion. The scale of κ ranges between 0-1, with higher numbers representing greater correlation between the model prediction and observations.

RESULTS AND DISCUSSION

Factory Calibration

In general, under laboratory and field conditions, the factory-based calibrations of θ_v did not consistently achieve the required accuracy within the PWP to FC range of water contents. For the TDT sensor, the factory calibration performed well in most cases. For the Watermark sensors, on all tests the sensor did not achieve the required accuracy.

Table 2 and Table 3 show low MBE and RMSE and high κ values for the TDT sensor. This result indicates that the TDT's factory calibration was within the previously-described limits and thus performed very well. The MBE values for the Watermark's factory calibration in Table 2 show that this sensor overestimated measured θ_v in average 20.5±21.1% in the laboratory test. This is a large overestimation and in part it may be due to lack of appropiate equilibrium of water tension between the the sensor cap and soil during the three days that the probe was left in the container at a given soil water level.

Table 2. Comparison of the Factory Calibration-Based θ_v (θ_{v}_s, %) with Laboratory Measurements of θ_v (θ_{v}_g, %).

Soil Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	60	0.94	-1.2	3.9	0.95
Watermark	7	0.93	20.5	21.1	0.32

Table 3. Comparison of the Factory Calibration-based θ_v (θ_{v}_s, %) with Field Measurements of θ_v (θ_{v}_g, %).

Soil Type	Location	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	1	11	0.73	2.1	3.0	0.85
	2	11	0.83	1.8	2.9	0.92
	3	12	0.77	-1.8	3.3	0.90
Watermark	Composite*	15	0.87	11.2	12.6	0.48

*One equation represented readings from all field sensors.

However, in the field, the Watermark's factory calibration overestimation of θ_v was much less, i.e. 11.2±12.6% (Table 3). This seems to confirm that the Watermark sensor needed a longer time to attain equilibrium of soil water tension under laboratory conditions.

Laboratory Calibration

Soil-specific calibration equations developed in the laboratory yielded high levels of accuracy, well within the targeted statistical parameters, for both sensors. The MBE, RMSE and κ parameters, shown in Table 4, were each better than the parameters representing the factory calibrations.

Table 4. Comparison of the Laboratory-based Calibration of θ_v (θ_{v}_s, %) versus Laboratory Measurements of θ_v (θ_{v}_g, %)

Soil Type	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	Linear	60	0.94	0.0	1.8	0.98
Watermark	Logarithmic	7	0.94	0.0	1.1	0.98

Table 5 displays the results of comparing the use of the laboratory-derived calibration equations with field-measurements of θ_v (θ_{v}_g, %). For both sensors, applying the laboratory-derived equations to the field sensors' data yielded larger MBE, RMSE, and smaller κ values than when compared to measured data at the laboratory (in Table 4). With respect to the TDT sensor, the laboratory equations resulted in levels of accuracy that were very similar to the factory calibrations. However, applying the soil-specific calibration equation developed in the laboratory to the Watermark sensor installed in the field resulted in an average underestimation of 4.3±5.0% (Table 5).

Table 5. Comparison of the Laboratory-based Calibration of θ_v (θ_{v}_s, %) versus Field Measurements of θ_v (θ_{v}_g, %)

Soil Type	Location	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	1	Linear	11	0.73	2.0	2.8	0.83
	2	Linear	11	0.83	1.8	2.6	0.90
	3	Linear	12	0.77	-1.8	3.1	0.89
Watermark	Composite*	Logarithmic	15	0.79	-4.3	5.0	0.73

*One equation represented measurements from all field sensors.

Field Calibration

The field-based calibration equations developed for both sensors, within the PWP to FC range of water contents, showed higher levels of accuracy than the factory- or laboratory-derived equations. As shown in Table 6, the RMSE values were consistently low (and κ values high) for both sensors and errors well within the ideal statistical targets.

Table 6. Comparison of the Field-based Calibration of θ_v (%) versus Field Measurements of θ_v (%).

Soil Type	Location / Depth (cm)	Eqn. Type	Sample Size (n)	R^2	MBE (%)	RMSE (%)	κ
TDT	1	Linear	11	0.73	0.0	1.9	0.91
	2	Linear	11	0.83	0.0	1.9	0.95
	3	Linear	12	0.74	0.0	2.4	0.93
Watermark	Composite*	Logarithmic	15	0.81	0.0	1.6	0.94

*One equation represented measurements taken with all field sensors.

The different derived equations were applied to the field data from the TDT sensor in treatment 1, results are shown in Figure 1. This treatment was fully irrigated (no crop water stress). It is assumed that right after irrigation the soil around the soil moisture sensors reached complete saturation. Considering a porosity of 45%, the TDT's factory calibration measured levels of water content that were larger than porosity while the laboratory- and field-derived equations indicated complete saturation. It is evident in Figure 1 that the TDT responded well to small amounts of rainfall (≈3 mm on August 19th), and all calibration equations resulted in water content levels similar to values derived from gravimetric field measurements.

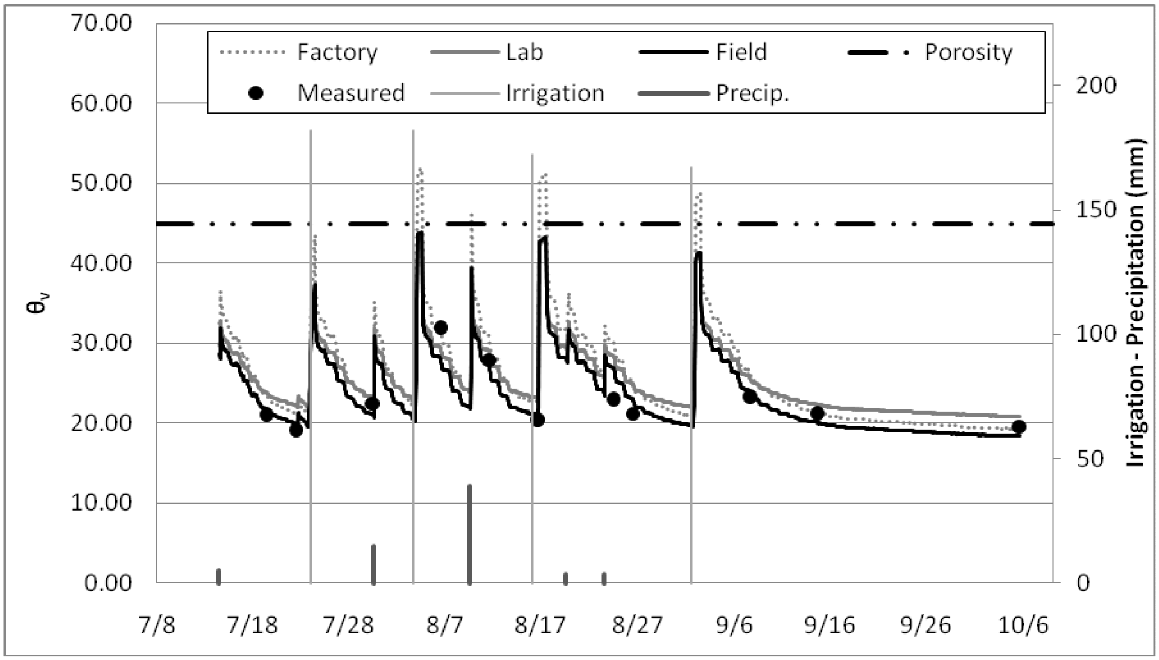

Figure 1. TDT soil water content sensor calibration curves for Treatment 1.

CONCLUSIONS

This research evaluated the performance of Watermark soil water potential and TDT soil water content sensors under laboratory and field conditions in a sandy clay loam soil. Sensor measured soil water content values were compared with corresponding values derived from gravimetric samples. Soil potential (tension) values from the watermark were converted to volumetric soil water content for the evaluation. Linear calibration equations were developed for the TDT sensor while a logarithmic calibration equation was developed for the Watermark sensor. According to laboratory tests, the TDT's factory-recommended calibration performed very well with errors less than 1.2±3.9%. In the case of the Watermark sensor, the factory-recommended equation, evaluated with measured soil water content from a corn irrigated field, in average overestimated soil water content by 11.2±12.6%.

Finally, field-derived calibration equations developed for both sensors resulted in higher accuracy than the factory- or laboratory-derived equations. The resulting mean bias error (MBE) and root mean square error (RMSE) for the TDT sensor was 1.8±2.6% and for the Watermark sensor -4.3±5.0%, respectively.

These results indicate that the TDT soil water content sensor was accurate and consistent in measuring soil moisture. In the case of the watermark sensor the accuracy was less than expected. However, more field data still are needed to further conclude on the accuracy and reliability of the watermark sensor.

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ET-BASED IRRIGATION SCHEDULING

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The water requirement of a crop must be satisfied to achieve potential yields. The crop water requirement is also called crop evapotranspiration and is usually represented as ET_c. Evapotranspiration is a combination of two processes – evaporation of water from the ground surface or wet surfaces of plants; and transpiration of water through the stomata of leaves. The water requirement can be supplied by stored soil water, precipitation, and irrigation. Irrigation is required when ET_c (crop water demand) exceeds the supply of water from soil water and precipitation. As ET_c varies with plant development stage and weather conditions, both the amount and timing of irrigation are important. Estimates of ET_c can be included in a simple water balance (accounting) method of irrigation scheduling to estimate the required amount and timing of irrigation for crops. This method can be used if initial soil water content in the root zone, ET_c, precipitation, and the available water capacity of the soil are known.

The soil in the root zone has an upper as well as a lower limit of storing water that can be used by crops. The upper limit is called the field capacity (FC), which is the amount of water that can be held by the soil against gravity after being saturated and drained; typically attained after 1 day of rain or irrigation for sandy soils and from 2 to 3 days for heavier-textured soils that contain more silt and clay. The lower limit is called permanent wilting point (PWP), which is the amount of water remaining in the soil when the plant permanently wilts because it can no longer extract water. The available water capacity (AWC), or total available water, of the soil is the amount of water between these two limits (AWC = FC – PWP) and is the maximum amount of soil water that can be used by the plants. The AWC of soil is typically expressed in terms of inches of water per inch of soil depth. Available water capacity values for specific soils can be obtained from county soil surveys or online at http://websoilsurvey.nrcs.usda.gov/app/.

SIMPLE WATER BALANCE FOR IRRIGATION SCHEDULING

As the crop grows and extracts water from the soil to satisfy its ET_c requirement, the stored soil water is gradually depleted. In general, the net irrigation requirement is the amount of water required to refill the root zone soil water content back up to field capacity. This amount, which is the difference between field capacity and current soil water level, corresponds to the soil water deficit (D). The irrigation manager can keep track of D, which gives the net amount of irrigation water to apply. On a daily basis, D can be estimated using the following accounting equation for the soil root zone:

$$D_c = D_p + ET_c - P - Irr - U + SRO + DP \qquad [1]$$

where D_c is the soil water deficit (net irrigation requirement) in the root zone on the current day, D_p is the soil water deficit on the previous day, ET_c is the crop evapotranspiration rate for the current day, P is the gross precipitation for the current day, Irr is the net irrigation amount infiltrated into the soil for the current day, U is upflux of shallow ground water into the root zone, SRO is surface runoff, and DP is deep percolation or drainage.

The last three variables in equation 1 (U, SRO, DP) are difficult to estimate in the field. In many situations, the water table is significantly deeper than the root zone and U is zero. Also, SRO and DP can be accounted for in a simple way by setting D_c to zero whenever water additions (P and Irr) to the root zone are greater than $D_p + ET_c$. Using these assumptions, equation 1 can be simplified to:

$$D_c = D_p + ET_c - P - Irr \qquad \text{(if } D_c \text{ is negative, then set it to 0.0)} \qquad [2]$$

Take note that D_c is set equal to zero if its value becomes negative. This will occur if precipitation and/or irrigation exceed ($D_p + ET_c$) and means that water added to the root zone already exceeds field capacity within the plant root zone. Any excess water in the root zone is assumed to be lost through SRO or DP.

The amounts of water used in the equations are typically expressed in depths of water per unit area (e.g., inches of water per acre). Equation 2 is a simplified version of the soil water balance with several underlying assumptions. First, any water additions (P or Irr) are assumed to readily infiltrate into the soil surface and the rates of P or Irr are assumed to be less than the long term steady state infiltration rate of the soil. Actually, some water is lost to surface runoff if precipitation or irrigation rates exceed the soil infiltration rate. Thus, equation 2 will under-estimate the soil water deficit or the net irrigation requirement if P or Irr rates are higher than the soil infiltration rate. Knowledge of effective precipitation (P – SRO – DP), irrigation, and soil infiltration rates (e.g. inches per hour) are required to obtain more accurate estimates of D_c. Secondly, water added to the root zone from a shallow water table (U) is not considered. Groundwater contributions to soil water in the root zone must be subtracted from the right hand side of the equation in case of a shallow water table. Equation 2 will over-estimate D_c if any actual soil water additions from groundwater are neglected.

It is a good practice to occasionally check (e.g., once a week) if D_c from equation 2 is the same as the actual deficit in the field (soil water content readings using soil moisture sensors). Remember that D_c is the difference between field capacity and current soil water content. Therefore, the actual deficit in the field can be determined by subtracting the current soil water content from the field capacity of the root zone. If D_c from equation 2 is very different from the observed deficit, then use the observed deficit as the D_c value for the next day. These corrections are necessary to compensate for uncertainties in the water balance variables. Field measurements of current soil water content can be performed using the gravimetric method (weighing of soil samples before and after drying) or using soil water sensors like gypsum blocks (resistance method).

In irrigation practice, only a percentage of AWC is allowed to be depleted because plants start to experience water stress even before soil water is depleted down to PWP. Therefore, a management allowed depletion (MAD, decimal fraction) of the AWC must be specified. Values of MAD can range from 0.20 for crops highly sensitive to water stress to 0.65 for crops with high tolerance to water stress. Also, MAD is lower for more sensitive growth phases of the crop (e.g., reproductive phase). The rooting depth and MAD for a crop will change with developmental stage. The MAD can be expressed in terms of depth of water (d_{MAD}; inches of water) using the following equation.

$$d_{MAD} = (MAD) * AWC * D_{rz} \qquad [3]$$

where MAD is management allowed depletion (decimal fraction), AWC is available water capacity of the root zone (inch of water per inch of soil), and D_{rz} is depth of root zone (inches).

The value of d_{MAD} can be used as a guide for deciding when to irrigate. Typically, irrigation water should be applied when the soil water deficit (D_c) approaches d_{MAD}, or when $D_c \geq d_{MAD}$. To minimize water stress on the crop, D_c should be kept less than d_{MAD}. If the irrigation system has enough capacity, then the irrigator can wait until D_c approaches d_{MAD} before starting to irrigate. The net irrigation amount equal to D_c can be applied to bring the soil water deficit to zero. Otherwise, if the irrigation system has limited capacity (maximum possible irrigation amount is less than d_{MAD}), then the irrigator should not wait for D_c to approach d_{MAD}, but should irrigate more frequently to ensure that D_c does not exceed d_{MAD}. However, keep in mind that more frequent irrigations increase evaporation of water from the soil surface, which is considered a loss. In addition, when rainfall is in the forecast, the irrigator might want to leave the root zone below field capacity to allow for storage of forecasted precipitation.

ESTIMATING CROP ET

Crop evapotranspiration (ET_c), in inches per day, is estimated as:

$$ET_c = ET_r * K_c * K_s \qquad [4]$$

where ET_r is the evapotranspiration rate (inches/day) from a reference crop (e.g., alfalfa), K_c is a crop coefficient that varies by crop development stage (ranges from 0 to 1), and K_s is a water stress coefficient (ranges from 0 to 1). A K_s of 1 means that the crop is not experiencing water stress, so a value of 1 can be assumed for fully irrigated conditions. At any given point in the growing season, the K_c for a crop is simply the ratio of its ET over the reference crop ET. The K_c can be thought of as the fraction of the reference crop ET that is used by the actual crop. Values of K_c typically range from 0.2 for young seedlings to 1.0 for crops at peak vegetative stage with canopies fully covering the ground. In some instances, peak K_c might reach 1.05-1.10, for crops showing similar biomass characteristics as alfalfa, when the soil and canopies are wet (after irrigation/rain). An example crop coefficient curve (K_c values that change with crop development) is shown in Figure 1. Crop coefficient values for commonly grown crops are provided by Allen et al. (1998; 2007).

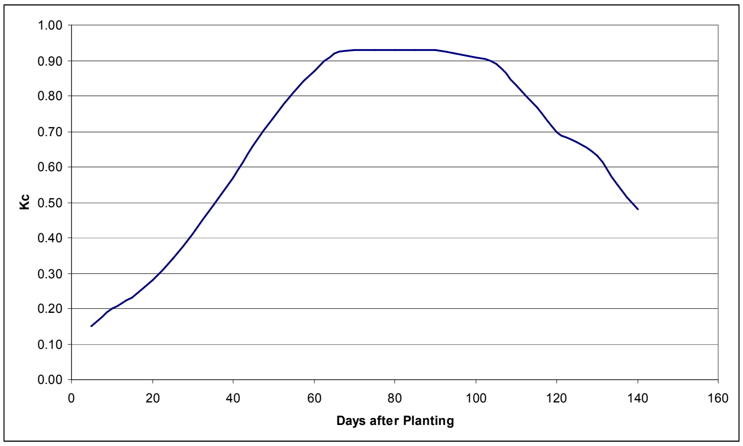

Figure 1. Example crop coefficient curve that shows K_c values that change with crop development.

Reference crop evapotranspiration (ET_r) can be calculated from daily weather data. One equation that is being widely adopted for estimating ET_r is the ASCE standardized reference ET equation (Allen et al., 2005). The Colorado Agricultural Meteorological Network (www.CoAgMet.com) is one example of an online source of daily ET_r values for various locations. Similar sources of ET_r can also be found in other states.

In cases when water availability is limited (e.g., lack of precipitation or irrigation), then K_s will be less than 1, and crop ET_c will not occur at the potential (non-water-limited) rate. The water stress coefficient can be estimated by (Allen et al., 1998):

$$K_s = [TAW - D] / [(1 - MAD) * TAW] \qquad (K_s = 1 \text{ if } D < d_{MAD}) \qquad [5]$$

where TAW is total available water in the soil root zone (inches), D is the soil water deficit (inches), and MAD is management allowed depletion (decimal fraction). The value of TAW can be calculated from:

$$TAW = AWC * D_{rz} \qquad [6]$$

where AWC is available water capacity of the root zone (inch of water/inch of soil) and D_{rz} is the total depth of the root zone (inches). In equation 5, MAD is specifically defined as the fraction of AWC that a crop can extract from the root zone without suffering water stress. Note that K_s should be set equal to one when D is less than d_{MAD}.

Crop Coefficients from a Weighing Lysimeter

An accurate way to measure ET rates of crops is to use a precision weighing lysimeter that directly measures ET based on changes in weight of an intact block of soil (monolith) containing an actively growing crop. A diagram of a precision weighing lysimeter is shown in Figure 2 and detailed descriptions have been given by Marek et al. (1988). As the crop actively growing in the monolith consumes water via ET, a sensitive weighing scale detects the drop in weight that can easily be converted to equivalent ET. The scale can also detect water inputs (precipitation, irrigation) and drainage. The lysimeter and surrounding field are managed similarly so that crop ET values from the lysimeter are representative of the entire field.

In the lower Arkansas River Basin of Colorado, two weighing lysimeters were installed to directly measure the ET of locally-grown crops and develop crop coefficients that are representative of local growing conditions. The lysimeters are located at the Colorado State University (CSU) – Arkansas Valley Research Center (AVRC) at Rocky Ford, Colorado. The monolith tank dimensions of the large lysimeter are 10 feet wide by 10 feet long by 8 feet deep (3 m x 3 m x 2.4 m). A smaller lysimeter, which is meant to grow an alfalfa reference crop, has monolith tank dimensions of 5 feet wide x 5 feet long x 8 feet deep (1.5 m x 1.5 m x 2.4 m). More details about the lysimeters at Rocky Ford, Colorado are given by Andales et al. (2010).

Daily crop coefficients are calculated by taking the ratio of crop ET from the lysimeter and alfalfa reference ET calculated from the ASCE standardized reference ET equation (Allen et al., 2005). So far, preliminary crop coefficient curves for 4 cutting cycles of alfalfa hay have been developed (2008-2010 data).

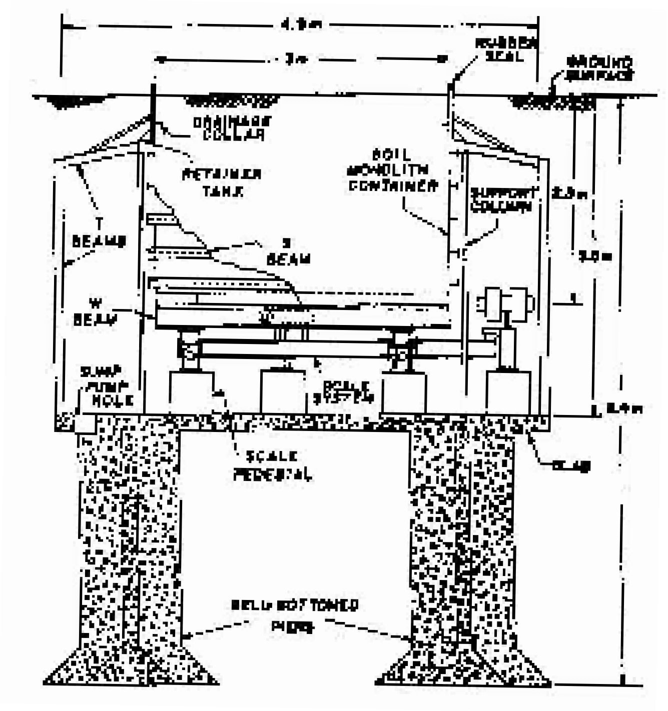

Figure 2. Diagram of a precision weighing lysimeter (Marek et al., 1988), similar to one installed at Rocky Ford in the lower Arkansas River Basin of southeast Colorado.

AN EXAMPLE FROM NORTHEAST COLORADO

Equations 2 through 6 can easily be entered as formulas into a spreadsheet, with columns for daily values of P, Irr, D_{rz}, TAW, ET_r, K_c, K_s, ET_c, and D_c. Values of P, Irr, D_{rz}, and ET_r can be input in the spreadsheet on a daily basis, and D_c calculated automatically. This was done for a center pivot-irrigated corn field near Greeley, Colorado for the 2010 growing season (Figure 3). The daily soil water deficit was calculated using equation 2. At the start of the season, the root zone was approximately at field capacity and the initial deficit (D_p) was assumed to be zero. For simplicity, the K_s value was assumed equal to 1 (no water stress) throughout the season because the field was being fully irrigated. The deficit values in Figure 3 are represented as negative values to intuitively represent reductions in soil water content.

Stored soil moisture and precipitation during the seedling and early vegetative phases of the corn crop were generally adequate, except for a short period from late May to early June when the deficit exceeded the d_{MAD}. However, significant rains from June 10 to 14 brought the deficit to zero and allowed for a further delay in running the center pivot. The center pivot system was turned on June

27, when the soil water deficit began approaching d_{MAD} and rain was not in the forecast. For most of the vegetative and reproductive corn phases, the deficit did not exceed d_{MAD}. Irrigations were reduced after the reproductive phase and eventually stopped as the corn grains matured. This example shows that estimated crop ET used in a simple water balance approach can help track soil water deficits for determining irrigation amount and timing.

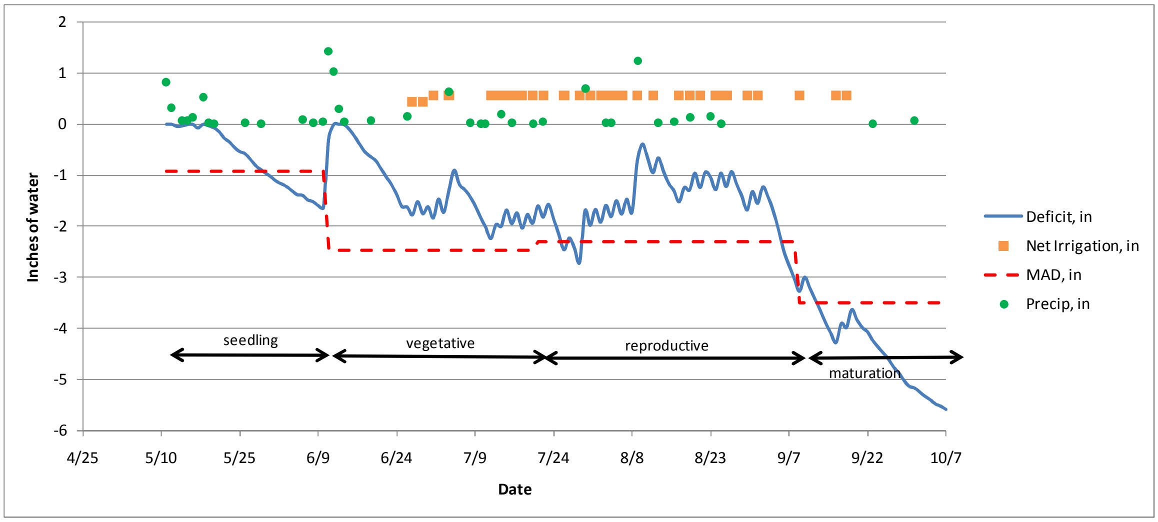

Figure 3. Soil water deficit, net irrigation, and precipitation in a center pivot-irrigated corn field near Greeley, CO during the 2010 growing season. Daily values of corn ET_c estimated from equation 4 were used to estimate daily soil water deficit (equation 2).

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UTILIZING SOIL MOISTURE READINGS IN IRRIGATION SCHEDULING

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BACKGROUND

Need to Check Soil Moisture

Irrigation scheduling is deciding when and how much to irrigate. A variety of procedures are available, but all involve monitoring of some indicator(s) to determine irrigation need. Checking soil moisture content is one of the most common procedures. This can range from kicking clods, turning it with a shovel, pulling cores with a soil probe, using the ‘appearance and feel method’ to estimate soil water content, or using sensors to measure soil moisture.

Crop water use or ET methods of irrigation scheduling also require periodic checks of soil moisture. These are commonly referred to as the water budget or ‘checkbook method’ of irrigation scheduling. However, it is important to validate the ‘checkbook balance’ at least every one or two weeks by comparing it to field-measured soil moisture. If there is a discrepancy, reconcile the ‘checkbook balance’ by using the measured soil moisture content going forward.

Types of Soil Moisture Readings

Soil moisture measurements can be obtained many ways, some more readily than others. However, effective use of soil moisture readings requires experience and judgment . . . and, in many cases, just good old common sense. They are another tool, another source of information. They should be duly evaluated and considered before relying upon them for critical decisions.

Some measurements are semi-qualitative while others provide greater quantitative accuracy. Several of the more common and well known are included below.

Method	Advantages	Disadvantages
Appearance and Feel	Easy, simple, accuracy improves with experience.	Lower accuracy, labor intensive.
Gravimetric (oven drying)	High accuracy with increased sampling, direct measure.	Very labor intensive, delays to obtain data.
Tensiometers (soil moisture tension)	Instantaneous, approximates soil moisture content.	High maintenance, tension breaks, freezing temperatures.
Electrical Resistance (soil matric potential)	Instantaneous, increased range, approximates soil moisture content.	Slower response, less sensitive at low moisture, affected by soil salinity.
Capacitance and FDR (frequency domain)	High accuracy, volumetric water content and salinity.	Highly influenced by adjacent moisture/voids.
TDR and TDT (time domain)	High accuracy, volumetric water content and salinity, robust calibration.	Highly influenced by adjacent moisture/voids.
Water Budget or Checkbook	Estimates the soil moisture balance.	Needs calibration and periodic adjustments.
Neutron Probe	High accuracy, relative ease of deep readings, repeatable.	High cost, regulatory requirements.

METHODS AND PROCEDURES

Quantity vs. Quality

Regardless of the method utilized to measure soil moisture, it is critical the irrigator understand that one measurement is almost never representative of the entire field. A single soil moisture measurement is for one point at a given time. It cannot reasonably be assumed to represent the entire field. It is essential to obtain additional measurements. However, this does not mean that purchasing more hardware is always required.

The ‘checkbook method’ is inherently an average for the field, but it does need the periodic ‘reality check’ to make sure it is representative of soil moisture levels in the field. This can be accomplished by hand probing and use of the ‘appearance and feel method’. It could also utilize an automated soil moisture monitoring station sited in a representative area of the field. Significant improvements in soil moisture sensors have occurred in recent years, making them more accurate, reliable, and economical.

Selecting Locations

Placement of soil moisture sensors is very important. For representative readings the sensor must typically be installed in the principle soil type, within the active crop root zone, and avoiding high spots, slope changes, or depressions where runoff may collect. If the sensor requires periodic visits for service or to obtain readings, it is also important for it to be reasonably accessible.

Insertion or Slurry Bedding of Sensors

It is not okay to simply dig a hole and backfill around a soil moisture sensor. Destruction of roots and soil structure must be minimized. Water settling is also taboo. For soil moisture sensors to provide accurate readings, they must be in full direct contact with undisturbed soil whenever possible. Air voids, large roots, rocks, etc. must be avoided. Direct, clean insertion of sensors into naturally consolidated soil is typically preferred. It provides for near immediate availability of representative moisture readings.

However, sometimes the soil is too dry, hard, or gravelly to safely allow installation by insertion, even with a pilot slot or hole. The soil would then be screened, mixed into a slurry (consistency of thick pudding) and the sensor installed undamaged with full soil contact, howbeit not natural and undisturbed. However, it may be some time before this excess moisture is depleted, especially at greater depths and in heavier soils. Several weeks may pass before the sensor will provide readings representative of field conditions. The deeper the sensor is to be installed, generally the greater the difficulty with proper installation.

Avoiding the potential for preferential flow of surface water to the sensor is very important. Small surface mounding of soil around the sensor to avoid surface puddling, good compaction and sealing around wires, etc. will help prevent extra water from reaching the sensor and falsely elevating the readings.

Protection of Sensors

Unnecessary replacement of hardware should be avoided. Besides the expense of purchasing and re-installing replacement equipment, the desired soil moisture information is also lost for some period of time.

‘Losing’ the location of sensors installed in tall corn because of poor flagging and mapping is expensive (and embarrassing), especially when eventually ‘found’ by the silage cutter. Inexpensive hand-held GPS units are a great tool for preventing such mishaps.

Tensiometers are liquid filled and will freeze and break if installed too early in the spring or left in the field too late in the fall. Always use distilled water and the anti-bacterial dye provided by the manufacturer to prevent plugging of the ceramic tip.

Rodents (and even deer) love to chew on exposed sensor wires, etc. Placing them inside PVC conduit or braided stainless steel sheathing has proven effective. Rodents have been known to tunnel adjacent to sensors installed at shallow depths and wreak havoc in multiple ways.

If a field is grazed after harvest and sensors are left over-winter, the sensors must be protected from damage. This is not unusual in alfalfa hay fields. Be sure the ‘protection’ does not alter the soil moisture conditions from being representative of the rest of the field. A sensor station fenced off will often become drier because of taller vegetation and increased crop water use during the shoulder seasons.

Automated Soil Moisture Stations

Installation of an automated soil moisture station can provide continuous measurement of soil moisture levels. When the data is processed graphically, the changes in soil moisture due to extraction by the crop and replenishment by rainfall and irrigation are readily grasped and understood. With sensors at multiple depths, the slow drying of the deeper soil levels typical under many center-pivot sprinklers becomes evident.

The benefits of utilizing sensors that provide accurate *volumetric* measurement of soil moisture is readily realized with automated stations. The calculated soil moisture balance directly reflects the depth of effective rainfall, the net depth of applied irrigation by a center pivot sprinkler, etc. This direct correlation to known events helps strengthen grower confidence in the equipment and procedures.

When coupled with radio telemetry, this information can be available to the irrigator 24/7. When he needs to make an irrigation decision, the real-time status of soil moisture levels is at his fingertips. This is a great advantage, but one that comes at some cost. Not all irrigators are equally motivated to adopt these improved practices, even when subsidized, whole or in part.

THE NORTHERN WATER EXPERIENCE

Manual Readings

Beginning in 1982, Northern Water provided a limited irrigation scheduling service for area producers. The program was intended to be educational and assist producers for only one to two years in a couple of their fields. These demonstrations used the 'checkbook method' coupled with soil moisture readings obtained from tensiometers. The program proved popular but was limited to the number of fields a single technician could service each week to manually obtain the soil moisture readings.

Automated Monitoring

The program evolved to include automated soil moisture monitoring stations. Sensors were installed in each of the four top feet of root zone and connected to a small data logger with battery and solar panel. Data was downloaded as frequently as once per day via cellular phone telemetry. Graphical summary reports were routinely provided to growers via email.

Although the computer programs utilized the 'checkbook' method of maintaining a soil water balance, that balance was 'reconciled' at the end of each day with the soil water content measured by the soil moisture sensors. The procedure was heavily weighted to follow the sensor readings. However, the crop water use information obtained from local weather stations did fill-in periods when soil moisture data was not available, such as early in the spring or late in the fall. It also provided estimates or predictions of future crop water use for trending, etc.

Unfortunately, the staff position at Northern Water necessary to continue this irrigation scheduling service was eliminated in 2007. Local soil conservation districts have expressed interest in continuing similar services for their producers.

Summary and Conclusions

Historically, advanced irrigation scheduling has not been for everyone. Many times, simpler methods seemed wholly satisfactory. However, increasing pressures are directed towards irrigated agriculture to produce more, with reduced inputs, and without cost increases to consumers. It is highly unlikely this can be attempted without utilizing the best available tools, including advanced methods of irrigation scheduling. Fortunately, improved methods and better equipment are available today than was available just a few years ago.

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CORN PRODUCTION WITH SPRAY, LEPA, AND SDI

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ABSTRACT

Corn is a major irrigated crop in the U.S. Great Plains with a large irrigation requirement making efficient, effective irrigation technology important. The objective of this paper was to compare corn productivity for different irrigation methods and irrigation rates in 2009 and 2010 at Bushland, Texas. Irrigation methods included mid-elevation spray application (MESA), low elevation spray application (LESA), low energy precision application (LEPA), and subsurface drip irrigation (SDI). Each irrigation method was evaluated at four irrigation rates, which were 25, 50, 75, and 100% of meeting the full crop water requirement. There were no significant differences in grain yield and water use efficiency for MESA, LESA, and SDI for the 100% irrigation rate in 2009 and for all irrigation rates in 2010. In 2009, SDI resulted in significantly greater grain yield and water use efficiency compared with all other methods at the 50 and 75% irrigation rates; little measurable grain yield resulted for all methods at the 25% rate. However, 2009 was not a typical production year because an irrigation system failure occurred just before anthesis, and unusually high atmospheric demands followed, resulting in soil water shortages in all plots during the most water-sensitive development stages, with consistent lowering of grain yield. In both years, LEPA resulted in lower yield, soil water content, and water use efficiency compared with the other methods at the 75 and 100% rates, which was partially attributed to furrow dike erosion and plot runoff. The relative response of corn to MESA, LESA, LEPA, and SDI was much different compared with other crops that were evaluated in previous experiments; these included grain sorghum, soybean, and cotton.

INTRODUCTION

Grain corn is a major irrigated crop in the U.S. Great Plains that has been mostly produced for beef cattle feed and more recently as a feedstock for ethanol. In the semiarid Southern High Plains, nearly all corn production requires irrigation and is dependent on pumping from the Ogallala Aquifer, which has been declining since large-scale development of irrigation in the region because pumping has exceeded recharge. Within the Texas portion of the Southern High Plains, approximately 75 percent of the irrigated area is with center pivot sprinklers, with the remaining 20 and 5 percent comprising gravity (i.e., furrow water) and subsurface drip irrigation (SDI), respectively (Colaizzi et al., 2009).

Most SDI has been installed in the cotton producing region centered around Lubbock, Texas. For both full and deficit irrigation rates, cotton lint yield and water use efficiency have been shown to be consistently greater for full and deficit irrigation rates under SDI compared with sprinklers, including both mid elevation spray application (MESA) and low elevation spray application (LESA) configurations. Cotton response to low energy precision application (LEPA) has also been more favorable compared with MESA or LESA, but still not as favorable as SDI (Bordovsky and Porter, 2003; Colaizzi et al., 2010). This is thought to be related to SDI maintaining warmer soil temperatures near the surface because less evaporative cooling occurs relative to MESA, LESA, or LEPA, which apply water directly to the soil surface and/or plant canopy (Colaizzi et al., 2010). Sufficiently warm soil and plant microclimate is critical for cotton production in semiarid regions with high elevations because cool nighttime temperatures usually occur throughout the year. Other studies have shown that SDI resulted in greater grain yield and water use efficiency for grain sorghum (Colaizzi et al., 2004) and soybean (Colaizzi et al., 2010) at deficit irrigation rates because lower evaporative losses for SDI relative to sprinklers resulted in greater soil water being available for plant transpiration, which was also observed for cotton. As irrigation well capacities decline, Great Plains producers are increasingly being forced to adopt deficit irrigation strategies. Since SDI has been shown to increase crop water productivity relative to MESA, LESA, and LEPA at deficit irrigation rates for some crops, there has been continued adoption of SDI in the Great Plains (USDA-NASS, 2008).

Corn response to various rates of deficit and full irrigation has been evaluated in the Great Plains using sprinkler irrigation (Howell et al., 1989; 2002; Payero et al., 2006), LEPA (Howell et al., 1995), and SDI (Howell et al., 1997; Lamm, 2004; Payero et al., 2009). However, it appears that only Schneider and Howell (1998) and Lamm (2004) directly compared corn response to different irrigation methods, where the irrigation system itself was a randomized and replicated treatment. Schneider and Howell (1998) compared spray and LEPA, and Lamm (2004) was limited to SDI vs. simulated LEPA, where water for the simulated LEPA treatment was applied by stationary tubing into furrow basins. No study has directly compared corn production under SDI with moving spray or LEPA packages commonly used with center pivots in the Great Plains. The objective of this research was to compare corn water productivity using MESA, LESA, LEPA, and SDI across a range of irrigation rates.

EXPERIMENTAL PROCEDURE

This research was conducted at the USDA Agricultural Research Service Conservation and Production Research Laboratory at Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 3,900 ft elevation above mean sea level). The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2011) with slow permeability due to a dense B21t horizon that is 6 to 20 inches below the surface. A calcic horizon begins at approximately 4 ft below the surface.

The relative performance of MESA, LESA, LEPA, and SDI were compared for irrigation rate treatments ranging from near dryland to meeting full crop evapotranspiration (ETc) in a strip-split block design. The irrigation rate treatments were designated I_0, I_{25}, I_{50}, I_{75}, and I_{100}, where the subscripts were the percentage of irrigation applied relative to meeting full ETc. The I_0 plots were similar to dryland production, in that they received only enough irrigation around planting to ensure crop establishment; but irrigated fertility and seeding rates were used. Each rain event was measured manually by a gauge located at the field site. Each plot was 30 ft wide by 39 ft long and contained 12 raised beds with east-west orientation and 30-inch centers, with the crop planted in the centers of the raised beds. Dikes were installed in all furrows following emergence to control run on and runoff of irrigation water and rain (Schneider and Howell, 2000; Howell et al., 2002).

The MESA, LESA, and LEPA methods (see Table 1 for details on application devices) were applied with a hose-fed, three-span lateral-move irrigation system, where each span contained a complete block (i.e., a replicate), resulting in three replications for each treatment. The LEPA method used double-ended drag socks in 2009; however, the drag socks were sometimes caught by plants and pulled off as the drop moved through after plants reached heights of about 5 ft, resulting in excessive furrow dike erosion. Several attempts to lower the height and strengthen the drag sock connection were not successful. Therefore, the LEPA treatment used low-impact bubblers without socks in 2010. Irrigation rate treatments were imposed by varying the speed of the lateral-move. The SDI method consisted of drip laterals installed with a shank injector beneath alternate furrows at the 12-inch depth, where irrigation treatments were imposed by varying emitter flow rates and spacing (Table 2).

Corn (Pioneer 33B54 BT, RR[1]) was planted in the 2009 and 2010 seasons. Cultural practices were similar to those practiced in the region for high crop yields (Table 3). Volumetric soil water was measured by gravimetric samples to the 6-ft depth in 1-ft increments at planting and harvest. Soil water was also measured during the crop season by neutron probe (NP) to the 10-ft depth in 8-inch increments (Evett and Steiner, 1995) using a depth control stand, which allowed accurate measurement of soil water at shallow (4-inch) depths (Evett et al., 2003). The NP meters were field-calibrated and achieved accuracies better than 0.005 $in.^3$ $in.^{-3}$, including the 4-inch depth near the surface. Both gravimetric and NP were measured near the center of each plot (i.e., sixth row from the south and 20 ft from plot edge) and in the center of the raised bed.

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[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Table 1. Sprinkler irrigation application device information [a].

Applicator	Model [b]	Options	Applicator height from furrow surface (ft)
LEPA, 2009	Super Spray head	Double-ended drag sock [c]	0
LEPA, 2010	Quad spray	Bubbler	1.0
LESA	Quad IV	Flat, medium-grooved spray pad	1.0
MESA	Low-drift nozzle (LDN) spray head	Single, convex, medium-grooved spray pad	5.0

[a] All sprinkler components manufactured by Senninger Irrigation, Inc., Orlando, Fla., except where noted.

[b] All devices equipped with 10 psi pressure regulators and No. 17 (0.27-inch) plastic spray nozzles, giving a flow rate of 6.5 gpm.

[c] Manufactured by A. E. Quest and Sons, Lubbock, Tex.

Table 2. Subsurface drip irrigation (SDI) dripline information [a].

Irrigation rate	Emitter Flow Rate (gph)	Emitter Spacing (in.)	Emitter Application Rate (in. h^{-1})
I_0 [b]	--	--	--
I_{25}	0.18	36	0.019
I_{50}	0.24	24	0.038
I_{75}	0.24	16	0.057
I_{100}	0.24	12	0.076

[a] All SDI dripline manufactured by Netafim USA, Fresno, Calif.

[b] Smooth tubing, no emitters

Irrigations were scheduled based on NP measurements, usually at weekly intervals during the irrigation season. Early in the season, irrigation water was applied when the average soil water deficit in the root zone of the I_{100} treatment reached 1.0 inch below field capacity, where field capacity was 4.0 inches per ft (0.33 in.^{3} in.$^{-3}$) of the soil profile. From about the middle of the vegetative stage (10-leaf) to termination of irrigations, the appropriate irrigation amount was applied on a weekly basis in 1.0-inch increments to avoid over-filling the furrow dike basins. All sprinkler plots were irrigated on the same day, with the deficit (I_{25}, I_{50}, and I_{75}) treatments receiving proportionately less water by increasing the speed of the lateral move system. The SDI plots had the same amount of water applied as the sprinkler plots except the duration of each irrigation event was longer.

Table 3. Agronomic and irrigation data for the 2009 and 2010 seasons.

Variable	2009	2010
Fertilizer applied	150 lb ac^{-1} preplant N 130 lb ac^{-1} preplant P 240 lb ac^{-1} irr N (I_{100}) [a]	150 lb ac^{-1} preplant N 65 lb ac^{-1} preplant P 150 lb ac^{-1} irr N (I_{100}) [a] 90 lb ac^{-1} preplant S
Herbicide applied	2.0 qt ac^{-1} Bicep	1.5 lb ac^{-1} Atrazine
Insecticide applied	NONE	NONE
Gravimetric soil water samples	30-Apr 5-Nov	20-May 6-Oct
Corn variety	Pioneer 33B54 BT, RR	Pioneer 33B54 BT, RR
Plant density	35,000 seeds ac^{-1}	35,700 seeds ac^{-1}
Planting date	29-Apr	12-May
Harvest date	15-Sep	15-Sep
Preplant irrigation	3.0 inches	0.8 inches
First treatment irrigation	1-Jun	11-Jun
Last irrigation	28-Aug	26-Aug
I_0 irrigation [b]	3.0 inches	1.8 inches
I_{25} irrigation [b]	7.2 inches	7.1 inches
I_{50} irrigation [b]	11.4 inches	12.2 inches
I_{75} irrigation [b]	15.6 inches	17.5 inches
I_{100} irrigation [b]	19.7 inches	22.8 inches
Precipitation	10.0 inches	8.7 inches

[a] Liquid urea 32-0-0 injected into irrigation water; deficit irrigation treatments received proportionately less.

[b] Includes preplant irrigation

Grain yield, final plant population, kernel mass, number of ears, and kernels per ear were determined by hand harvesting two adjacent rows along a 21.5 ft length in the center of each plot (resulting in a 107.5 ft^2 sample area). Ears were shelled by hand and kernels were oven dried at 160°F for 5 days. Dry yield mass was converted to 15.5 percent moisture (wet basis), and reported as volume (i.e., 56.0 lb. per bu at 15.5% wet basis). Kernel mass was determined from three 500-kernel subsamples, and kernels per ear was calculated as yield mass per area divided by kernel mass divided by ears per area. Yield components, seasonal water use (irrigation applied + precipitation + change in soil water storage), and water use efficiency were compared using the SAS PROC MIXED procedure (Littell et al., 2006). Water use efficiency (bu ac^{-1} $in.^{-1}$) was defined as the ratio of economic yield (Y, bu ac^{-1}) to seasonal water use (ETc, inches) (Bos, 1980). Any differences in these parameters were tested using least squared differences ($\alpha \leq$

0.05), and means were separated by letter groupings using a macro by Saxton (1998).

RESULTS AND DISCUSSION

The 2009 season began with planting on April 29, reaching anthesis on July 8, and black layer by September 3 (Table 4). Hand samples used to determine yield and yield components were obtained on September 15.On June 3 (8 leaf stage), some hail damage occurred, which the plants appeared to have outgrown in two weeks. The tassel and silk stages coincided with high temperatures, high wind speeds, and low relative humidity, resulting in crop evapotranspiration approaching almost 0.50 in. d^{-1} for several days. The unusually high temperatures during silking are believed to have affected pollen viability. Rainfall during the 2009 season totaled 10.0 inches (Table 3), which was somewhat below the 12.3-inch average from April 29 to September 15. In 2010, planting was delayed until May 12 because of cold and wet conditions during the El Niño winter and spring (Table 4). Very warm conditions during May and June resulted in rapid growing degree day accumulation, and the 2010 crop reached anthesis near the same time as the 2009 crop. The 2010 crop reached black layer by September 8, and hand samples were obtained on September 15. Total rainfall during the season was 8.7 inches (Table 3), which was also below average.

Table 4. Dates and cumulative growing degree days (GDD) for corn development stages, where GDD were computed using baseline and maximum temperatures of 50 and 86 °F, respectively.

	2009		2010	
	Date	GDD (°F)		GDD (°F)
Plant	29-Apr	0	12-May	0
Emerged	13-May	158	28-May	258
4-leaf	21-May	277	3-Jun	387
5-leaf	25-May	339	5-Jun	433
6-leaf	28-May	378	8-Jun	515
8-leaf	3-Jun	484	11-Jun	591
10-leaf	12-Jun	668	14-Jun	664
12-leaf	15-Jun	739	17-Jun	737
14-leaf	4-Jul	1206	5-Jul	1184
Tassel	8-Jul	1298	10-Jul	1290
Silk	15-Jul	1481	15-Jul	1422
Blister	21-Jul	1626	23-Jul	1630
Milk	30-Jul	1817	28-Jul	1753
Dough	4-Aug	1929	6-Aug	1981
Dent	11-Aug	2109	12-Aug	2137
Black layer	3-Sep	2623	8-Sep	2758

Grain yields in 2009 were much lower than expected except for the MESA, LESA, and SDI methods at the I_{100} irrigation rate (Table 5). There was essentially no yield for all irrigation methods at the I_0 and I_{25} rates, and only SDI resulted in more than 10 bu ac^{-1} at the I_{50} rate. At the I_{75} rate, MESA, LESA, and LEPA resulted in less than 100 bu ac^{-1}, and SDI only 188.8 bu ac^{-1}. Previous studies at our location using LEPA at the I_{80} rate and SDI at the I_{67} rate resulted in 200 to 235 bu ac^{-1} (Howell et al., 1995; 1997). Grain yield was reduced in 2009 mainly from failure of ears to produce kernels, as numerous blank cobs were observed. Final plant population and kernel mass, however, were as expected and were similar to those reported at Bushland, Texas (Howell et al., 1995; 1997) and at Colby, Kansas (Lamm, 2004). Seasonal water use was less for SDI at I_{25} and I_{50} compared with the other methods, resulting in greater water use efficiency. At I_{75}, there were no differences in seasonal water use; at I_{100}, LEPA used 1.5 to 2.0 inches more than the other methods. Overall, seasonal water use was similar to that reported in previous studies (Howell et al., 1995; 1997), but since grain yield was relatively low, water use efficiency was also relatively low except for MESA, LESA, and SDI at I_{100} and SDI at I_{75}.

In 2010, most grain yields were similar to previous studies (Howell et al., 1995; 1997) at the I_{75} and I_{100} rates, and greater than expected at the I_{25} and I_{50} rates (Table 6). However, grain yield using LEPA was significantly less compared with the other methods at the I_{75}, and I_{100} rates. The low grain yield using LEPA was inconsistent with previous studies at our location (e.g., Howell et al., 1995; Schneider and Howell, 1998). As discussed later, although soil water depletion in the LEPA method was greater compared with the other methods, it did not appear to be enough in the I_{100} rate to cause yield-reducing water stress. At I_{50}, grain yield for MESA was similar to LEPA. Grain yield differences were related to both kernel mass and kernels per ear; these yield components were within the expected ranges. Plant population was slightly greater for LEPA at I_{50}, I_{75}, and I_{100} rates. For each irrigation rate, there were no differences in seasonal water use among irrigation methods. Therefore, water use efficiency followed nearly the same trends as grain yield, with LEPA having less water use efficiency compared with the other irrigation methods.

The kernel set failure observed in 2009 was likely the result of water shortages in the soil profile during anthesis, which coincided with very high atmospheric demand and high temperatures. The soil water shortages were due to irrigation system operational problems followed by unusually high crop water demand. The combination of greater sensitivity to water stress during anthesis (e.g., Payero et al., 2009) and greater atmospheric demand would both serve to decrease the readily available soil water in the root zone (RAW), as defined by FAO 56 (Allen et al., 1998). If soil water depletion in the root zone exceeds RAW, the crop experiences water stress, which may reduce yield. This is illustrated by comparing RAW with measured soil water depletion in the root zone during the season (Fig. 1). Also shown is the total available soil water in the root zone

Table 5. Corn response for 2009 season.

Irrig. rate [a]	Irrig. method	Grain yield 15.5% wb [b] bu ac^{-1}		Final plant pop. plants ac^{-1}		Kernel mass mg		Kernels per ear		Seasonal water use inches		Water use efficiency bu ac^{-1} in^{-1}	
I$_{25}$ (7.2)	MESA	0.0	a [c]	34,143	a	0	b	0	b	15.3	ab	0.0	a
	LESA	0.0	a	33,603	a	0	b	0	b	15.7	ab	0.0	a
	LEPA	0.3	a	32,793	a	0	b	0	b	16.6	a	0.0	a
	SDI	3.6	a	33,198	a	105	a	567	a	14.8	b	0.2	a
I$_{50}$ (11.4)	MESA	7.5	b	33,333	a	322	a	26	b	19.9	ab	0.4	b
	LESA	8.8	b	32,928	a	307	a	29	b	20.7	ab	0.4	b
	LEPA	8.9	b	34,008	a	301	a	50	b	21.4	a	0.4	b
	SDI	70.9	a	33,738	a	310	a	186	a	19.8	b	3.6	a
I$_{75}$ (15.6)	MESA	37.5	c	34,278	a	341	a	89	c	24.1	a	1.5	c
	LESA	77.3	b	32,659	a	347	a	186	b	24.7	a	3.1	b
	LEPA	30.1	c	33,873	a	312	a	96	c	25.2	a	1.2	c
	SDI	188.8	a	33,468	a	357	a	433	a	25.4	a	7.4	a
I$_{100}$ (19.7)	MESA	214.9	a	34,683	a	348	a	477	ab	28.0	b	7.7	a
	LESA	235.5	a	33,873	a	349	a	525	a	28.5	b	8.3	a
	LEPA	103.0	b	33,198	a	349	a	256	b	30.2	a	3.4	b
	SDI	233.0	a	34,413	a	348	a	527	a	28.5	b	8.2	a
Irrigation rate averages													
I$_{0}$ (3.0)		0.0	c [d]	30,769	b	0	c	0	b	10.5	e	0.0	c
I$_{25}$ (7.2)		1.0	c	33,434	a	26	c	142	b	15.6	d	0.1	c
I$_{50}$ (11.4)		24.0	c	33,502	a	310	b	73	b	20.4	c	1.2	c
I$_{75}$ (15.6)		83.4	b	33,570	a	339	a	201	b	24.8	b	3.3	b
I$_{100}$ (19.7)		196.6	a	34,042	a	349	a	446	a	28.8	a	6.9	a
Irrigation method averages													
	MESA	65.0	bc [e]	34,109	a	253	ab	148	b	21.8	b	2.4	bc
	LESA	80.4	b	33,266	a	251	ab	185	b	22.4	ab	3.0	b
	LEPA	35.5	c	33,468	a	240	b	100	b	23.3	a	1.3	c
	SDI	124.1	a	33,704	a	280	a	428	a	22.1	b	4.9	a

[a] Numbers in parenthesis are seasonal irrigation totals for each irrigation rate (inches).

[b] Yields were converted from dry mass to 15.5 percent moisture content by mass (wet basis) and 56.0 lb bu^{-1}.

[c] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within an irrigation rate.

[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation rate averages.

[e] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation method averages.

Table 6. Corn response for 2010 season.

Irrig. rate [a]	Irrig. method	Grain yield 15.5% wb [b] bu ac^{-1}		Final plant pop. plants ac^{-1}		Kernel mass mg		Kernels per ear		Seasonal water use inches		Water use efficiency bu ac^{-1} in^{-1}	
I_{25}	MESA	90.1	a [c]	35,088	a	207	bc	328	a	18.2	a	5.0	a
(7.1)	LESA	101.9	a	34,548	a	217	ab	363	a	18.2	a	5.6	a
	LEPA	90.7	a	35,088	a	228	a	309	a	18.1	a	5.0	a
	SDI	82.6	a	34,008	a	193	c	349	a	17.8	a	4.7	a
I_{50}	MESA	180.1	b	35,223	a	274	b	484	a	22.6	a	8.0	ab
(12.2)	LESA	196.9	ab	34,683	a	284	ab	522	a	22.4	a	8.8	a
	LEPA	175.1	b	35,493	a	276	b	461	a	23.0	a	7.6	b
	SDI	202.3	a	34,278	a	296	a	522	a	22.6	a	9.0	a
I_{75}	MESA	233.5	a	33,603	b	316	a	574	a	27.7	a	8.5	a
(17.5)	LESA	231.0	a	34,008	ab	322	a	556	a	27.1	a	8.5	a
	LEPA	194.3	b	36,167	a	309	a	453	b	28.0	a	7.0	b
	SDI	237.5	a	35,088	ab	316	a	562	a	26.9	a	8.8	a
I_{100}	MESA	246.7	a	34,008	ab	326	b	575	a	31.6	a	7.8	a
(22.8)	LESA	235.4	a	32,659	b	348	a	557	ab	32.1	a	7.3	a
	LEPA	195.3	b	35,762	a	291	c	489	b	32.2	a	6.1	b
	SDI	249.1	a	34,278	ab	333	ab	565	a	32.1	a	7.8	a
Irrigation rate averages													
I_0 (1.8)		18.5	d [d]	33,828	a	194	c	140	c	13.3	e	1.4	d
I_{25} (7.1)		91.3	c	34,683	a	211	c	337	b	18.1	d	5.1	c
I_{50} (12.2)		188.6	b	34,919	a	282	b	497	a	22.6	c	8.3	a
I_{75} (17.5)		224.1	a	34,717	a	316	a	536	a	27.4	b	8.2	a
I_{100} (22.8)		231.6	a	34,177	a	325	a	547	a	32.0	a	7.2	b
Irrigation method averages													
	MESA	187.6	a [e]	34,481	a	281	ab	490	ab	25.0	a	7.3	a
	LESA	191.3	a	33,974	a	293	a	500	a	24.9	a	7.6	a
	LEPA	163.9	b	35,628	a	276	b	428	b	25.4	a	6.4	b
	SDI	192.9	a	34,413	a	284	ab	500	a	24.8	a	7.6	a

[a] Numbers in parenthesis are seasonal irrigation totals for each irrigation rate (inches).

[b] Yields were converted from dry mass to 15.5 percent moisture content by mass (wet basis) and 56.0 lb bu^{-1}.

[c] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within an irrigation rate.

[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation rate averages.

[e] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation method averages.

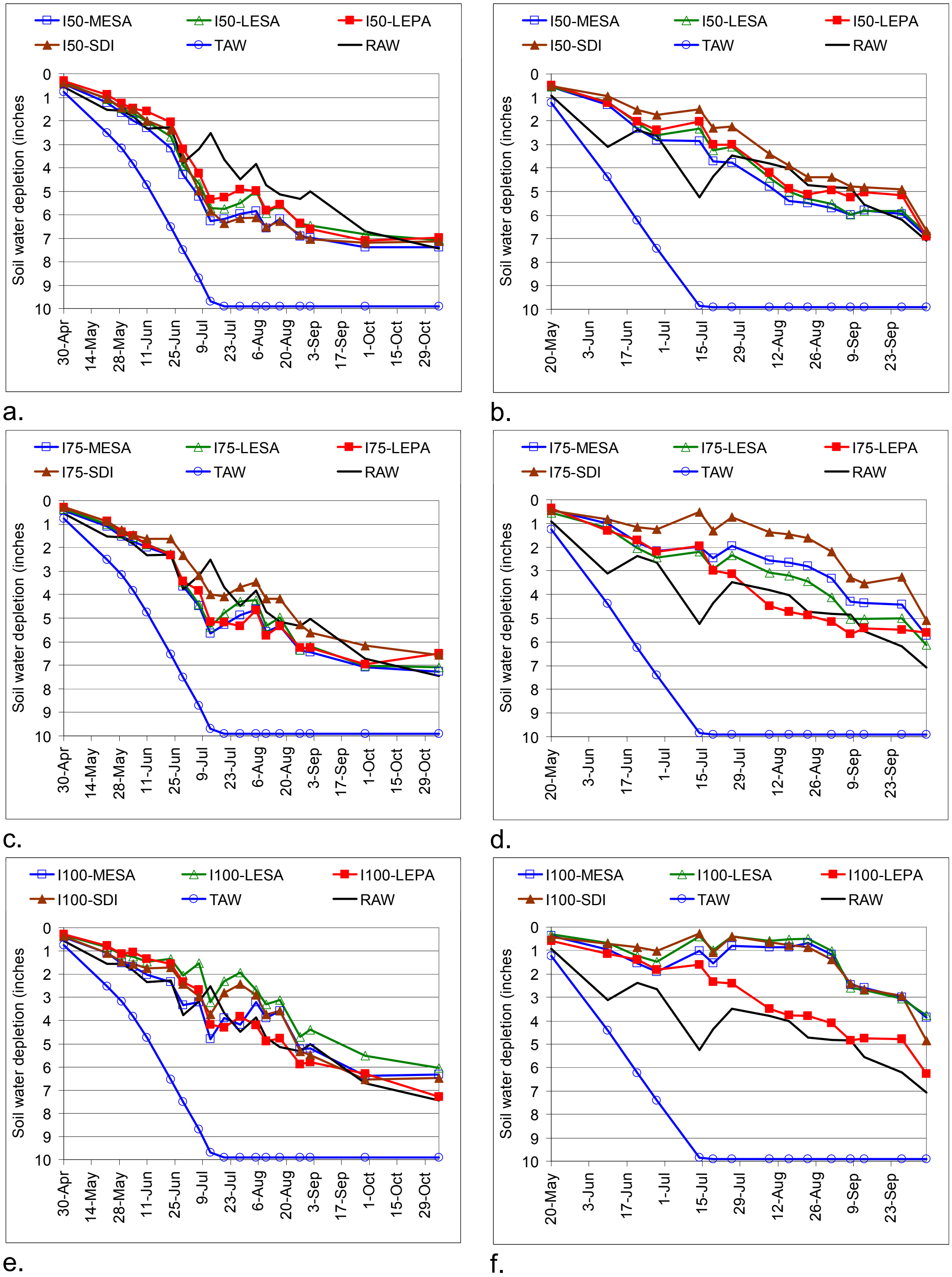

Figure 1. Soil water depletion, total available soil water (TAW), and readily available soil water (RAW) in the root zone for (a) 2009 I_{50}; (b) 2010 I_{50}; (c) 2009 I_{75}; (d) 2010 I_{75}; (e) 2009 I_{100}; (f) 2010 I_{100}.

(TAW). Assuming a maximum root depth of 6 ft, the Pullman clay loam soil at the study location has about 10.0 inches of maximum TAW, with the lower and upper limits of plant extractable water at 14.0 (~0.19 $in.^3$ $in.^{-3}$) and 24.0 inches (~0.33 $in.^3$ $in.^{-3}$), respectively (USDA-NRCS, 2011). RAW is generally around 50 percent of TAW for most crops including corn during the growing season. However, RAW depends on crop species and the soil water – matric potential relationship, and varies with time according to crop growth stage and atmospheric demand. RAW can be adjusted from a base value in terms of ETc, which accounts for the crop growth stage and atmospheric demand. The FAO 56 procedure recommends that RAW be increased if ETc exceeds 0.20 in. d^{-1}, and decreased if ETc is below this value. The resulting RAW was computed using a daily soil water balance based on FAO 56 procedures, and shown on days when soil water contents were measured in 2009 and 2010 (Fig. 1).

Soil water depletion and RAW were different in the two seasons evaluated (Fig. 1). In 2009, soil water depletion generally increased throughout the season. Soil water depletion in the I_{100} irrigation rate was below RAW until around silking (July 15), but then increased (Fig. 1e). At that time, high temperatures (over 100°F) and winds (40 mph gusts) resulted in ETc reaching almost 0.50 in. d^{-1} (data not shown). Consequently, the adjustment to RAW using the FAO 56 procedure resulted in RAW decreasing from almost 4.0 to 2.5 inches. Since soil water depletion was greater than RAW, the crop would have experienced water stress that likely reduced yield, especially since the water stress occurred during anthesis. Later in July, the unusually high atmospheric demand abated, and soil water depletion fell below RAW in all irrigation methods except LEPA. As expected, soil water depletion in the I_{75} (Fig. 1c) and I_{50} (Fig. 1a) irrigation rates were even greater compared with I_{100}. In 2010, soil water depletion in the I_{100} irrigation rate was well below RAW throughout the season except for LEPA (Fig. 1f). In contrast to 2009, RAW increased to over 5.0 inches around anthesis (July 10) in 2010 due to low atmospheric demand from relatively cool and wet conditions. Soil water depletion at I_{100} in 2010 (MESA, LESA, and SDI; Fig. 1f) generally varied about the 1.0-inch level until irrigations were terminated (August 26). This reflected the intended full irrigation treatment, which unfortunately was not achieved in 2009 due to irrigation system operational problems followed by high atmospheric demand coinciding with anthesis. Total rainfall plus irrigation for the I_{100} rate in 2009 and 2010 was 29.7 and 31.5 inches, respectively (Table 3, or 1.8 inches less in 2009).

The LEPA grain yield and water use efficiency depressions relative to the other methods may have resulted from runoff from the hand sample areas in the I_{75} and I_{100} rates, which were sometimes indicated by increases in LEPA soil water depletion (Fig. 1). In 2010, the LEPA soil water contents declined below the other methods from July 14 to the end of the season (Figs. 1d and 1f); as noted previously, LEPA grain yields were also significantly less than the other methods at I_{75} and I_{100} (Table 6). Greater furrow dike erosion was observed for the LEPA bubblers (used in 2010) compared with the drag socks (used in 2009). In 2009, initial soil water content for the I_{100} LEPA treatment was greater than the other methods, but this fell below the other methods (i.e., soil water depletion increased) by August (Fig. 1e). Also as noted previously, seasonal water use was significantly greater, but grain yield was significantly less than the other methods (Table 5). This may have also resulted from runoff from the hand sample and neutron access tube areas of the plots. Drag socks were sometimes caught on plants and were pulled from the applicator as the lateral move passed through, resulting in erosion of furrow dikes.

Differences in grain yield and water use efficiency were sometimes correlated to differences in soil water content. The SDI method resulted in the least soil water depletion compared with the other methods for the I_{75} rate in 2009 and the I_{50}, I_{75}, and I_{100} rates in 2010, which was not surprising since losses to evaporation should be minimized with SDI (Fig. 1). However, SDI resulted in significantly greater grain yield compared with the other methods only for I_{50} and I_{75} in 2009, and SDI grain yield was similar to MESA and/or LESA for I_{50} and I_{75} in 2010 and I_{100} in 2009 and 2010 (Tables 5 and 6). One anomalous result that could not be explained in terms of soil water content occurred in 2009 for the I_{50} rate. Here, soil water depletion was the least for LEPA during most of the season, but soil water depletion for SDI was similar to or greater than MESA and LESA (Fig. 1a). However, only SDI had appreciable grain yield (Table 5). Also, at the I_{25} rate in 2010 (Table 6), there were no significant differences in grain yield or water use efficiency among irrigation methods, and SDI resulted in numerically the least grain yield and water use efficiency compared with the other methods as kernel mass was significantly the least. The only apparent differences in soil water depletion for the I_{25} rate were observed for MESA, which was around 0.75 inches greater than the other methods by the end of the season (data not shown). This was in sharp contrast to other crops, where SDI consistently resulted in greater yield and water use efficiency compared with other methods at the I_{25} rate, as described next.

Corn response to different irrigation methods was vastly different from the responses of grain sorghum, soybean, and cotton, which were evaluated in previous experiments (Colaizzi et al., 2004; 2010). To review, there were three main aspects of grain yield differences for corn, including 1) yield being much lower than expected in 2009 for deficit irrigation rates; 2) yield depressions for LEPA relative to the other irrigation methods; and 3) yield being much greater for SDI compared with the other methods for I_{50} and I_{75} (2009 only). These differences could be explained mostly in terms of differences in soil water contents and the timing of soil water shortages (except for SDI at the I_{50} rate in 2009). Four seasons of cotton were also evaluated in a previous experiment (Colaizzi et al., 2010). At all irrigation rates, SDI consistently resulted in the largest lint yield compared with all other methods, and LEPA consistently out-yielded MESA and LESA. For three seasons of grain sorghum and one season of soybean (planted after cotton was destroyed by hail), SDI also resulted in significantly greater yield and water use efficiency compared with all other methods, but only at the I_{25} and I_{50} rates. Also at these rates, grain sorghum and soybean responses were nearly the same for MESA and LEPA, but numerically less for LESA. At the I_{75} and I_{100} rates, however, grain sorghum yield was greater for MESA and LESA compared with LEPA and SDI, which appeared to be related to over irrigation in some years. The grain sorghum, soybean, and cotton evaluations all used LEPA drag socks, and no consistent yield depressions were observed for LEPA compared with the other irrigation methods as were observed for corn. Furthermore, the yield depressions were inconsistent with previous studies of corn irrigated with LEPA at our location (Howell et al., 1995; Schneider and Howell, 1998). The consistently greater lint yield response of cotton for SDI was most likely related to reductions in evaporative cooling of the soil surface compared with the spray methods, as indicated by near-surface soil temperature measurements (Colaizzi et al., 2010). The greater grain yield for sorghum and soybean with SDI compared with the other methods at low (I_{25} and I_{50}) irrigation rates was more likely related to reductions in evaporative losses, as SDI resulted in greater soil water content that could be partitioned to plant transpiration, and these crops are not as thermally-sensitive as cotton.

Finally, although SDI did not result in consistently better corn water productivity compared with the other irrigation methods, it should be noted that small plot studies have limitations in that they cannot represent every situation inherent in large-scale operations. For example, there is anecdotal evidence from producers, extension personnel, and crop consultants that SDI results in field environments less favorable to weeds, pests, and other diseases, which may greatly reduce the costs of herbicides, pesticides, and other inputs, which are significant, especially in light of increasingly stringent environmental regulations. Therefore, although crop water productivity is a key criterion in selecting the most profitable irrigation method, numerous other factors apply. In addition, the results of this study were based on only two seasons using a single corn variety, and the first season clearly represented a worst-case scenario in terms of the sequence of irrigation, crop development, and weather events. As new seed varieties are introduced that are more drought tolerant and disease resistant, it is plausible that they will have different responses in terms of crop water productivity, which will warrant continued field studies in irrigation system comparison.

CONCLUSION

Corn grain yield and water use efficiency were not significantly different among mid-elevation spray application (MESA), low elevation spray application (LESA), and subsurface drip irrigation (SDI) for the full irrigation rate in 2009 and all irrigation rates (I_{25}, I_{50}, I_{75}, and I_{100}, where the subscript is the percentage of full irrigation) in 2010. The SDI method sometimes resulted in greater soil water content compared with MESA or LESA, but this did not always translate to differences in grain yield, apparently because in some cases the soil water contents were sufficient to avoid water stress. The SDI method resulted in significantly greater grain yield and water use efficiency compared with all other irrigation methods only for the I_{50} and I_{75} rates in 2009; however, the 2009 season was not representative of typical conditions because several events resulted in soil water shortages during anthesis, and crop yields were much lower than expected. The low energy precision application (LEPA) method resulted in reduced yield, soil water contents, and water use efficiency compared with the other methods at the I_{75} and I_{100} rates, which appeared to result from furrow dike erosion and runoff from the hand sample and soil water measurement areas of the plots. Corn response to the different irrigation methods was very different from other crops evaluated in previous experiments, which included grain sorghum, soybean, and cotton. In particular, cotton lint yield and water use efficiency were significantly greater for all irrigation rates for SDI compared with all other methods, and LEPA also resulted in consistently better response compared with MESA or LESA.

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Twenty-Two Years of SDI Research in Kansas

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Abstract

This paper will summarize research efforts with subsurface drip irrigation in Kansas that has occurred during the period 1989 through 2010. Special emphasis will be made on brief summaries of the different types of research that have been conducted including water and nutrient management for the principal crops of the region, SDI design parameters and system longevity and economics. Annual system performance evaluations have shown that dripline flowrates are within 5% of their original values. Economic analysis shows that systems with such longevity can be cost competitive even for the lower-valued commodity crops grown in the region.

Introduction and Brief History

Subsurface drip irrigation (SDI) technologies have been a part of irrigated agriculture since the 1960s, but have advanced at a more rapid pace during the last 20 years (Camp et al. 2000). In the summer of 1988, K-State Research and Extension issued an in-house request for proposals for new directions in research activity. A proposal entitled Sustaining Irrigated Agriculture in Kansas with Drip Irrigation was submitted by irrigation engineers Freddie Lamm, Harry Manges and Dan Rogers and agricultural economist Mark Nelson. This project led by principal investigator Freddie Lamm, KSU Northwest Research-Extension Center (NWREC), Colby, was funded for the total sum of

$89,260. This project financed the initial development of the NWREC SDI system that was expressly designed for research. In March of 1989, the first driplines were installed on a 3 acre study site which has 23 separately controlled plots. This site has been in continuous use in SDI corn production since that time, being initially used for a 3-year study of SDI water requirements for corn. In addition, it is considered to be a benchmark area that is also being monitored annually for system performance to determine SDI longevity. In the summer of 1989, an additional 3 acres was developed to determine the optimum dripline spacing for corn production. A small dripline spacing study site was also developed at the KSU Southwest Research-Extension Center (SWREC) at Garden City in the spring of 1989.

In the summer of 1989, further funding was obtained through a special grant from the US Department of Agriculture (USDA). This funding led to expansion of the NWREC SDI research site to a total of 13 acres and 121 different research plots. This same funding provided for a 10 acre SDI research site at Holcomb, Kansas administered by the SWREC. By June of 1990, K-State Research and Extension had established 10 ha of SDI research facilities and nearly 220 separately controlled plot areas.

Over the course of the past 22 years, additional significant funding has been obtained to conduct SDI research from the USDA, the Kansas Water Resources Research Institute, special funding from the Kansas legislature, the Kansas Corn Commission, Pioneer Hi-Bred Inc., the Mazzei Injector Corporation and Syngenta. Funding provided by the Kansas legislature through the Western Kansas Irrigation Research Project (WKIRP) allowed for the expansion of the NWREC site by an additional 1 acres and 46 additional research plots in 1999. An additional 22 plots were added in 2000 to examine swine wastewater use through SDI and 12 plots were added in 2005 to examine emitter spacing. Three research block areas originally used in a 1989 dripline spacing study have been refurbished with new 5 ft spaced driplines to examine alfalfa production and emitter flowrate effects on soil water redistribution. The NWREC SDI research site comprising 19 acres and 201 different research plots is the largest facility devoted expressly to small-plot row crop research in the Great Plains and is probably one of the largest such facilities in the world.

Since its beginning in 1989, K-State SDI research has had three purposes: 1) to enhance water conservation; 2) to protect water quality, and 3) to develop appropriate SDI technologies for Great Plains conditions. The vast majority of the research studies have been conducted with field corn because it is the primary irrigated crop in the Central Great Plains. Although field corn has a relatively high water productivity (grain yield/water use), it generally requires a large amount of irrigation because of its long growing season and its sensitivity to water stress over a great portion of the growing period. Of the typical commodity-type field crops grown in the Central Great Plains, only alfalfa and similar forages would require more irrigation than field corn. Any significant effort to reduce the overdraft of the Ogallala aquifer, the primary water source in the Central Great Plains, must address the issue of irrigation water use by field corn. Additional crops that have been studied at the NWREC SDI site are soybean, sunflower, grain sorghum, alfalfa and demonstration trials of melons and vegetables.

General Study Procedures

This report summarizes several studies conducted at the KSU Northwest and Southwest Research-Extension Centers at Colby and Garden City, Kansas, respectively. A complete discussion of all the employed procedures lies beyond the scope of this paper.

For further information about the procedures for a particular study the reader is referred to the accompanying reference papers when so listed. These procedures apply to all studies unless otherwise stated.

The two study sites were located on deep, well-drained, loessial silt loam soils. These medium-textured soils, typical of many western Kansas soils, hold approximately 18.9 inches of plant available soil water in the 8 ft profile at field capacity. Study areas were nearly level with land slope less than 0.5% at Colby and 0.15% at Garden City. The climate is semi-arid, with an average annual precipitation of 18 inches. Daily climatic data used in the studies were obtained from weather stations operated at each of the Centers.

Most of the studies have utilized SDI systems installed in 1989-90 (Lamm et al., 1990). The systems have dual-chamber drip tape installed at a depth of approximately 16 to 18 inches with a 60-inch spacing between dripline laterals. Emitter spacing was 12 inches and the dripline flowrate was 0.25 gpm/100 ft. The corn was planted so each dripline lateral is centered between two corn rows (Fig. 1).

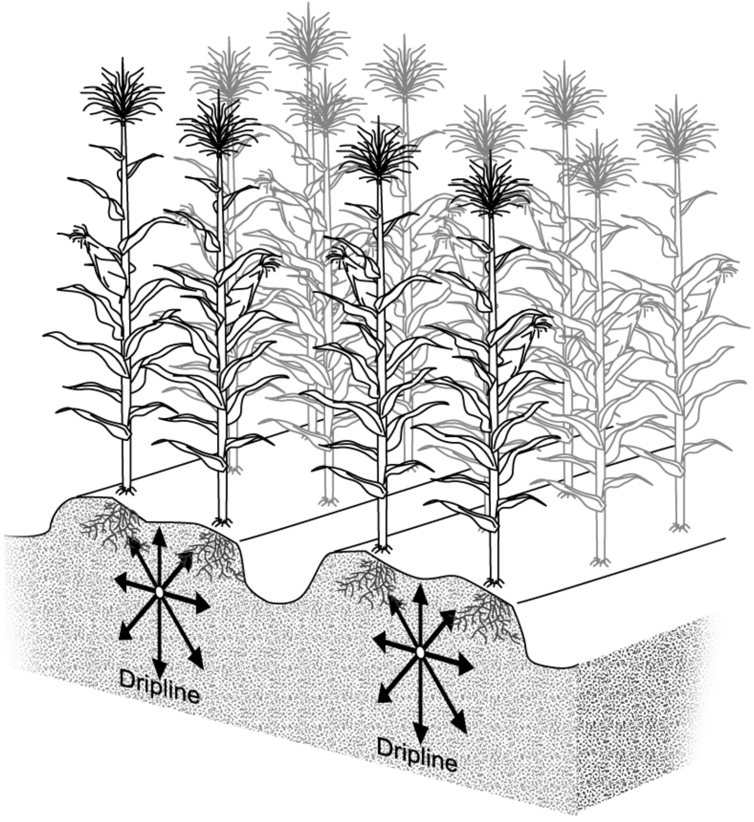

Figure 1. Physical arrangement of the subsurface dripline in relation to the corn rows.

A modified ridge-till system was used in corn production with two corn rows, 30 inches apart, grown on a 60 inch wide bed. Flat planting was used for the dripline spacing studies conducted at both locations. In these dripline spacing studies, it was not practical to match bed spacing to dripline spacing with the available tillage and harvesting equipment. Additionally at Garden City, corn rows were planted perpendicular to the driplines in the dripline spacing study. All corn was grown with conventional production practices for each location. Wheel traffic was confined to the furrows.

Reference evapotranspiration and actual evapotranspiration (AET) were calculated using a modified Penman combination equation similar to the procedures outlined by Kincaid and Heermann (1974). The specifics of the calculations are fully described by Lamm et al. (1995).

Irrigation was scheduled using a water budget to calculate the root zone depletion with precipitation and irrigation water amounts as deposits and calculated daily corn water use (AET) as a withdrawal. If the root-zone depletion became negative, it was reset to zero. Root zone depletion was assumed to be zero at crop emergence. Irrigation was metered separately onto each plot. Soil water amounts were monitored weekly in each plot with a neutron probe in 12 inch increments to a depth of 8 ft.

Results and Discussion

Water Requirement and Irrigation Capacity Studies

Research studies were conducted at Colby from 1989-1991 to determine the water requirement of subsurface drip-irrigated corn. Careful management of SDI systems reduced net irrigation needs by nearly 25%, while still maintaining top yields of 200 bu/a (Lamm et. al., 1995). The 25% reduction in irrigation needs potentially translates into 35-55% savings when compared to sprinkler and furrow irrigation systems which typically are operating at 85 and 65% application efficiency. Corn yields at Colby were linearly related to calculated crop water use (Figure 2), producing 19.6 bu/acre of grain for each inch of water used above a threshold of 12.9 inches (Lamm et al., 1995). The relationship between corn yields and irrigation is curvilinear (Figure 2.) primarily because of greater drainage for the heavier irrigation amounts (Figure 3).

SDI technology can make significant improvements in water productivity through better management of the water balance components. The 25% reduction in net irrigation needs is primarily associated with the reduction in in-season drainage, elimination of irrigation runoff and reduction in soil evaporation, all non-beneficial components of the water balance. Additionally, drier surface soils allow for increased infiltration of occasional precipitation events.

In a later study (1996-2001), corn was grown under 6 different SDI capacities (0, 0.10, 0.13, 0.17, 0.20 and 0.25 inches/day) and 4 different plant densities (33,100, 29,900, 26,800, and 23,700 plants/acre). Daily SDI application of even small amounts of water (0.10 inches) doubled corn grain yields from 92 to 202 bu/acre in extremely dry 2000 and 2001. Results suggested an irrigation capacity of 0.17 inches/day might be adequate SDI capacity when planning new systems in this region on deep silt loam soils (Lamm and Trooien, 2001). It was concluded that small daily amounts of water can be beneficial on these deep silt loam soils in establishing the number of sinks (kernels) for the accumulation of grain. The final kernel mass is established by grain filling conditions between the reproductive period and physiological maturity (last 50-60 days of crop season). Thus, the extent of soil water depletion during this period will have a large effect on final kernel mass and ultimately, corn grain yield. Increasing plant density from 22,500 to 34,500 plants/acre generally increased corn grain yields, particularly in good corn production years. There was very little yield penalty for increased plant density even when irrigation was severely limited or eliminated.

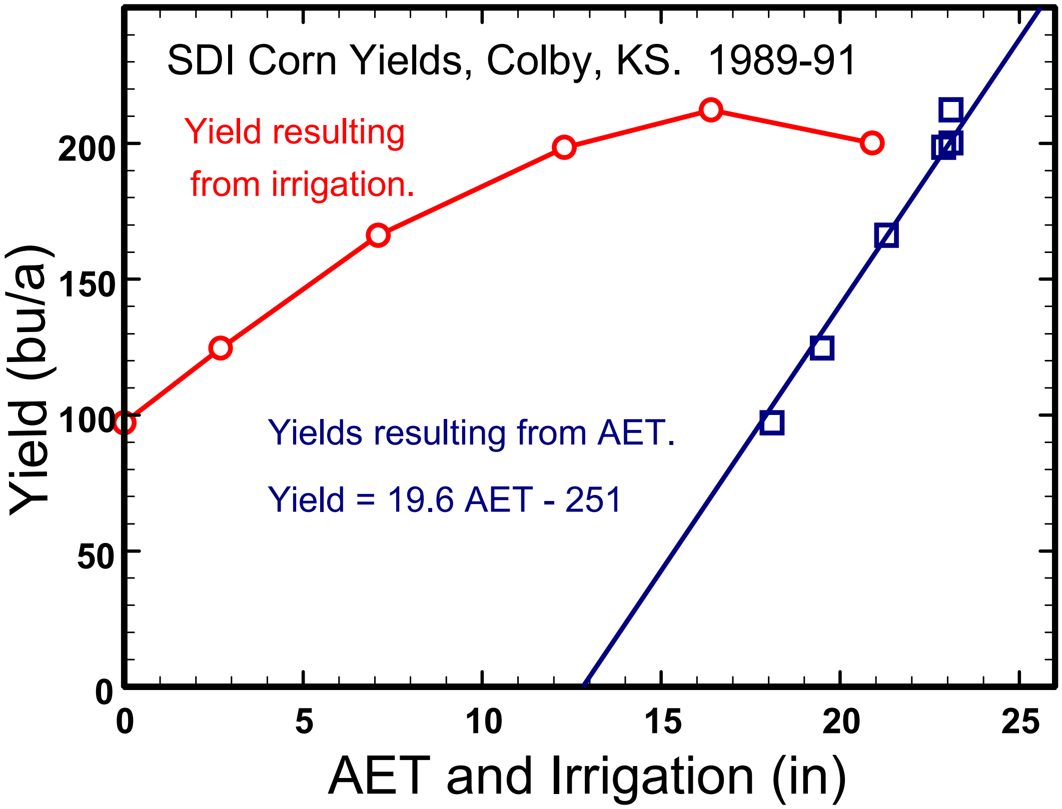

Figure 2. Corn yield as related to irrigation and calculated evapotranspiration (AET) in a SDI water requirement study, Colby, Kansas, 1989-1991.

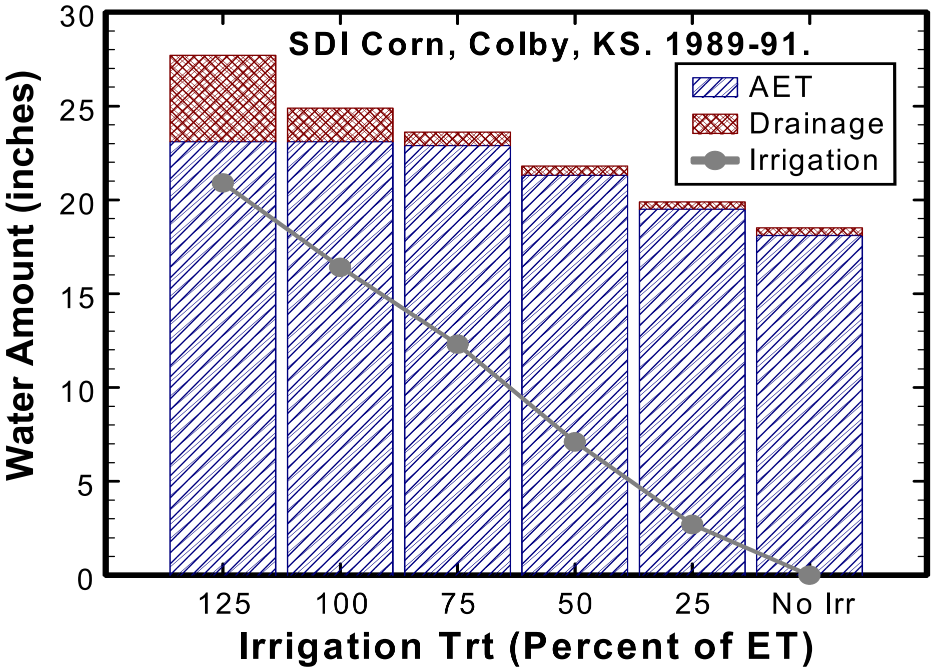

Figure 3. Calculated evapotranspiration (AET) and seasonal drainage as related to irrigation treatment in a SDI water requirement study, Colby, Kansas, 1989-1991.

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 4). 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.

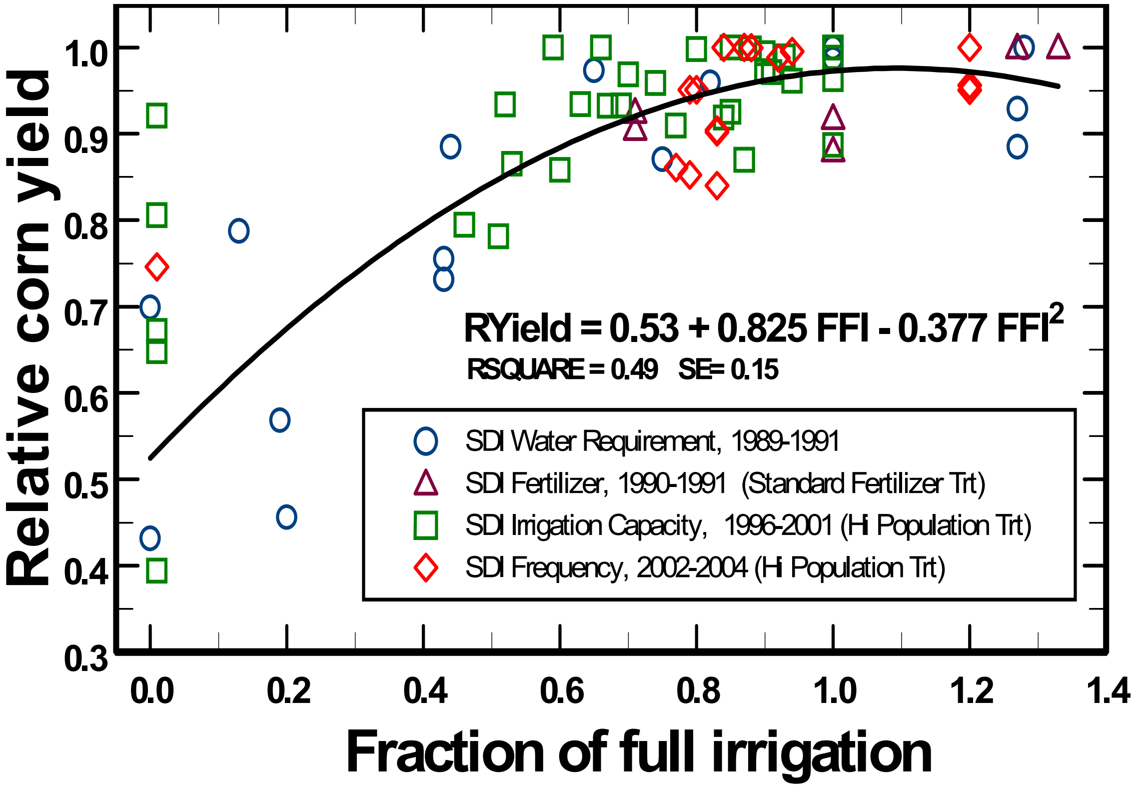

Figure 4. Relative corn grain yield for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

An examination of water productivity (WP) for the same four studies indicates that water productivity plateaus for levels of full irrigation ranging from 61% to 109% with less than 5% variation in WP (Figure 5). The highest 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. 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 these soils in this region.

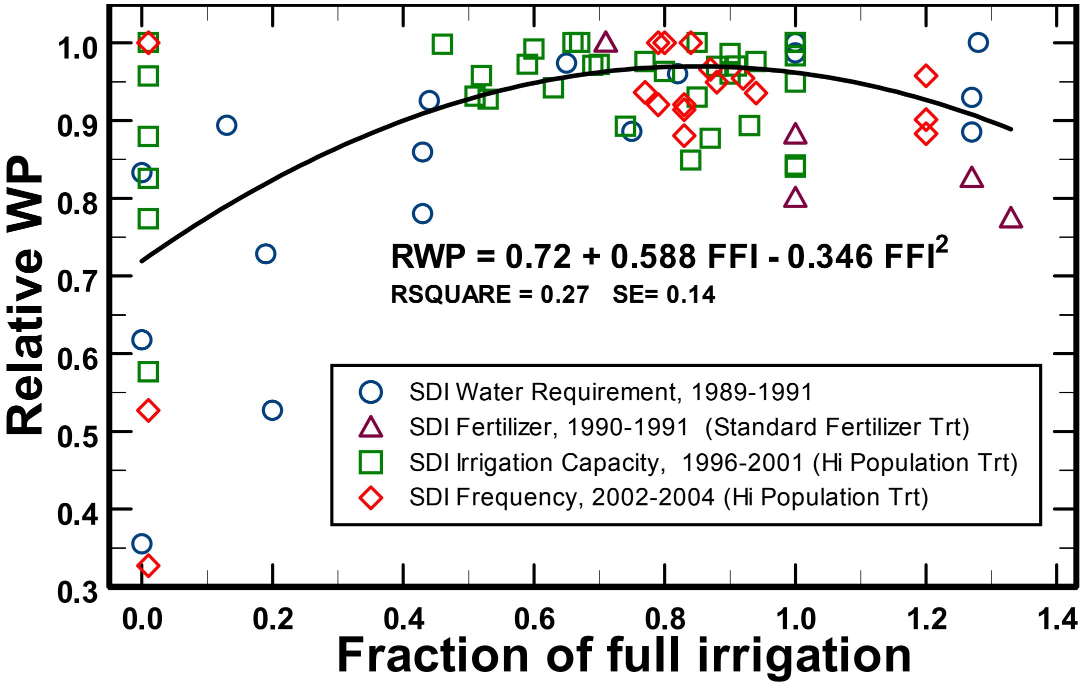

Figure 5. Relative water use productivity (WP) of corn for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

SDI Frequency

Typically, a smaller volume of soil is wetted with SDI as compared to other types of irrigation systems and as a result, crop rooting may be limited. Crops may benefit from frequent irrigation under this condition. However, in a study conducted at the KSU Southwest Research-Extension Center in Garden City, Kansas, corn yields were excellent (190 to 200 bu/acre) regardless of whether a frequency of 1, 3, 5, or 7 days was used for the SDI events (Caldwell et al., 1994). Higher irrigation water use efficiencies were obtained with the longer 7-day frequency because of improved storage of in-season precipitation and because of reduced drainage below the rootzone. The results indicate there is little need to perform frequent SDI events for fully-irrigated corn on the deep silt loam soils of western Kansas.

These results agree with a literature review of SDI (Camp, 1998) that indicated that SDI frequency is often only critical for shallow rooted crops on shallow or sandy soils. An additional study conducted in the U.S. Southern Great Plains indicated that SDI frequencies had little or no effect on corn yields provided soil water was managed within acceptable stress ranges (Howell et al., 1997).

In a 2002-2004 study at Colby, Kansas, four irrigation frequencies at a limited irrigation capacity were compared against fully irrigated and non-irrigated treatments (Lamm and Aiken, 2005). The hypothesis was that under limited irrigation, higher frequency with SDI might be beneficial during grain filling and the latter portion of the season as soil water reserves become depleted. The four irrigation frequencies were 0.15 in/day, 0.45 in/3 days, 0.75/5 days and 1.05/7days which are equivalent but limited capacities. As a point of reference, a 0.25 in/day irrigation capacity will match full irrigation needs for sprinkler irrigated corn in this region in most years. The fully irrigated treatment was limited to 0.30 in/day. The non-irrigated treatment only received 0.10 inches in a single irrigation to facilitate nitrogen fertigation for those plots. However, all 6 treatments were irrigated each year in the dormant season to replenish the soil water in the profile. Corn yields were high in all three years for all irrigated treatments (Figure 6.)

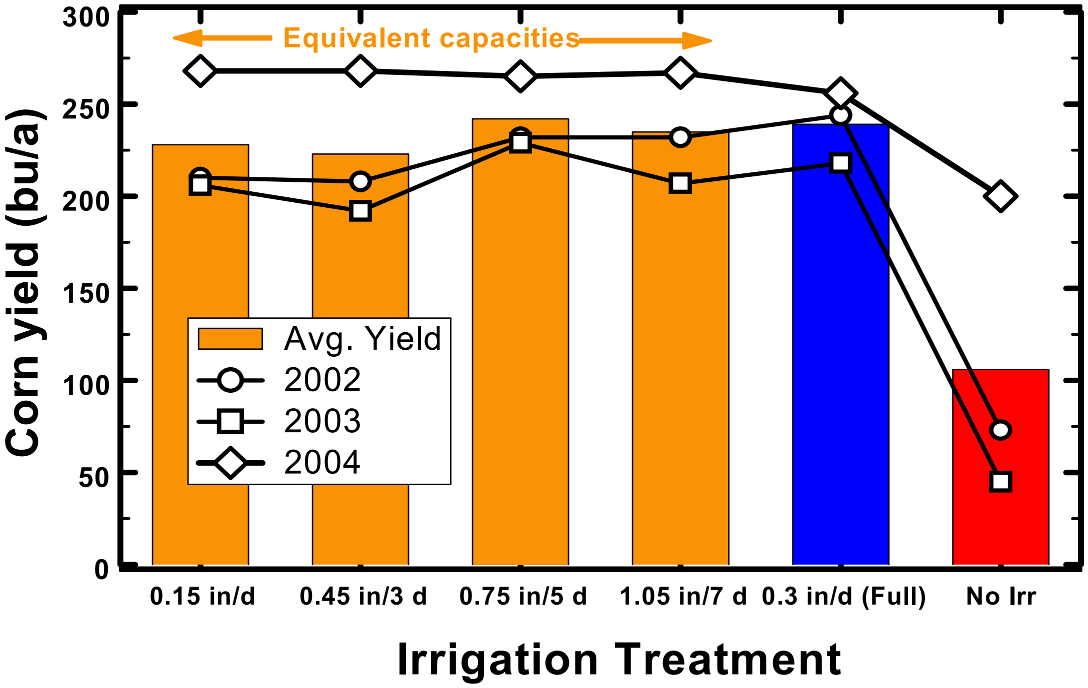

Figure 6. Corn grain yields as affected by irrigation treatment in a study examining SDI frequency under limited irrigation, Colby, Kansas, 2002 to 2004.

Only in 2002 did irrigation frequency significantly affect yields and the effect was the opposite of the hypothesis. In the extreme drought year of 2002, the less frequent irrigation events with their larger irrigation amounts (0.75 in/5 days and 1.05 in/7 days) resulted in yields approximately 10 to 20 bu/acre higher. The yield component most greatly affected in 2002 was the kernels/ear and was 30-40 kernels/ear higher for the less frequent events. It is suspected that the larger irrigation amounts for these less frequent events sent an early-season signal to the corn plant to set more potential kernels. Much of the potential kernel set occurs before the ninth leaf stage (corn approximately 2 to 3 ft tall), but there can be some kernel abortion as late as two weeks after pollination. The results suggest that irrigation frequencies from daily to weekly should not have much effect on corn yields in most years.

Optimal Dripline Spacing

Increasing the spacing of dripline laterals would be one of the most important factors in reducing the high investment costs of SDI. Soil type, dripline installation depth, crop type and the reliability and amount of in-season precipitation are major factors that determine the maximum dripline spacing.

Two studies have been conducted in semi-arid western Kansas to determine the optimum dripline spacing (installed at a depth of 16 to 18 inches) for corn production on deep, silt-loam soils (Spurgeon, et al., 1991; Manges et al., 1995; Darusman et al., 1997; Lamm et al., 1997a). The first study at the KSU Southwest Research-Extension Center at Garden City, Kansas evaluated 4 dripline spacings (2.5, 5, 7.5, and 10 ft) with corn planted in 30-inch spaced rows perpendicular to the dripline lateral. The other study at the KSU Northwest Research-Extension Center at Colby, Kansas evaluated 3 spacings (5, 7.5 and 10 ft) with corn planted in 30-inch spaced rows parallel to the driplines. Average yields for corresponding treatments were similar between sites even though row orientation was different (Table 1).

Table 1. Corn yields obtained with various dripline spacing treatments under full and reduced irrigation at Garden City and Colby, Kansas, 1989-91.

Spacing treatment	Irrigation treatment	Dripline ratio in relation to 5-ft. trt.	Corn yield (bu/a) Garden City 1989-91	Corn yield (bu/a) Colby 1990-91
2.5 ft.	Full irrigation	2.00	230	----
5.0 ft	Full irrigation	1.00	218	216
7.5 ft	Full Irrigation	0.67	208	204
7.5 ft	Reduced irrigation (67%)	0.67	----	173
10.0 ft	Full irrigation	0.50	194	194
10.0 ft	Reduced irrigation (50%)	0.50	----	149

The highest average yield was obtained by the 2.5-ft dripline spacing at Garden City, Kansas. However, the requirement of twice as much dripline (dripline ratio, 2.00) would be uneconomical for corn production as compared to the standard 5-ft dripline spacing. The results, when incorporated into an economic model, showed an advantage for the wider dripline spacings (7.5 and 10ft in some higher rainfall years. However, the standard 5 ft dripline spacing was best when averaged over all years for both sites. When subsurface driplines are centered between alternate pairs of 30-inch spaced corn rows, each corn row is within 15 inches of the nearest dripline (Figure 1.)

Wider dripline spacings will not consistently (year-to-year) or uniformly (row-to-row) supply crop water needs. In 1990 at Colby, yields for the 5 ft and 7.5 ft dripline spacings were equal when full irrigation was applied, partially because soil water reserves were high at planting. In 1991, following a dry winter, yields for the wider 7.5 ft dripline spacing were reduced by 25 bu/acre (Lamm et al., 1997a). Similar results were reported by Spurgeon et al. (1991) at Garden City. The studies at Colby also sought to resolve whether equivalent amounts of water should be applied to the wider dripline spacings or whether irrigation should be reduced in relation to the dripline ratio. Yields were always lower for the corn rows furthest from the dripline in the wider dripline spacings regardless of which irrigation scheme was used (Figure 7). However in 1991, there was complete crop failure in the corn rows furthest from the dripline when irrigation was reduced in relation to the dripline ratio. Full irrigation on the wider dripline spacings at Colby resulted in excessive deep percolation (Darusman et al., 1997) and reduced overall water productivity (Lamm et al., 1997a). Soils having a restrictive clay layer below the dripline installation depth might allow a wider spacing without affecting crop yield. Wider spacings may also be allowable in areas of increased precipitation as the dependency of the crop on irrigation is decreased (Powell and Wright, 1993).

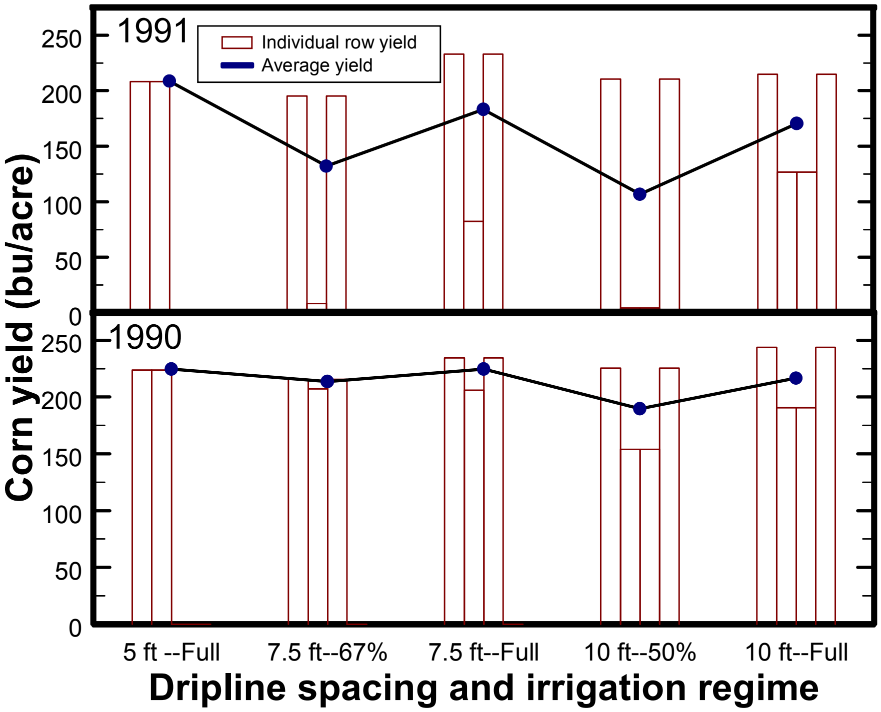

Figure 7. Corn yield distribution as affected by dripline spacing and irrigation regime, Colby, Kansas, 1990-1991. Note: Individual row yields are mirrored about a centerline half way between two adjacent driplines for display purposes.

One of the inherent advantages of a SDI system is the ability to irrigate only a fraction of the crop root zone. Careful attention to proper dripline spacing is, therefore, a key factor in conserving water and protecting water quality. These research studies at Colby and Garden City, Kansas determined that driplines spaced 5 ft apart are most economical for corn grown in rows spaced 30 inches apart at least on the deep silt loam soils of the region. However, different soil types, such as sands, or different crops with less extensive root systems might require closer dripline spacing.

Dripline Depth

In some areas, SDI has not been readily accepted because of problems with root intrusion, emitter clogging and lack of visual indicators of the wetting pattern. In high value crops, these indeed can be valid reasons to avoid SDI. However, in the Central Great Plains, with typically relatively low value commodity crops such as corn, only long term SDI systems where installation and investment costs can be amortized over many years, have any realistic chance of being economically justified. Kansas irrigators are beginning to try SDI on their own and there has been a lack of research-based information on appropriate depth for driplines. Camp (1998) reviewed a number of SDI studies concerning depth of installation and concluded the results are often region specific and optimized for a particular crop. Five dripline depths (8, 12, 16, 20 and 24 inches) were evaluated at Colby, Kansas for corn production and SDI system integrity and longevity (Lamm and Trooien, 2005). System longevity was evaluated by monitoring individual flowrates and pressures at the end of each cropping season to estimate system degradation (clogging) with time. There was no appreciable or consistent effect on corn grain yields during the period 1999-2002 (Figure 8.).

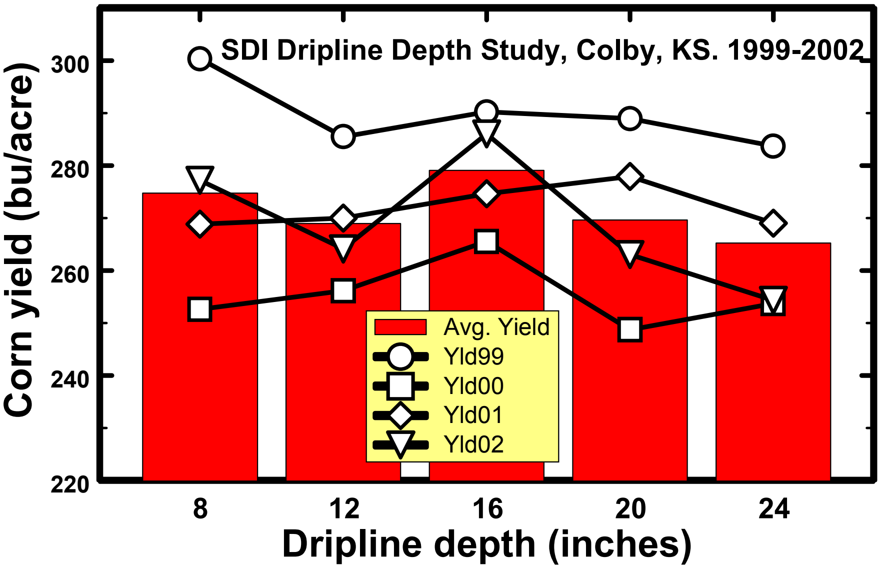

Figure 8. Corn grain yields as affected by dripline depth, 1999-2002, Colby, Kansas.

The study area has not been used to examine the effects of dripline depth on germination in the spring, but damp surface soils were sometimes observed for the 8 and 12 inch dripline depths during the irrigation season, but not for the deeper depths. There was a tendency to have slightly more late season grasses for the shallower 8 and 12 inch depths, but the level of grass competition with the corn is not intense. The dripline depth study was managed with the modified ridge-till system (5-ft bed) as shown in Figure 1. Cultivation for weeds in early summer has been routinely practiced and there were no instances of tillage tool damage to the shallow 8 inch depth driplines.

Similar dripline depth studies were conducted for soybean (2005 and 2007), grain sorghum (2006 and 2008) and sunflower (2004 and 2007). There were no significant differences in yields for any of the crops in any year as affected by dripline depth (Table 2.)

Table 2. Crop yield of soybean, grain sorghum and sunflower as affected by dripline depth, KSU Northwest Research-Extension Center, Colby Kansas, 2003-2008.

Dripline depth inches	**Soybean yield bu/acre**			**Grain Sorghum bu/acre**			**Sunflower lbs/acre**		
	2005	**2007**	**Mean**	**2006**	**2008**	**Mean**	**2004**	**2007**	**Mean**
8	80	76	78	166	153	159	3128	3487	3307
12	82	71	76	159	155	157	2838	3309	3074
16	80	76	78	165	169	167	2941	3580	3261
20	80	74	77	159	157	158	2992	3489	3241
24	78	78	78	155	141	148	2942	3497	3220
Mean	80	75	77	161	155	158	2968	3473	3220
LSD 0.05	NS	NS	-	NS	NS	-	NS	NS	-

Measurements of plot dripline flowrates during the period 1999 through 2008 indicated a tendency for the deeper driplines to have reduced flowrates and these flowrate reductions were statistically significant in 2001, 2006, 2007, and 2008. Although the reason for these plot flowrate reductions cannot be fully ascertained, it seems likely they were caused by emitter clogging related to an interaction between dripline depth and irrigation water quality for which the rationale was not determined.

Producer preference in choosing dripline depths in the range of 8 to 24 inches should be acceptable for crop production of these predominant summer crops in this region.

Emitter Spacing

The effect of emitter spacing (1, 2, 3, or 4 ft) on corn production and soil water redistribution was studied from 2005 to 2008 at the KSU Northwest Research-Extension Center at Colby, Kansas (Arbat et al., 2010).

Increased soil water content in directions parallel to the dripline as compared to perpendicular directions following two non-cropped irrigation events 8 months apart are indicative of increased preferential flow along SDI driplines or overlapping of the wetting zones of adjacent emitters. The fact that there were little or only minor differences in volumetric water contents adjacent to the emitter and at the midway point between emitters for the various emitter spacings during the course of three subsequent crop years provide further evidence of this preferential flow. There were no differences in corn grain yield or water productivity which suggests that under full irrigation that this range of emitter spacings (1 to 4 ft) is acceptable. Further research is being conducted to examine the effects of a smaller irrigation event amount (0.5 to 1 inch/event) under slightly deficit irrigation (75% of full irrigation) on corn production. Additional studies might examine shallow-rooted or tap-rooted crops that may not be able to explore as large a soil profile as corn.

Dripline Flushing

The velocity of dripline flushing in subsurface drip irrigation (SDI) systems affects system design and cost, management, performance and longevity. A 30-day field study was conducted at KSU Northwest Research Extension Center in 2004 to analyze the effect of four flushing velocities (0.75, 1.00, 1.50 and 2.00 ft/s) and three flushing frequencies (no flushing or flushing every 15 or 30 days) on SDI emitter discharge and sediments within the dripline and removed in the flushing water (Puig-Bargués et al. 2010). At the end of the field experiment (371 hours) the amount of solids carried away by the flushing water and retained in every lateral were determined as well as laboratory determination of emitter discharge for every single emitter within each dripline.

Greater dripline flushing velocities tended to result in greater amount of solids in the flushing water, but differences were not always statistically significant. Neither the frequency of flushing, nor the interaction of flushing frequency and velocity significantly affected the amount of solids in the flushing water. There was a greater concentration of solids in the beginning one-third of the 300-ft laterals particularly for treatments with no flushing or with slower dripline flushing velocities. As flushing velocity increased, there was a tendency for greater solids removal and/or more equal distribution within the dripline. At the end of the field study, the average emitter discharge as measured in the laboratory for a total of 3970 emitters was 0.169 gallons/hour which was approximately 2.5% less than the discharge for new and unused emitters. There were only 6 emitters that were nearly or fully clogged with discharges between 0 to 5% of new and unused emitters. Flushing velocity and flushing frequency did not have consistent significant effects on emitter discharge and those numerical differences that did exist were small (<3%). Emitter discharge was approximately 3% less for the distal ends of the driplines (last 20% of the dripline). Although not a factor in this study, increasing the duration of flushing may be a more important and also less expensive means (i.e., increased flushing events increases labor and greater flushing velocities can greatly increase SDI system costs through different pumping requirements and reduced zone size leading to needing more pipes, controls and connectors) of increasing the overall effectiveness of flushing given the manner in which sediments move within the dripline during flushing.

Nitrogen Fertilization with SDI

Because properly designed SDI systems have a high degree of uniformity and can apply small frequent irrigation amounts, excellent opportunities exist to better manage nitrogen fertilization with these systems. Injecting small amounts of nitrogen solution into the irrigation water can spoonfeed the crop, while minimizing the pool of nitrogen in the soil that could be available for percolation into the groundwater.

In a study conducted at the KSU Northwest Research-Extension Center at Colby, Kansas from 1990-91, there was no difference in corn grain yields between preplant surface-applied nitrogen and nitrogen injected into the driplines throughout the season. Corn yields averaged 225 to 250 bu/acre for the fully irrigated and fertilized treatments. Water use was increased (P=0.05) in 1991 and for the two year average by injection of N fertilizer with the SDI system. 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 (Lamm et. al., 2001). Nitrogen applied with SDI at a depth of 16 to 18 inches redistributed differently in the soil profile than surface-applied preplant nitrogen banded in the furrow (Figure 9*).* _*Since residual soil-nitrogen levels were higher where nitrogen was injected using SDI, it may be possible to obtain similar high corn yields using lower amounts of injected nitrogen.*_

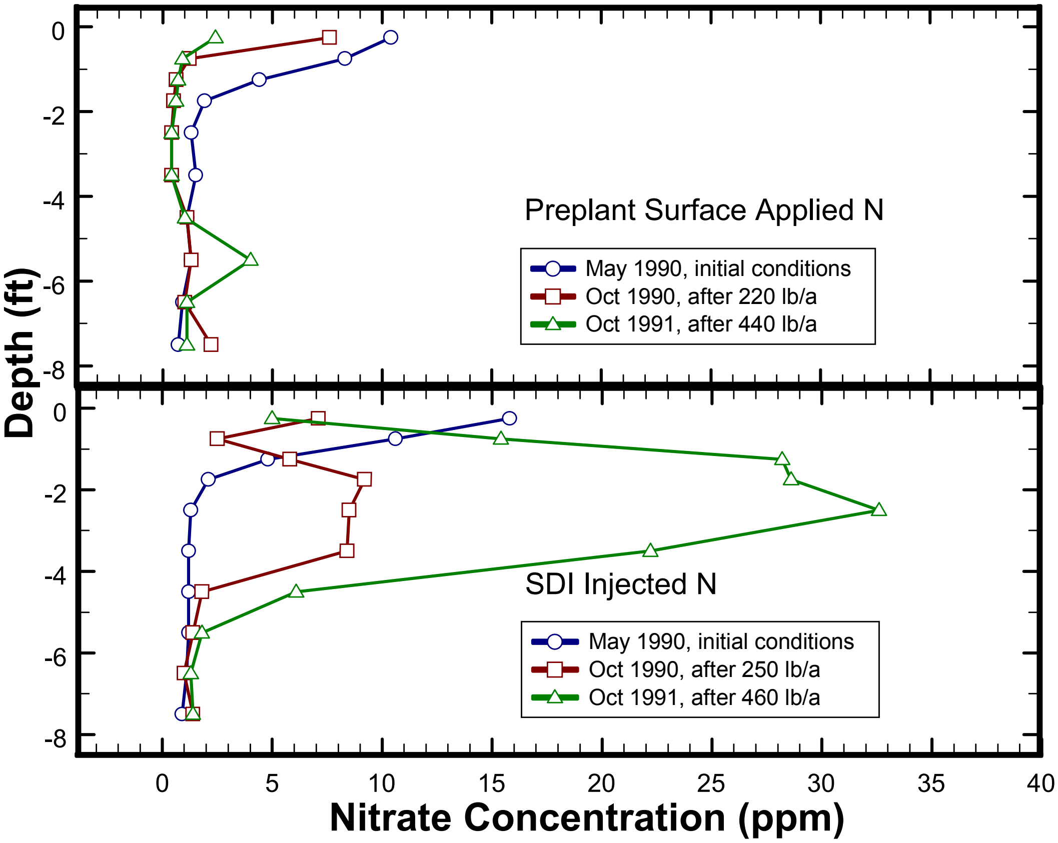

Figure 9. Nitrate concentrations in the soil profile for preplant surface-applied and SDI injected nitrogen treatments, Colby, Kansas, 1990-91. Data is for selected nitrogen fertilizer rate treatments with full irrigation (100% of AET).

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. 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, 90, 135, 180, 225, and 270 kg/ha. The final BMP was a nitrogen fertigation level of 180 kg/ha with other non-fertigation applications bringing the total applied nitrogen to approximately 215 kg/ha (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 180 kg/ha nitrogen fertigation rate (Figure 10). Average yields for the 180 kg/ha nitrogen fertigation rate was 13.4 Mg/ha. Corn yield to ANU ratio for the 180 kg/ha nitrogen fertigation rate was a high 53:1. The results emphasize that high-yielding corn production also can be efficient in nutrient and water use.

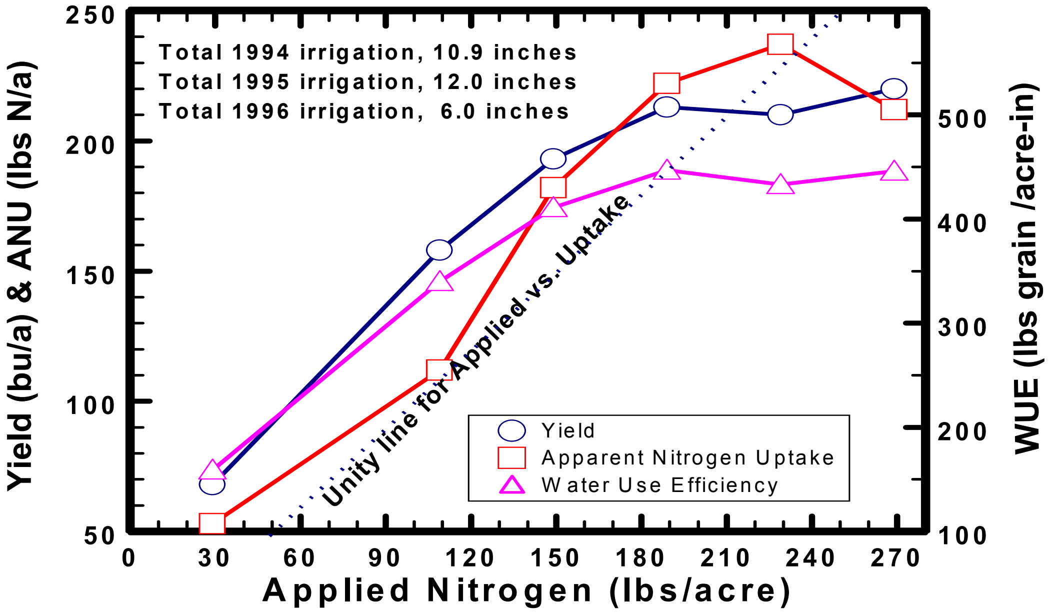

Figure 10. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water productivity as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded fertigation applied nitrogen by 30 lb/acre.

Comparison of SDI and Simulated LEPA Sprinkler Irrigation

A 7-year field study (1998-2004) compared simulated low energy precision application (LEPA) sprinkler irrigation to subsurface drip irrigation (SDI) for field corn production on deep silt loam soils at Colby, Kansas (Lamm, 2004). There was very little difference in average corn grain yields between system type (235 and 233 bu/acre for LEPA and SDI, respectively) across all comparable irrigation capacities (Figure 11). However, LEPA had higher grain yields for 4 extreme drought years (approximately 15 bu/acre) and SDI had higher yields in 3 normal to wetter years (approximately 15 bu/acre).

The difference in system types between years was unanticipated and remains unexplained. In the course of conducting this experiment it became apparent that system type was affecting grain yields particularly in the extreme drought years. Higher LEPA yields were associated with higher kernels/ear as compared to SDI (534 vs. 493 kernels/ear in dry years). Higher SDI yields were associated with higher kernel mass at harvest as compared to LEPA (347 vs. 332 mg/kernel in normal to wetter years). Although the potential number of kernels/ear is determined by hybrid genetics and early growth before anthesis, the actual number of kernels is usually set in a 2-3 week period centering around anthesis. Water and nitrogen availability and hormonal signals are key factors in determining the actual number of kernels/ear. The adjustment of splitting the fertilizer applications to both preplant and inseason in 2002 did not remove the differences in kernels/ear between irrigation system types. Hormonal signals sent by the roots may have been different for the SDI treatments in the drought years because SDI may have had a more limited root system. Seasonal water use was approximately 4% higher with LEPA than SDI and was associated with the period from anthesis to physiological maturity. Further research is being conducted to gain an understanding of the reasons between the shifting of the yield components (kernels/ear and kernel mass) between irrigation systems as climatic conditions vary.

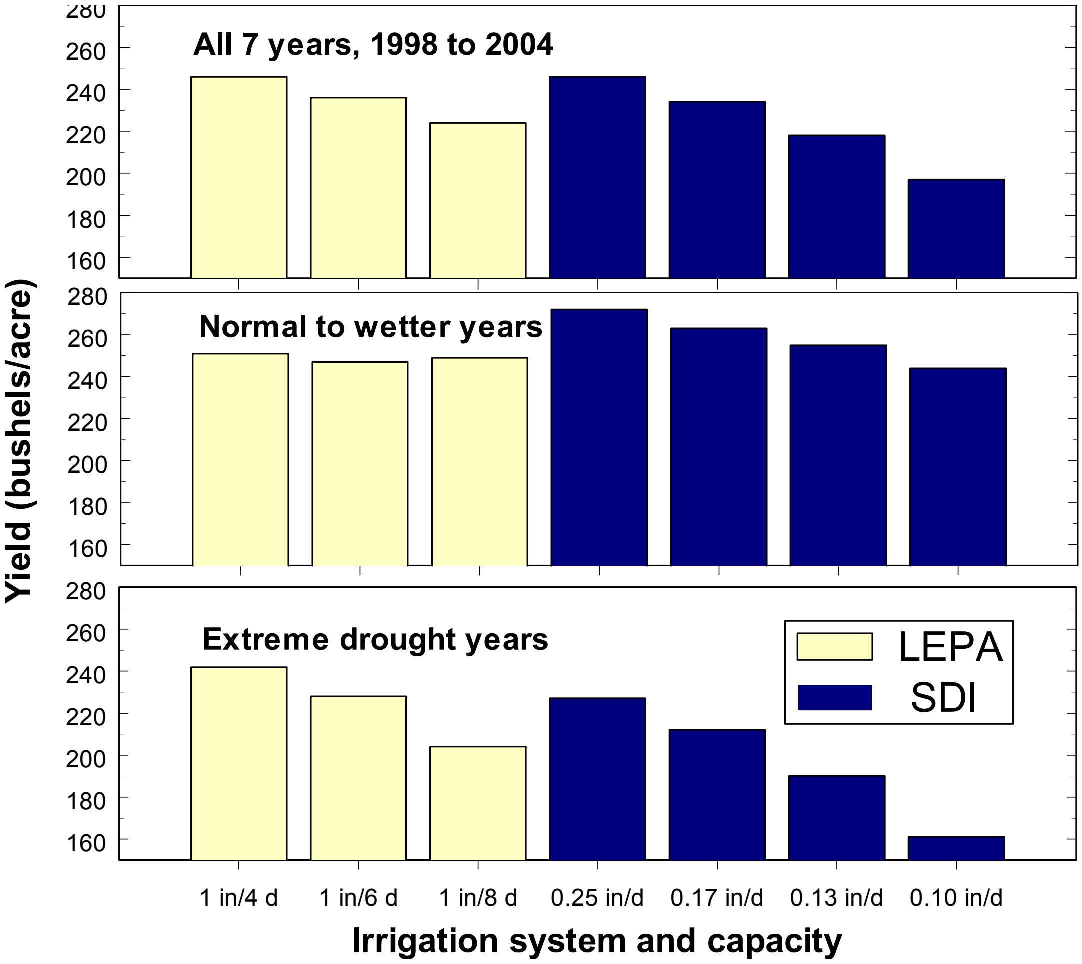

Figure 11. Variation in corn yields across years and weather conditions as affected by irrigation system type and capacity, Colby Kansas.

Additional studies were conducted to compare LEPA sprinkler irrigation to SDI for production of soybeans (2005), grain sorghum (2006 and 2008) and sunflower (2004 and 2007). In these studies, weather-based water-budget irrigation schedules were used to replace ET at replacement levels of 100, 80 and 60% for both types of irrigation system.

There were no significant differences in soybean yield but there was a trend towards SDI having greater yield at deficit irrigation levels and LEPA having greater yield at the full irrigation level (Table 3). Similar statistically non-significant results were obtained for sunflower with a trend towards SDI resulting in greater yields under deficit irrigation (0.6 and 0.8 ET) than LEPA, but LEPA having greater yields at full irrigation in both years. Grain sorghum tended to have greater yields with LEPA than with SDI at all levels of irrigation and was statistically significant in 2008. Further analysis and research is needed to determine the reasons for these results.

Table 3. Crop yield of soybean, grain sorghum and sunflower as affected by irrigation method and irrigation treatment, KSU Northwest Research-Extension Center, Colby Kansas, 2004-2010.

Irrigation method	Irrigation Treatment	Soybean yield bu/a			Grain Sorghum bu/a			Sunflower yield bu/a		
		2005	2010	Mean	2006	2008	Mean	2004	2007	Mean
SDI	100% ET	73	77	75	169	154 b*	161	3098	2824	2961
	80% ET	70	77	74	175	144 b	159	3442	3292	3367
	60% ET	70	70	70	155	131 c	143	3346	3273	3309
	Mean SDI	71	75	73	166	143	155	3295	3130	3212
LEPA	100% ET	75	73	74	179	170 a	174	3694	3354	3524
	80% ET	71	70	71	180	169 a	175	3285	2929	3107
	60% ET	63	71	67	175	160 a	167	3125	2729	2927
	Mean LEPA	69	71	70	178	167	172	3368	3004	3186
	LSD 0.05	NS	NS	-	NS	13	-	NS	NS	-

* *Values followed by the same lower case letter are not significantly different at the P=0.05 level.*

Alfalfa Production with SDI

Alfalfa, a forage crop, has high crop water needs and, thus, can benefit from highly efficient irrigation systems such as SDI. In some regions, the water allocation is limited by physical or institutional constraints, so SDI can effectively increase alfalfa production by increasing the crop transpiration while reducing or eliminating soil evaporation. Since alfalfa is such a high-water user and has a very long growing season, irrigation labor requirements with SDI can be reduced relative to less efficient alternative irrigation systems that would require more irrigation events (Hengeller, 1995). A major advantage of SDI for alfalfa is the ability to continue irrigating immediately prior, during, and immediately after the multiple seasonal harvests. Continuation of irrigation reduces the amount of water stress on the alfalfa and thus can increase forage production which is generally linearly related to transpiration.

A study was conducted from 2004 through 2007 to evaluate alfalfa production using an SDI system with an 5-ft dripline spacing and a 20-inch dripline depth on a deep silt loam soil at the KSU Northwest Research-Extension Center at Colby, Kansas. Alfalfa production and quality was evaluated with respect to three irrigation levels (trts. designed to replace 70, 85 and 100% of ETc) and at three perpendicular horizontal distances from the dripline (0, 15 and 30 inches).

There were not large differences in annual yield between irrigation levels but over the course of each season there would tend to be a slight reduction in alfalfa yield with increasing distance from the dripline. This reduction was greater for the 70% ET treatment and resulted in reduced overall annual yields (Figure 12). However, crude protein (a measure of alfalfa quality) and digestibility was greater at the greater distances and reduced ET. This helped compensate for the yield reduction.

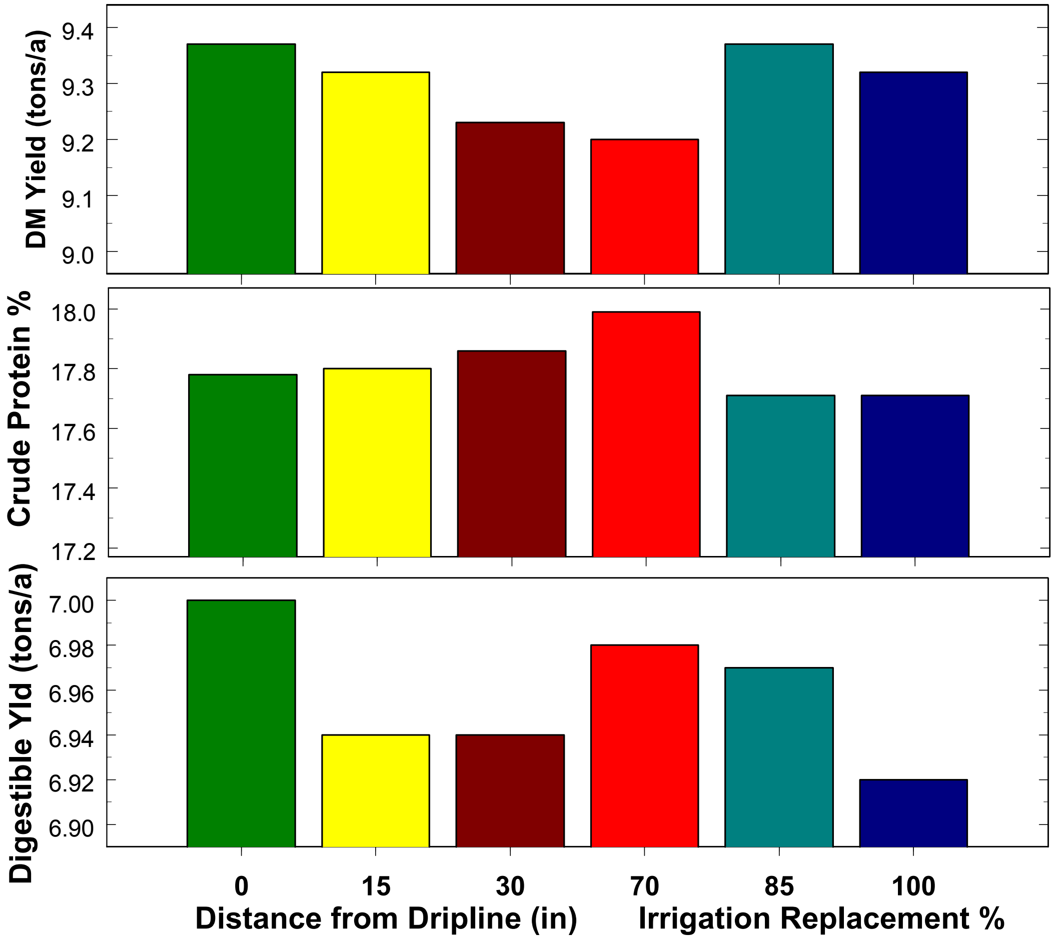

Figure 12. Dry matter yield, percentage crude protein and digestible dry matter yield as affected by perpendicular horizontal distance from dripline and irrigation level, KSU Northwest Research-Extension Center, Colby Kansas. Data is averaged over the years, 2005 through 2007.

Additional data collected from a field demonstration study conducted by K-State indicates that a 40-inch spacing of dripline for alfalfa may recover the additional investment cost. This is more so for the traditional alfalfa growing areas in Kansas which tend to have comparatively light textured soils (Alam et al., 2009).

Application of Livestock Effluent with SDI

Subsurface drip irrigation (SDI) can be successfully used for application of livestock effluent to agricultural fields with careful consideration of design and operational issues. Primary advantages are that exposure of the effluent to volatilization, leaching, runoff into streams, and humans can be reduced while the primary disadvantages are related to system cost and longevity, and the fixed location of the SDI system.

An engineering feasibility study (1998 to 2002, commercial beef feedlot in Gray County, Kansas) conducted by Kansas State University with beef feedlot effluent has indicated that driplines with discharge of 0.4 to 1 gal/hr-emitters can be used successfully with little clogging. However, the smaller emitter sizes normally used with high quality groundwater in the Central Great Plains may be risky for use with beef feedlot effluent. The discharge 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 13). The three driplines with the highest flow rate emitters (0.4, 0.6, 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.

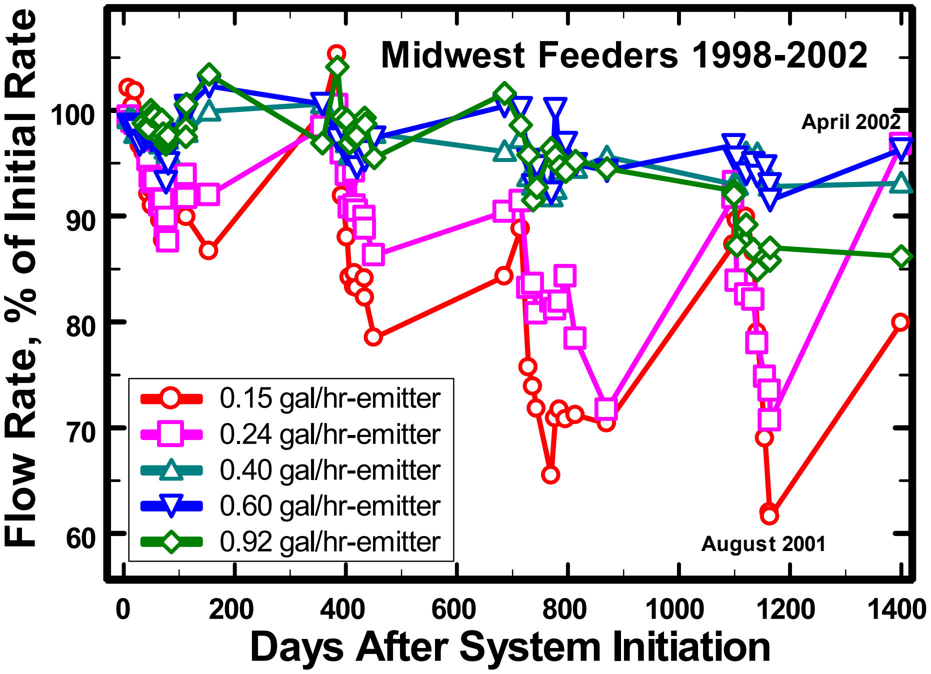

Figure 13. Decrease in emitter discharge during four seasons of operation of an SDI system with biological effluent at Midwest Feeders, Ingalls, Kansas, 1998 to 2002.

A second livestock effluent study using SDI was conducted in 2000 through 2001 at the KSU Northwest Research-Extension Center, Colby, Kansas (Lamm et al.,2006; Lamm et al., 2007). The overall objective of this project was to compare the environmental, cropping, and irrigation system impacts of swine effluent applied with SDI or simulated LEPA sprinkler irrigation. SDI tended to have greater corn yields (Table 4) and better nutrient utilization (Data not shown) than low-energy precision application (LEPA) center pivot sprinklers.

Table 4. Yield component and water use data for corn in a swine effluent study, KSU Northwest Research-Extension Center, Colby Kansas, 2000 to 2001.

Irrigation System & Effluent Amount	Irrigation inches	Applied N[1] lb/a	Grain yield bu/a	Water use[2] inches	WP[3] lb/acre-in
Year 2000					
SDI, Control	19.5	245	253	30.1	472
SDI, 1.0 inch effluent	19.5	229	252	30.4	464
SDI, 2.0 inches effluent	19.5	388	260	29.5	492
LEPA, 0.6 inches effluent	20.0	155	237	33.2	399
LEPA, 1.0 inches effluent	20.0	229	250	32.8	427
LEPA, 2.0 inches effluent	20.0	388	246	33.2	415
LSD P=0.05			NS	1.5	51
Year 2001					
SDI, Control	18.0	244	262	28.5	517
SDI, 1.0 inch effluent	18.0	209	270	27.4	553
SDI, 2.0 inches effluent	18.0	356	267	28.1	531
LEPA, 0.6 inches effluent	18.0	143	214	28.2	427
LEPA, 1.0 inches effluent	18.0	209	251	28.7	493
LEPA, 2.0 inches effluent	18.0	356	237	30.3	439
LSD P=0.05			22	NS	53
Mean of both years 2000 - 2001					
SDI, Control			258	29.3	495
SDI, 1.0 inch effluent			261	28.9	509
SDI, 2.0 inches effluent			263	28.8	512
LEPA, 0.6 inches effluent			225	30.7	413
LEPA, 1.0 inches effluent			251	30.8	460
LEPA, 2.0 inches effluent			241	31.7	427
LSD P=0.05			20	1.0	35

[1] Total applied N-P-K from the 3 sources: starter treatment at planting (30 lb/acre N + 45 lb/ac P_20_5), wastewater application, and the naturally occurring amount in the irrigation water (0.75 lbs/acre-in).

[2] Seasonal change of soil water storage in the 8-ft profile plus irrigation and precipitation.

[3] Water productivity (WP) is defined as grain yield in lbs/acre divided by total water use in inches.

Economics of SDI

SDI has not been typically used for row crop production in the Central Great Plains. Typically, SDI has much higher investment costs as compared to other pressurized irrigation systems such as full size center pivot sprinklers. However, there are realistic scenarios where SDI can directly compete with center pivot sprinklers for corn production in the Central Great Plains. As field size decreases, SDI can more directly compete with center pivot sprinklers because of increasing higher ratio of center pivot sprinkler (CP) costs to irrigated area (Figure 14). Small and irregular shape fields may be ideal candidates for SDI.

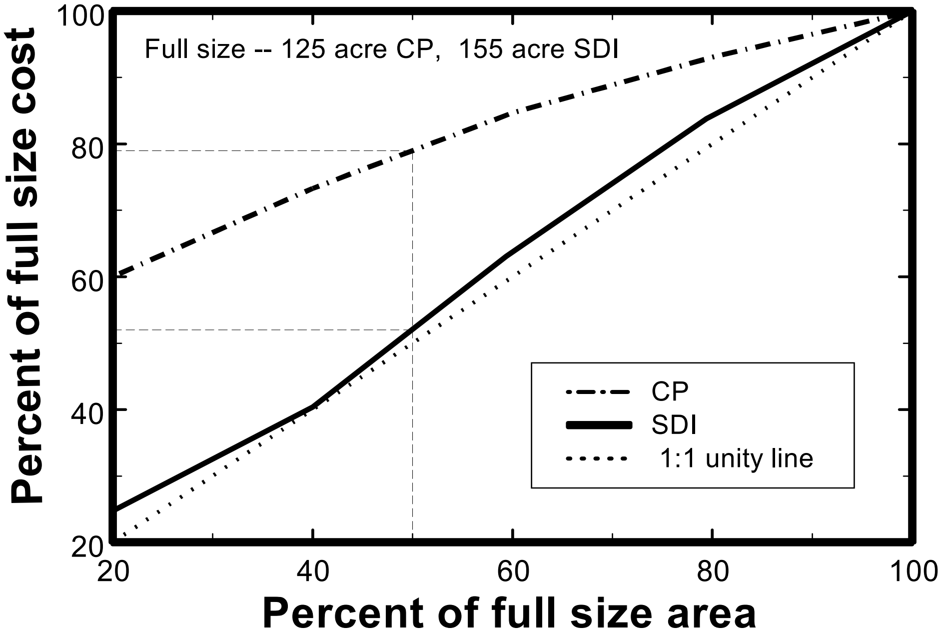

Figure 14. Center pivot sprinkler (CP) and SDI system costs as related to field size. (after O'Brien et al., 1997)

Economic comparisons of CP and SDI systems are sensitive to the underlying assumptions used in the analysis (Lamm et. al., 2003). The results show that these comparisons are very sensitive to size of CP irrigation system, shape of field (full vs. partial circle CP system), life of SDI system, SDI system cost with advantages favoring larger CP systems and cheaper, longer life SDI systems. The results are moderately sensitive to corn yield, corn harvest price, yield/price combinations and very sensitive to higher potential yields with SDI with advantages favoring SDI as corn yields and price increase. A Microsoft Excel spreadsheet template has been developed for comparing CP and SDI economics and is available for free downloading from the internet at http://www.ksre.ksu.edu/sdi/Software/SDISoftware.htm .

System life of SDI

SDI system life must be at least 10-15 years to reasonably approach economic competitiveness with full sized center pivot sprinkler systems that typically last 20-25 years. Using careful and consistent maintenance, a 20 year or longer SDI system life appears obtainable when high quality water from the Ogallala aquifer is used. The system performance of the K-State SDI research plots has been monitored annually since 1989 with few signs of significant degradation (Figure 15). The benchmark study area has received shock chlorination approximately 2-3 times each season, but has not received any other chemical amendments, such as acid. The water source at this site has a TDS of 279, hardness of 189.1, and pH of 7.8. This water source would be considered a moderate chemical clogging hazard according to traditional classifications (Nakayama and Bucks, 1986). It is possible that the depth of the SDI system (16 to 18 inches) has reduced the chemical clogging hazards due to less temperature fluctuations and negligible evaporation directly from the dripline.

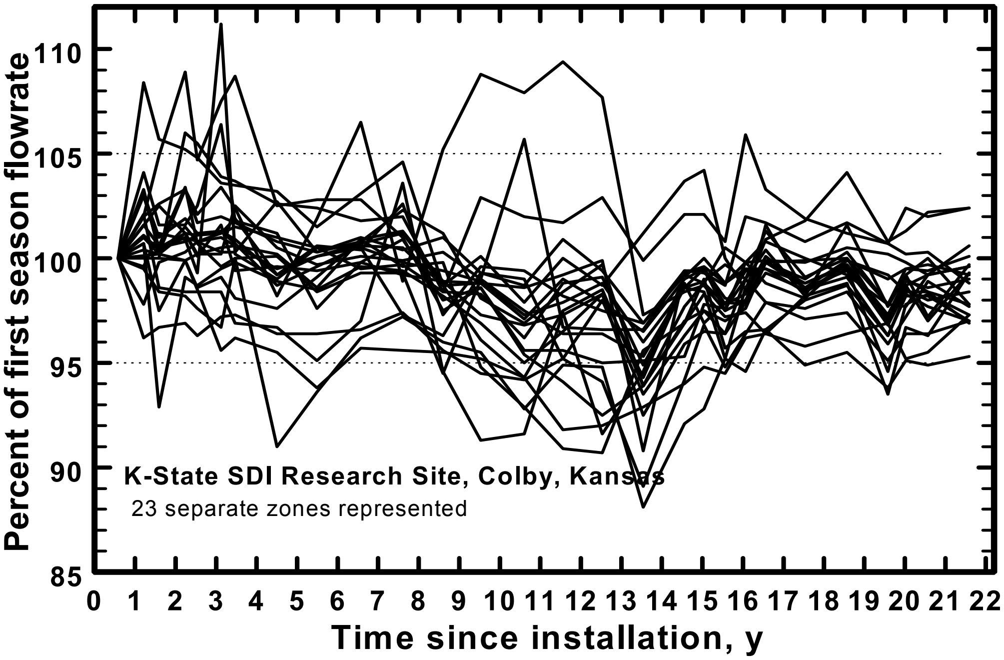

Figure 15. Stability in zone flowrates from the initial first season as related to time for an SDI system installed at Kansas State University, Colby, Kansas, 1989-2010.

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. It is K-State's hope that by developing a knowledge base in advance of the irrigator adoption phase that the misapplication of SDI technology and overall system failures can be minimized. Economics of the typical Great Plains row crops will not allow frequent system replacement or major renovations. Irrigators must carefully monitor and maintain the SDI system to assure a long system life. Continued or new areas of research are concentrating on optimizing allocations of water, seed, and nutrients, utilizing livestock wastewater, developing information about SDI use with other crops besides corn, soil water redistribution, water and chemical application uniformity, and finally system design characteristics and economics with a view towards system longevity.

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Several K-State faculty members have conducted and contributed to the progress of KSU SDI corn research over the years since 1989. These include, Freddie Lamm, Bill Spurgeon, Todd Trooien, Harry Manges, Danny Rogers, Mahbub Alam, Loyd Stone, Alan Schlegel, Gary Clark, Rob Aiken, Dan O'Brien, Troy Dumler, Kevin Dhuyvetter, Mark Nelson, Norm Klocke, Keith Harmoney, and Sandy Johnson.

[1] Mention of tradenames is for informational purposes only and does not constitute endorsement by the authors or by the institutions they serve.

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USING THE K-STATE CENTER PIVOT SPRINKLER AND SDI ECONOMIC COMPARISON SPREADSHEET - 2011

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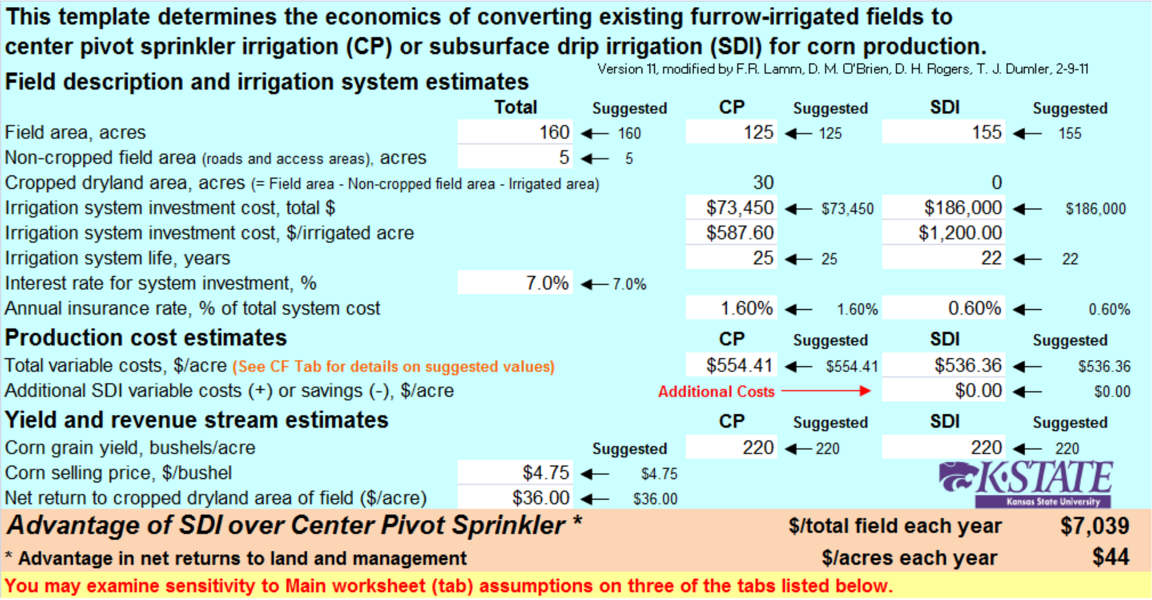
INTRODUCTION

In much of the Great Plains, the rate of new irrigation development is slow or zero. Although the Kansas irrigated area, as reported by producers through annual irrigation water use reports, has been approximately 3 million acres since 1990, there has been a dramatic shift in the methods of irrigation. During the period since 1990, the number of acres irrigated by center pivot irrigation systems increased from about 50 per cent of the total irrigated acreage base to about 90 percent of the base area. In 1989, subsurface drip irrigation (SDI) research plots were established at Kansas State University Research Stations to investigate SDI as a possible additional irrigation system option. Early industry and producers surveys have indicated a small but steady increase in adoption. Field area as reported by the 2006 Kansas Irrigation Water Use Report indicated that 10,250 acres were exclusively irrigated by SDI systems and an additional 8,440 acres were irrigated partly by SDI in combination with another system type such as an irrigated SDI corner of a center pivot sprinkler or a surface gravity-irrigated field partially converted to SDI. Although Kansas SDI systems represent less than 1 percent of the irrigated area, producer interest still remains high because SDI can potentially have higher irrigation efficiency and irrigation uniformity. As the farming populace and irrigation systems age, there will likely be a continued momentum for conversion to modern pressurized irrigation systems. Both center pivot sprinkler irrigation (CP) and subsurface drip irrigation (SDI) are options available to the producer for much of the Great Plains landscape (low slope and deep silt loam soils). Pressurized irrigation systems in general are a costly investment and this is particularly the case with SDI. Producers need to carefully determine their best investment options.

In the spring of 2002, a free Microsoft Excel[1] spreadsheet template was introduced by K-State Research and Extension for making economic comparisons of CP and SDI. Since that time, the spreadsheet has been periodically updated to reflect changes in input data, particularly system and corn production costs. The spreadsheet also provides sensitivity analyses for key factors. This paper will discuss how to use the spreadsheet and the key factors that most strongly affect the comparisons. The template has five worksheets (tabs), the Main, CF, Field size & SDI life, SDI cost & life, Yield & price tabs. Most of the calculations and the result are shown on the Main tab (Figure 1.).



This template determines the economics of converting existing furrow-irrigated fields to center pivot sprinkler irrigation (CP) or subsurface drip irrigation (SDI) for corn production.

Version 11, modified by F.R. Lamm, D. M. O'Brien, D. H. Rogers, T. J. Dumler, 2-9-11

Field description and irrigation system estimates	**Total**	**Suggested**	**CP**	**Suggested**	**SDI**	**Suggested**
Field area, acres	160	← 160	125	← 125	155	← 155
Non-cropped field area (roads and access areas), acres	5	← 5				
Cropped dryland area, acres (= Field area - Non-cropped field area - Irrigated area)			30		0	
Irrigation system investment cost, total $			$73,450	← $73,450	$186,000	← $186,000
Irrigation system investment cost, $/irrigated acre			$587.60		$1,200.00	
Irrigation system life, years			25	← 25	22	← 22
Interest rate for system investment, %	7.0%	← 7.0%				
Annual insurance rate, % of total system cost			1.60%	← 1.60%	0.60%	← 0.60%
Production cost estimates			**CP**	**Suggested**	**SDI**	**Suggested**
Total variable costs, $/acre (See CF Tab for details on suggested values)			$554.41	← $554.41	$536.36	← $536.36
Additional SDI variable costs (+) or savings (-), $/acre			Additional Costs	→	$0.00	← $0.00
Yield and revenue stream estimates			**CP**	**Suggested**	**SDI**	**Suggested**
Corn grain yield, bushels/acre		**Suggested**	220	← 220	220	← 220
Corn selling price, $/bushel	$4.75	← $4.75				
Net return to cropped dryland area of field ($/acre)	$36.00	← $36.00				

Advantage of SDI over Center Pivot Sprinkler *	**$/total field each year**	**$7,039**
*** Advantage in net returns to land and management**	**$/acres each year**	**$44**

You may examine sensitivity to Main worksheet (tab) assumptions on three of the tabs listed below.

Figure 1. Main worksheet (tab) of the economic comparison spreadsheet template indicating the 18 required variables (white input cells) and their suggested values when further information is lacking or uncertain.

ANALYSES METHODS AND ECONOMIC ASSUMPTIONS

There are 18 required input variables required to use the spreadsheet template, but if the user does not know a particular value there are suggested values for each of them. The user is responsible for entering and checking the values in the unprotected input cells. All other cells are protected on the Main worksheet (tab). Some error checking exists on overall field size and some items (e.g. overall results and cost savings) are highlighted differently when different results are indicated. Details and rationales behind the input variables are given in the following sections.

Field & irrigation system assumptions and estimates

Many of the early analyses assumed that an existing furrow-irrigated field with a working well and pumping plant was being converted to either CP or SDI and this still may be the base condition for some producers. However, the template can also be used to consider options for a currently center pivot irrigated field that needs to be replaced. The major change in the analysis for the replacement CP is that the cost for the new center pivot probably would not have to include buried underground pipe and electrical service in the initial investment cost. The analysis also assumes the pumping plant is located at the center of one of the field edges and is at a suitable location for the initial SDI distribution point (i.e. upslope of the field to be irrigated). Any necessary pump modifications (flow and pressure) for the CP or SDI systems are assumed to be of equal cost and thus are not considered in the analysis. However, they can easily be handled as an increased system cost for either or both of the system types.

Land costs are assumed to be equal across systems for the overall field size with no differential values in real estate taxes or in any government farm payments. Thus, these factors “fall out” or do not economically affect the analyses.

An overall field size of 160 acres (square quarter section) was assumed for the base analysis. This overall field size will accommodate either a 125 acre CP system or a 155 acre SDI system. It was assumed that there would be 5 noncropped acres consumed by field roads and access areas. The remaining 30 acres under the CP system are available for dryland cropping systems.

Irrigation system costs are highly variable at this point in time due to rapid fluctuations in material and energy costs. Cost estimates for the 125 acre CP system and the 155 acre SDI system are provided on the current version of the spreadsheet template based on discussions with dealers and Dumler et al. (2007), but since this is the overall basis of the comparison, it is recommended that the user apply his own estimates for his conditions. In the base analyses, the life for the two systems is assumed to be 25 and 22 years for the CP and SDI systems, respectively. No salvage value was assumed for either system. This assumption of no salvage value may be inaccurate, as both systems might have a few components that may be reusable or available for resale at the end of the system life. However, with relatively long depreciation periods of 22 and 25 years and typical financial interest rates, the zero salvage value is a very minor issue in the analysis. System life is a very important factor in the overall analyses. However, the life of the SDI system is of much greater economic importance in analysis than a similar life for the CP system because of the much higher system costs for SDI. Increasing the system life from 22 to 25 years for SDI would have a much greater economic effect than increasing the CP life from 22 to 25 years.

When the overall field size decreases, thus decreasing system size, there are large changes in cost per irrigated acre between systems. SDI costs are nearly proportional to field size, while CP costs are not proportional to field size (Figure 2). Quadratic equations were developed to calculate system costs when less than full size 160 acre fields were used in the analysis (Obrien et al., 1998):

$$CPcost\% = 44.4 + (0.837 \times CPsize\%) - (0.00282 \times CPsize\%^2) \qquad \text{(Eq. 1)}$$

$$SDIcost\% = 2.9 + (1.034 \times SDIsize\%) - (0.0006 \times SDIsize\%^2) \qquad \text{(Eq. 2)}$$

where CPcost% and CPsize%, and SDIcost% and SDIsize% are the respective cost and size % in relation to the full costs and sizes of irrigation systems fitting within a square 160 acre block.

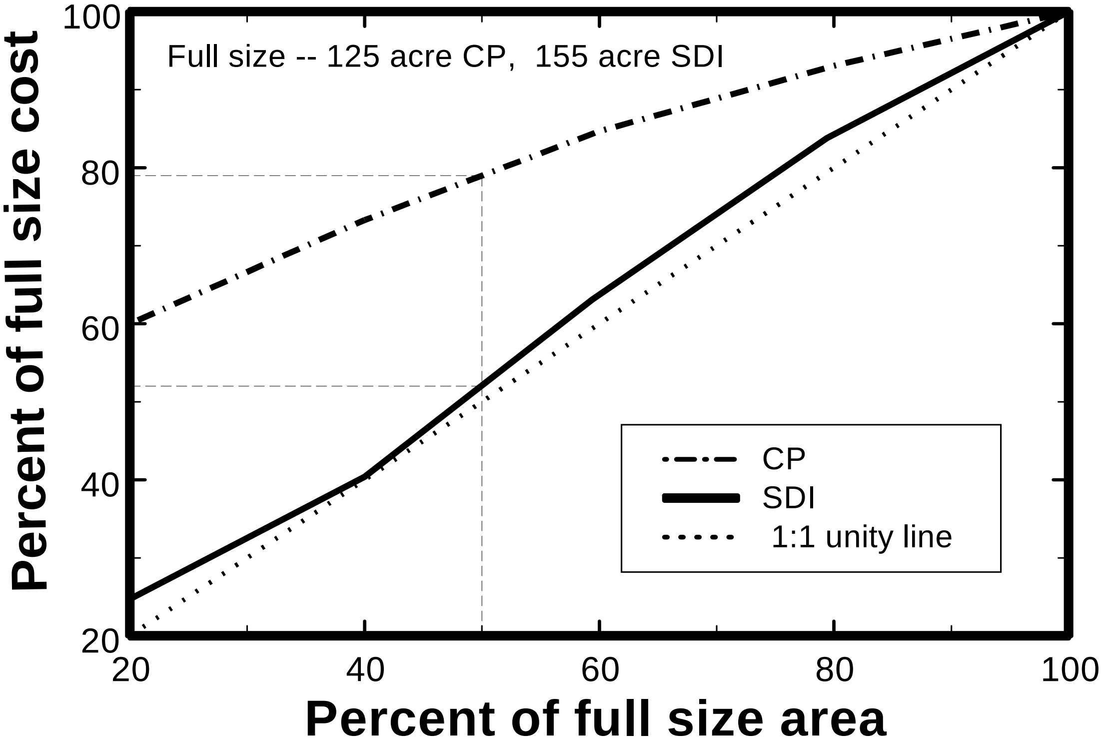


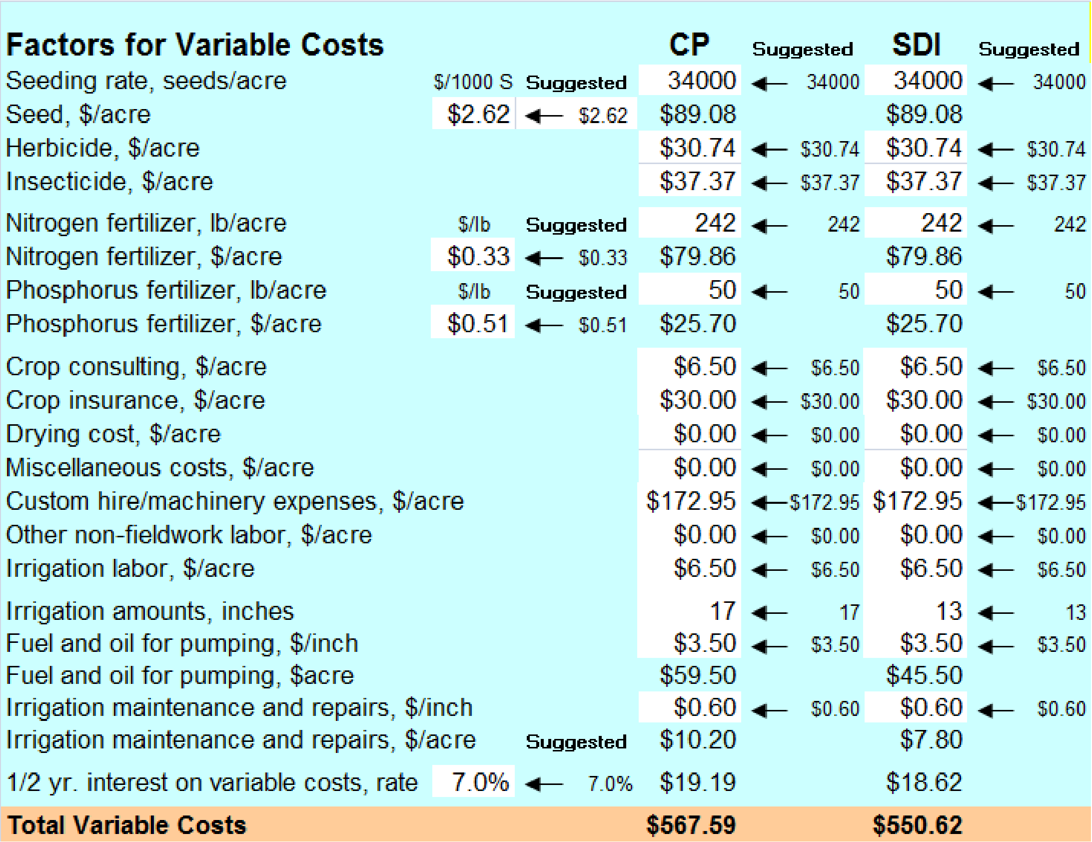
Figure 2. CP and SDI system costs as related to field size. (after O'Brien et al., 1998)

The annual interest rate can be entered as a variable, but is currently assumed to be 7.0%. The total interest costs over the life of the two systems were converted to an average annual interest cost for this analysis. Annual insurance costs were assumed to be 1.6% of the total system cost for the center pivot sprinkler and 0.6% for the SDI system, but can be changed if better information is available. The lower value for the SDI was based on the assumption that only about 40% of the system might be insurable. Many of the SDI components are not subject to the climatic conditions that are typically insured hazards for CP systems. However, system failure risk is probably greater with SDI systems which might influence any obtainable insurance rate. The cost of insurance is a minor factor in the economic comparison when using the current values.

Production cost assumptions and estimates

The economic analysis expresses the results as an advantage of SDI or alternatively CP systems in net returns to land and management. Thus, many fixed costs do not affect the analysis and can be ignored. Additionally, the analysis does not indicate if either system is ultimately profitable for corn production under the assumed current economic conditions.

Production costs were adapted from KSU estimates (Dumler et al., 2010). A listing of the current costs is available on the CF worksheet (tab) (Figure 3) and the user can enter new values to recalculate variable costs that more closely match their conditions. The sum of these costs would become the new suggested Total Variable Costs on the Main worksheet (tab), but the user must manually change the input value on the Main worksheet (White input cell box) for the economic comparison to take effect. *The user may find it easier to just change the differential production costs between the systems on the Main tab rather than changing the baseline assumptions on the CF tab. This will help maintain integrity of the baseline production cost assumptions.*



Factors for Variable Costs				**CP**		Suggested	**SDI**		Suggested
Seeding rate, seeds/acre	$/1000 S		Suggested	34000	←	34000	34000	←	34000
Seed, $/acre	$2.62	←	$2.62	$89.08			$89.08		
Herbicide, $/acre				$30.74	←	$30.74	$30.74	←	$30.74
Insecticide, $/acre				$37.37	←	$37.37	$37.37	←	$37.37
Nitrogen fertilizer, lb/acre	$/lb		Suggested	242	←	242	242	←	242
Nitrogen fertilizer, $/acre	$0.33	←	$0.33	$79.86			$79.86		
Phosphorus fertilizer, lb/acre	$/lb		Suggested	50	←	50	50	←	50
Phosphorus fertilizer, $/acre	$0.51	←	$0.51	$25.70			$25.70		
Crop consulting, $/acre				$6.50	←	$6.50	$6.50	←	$6.50
Crop insurance, $/acre				$30.00	←	$30.00	$30.00	←	$30.00
Drying cost, $/acre				$0.00	←	$0.00	$0.00	←	$0.00
Miscellaneous costs, $/acre				$0.00	←	$0.00	$0.00	←	$0.00
Custom hire/machinery expenses, $/acre				$172.95	←	$172.95	$172.95	←	$172.95
Other non-fieldwork labor, $/acre				$0.00	←	$0.00	$0.00	←	$0.00
Irrigation labor, $/acre				$6.50	←	$6.50	$6.50	←	$6.50
Irrigation amounts, inches				17	←	17	13	←	13
Fuel and oil for pumping, $/inch				$3.50	←	$3.50	$3.50	←	$3.50
Fuel and oil for pumping, $acre				$59.50			$45.50		
Irrigation maintenance and repairs, $/inch				$0.60	←	$0.60	$0.60	←	$0.60
Irrigation maintenance and repairs, $/acre			Suggested	$10.20			$7.80		
1/2 yr. interest on variable costs, rate	7.0%	←	7.0%	$19.19			$18.62		
Total Variable Costs				**$567.59**			**$550.62**		

Figure 3. CF worksheet (tab) of the economic comparison spreadsheet template and the current production cost variables. Note that the sums at the bottom of the CF worksheet are the suggested values for total variable costs on the Main worksheet (tab).

The reduction in variable costs for SDI is attributable to an assumed 25% net water savings that is consistent with research findings by Lamm et al. (1995). This translates into a 17 and 13 inch gross application amount for CP and SDI, respectively. The current estimated production costs are somewhat high reflecting increased energy and other related input costs, but fortunately crop revenues have also increased due to high demand for corn for ethanol production. This fact is pointed out because a lowering of overall variable costs favors SDI, since more irrigated cropped acres are involved, while higher overall variable costs favors CP production. The variable costs for both irrigation systems represent typical practices for western Kansas.

Yield and revenue stream estimates

Corn grain yield is currently estimated at 220 bushels/acre in the base analysis with a corn price of $4.75/bushel (See values on Main worksheet). Net returns for the 30 cropped dryland acres for the CP system (corners of field) were assumed to be $36.00/acre which is essentially the current dryland crop cash rent estimate for Northwest Kansas. Government payments related to irrigated crop production are assumed to be spread across the overall field size, and thus, do not affect the economic comparison of systems.

Sensitivity analyses

Changes in the economic assumptions can drastically affect which system is most profitable and by how much. Previous analyses have shown that the system comparisons are very sensitive to assumptions about

- Size of CP irrigation system
- Shape of field (full vs. partial circle CP system)
- Life of SDI system
- SDI system cost

with advantages favoring larger CP systems and cheaper, longer life SDI systems.

The results are very sensitive to

- any additional production cost savings with SDI.

The results are moderately sensitive to

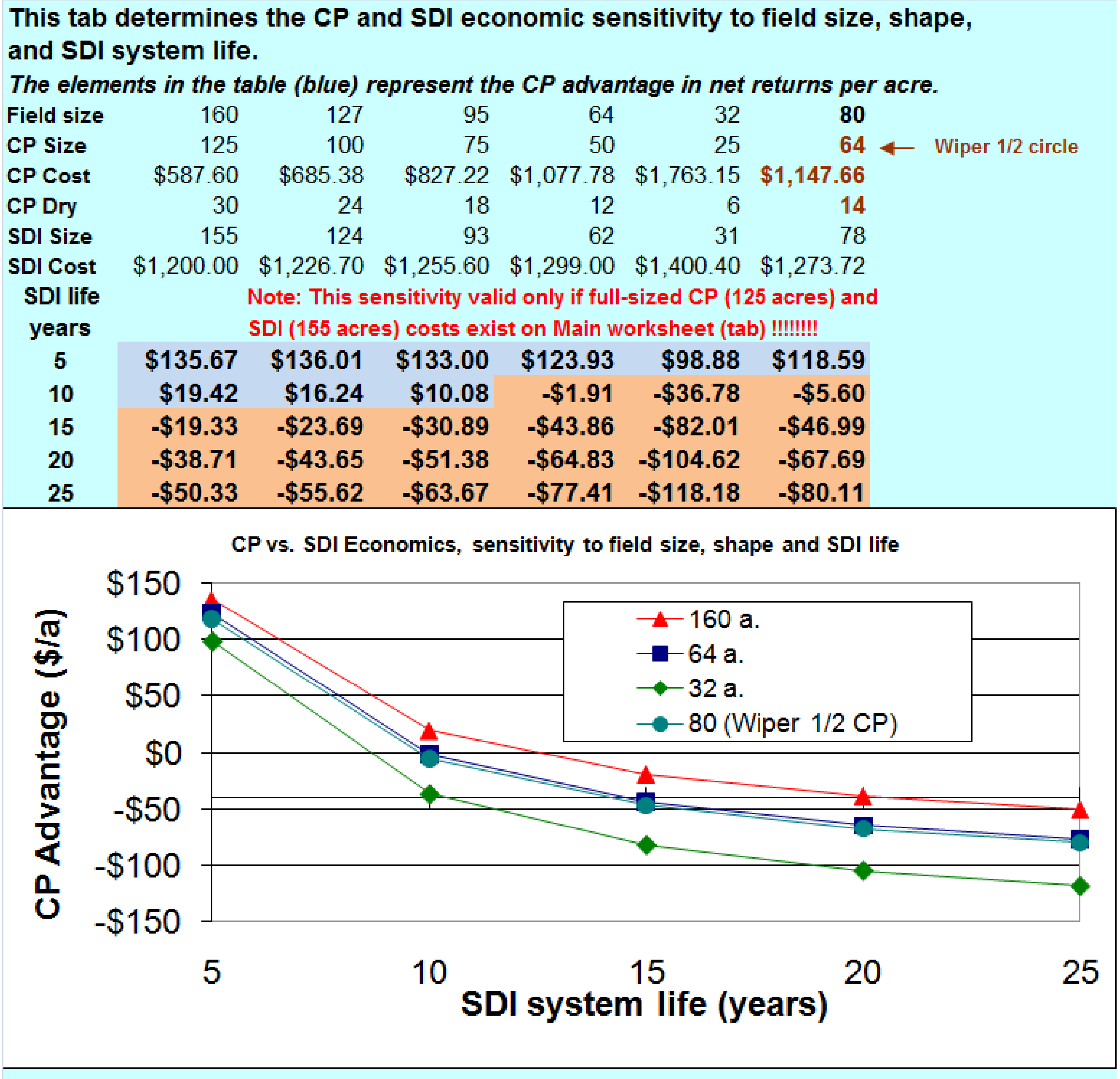
- corn yield
- corn price
- yield/price combinations

and very sensitive to

- higher potential yields with SDI

with advantages favoring SDI as corn yields and price increase.

The economic comparison spreadsheet also includes three worksheet (tabs) that display tabular and graphical sensitivity analyses for field size and SDI system life (Figure 4), SDI system cost and life (Figure 5), and corn yield and selling price (Figure 6). These sensitivity analysis worksheets will automatically update when different assumptions are made on the Main worksheet. The elements in light blue of the sensitivity tables indicate cases where CP systems are more profitable while elements with negative signs in reddish brown are cases where SDI is more profitable.



This tab determines the CP and SDI economic sensitivity to field size, shape, and SDI system life.

The elements in the table (blue) represent the CP advantage in net returns per acre.

Field size	160	127	95	64	32	**80**	
CP Size	125	100	75	50	25	**64**	← Wiper 1/2 circle
CP Cost	$587.60	$685.38	$827.22	$1,077.78	$1,763.15	**$1,147.66**	
CP Dry	30	24	18	12	6	**14**	
SDI Size	155	124	93	62	31	78	
SDI Cost	$1,200.00	$1,226.70	$1,255.60	$1,299.00	$1,400.40	$1,273.72	
SDI life years	**Note: This sensitivity valid only if full-sized CP (125 acres) and SDI (155 acres) costs exist on Main worksheet (tab) !!!!!!!!**						
5	**$135.67**	**$136.01**	**$133.00**	**$123.93**	**$98.88**	**$118.59**	
10	**$19.42**	**$16.24**	**$10.08**	**-$1.91**	**-$36.78**	**-$5.60**	
15	**-$19.33**	**-$23.69**	**-$30.89**	**-$43.86**	**-$82.01**	**-$46.99**	
20	**-$38.71**	**-$43.65**	**-$51.38**	**-$64.83**	**-$104.62**	**-$67.69**	
25	**-$50.33**	**-$55.62**	**-$63.67**	**-$77.41**	**-$118.18**	**-$80.11**	

Figure 4. The Field size & SDI life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

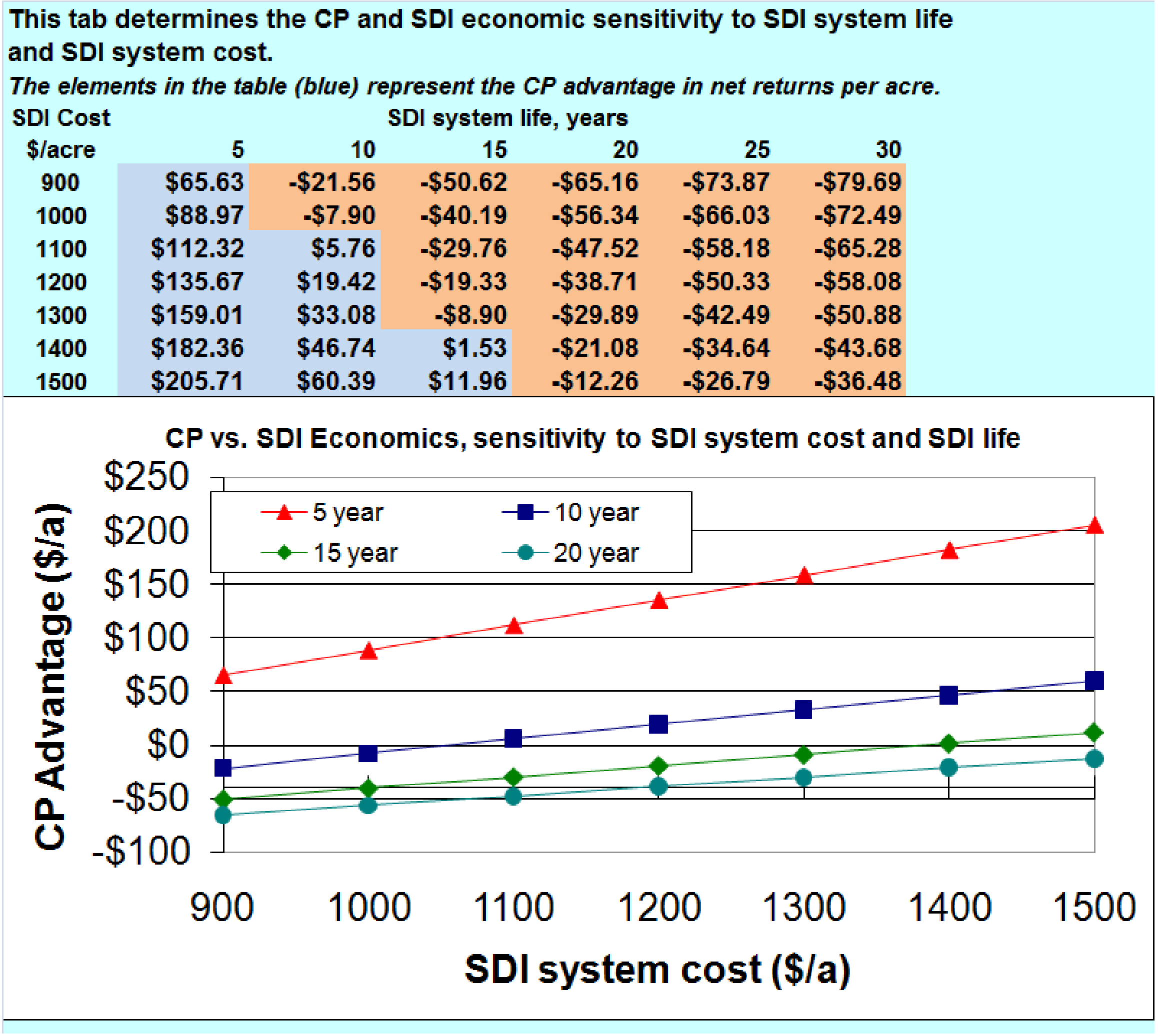
SOME KEY OBSERVATIONS FROM PREVIOUS ANALYSES

Users are encouraged to “experiment” with the input values on the Main worksheet (tab) to observe how small changes in economic assumptions can vary the bottom line economic comparison of the two irrigation systems. The following discussion will give the user “hints” about how the comparisons might be affected.

Smaller CP systems and systems which only complete part of the circle are less competitive with SDI than full size 125 acre CP systems This is primarily because the CP investment costs ($/ irrigated acre) increase dramatically as field size decreases (Figure 2 and 4) or when the CP system cannot complete a full circle. It should also be pointed out that part of the economic competitiveness of the higher priced SDI systems with lower priced CP systems occurs simply because less land area of the field is in dryland crop production.

Increased longevity for SDI systems is probably the most important factor for SDI to gain economic competitiveness with CP systems. A research SDI system at the KSU Northwest Research-Extension Center in Colby, Kansas has been operated for 22 years with very little performance degradation, so long system life is possible. There are a few SDI systems in the United States that have been operated for over 25 years without replacement (Lamm and Camp, 2007). However, a short SDI system life that might be caused by early failure due to clogging, indicates a huge economic disadvantage that would preclude nearly all adoption of SDI systems (Figure 4). Although SDI cost is an important factor, long SDI system life can help reduce the overall economic effect (Figure 5). The CP advantage for SDI system lives between 15 and 20 years is greatly diminished as compared to the difference between 10 and 15 year SDI system life. The sensitivity of CP system life and cost is much less because of the much lower initial CP cost and the much longer assumed life. Changing the CP system life from 25 to 20 years will not have a major effect on the economic comparison. However, in areas where CP life might be much less than 25 years due to corrosive waters, a sensitivity analysis with shorter CP life is warranted.

The present baseline analysis already assumes a 25% water savings with SDI. There are potentially some other production cost savings for SDI such as fertilizer and herbicides that have been reported for some crops and some locales. For example, there have been reports from other regions of less broadleaf and grassy weed pressure in SDI where the soil surface remains drier less conducive to germination of weed seeds (Lamm and Camp, 2007). Small changes in the assumptions can make a sizable difference in the economic analysis because there are more irrigated acres under the SDI system.



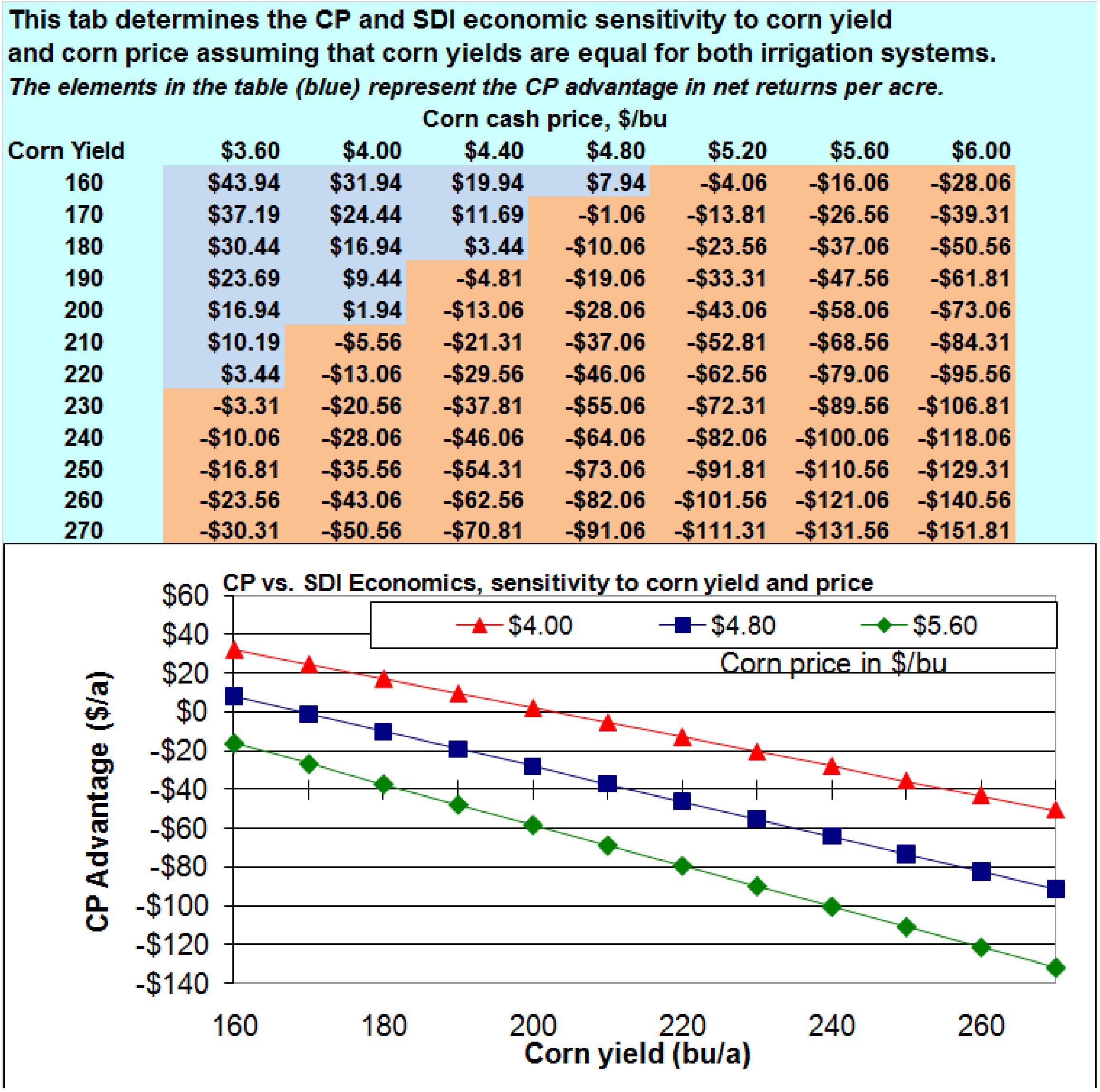
This tab determines the CP and SDI economic sensitivity to SDI system life and SDI system cost.

The elements in the table (blue) represent the CP advantage in net returns per acre.

SDI Cost	SDI system life, years					
$/acre	5	10	15	20	25	30
900	$65.63	-$21.56	-$50.62	-$65.16	-$73.87	-$79.69
1000	$88.97	-$7.90	-$40.19	-$56.34	-$66.03	-$72.49
1100	$112.32	$5.76	-$29.76	-$47.52	-$58.18	-$65.28
1200	$135.67	$19.42	-$19.33	-$38.71	-$50.33	-$58.08
1300	$159.01	$33.08	-$8.90	-$29.89	-$42.49	-$50.88
1400	$182.36	$46.74	$1.53	-$21.08	-$34.64	-$43.68
1500	$205.71	$60.39	$11.96	-$12.26	-$26.79	-$36.48

Figure 5. The SDI cost and life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

It has already been stated that higher corn yields and higher corn prices improve the SDI economics. These results can be seen on the Yield and Price sensitivity worksheet (tab) on the Excel template (Figure 6). This result occurs because of the increased irrigated area for SDI in the given 160 acre field. The significance of yield and price can be illustrated by taking one step further in the economic analysis, that being the case where there is a yield difference between irrigation systems. Combining a greater overall corn yield potential with an additional small yield advantage for SDI on the Main tab can allow SDI to be very competitive with CP systems.



This tab determines the CP and SDI economic sensitivity to corn yield and corn price assuming that corn yields are equal for both irrigation systems.

The elements in the table (blue) represent the CP advantage in net returns per acre.

	Corn cash price, $/bu						
Corn Yield	$3.60	$4.00	$4.40	$4.80	$5.20	$5.60	$6.00
160	$43.94	$31.94	$19.94	$7.94	-$4.06	-$16.06	-$28.06
170	$37.19	$24.44	$11.69	-$1.06	-$13.81	-$26.56	-$39.31
180	$30.44	$16.94	$3.44	-$10.06	-$23.56	-$37.06	-$50.56
190	$23.69	$9.44	-$4.81	-$19.06	-$33.31	-$47.56	-$61.81
200	$16.94	$1.94	-$13.06	-$28.06	-$43.06	-$58.06	-$73.06
210	$10.19	-$5.56	-$21.31	-$37.06	-$52.81	-$68.56	-$84.31
220	$3.44	-$13.06	-$29.56	-$46.06	-$62.56	-$79.06	-$95.56
230	-$3.31	-$20.56	-$37.81	-$55.06	-$72.31	-$89.56	-$106.81
240	-$10.06	-$28.06	-$46.06	-$64.06	-$82.06	-$100.06	-$118.06
250	-$16.81	-$35.56	-$54.31	-$73.06	-$91.81	-$110.56	-$129.31
260	-$23.56	-$43.06	-$62.56	-$82.06	-$101.56	-$121.06	-$140.56
270	-$30.31	-$50.56	-$70.81	-$91.06	-$111.31	-$131.56	-$151.81

Figure 6. The Yield and Price worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

AVAILABILITY OF FREE SOFTWARE

A Microsoft Excel spreadsheet template has been developed to allow producers to make their own comparisons. It is available on the SDI software page of the K-State Research and Extension SDI website at http://www.ksre.ksu.edu/sdi/.

ACKNOWLEDGMENTS

This paper is also part of a three-year long 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/. Watch for this logo.

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[1] *Mention of tradenames is for informational purposes and does not constitute endorsement by Kansas State University.*

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EVALUATING ENERGY USE FOR PUMPING IRRIGATION WATER

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ENERGY USE IN IRRIGATON

Irrigation of 13.8 million acres of cropland accounts for a large portion of the energy used in Colorado, Nebraska, and Kansas. Analysis of data from the 2008 USDA Farm and Ranch Irrigation Survey shows that the average energy use for irrigating crops in Nebraska alone would be equivalent to about 340 million gallons of diesel fuel annually if all pumps were powered with diesel engines. While use varies depending on annual precipitation, average yearly energy consumption in Nebraska is equivalent to about 40 gallons of diesel fuel per acre irrigated.

The cost to irrigate a field is determined by the amount of water pumped and the cost to apply a unit (acre-inch) of water (Figure 1). Factors that determine pumping costs include those that are fixed for a given location (in the ovals in Figure 1) and those that producers can influence. The factors that producers can influence include: irrigation scheduling, application efficiency, efficiency of the pumping plant, and the pumping pressure required for center pivot system. Pumping costs can be minimized by concentrating on these factors. Irrigators may also consider changing the type of energy used to power irrigation if they determine that one source provides a long-term advantage.

Irrigation scheduling can minimize the total volume of water applied to the field. Demonstration projects in central Nebraska have indicated that 1.5-2.0 inches of water can be saved by monitoring soil water and estimating crop water use rates. The goal is to maximize use of stored soil water and precipitation to minimize pumping.

Improving the efficiency of water application is a second way to conserve energy. Water application efficiency is a comparison between the depth of water pumped and the depth stored in the soil where it is available to the crop. Irrigation systems can lose water to evaporation in the air or directly off plant foliage. Water is also lost at the soil surface as evaporation or runoff. Excess irrigation and/or rainfall may also percolate through the crop root zone leading to deep percolation. For center pivots, water application efficiency is based largely on the sprinkler package. High pressure impact sprinklers direct water upward into the air and thus there is more opportunity for wind drift and in-air evaporation. In addition, high pressure impact sprinklers apply water to foliage for 20-40 minutes longer than low pressure spray heads mounted on drop tubes. The difference in application time results in less evaporation directly from the foliage for low pressure spray systems. Caution should be used so that surface runoff does not result with a sprinkler package. Good irrigation scheduling should minimize deep percolation.

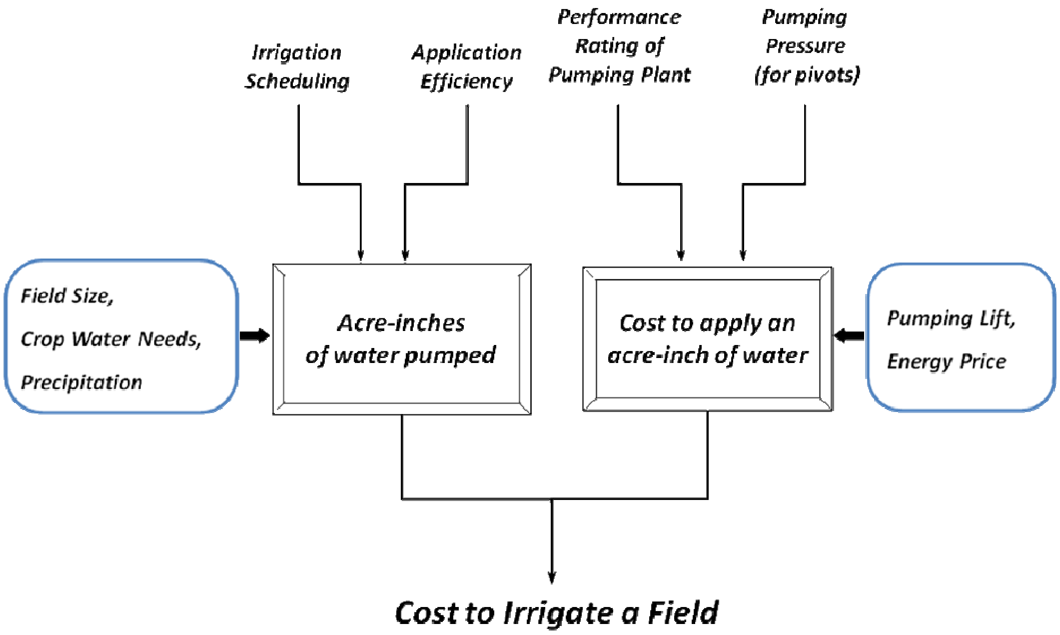


Figure 1. Diagram of factors affecting irrigation pumping costs.

Energy use can also be reduced by lowering the operating pressure of the irrigation system. One must keep in mind that lowering the operating pressure will reduce pumping cost per acre-inch, but reducing the pressure almost always results in an increased water application rate for a center pivot. The key is to ensure that the operating pressure is sufficient to eliminate the potential for surface runoff. Field soil characteristics, surface roughness, slope and tillage combine to control how fast water can be applied to the soil surface before surface runoff occurs. If water moves from the point of application, the savings in energy resulting from a reduction in operating pressure is counterbalanced by the need to pump more water to ensure that all portions of the field receive at least the desired amount of water.

Finally, energy can be conserved by ensuring that the pumping plant is operating as efficiently as possible. Efficient pumping plants require properly matched pumps, systems and power sources. By keeping good records of the amount of water pumped and the energy used, you can discover if extra money is being spent on pumping the water and how much you can afford to spend to fix components that are responsible for increased costs.

This document describes a method to estimate the cost of pumping water and to compare the amount of energy used to that for a well maintained and designed pumping plant. The results can help determine the feasibility of repairs.

ENERGY REQUIREMENTS

The cost to pump irrigation water depends on the type of energy used to power the pumping unit. Electricity and diesel fuel are used to power irrigation for about 76% of the land irrigated in the region. Nebraska uses electricity or diesel fuel to power pumping plants used to irrigate approximately 7.58 million acres of cropland. Natural gas and Propane are used on about 20 and 4% of the land in the 3-state region, respectively. Kansas leads the region in the use of natural gas for pumping plant power with approximately 1.4 million acres irrigated. Very little land is irrigated with gasoline powered engines.

The cost to pump an acre-inch of water depends on:

- The work produced per unit of energy consumed,
- The distance water is lifted from the groundwater aquifer or surface water source to the pump outlet,
- The discharge pressure at the pump outlet,
- The performance rating of the pumping plant, and
- The cost of a unit of energy.

The amount of work produced per unit of energy depends on the source used to power the pump (Table 1). One gallon of diesel fuel will generate about 139,000 BTU of energy if completely burned. The energy content can also be expressed as the horsepower-hours of energy per gallon of fuel (*i.e.,* 54.5 hp-hr/gallon). Not all of the energy contained in the fuel can be converted to productive work when the fuel is burned in an engine. The Nebraska Pumping Plant Performance Criteria (NPPPC) was developed to provide an estimate of the amount of work that can be obtained from a unit of energy by a well designed and managed pumping plant (Table 1). Values were developed from testing engines and motors to determine how much work (expressed as horsepower-hours) could be expected from a unit of energy. An average efficiency for the pump and drive system for well designed and maintained pumping plants was used to provide the amount of work that could be expected from a “good” pumping plant.

The overall performance of the engine/motor and pump system is expressed as water horsepower hours (whp-hr). Research conducted to develop the NPPPC showed that diesel engines produced about 16.7 hp-hr of work per gallon of diesel fuel and that good pumping plants would produce about 12.5 whp-hr/gallon of diesel fuel. The performance of the engine and pumping plant systems can also be expressed as an efficiency, *i.e.,* the ratio of the work done compared to the energy available in the fuel. Results show that a diesel engine that meets the Nebraska Pumping Plant Criteria is only about 30% efficient and that the overall efficiency is only about 23%. Diesel engines are more efficient than spark engines (Table 1).

The amount of energy required for a specific system depends on the location of the water source relative to the elevation of the pump discharge. For groundwater the pumping lift depends on the distance from the pump base to the water level when not pumping (static water level) plus the groundwater drawdown as shown in Figure 2. Note that the lift is not the depth of the well or the depth that the pump bowls are located in the well. The lift may increase over time if groundwater levels decline during the summer or over the years. It is best to measure the pumping lift directly but the value can be estimated from well registration information for initial estimates. Well registration information for the 3-state region can be obtained on the internet at the following URL's:
Colorado: http://www.dwr.state.co.us/WellPermitSearch/default.aspx
Kansas: *http://www.kgs.ku.edu/Magellan/WaterWell/index.html*
Nebraska: *http://dnrdata.dnr.ne.gov/wellssql/* .

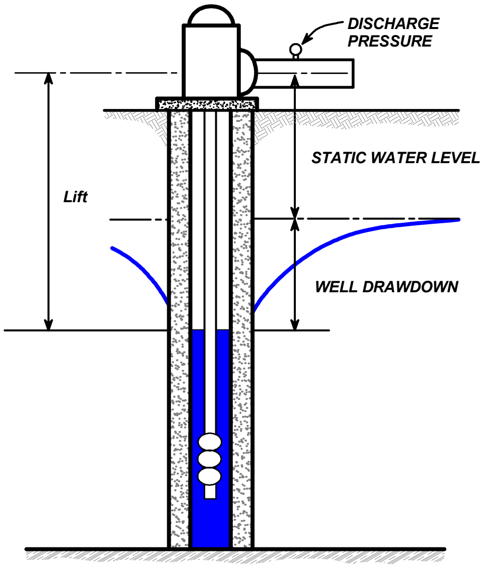


Figure 2. Diagram of pumping lift and discharge pressure measurements needed to assess pumping efficiency.

PUMPING PLANT EFFICIENCY

The amount of energy required for a properly designed and maintained pumping plant to pump an acre-inch of water can be determined from Tables 2 and 3.

Table 1. Energy Content of Fuels for Powering Irrigation Engines[‡]

Energy Source	Average Energy Content		Nebraska Pumping Plant Performance Criteria		Engine or Motor Efficiency %	Pumping Plant Conversion %
	BTU	Horsepower hour	Engine or Motor Performance hp-hr/unit	Pumping Plant Performance whp-hr/unit[†]		
1 gallon of diesel fuel	138,690	54.5	16.7	12.5	31	23
1 gallon of gasoline	125,000	49.1	11.5	8.66	23	18
1 gallon of liquefied petroleum gas (LPG)	95,475	37.5	9.20	6.89	25	18
1 thousand cubic foot of natural gas	1,020,000	401	82.2	61.7	21	15
1 therm of natural gas	100,000	39.3	8.06	6.05	21	15
1 gallon of ethanol [✓]	84,400	33.2	7.80	5.85	X	X
1 gallon of gasohol (10% ethanol, 90% gasoline)	120,000	47.2	11.08	8.31	X	X
1 kilowatt-hour of electrical energy	3,412	1.34	1.18	0.885	88	66

[‡] Conversions: 1 horsepower = 0.746 kilowatts, 1 kilowatt-hour = 3412 BTU, 1 horsepower-hour = 2,544 BTU

[†] Assumes an overall efficiency of 75% for the pump and drive.

[✓] Nebraska Pumping Plant Criteria for fuels containing ethanol were estimated based on the BTU content of ethanol and the performance of gasoline engines.

For example, a producer who has a system with a pumping lift of 150 feet and operates at a pump discharge pressure of 60 pounds per square inch (psi) would require 2.63 gallons of diesel fuel to apply an acre-inch of water. If the producer uses electricity the value of 2.63 should be multiplied by the factor in Table 3 to convert energy units. So, for electricity (2.63 x 14.12) = 37 kilowatt-hours would be needed per acre inch of water from a well with a pumping lift of 150 feet and an outlet pressure of 60 psi.

The amount of energy required for an actual pumping plant depends on the efficiency of the pump and power unit. If the pumping plant is not properly maintained and operated, or if conditions have changed since the system was installed, the pumping plant may not operate as efficiently as listed in Table 2. The energy needed for an actual system is accounted for in the NPPPC. Table 4 can be used to determine the impact of a performance rating less that 100%. For a performance rating of 80% the multiplier is 1.25, so the amount of energy used would be 25% more than for a system operating as shown in Table 2. The amount of diesel fuel for the previous example would be (2.63 x 1.25) = 3.29 gallons per acre-inch of water.

Table 2. Gallons of diesel fuel required to pump an acre-inch at a performance rating of 100%.

Lift	**Pressure at Pump Discharge, psi**						
feet	**10**	**20**	**30**	**40**	**50**	**60**	**80**
0	0.21	0.42	0.63	0.84	1.05	1.26	1.69
25	0.44	0.65	0.86	1.07	1.28	1.49	1.91
50	0.67	0.88	1.09	1.30	1.51	1.72	2.14
75	0.89	1.11	1.32	1.53	1.74	1.95	2.37
100	1.12	1.33	1.54	1.75	1.97	2.18	2.60
125	1.35	1.56	1.77	1.98	2.19	2.40	2.83
150	1.58	1.79	2.00	2.21	2.42	**2.63**	3.05
200	2.03	2.25	2.46	2.67	2.88	3.09	3.51
250	2.49	2.70	2.91	3.12	3.33	3.54	3.97
300	2.95	3.16	3.37	3.58	3.79	4.00	4.42
350	3.40	3.61	3.82	4.03	4.25	4.46	4.88
400	3.86	4.07	4.28	4.49	4.70	4.91	5.33

Table 3. Conversions factors for other energy sources.

Energy Source	**Units**	**Multiplier**
Diesel	gallons	1.00
Electricity	kilowatt-hours	14.12
Propane	gallons	1.814
Gasoline	gallons	1.443
Natural Gas	1000 cubic feet	0.2026

Table 4. Multiplier when pumping plant performance rating is less than 100%.

Rating, %	100	90	80	70	50	30
Multiplier	1.00	1.11	1.25	1.43	2.00	3.33

Producers can use Tables 2-4 and their energy records to estimate the performance rating for their pumping plant and the amount of energy that could be saved if the pumping plant was repaired or if operation was adjusted to better match characteristics of the pump and power unit.

Producers can also use hourly performance to estimate how well their pumping plant is working. For the hourly assessment an estimate of the pumping lift, discharge pressure, flow rate from the well and the hourly rate of energy consumption are required. The acre-inches of water pumped per hour can be determined from in Table 5.

Table 5. Volume of water pumped per hour.

Pump Discharge gpm	**Water Pumped per Hour acre-inch/hr**	**Pump Discharge gpm**	**Water Pumped per Hour, acre-inch/hr**
250	0.55	1250	2.76
300	0.66	1300	2.87
350	0.77	1350	2.98
400	0.88	1400	3.09
450	0.99	1500	3.31
500	1.10	1600	3.54
550	1.22	1700	3.76
600	1.33	1800	3.98
650	1.44	1900	4.20
700	1.55	2000	4.42
750	1.66	2100	4.64
800	1.77	2200	4.86
850	1.88	2400	5.30
900	1.99	2600	5.75
950	2.10	2800	6.19
1000	2.21	3000	6.63
1050	2.32	3200	7.07
1100	2.43	3400	7.51
1150	2.54	3600	7.96
1200	2.65	3800	8.40

The performance of the pumping plant (P_p) in terms of energy use per acre-inch of water is then the ratio of the hourly energy use divided by the volume of water pumped per hour:

$$P_p = \frac{\text{hourly fuel use rate (in gallons / hour}}{V_w \ \text{(in acre} - \text{inches / hour)}}$$

For example, suppose a pump supplies 800 gallons per minute and the diesel engine burns 5.5 gallons of diesel fuel per hour. A flow rate of 800 gpm is equivalent to 1.77 acre-inches per hour (Table 5). The pumping plant performance is computed as 5.5 gallons of diesel per hour divided by 1.77 acre-inches of water per hour. This gives 3.11 gallons of diesel per acre-inch.

Suppose that the pumping lift is 150 feet and the discharge pressure is 60 psi for this example. If the system operates at the Nebraska Pumping Plant Performance Criteria only 2.63 gallons of diesel per acre-inch would be required (Table 2). The pumping plant performance rating (R) would be:

$$R = \frac{100 \times \text{Value from Table 2}}{P_p} = \frac{100 \times 2.63}{3.11}$$

For this case the performance rating is 85 meaning that the system uses about 18% more diesel fuel than required for a system at the Nebraska Criteria. The multipliers in Table 2 can also be used with the hourly method for other energy sources.

PAYING FOR REPAIRS

Energy savings from repairing the pumping plant should be compared to the ability to pay for the repairs. The money that can be paid for repairs is determined by the length of the repayment period and the annual interest rate. These values are used to compute the series present worth factor (Table 6). The breakeven investment is the value of the annual energy savings times the series present worth factor.

The series present worth factor represents the amount of money that could be repaid at the specified interest rate over the repayment period. For example, for an interest rate of 7% and a repayment period of 10 years each dollar of annual savings is equivalent to $7.02 today. Only $4.10 could be invested today for each dollar of savings if the investment was to be repaid in 5 years rather than 10 years.

Example

Suppose a pivot was used on 130 acres to apply 13.5 inches of water. The pumping lift was about 125 feet and the discharge pressure was 50 psi. Energy use records for the past season show that 5500 gallons of diesel fuel were used. The average price of diesel fuel for the season was $3.00 per gallon.

Using the value of 2.19 gallons of diesel fuel per acre-inch from Table 2, an efficient pumping plant would require about 3843 gallons of diesel fuel for the year (*i.e.,* 2.19 gallons/acre-inches times 13.5 inches times 130 acres = 1755 acre-inches of water). The annual records show that 5500 gallons were used to pump the water, then the performance rating would be (3843 / 5500) x 100 = 70%. This shows that 1657 gallons of diesel fuel could be saved if the pumping plant performance was improved. The annual savings in pumping costs would be the product of the energy savings times the cost of diesel fuel; *i.e.,* $3/gallon times 1657 gallons/year = $4971/year. If a 5-year repayment period and 9% interest were used, the series present worth factor would be 3.89 from Table 6. The breakeven repair cost would be $4971 × 3.89 = $19,337. If repair costs were less than $19,337 then repairs would be feasible. If costs were more than $19,337 the repairs may not be advisable at this time.

Table 6. Series Present Worth Factor

Repayment Period, years	Annual Interest Rate					
	6%	**7%**	**8%**	**9%**	**10%**	**12%**
3	2.67	2.62	2.58	2.53	2.49	2.40
4	3.47	3.39	3.31	3.24	3.17	3.04
5	4.21	4.10	3.99	3.89	3.79	3.60
6	4.92	4.77	4.62	4.49	4.36	4.11
7	5.58	5.39	5.21	5.03	4.87	4.56
8	6.21	5.97	5.75	5.53	5.33	4.97
9	6.80	6.52	6.25	6.00	5.76	5.33
10	7.36	7.02	6.71	6.42	6.14	5.65
12	8.38	7.94	7.54	7.16	6.81	6.19
15	9.71	9.11	8.56	8.06	7.61	6.81
20	11.47	10.59	9.82	9.13	8.51	7.47
25	12.78	11.65	10.67	9.82	9.08	7.84

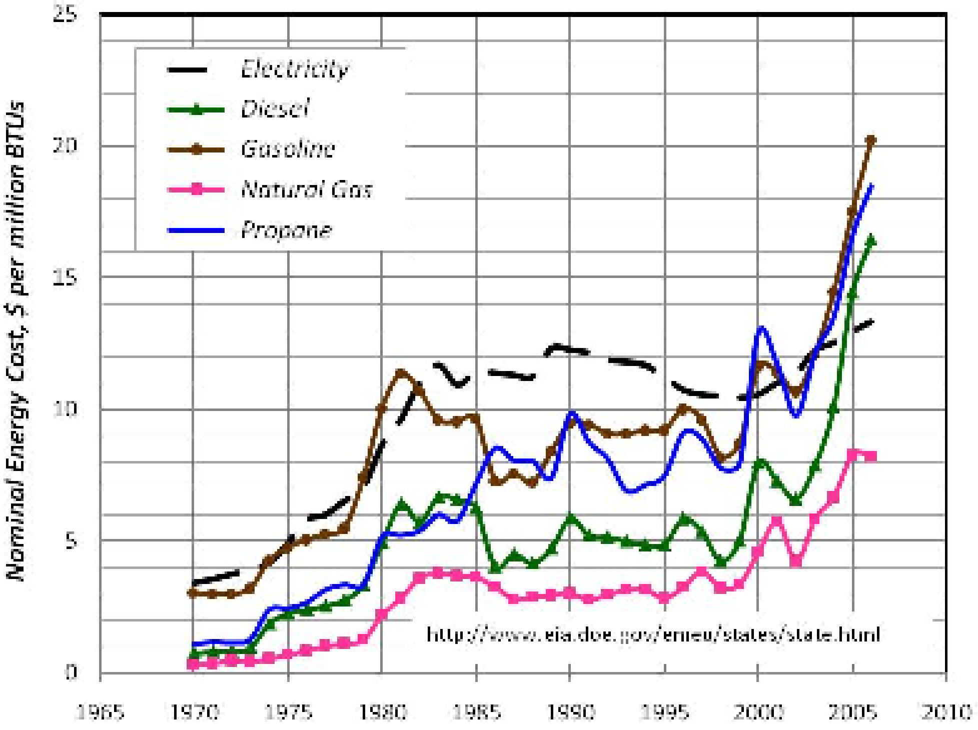
COMPARING ENERGY SOURCES

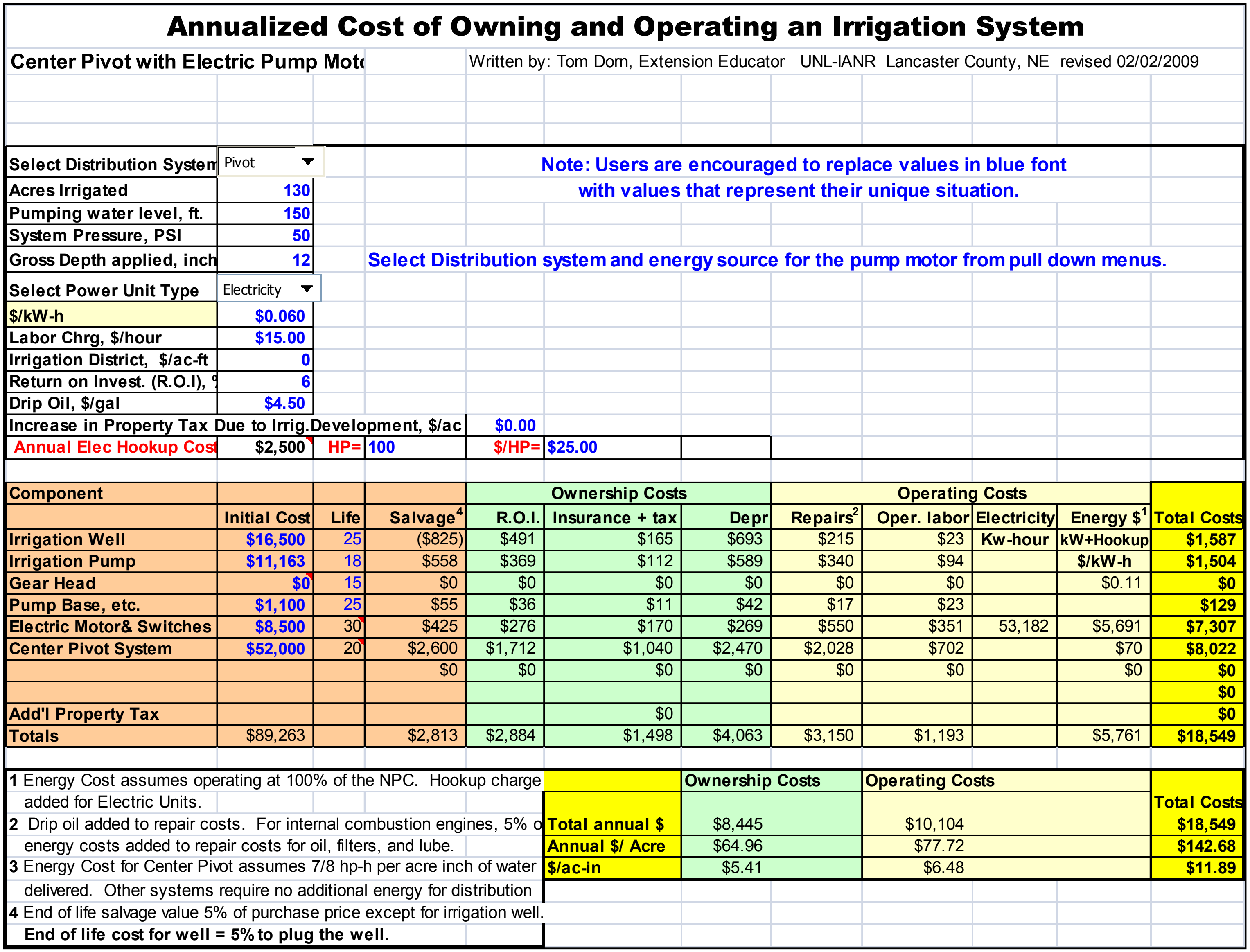
The optimal type of energy for powering irrigation engines depends on the long-term relative price of one energy source compared to another. Energy prices have varied considerably over time. The nominal cost of energy per million BTUs is illustrated in Figure 3 for the types used to power irrigation systems for the period from 1970 through 2006. These results show that electricity was expensive relative to other energy sources from about 1983 through about 2000. Electricity has become more favorable especially recently when fossil fuels prices have increased rapidly. While diesel fuel once was very economical the situation has recently changed.

Two methods can be used to analyze power source alternatives for irrigation. The previous section illustrated how to determine the amount one could afford to pay through annual energy savings if one changed from an energy source to another type. A more detailed analysis based on the average annual ownership cost can be found at the URL http://lancaster.unl.edu/ag/Crops/irrigate.shtml. A demonstration of the technique is illustrated to compare diesel and electricity as energy sources for a typical center pivot. Representative costs are included in Figure 4 for an electrically powered pivot and in Figure 5 for a pivot powered with a diesel engine. The cost for the electric motor should include any extra expenses for control panels and to bring three-phase service to the motor. The diesel engine should include the cost of the fuel tank and an electric generator if one is not present. The costs listed in the figures are approximate values and local conditions should be use for specific comparisons.

Results of using the spreadsheet to compare the total annual cost of an electrically powered and a diesel powered irrigation system are shown in Table 7 for a range of electricity and diesel fuel prices. The annual savings is the difference between the annual costs for diesel minus the cost for an electrically powered system. The results show that electricity is generally preferred except when diesel is less than $2.25 /gallon and electrical rates are above 8¢/kWh. If the price of electricity is 6¢/kWh and diesel fuel is $2.25 per gallon then switching to electricity could save over $3,000 annually as long as service can be brought to the field. Again, these are representative costs and producers should analyze their unique situation.

Figure 3. Historical energy prices since 1970.





Annualized Cost of Owning and Operating an Irrigation System

Center Pivot with Electric Pump Mot Written by: Tom Dorn, Extension Educator UNL-IANR Lancaster County, NE revised 02/02/2009

Select Distribution System	Pivot			
Acres Irrigated	130			
Pumping water level, ft.	150			
System Pressure, PSI	50			
Gross Depth applied, inch	12			
Select Power Unit Type	Electricity			
$/kW-h	$0.060			
Labor Chrg, $/hour	$15.00			
Irrigation District, $/ac-ft	0			
Return on Invest. (R.O.I),	6			
Drip Oil, $/gal	$4.50			
Increase in Property Tax Due to Irrig.Development, $/ac	$0.00			
Annual Elec Hookup Cost	$2,500	HP= 100	$/HP=	$25.00

Note: Users are encouraged to replace values in blue font with values that represent their unique situation.

Select Distribution system and energy source for the pump motor from pull down menus.

Component				Ownership Costs			Operating Costs				
	Initial Cost	Life	Salvage[4]	R.O.I.	Insurance + tax	Depr	Repairs[2]	Oper. labor	Electricity	Energy $[1]	Total Costs
Irrigation Well	$16,500	25	($825)	$491	$165	$693	$215	$23	Kw-hour	kW+Hookup	$1,587
Irrigation Pump	$11,163	18	$558	$369	$112	$589	$340	$94		$/kW-h	$1,504
Gear Head	$0	15	$0	$0	$0	$0	$0	$0		$0.11	$0
Pump Base, etc.	$1,100	25	$55	$36	$11	$42	$17	$23			$129
Electric Motor& Switches	$8,500	30	$425	$276	$170	$269	$550	$351	53,182	$5,691	$7,307
Center Pivot System	$52,000	20	$2,600	$1,712	$1,040	$2,470	$2,028	$702		$70	$8,022
			$0	$0	$0	$0	$0	$0		$0	$0
											$0
Add'l Property Tax					$0						$0
Totals	$89,263		$2,813	$2,884	$1,498	$4,063	$3,150	$1,193		$5,761	$18,549

1 Energy Cost assumes operating at 100% of the NPC. Hookup charge added for Electric Units.

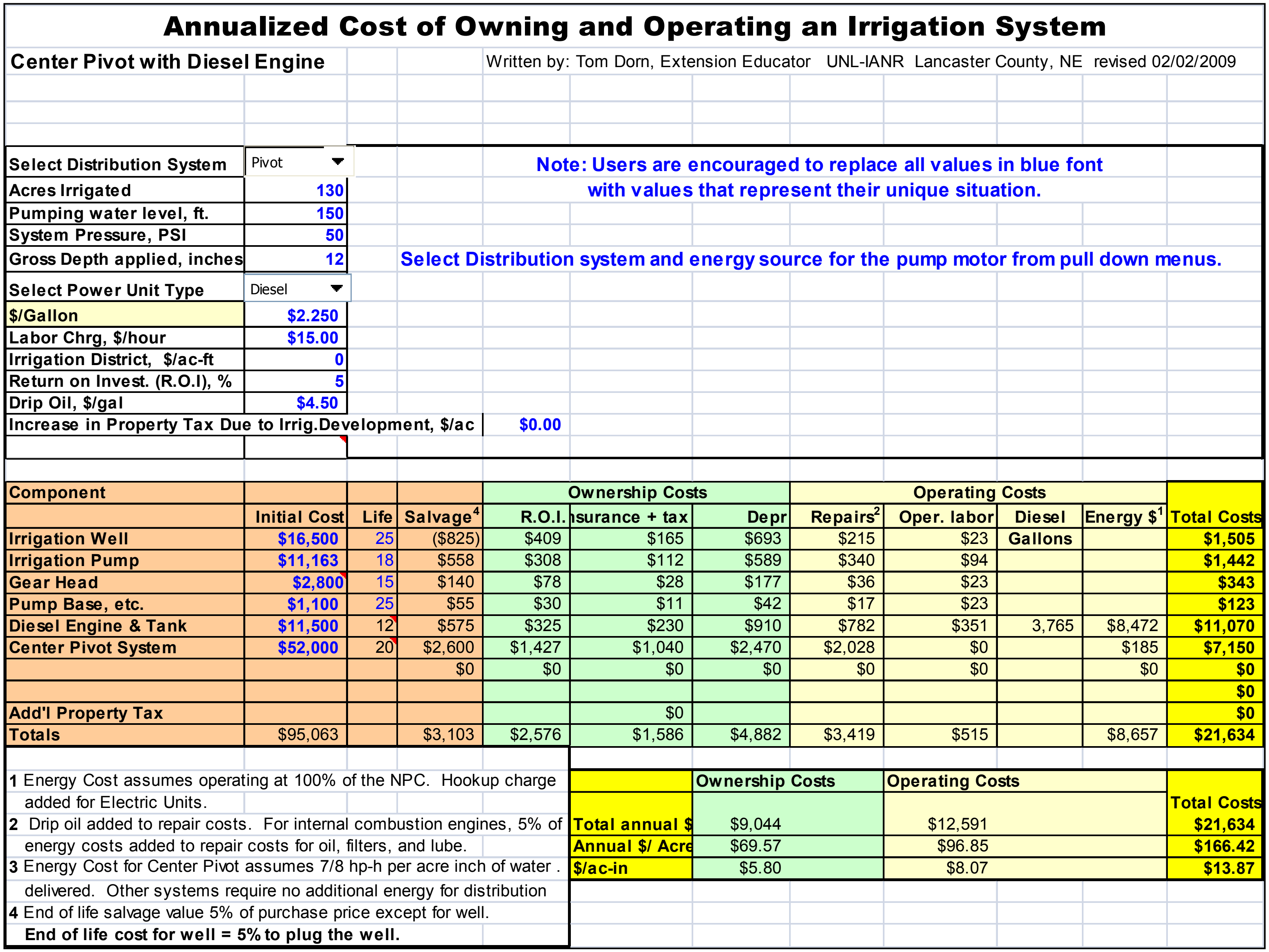
2 Drip oil added to repair costs. For internal combustion engines, 5% o energy costs added to repair costs for oil, filters, and lube.

3 Energy Cost for Center Pivot assumes 7/8 hp-h per acre inch of water delivered. Other systems require no additional energy for distribution

4 End of life salvage value 5% of purchase price except for irrigation well. **End of life cost for well = 5% to plug the well.**

	Ownership Costs	Operating Costs	Total Costs
Total annual $	$8,445	$10,104	$18,549
Annual $/ Acre	$64.96	$77.72	$142.68
$/ac-in	$5.41	$6.48	$11.89

Figure 4. Detailed analysis for an electrically powered center-pivot irrigated field with the conditions shown.



Annualized Cost of Owning and Operating an Irrigation System

Center Pivot with Diesel Engine Written by: Tom Dorn, Extension Educator UNL-IANR Lancaster County, NE revised 02/02/2009

Select Distribution System	Pivot
Acres Irrigated	**130**
Pumping water level, ft.	**150**
System Pressure, PSI	**50**
Gross Depth applied, inches	**12**
Select Power Unit Type	Diesel
$/Gallon	**$2.250**
Labor Chrg, $/hour	**$15.00**
Irrigation District, $/ac-ft	**0**
Return on Invest. (R.O.I), %	**5**
Drip Oil, $/gal	**$4.50**
Increase in Property Tax Due to Irrig.Development, $/ac	**$0.00**

Note: Users are encouraged to replace all values in blue font with values that represent their unique situation.

Select Distribution system and energy source for the pump motor from pull down menus.

Component				**Ownership Costs**			**Operating Costs**				
	Initial Cost	**Life**	**Salvage**[4]	**R.O.I.**	**nsurance + tax**	**Depr**	**Repairs**[2]	**Oper. labor**	**Diesel Gallons**	**Energy $**[1]	**Total Costs**
Irrigation Well	**$16,500**	25	($825)	$409	$165	$693	$215	$23			**$1,505**
Irrigation Pump	**$11,163**	18	$558	$308	$112	$589	$340	$94			**$1,442**
Gear Head	**$2,800**	15	$140	$78	$28	$177	$36	$23			**$343**
Pump Base, etc.	**$1,100**	25	$55	$30	$11	$42	$17	$23			**$123**
Diesel Engine & Tank	**$11,500**	12	$575	$325	$230	$910	$782	$351	3,765	$8,472	**$11,070**
Center Pivot System	**$52,000**	20	$2,600	$1,427	$1,040	$2,470	$2,028	$0		$185	**$7,150**
			$0	$0	$0	$0	$0	$0		$0	**$0**
											$0
Add'l Property Tax					$0						**$0**
Totals	$95,063		$3,103	$2,576	$1,586	$4,882	$3,419	$515		$8,657	**$21,634**

1 Energy Cost assumes operating at 100% of the NPC. Hookup charge added for Electric Units.

2 Drip oil added to repair costs. For internal combustion engines, 5% of energy costs added to repair costs for oil, filters, and lube.

3 Energy Cost for Center Pivot assumes 7/8 hp-h per acre inch of water . delivered. Other systems require no additional energy for distribution

4 End of life salvage value 5% of purchase price except for well.
End of life cost for well = 5% to plug the well.

	Ownership Costs	**Operating Costs**	**Total Costs**
Total annual $	$9,044	$12,591	**$21,634**
Annual $/ Acre	$69.57	$96.85	**$166.42**
$/ac-in	$5.80	$8.07	**$13.87**

Figure 5. Detailed analysis for a center-pivot irrigated field powered with diesel fuel for the field conditions shown.

Table 7. Annual Savings by Using Electricity

Electricity		Diesel Fuel Cost, $ / gallon			
		1.75	2.00	2.25	2.50
Price, $ / kWh	Total Annual Costs	$19,616	$20,625	$21,634	$22,643
0.06	$18,549	$1,067	$2,076	$3,085	$4,094
0.07	$19,119	$497	$1,506	$2,515	$3,524
0.08	$19,689	-$73	$936	$1,945	$2,954
0.09	$20,259	-$643	$366	$1,375	$2,384
0.10	$20,829	-$1,213	-$204	$805	$1,814

SUMMARY

This publication demonstrates methods to estimate the potential for repairing pumping plants to perform at the Nebraska Pumping Plant Performance Criteria and the annual cost for varying energy sources. Producers frequently have several questions regarding the procedures.

First they want to know ***"Can actual pumping plants perform at a level equal to the Criteria"***. Tests of 165 pumping plants in the 1980's indicated that 15% of the systems actually performed at a level above the Criteria. So producers can certainly achieve the standard. Recent evaluations in Nebraska have identified pumping plants that were operating at above 100% of the NPPPC, but many were between 80 and 100% of the NPPPC.

The second question is ***"What level of performance can producers expect for their systems?"*** Tests on 165 systems in Nebraska during the 1980s produced an average performance rating of 77% which translates to an average energy savings of 30% by improving performance. Tests on 200 systems in North Dakota in 2000 produced very similar results. These values illustrate that half of the systems in the Great Plains could be using much more energy than required. The simplified method can help determine if your system could be inefficient.

The third issue focuses on ***"What should I do if the simplified method suggests that there is room for improving the efficiency?"*** You should first determine if the irrigation system is being operated as intended. You need to know if the pressure, lift and flow rate are appropriate for the irrigation system. For example, some systems were initially installed to deliver water for furrow irrigation and are now used for center-pivot systems. If the pumping plant is not redesigned, conditions for the new system are likely not appropriate and you need to work with a well driller/pump supplier to evaluate the design of the system.

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FLOWMETER MAINTENANCE AND ISSUES

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INTRODUCTION

In 1945 the Water Appropriation Act was passed by the Kansas Legislature that set forth a number of provisions, including: “All water within the state of Kansas is hereby dedicated to the use of the people of the state, subject to the control and regulation of the state…”. In the late 1960’s people in the rapidly developing groundwater areas of the state became concerned over declining water levels and the lack of state policy to address the resource concerns. There was strong interest in more local control of the water issues and implementation of water law. This led to the establishment of the Groundwater Management Act in 1972, which set forth the state policy recognizing local management as the best approach. In 1976 the Southwest Kansas Groundwater Management District No. 3(GMD3) was established. Today, GMD3 covers all or parts of the 12 counties in southwest Kansas. GMD3 is the largest district in Kansas covering 8425 square miles that include over 10,000 active non-domestic wells with an average of just under 2 million acre feet of water use reported annually.

IMPLEMENTATION OF FLOWMETERS IN GMD3

Information is the key to good management. In 1992, GMD3 started a flowmeter program which required that all active, non-domestic wells be equipped with an approved water flowmeter. This was done on a four year rotational basis with all wells located in the SE quarter of each section required to have a flowmeter installed in 1992. That was then followed by the NE quarter in 1993, NW quarter in 1994 and the SW quarter in 1995. Flowmeters are required on all non-domestic wells that are active. If the well/land is in a conservation program, it is not required to have a flowmeter installed, but the flowmeter is required prior to the well being put back into service.

The flowmeters must be on the State's list of acceptable flowmeters. In the beginning, it was required that the flowmeter either have sufficient spacing from pipe obstructions or have straightening vanes. But spacing could be waived if the flowmeter installation was verified to be accurate. A main issue on the installation was measurement of all the water pumped from a point of diversion. It remains to this day the responsibility of the well owner to insure the flowmeter continues to operate satisfactorily. The operator was required to report the meter readings on the annual water use reports submitted to the state that are required by statute.

EARLY MONITORING AND COMPLIANCE

In the early stages of the metering program, we would do random inspection or a full inspection of a particular instillation if there was a compliance issue. We tried a self monitoring method with the producers. If they found their meter was not working correctly they were to notify our office and we would issue a "Safety" tag that would be placed at the location while the meter was removed. This allowed us to track the flowmeters and gave inspectors a visual sign that the meter had permission to be taken off for service. The tags were good for 15 working days. We would schedule follow up visits to ensure that the service had corrected any problems and the meter was now working correctly.

In 2003 GMD3 implemented a seasonal meter inspection program. Our office would hire three to four seasonal employees and assign them hundreds of wells to inspect. The program was to visit two thousand or more wells a year. The information they collected was submitted to our office bi-monthly. This type of program has continued to today. If a problem or a noncompliant meter is found, our office is notified within 24 hours. This starts the process to have the noncompliance corrected in a timely manner. The data taken from these inspections also allows us to monitor the pumping rates and supply changes across the District.

CURRENT ISSUES

The flowmeter is a mechanical device that can be prone to malfunctions and be cause for unreliability if they are not properly installed and maintained, or have faulty parts or instillation. Through the years of the GMD3 metering program we have seen a lot of different issues, but we will discuss the most common.

The most common issue we see is that the flowmeter is just not working which could be due to a variety of reasons. There could be something lodged in the propeller preventing it to spin. It could also, for example, have impeller bearings that locked up or any of several other mechanical failures. The operators do not always catch these failures, because the instantaneous reading could still be working, but the totalizer, which is the accurate part of the mechanics, may fail. These two functions, on certain flowmeters, sometimes work independently of each other. Since it is the totalizer that must be reported every year, it is critical to make sure that mechanism is always functioning. Meters that are found not working, must be repaired right away and the operator must then submit a flowmeter repair/replacement report to our office or the State. We have also recently begun to ask for a copy of the invoice as documentation of the repairs .

We do see quite a few cases in the field where the meter register is not readable. The biggest reason for this is moisture inside the lens. We have talked to most of the manufacturers and have been told that if there is moisture inside the meter, it is not reliable and could fail at any time. This is another case where the operator will need to send the meter in for repair and report to us when it is fixed and installed.

A requirement of the State is that all flowmeters must have a manufacturer's seal on it. The seal indicates the manufacturer's warranted reliability. And, the lack of a seal can sometimes indicate that the meter was tampered with. Unfortunately, over time, the seal can just fall off from exposure. In this case the operator has two alternatives. If they believe that the meter is working properly and it is just missing the seal, our office can perform a flow verification test. If the installed meter is within +/- 6%, we will put our seal on the meter, and that is acceptable. If the operator has any concern about how the flowmeter is operating, the meter must be sent to a certified repair person and they will put a seal on it after confirming accuracy.

We also see cases when the flowmeter is not installed properly in the pipe. This can mean it is on backwards, not installed where it will measure all of the water being diverted or does not meet current meter installation requirements. Today, if a well is redrilled or if the operator installs a new flowmeter, it must have at least 5 pipe diameters upstream and 2 diameters downstream of unobstructed straight run from the meter sensor. This rule applies unless the manufacturer has more stringent requirements. The meter must also have straightening vanes and be installed in a manufacturer approved measuring chamber. If spacing is not met the operator will have to make adjustments to the installation to make sure it meets current regulations. These regulations are intended to assure that in most cases, the flowmeter will function properly and an accurate measurement will likely occur.

In many areas within the District, the wells can no longer pump at the rate they were originally certified as producing. This can lead to a flowmeter not having a full flow of pipe across the measuring device. The operator will again need to make the proper corrections to ensure that there is a full flow of pipe across the meter or the meter performance will be compromised.

SERVICES PROVIDED

Our office continues to work with operators to achieve the best records are maintained in order to managing the water in our District. We can't manage the resource without good information. There are several services that we provide to assist water users.

In order to give the operators the best information on flowmeters, our office is constantly in contact with meter manufacturers. We try to keep up to date with the new technology in flowmeters and have a good understanding of how the meters work. This allows us to help operators determine what the problems might be for their installed meters and provide the best solution to the operator.

We continue to stress the importance of maintaining a properly working flowmeter. A good way to look at it is that the flowmeter needs to be treated just like any other equipment the operator uses. It is always good to do routine inspections and maintenance on the flowmeter. A well maintained meter will be more able function properly and most of the time, require less costly repairs.

GMD3 has staff that is certified by the State to perform flow verification tests on installed flowmeters to determine accuracy. We are also required to have our non-intrusive meters certified every year for accuracy traceable to NIST standards. We also perform random tests across the District throughout the year and at the request of the operators.

The best and sometimes most difficult thing to do is education of the operators on how to maintain the flowmeters and use them to their full potential. We are constantly encouraging people to time their meters and do simple, easy inspections on the flowmeters. If the operators would do self-inspections on the meters they could avoid the more expensive repairs. We also try to let people see the advantage of taking ten minutes to calculate what the meters are actually registering. This is a good way to keep track of how much they have pumped and can give the operator the ability to determine if the meter is not totalizing correctly

If you have a properly working meter, it can help you monitor your water usage, which could prevent water right enforcement actions later on. The best example we can give the operators is to look at their water rights as a checking account. The can start the year out with a full allocation in their account. As they pump the well, they are withdrawing from the account. The flowmeters can indicate how much is withdrawn and how much is left. It is also a good comparison to say that if you overdraw your checking account, there can be severe penalty. This is the case if you overpump your water right.

In this day and age, it is easy to get information out to a lot of people by using the internet. We offer a lot of different types of assistance from our webpage, and soon will offer even more. If the operator has to repair their flowmeter they can get the report that they will need to turn into our office. There are instructions of how to time your meters, perform quick inspections, and spreadsheets that will help them keep track of their water account.

TEMERATURE LOGGERS

A new program we are working with is the installation of temperature loggers used in the shipping industry to track groundwater well operations. We have done some testing in the last couple of years with installing inexpensive temperature loggers on the discharge pipe to record the temperature of the pipe every 15 to 30 minutes. When the well is pumping, the discharge pipe will maintain a fairly constant 60-65 degrees. This allows us to calculate how many hours the well operates. If we know the flow rate, we can estimate the amount of water pumped and when. This is a relatively easy way to back up the flowmeter data and gives our office valuable information about the timing of water applications. Currently we have the loggers installed on all of the wells that we are required to monitor by contract each year, as well as on some wells that have had noncompliance issues and need added supervision regarding well operations.

Give us a call if you have questions or would like to discuss this information further.

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EVALUATING CENTER PIVOT, NOZZLE-PACKAGE PERFORMANCE

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One definition of performance is: “operation: process or manner of functioning or operating.” The manner of functioning of a center pivot nozzle package is to deliver irrigation water to a targeted area. Good or successful performance in an irrigation setting with a growing crop most often implies that the application of irrigation water accomplished the goal of making the irrigation water available to the crop, usually by being distributed across the soil surface and infiltrated into the crops root zone where it can be accessed by the individual plants equally and, for the case of full irrigation capacity, in sufficient quantities to prevent yield limiting water stress. Another factor related to good performance is minimization of losses associated with the irrigation application, i.e. high irrigation efficiency.

Distribution Uniformity

Distribution uniformity is discussed by Rogers et al. 1997 and illustrated in Figure 1. It and can either indicate the degree of evenness in the depth of irrigation water applied to the soil or in the amount of the water infiltrated into the soil. The former may be associated with depths applied at the surface, based on catch-can measures for sprinkler systems. The latter associated with soil water measurements after infiltration, which are much more difficult to collect than surface measurements. This concept for uniformity was originally developed by Christiansen in 1942 for sprinkler systems. Generally, high uniformity is associated with the best crop growth conditions since each plant has equal opportunity to use applied water. Non-uniformity results in areas that are under-watered or overwatered. In particular, overwatered areas may cause a decrease in irrigation efficiency if the water moves below the crop root zone and therefore is lost for crop water use.

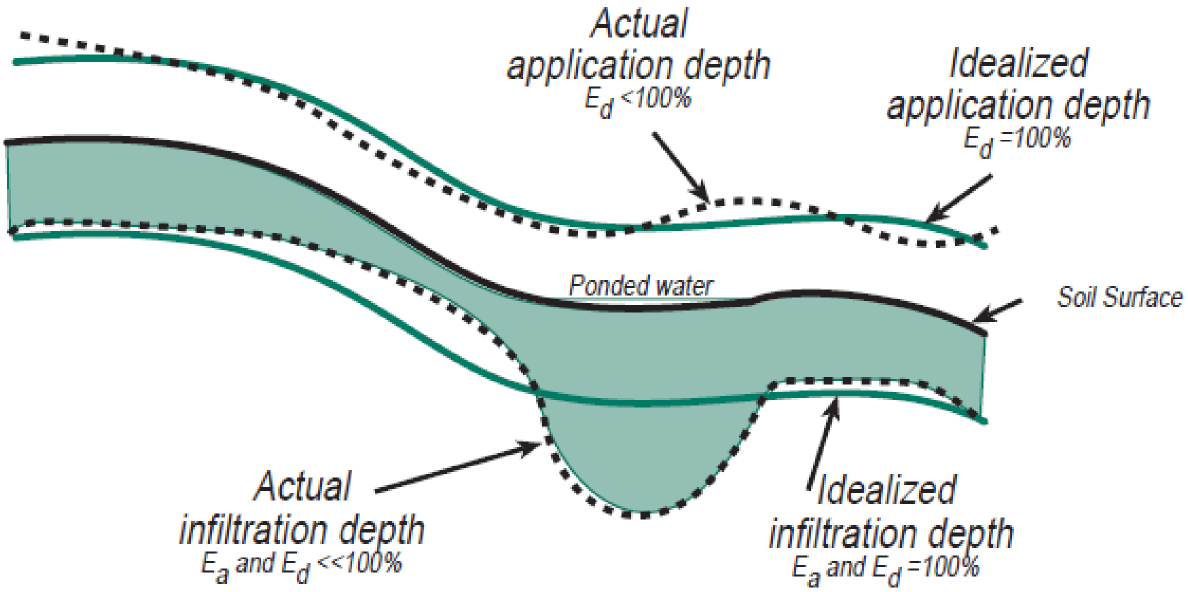


Figure 1: Illustration of a sprinkler package water distribution uniformity verses infiltrated water distribution uniformity in the soil (Rogers et al. 1997).

Irrigation Efficiency

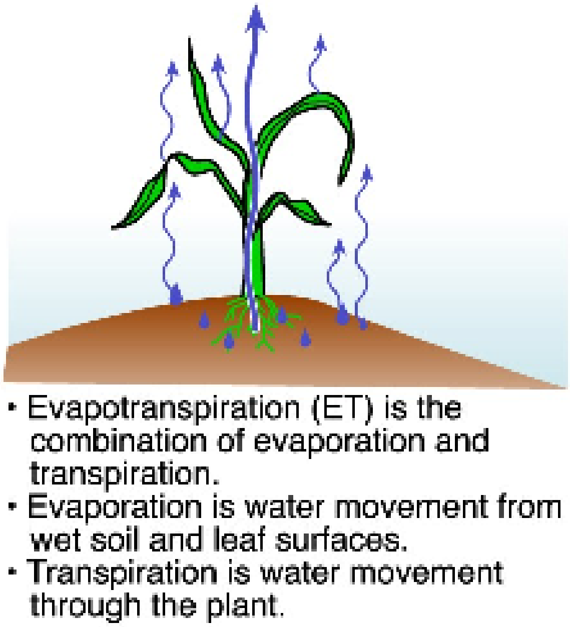
Irrigation efficiency can be defined as the percentage of water delivered to the field that is used beneficially (Rogers et al. 1997). This definition is a broad definition in that irrigation water may have more uses than simply satisfying crop water requirements. Other beneficial uses could include salt leaching, crop cooling, pesticide or fertilizer applications, or frost protection. However, most Kansas irrigation systems are single-purpose, which is to supply water for crop use.

Consumptive Use

Water diverted in Kansas for beneficial use, except for domestic water use, is subject to the terms and conditions of the Kansas Water Appropriation Act. This appropriation act allows the transfer of water use from one type of use to another as long as it does not increase the use of water beyond the original consumptive use. Consumptive use is the amount of water actually consumed while it is being applied to a beneficial use. The amount of consumptive use for various types of users can be large. For example, the consumptive use of water diverted for use in a cooling tower, where it is evaporated, is essentially 100 percent, while water passing through a turbine of a hydroelectric power plant has essentially zero consumptive use. The range of consumptive use for irrigation can be very large as well. For example, large-scale irrigation systems from a river diversion and canal system may have return flows to the river of up to 50 percent whereas a deficit-irrigated field in from a groundwater well in a low rainfall area may have little or no return of water to the groundwater. For many properly-designed and operated irrigation systems in low rainfall areas, consumptive use is often used (or confused) to be crop-water use.

Crop-water Use

An accepted method of estimating crop-water use is through the use of evapotranspiration (ET) which is calculated using weather information. The term evapotranspiration is the combination of two terms, evaporation and transpiration (Figure 2). Evaporation is water which returns to the atmosphere directly from wetted plant surfaces, wetted soil surfaces, or wetted residue cover. Transpiration refers to the water which is transported from soil water reserves through the root system, stems and leaves of a plant before being released to the atmosphere. A primary function of transpiration is cooling of the plant. An additional small amount (around the one percent range) of the water absorbed by the plant is used as part of the photosynthetic process. Nutrients are also transported as water moves from the soil into the plant.



- Evapotranspiration (ET) is the combination of evaporation and transpiration.
- Evaporation is water movement from wet soil and leaf surfaces.
- Transpiration is water movement through the plant.

Figure 2: Illustration of evaporation and transpiration (Rogers and Alam, 2007).

It is difficult to measure evaporation (E) and transpiration (T) separately, hence, the combined term, ET. In conventionally-tilled irrigated crops, the E portion of ET is generally about 30 percent of the seasonal crop water budget, but might be cut in half when high, surface-residue tillage systems are used. Early in the season, when the crop is small and does not cover or shade the soil surface, more sunlight and wind energy reaches the soil surface and a higher portion of the ET is the E portion. After the canopy closes, almost all ET becomes T. Evaporation can be suppressed in irrigated agriculture by increasing planting density to encourage rapid ground cover and by minimizing the frequency of canopy wetting by irrigation events when using sprinkler systems. The yield of a crop is generally proportional to the amount of crop-water use.

Modern center pivots and linear-move nozzle packages with proper design and installation and under good irrigation management tend to minimize irrigation losses by reducing the wetted radius of the nozzles and reducing the height of the nozzles above the crop canopy while also selecting and operating the systems to eliminate surface run off. The systems would also be managed to minimize deep percolation. Surface water movement of irrigation water under a center-pivot irrigation system should be eliminated with either a change in the operating procedures or a change in the nozzle-package design. Deep percolation of irrigation can be minimized with proper depth of application and irrigation scheduling; although, total elimination of deep percolation or drainage is not always possible due to the occurrence of large rainfall events. The remaining losses are due to water evaporation while the irrigation water is in flight, on the plant, or on the soil surface. These losses are, in essence, consumed (i.e. returned to the atmosphere).

Water evaporation from a plant surface will suppress transpiration as the evaporation process will serve to cool the plant as illustrated in Figure 3. Canopy evaporation greatly increases during the period of irrigation, so evaporation from surfaces should not be encouraged as the evaporation process occurs much more rapidly than plant transpiration. As much as 0.20 inches of water may be needed to wet a crop canopy. This amount of water could evaporate in several hours while on some days that same amount of water may have been sufficient for the entire day, if it were available for transpiration to the plant via the soil root zone. Therefore, many nozzle-package designs attempt to minimize evaporation losses using various nozzle configurations and placement strategies.

Irrigation water losses, as shown in Figure 4, can be divided into air losses, canopy losses, and soil losses. The center-pivot nozzle package system design and management should minimize (eliminate) surface runoff and deep percolation. Percolation losses may still occur due to unusual precipitation events. Although surface runoff and or water redistribution within a field still occur on some individual fields; in general, surface water losses have decreased over time due to sprinkler package designs which are better matched to field conditions. Also, changing cultural practices such as more adoption of no- or limited- tillage on fields result in high crop-residue covers that reduce the potential for surface run off and early season soil evaporation losses. Deep percolation losses have also been minimized as more irrigators adopt irrigation scheduling as a part of their management practice. There is also an increase in the number of low-irrigation capacity systems (meaning over-irrigation is less likely). Over 90 percent of Kansas irrigated acreage is watered by center-pivot irrigation systems which could, with proper package design and operation, eliminate irrigation water runoff. Deep percolation losses should be minimized

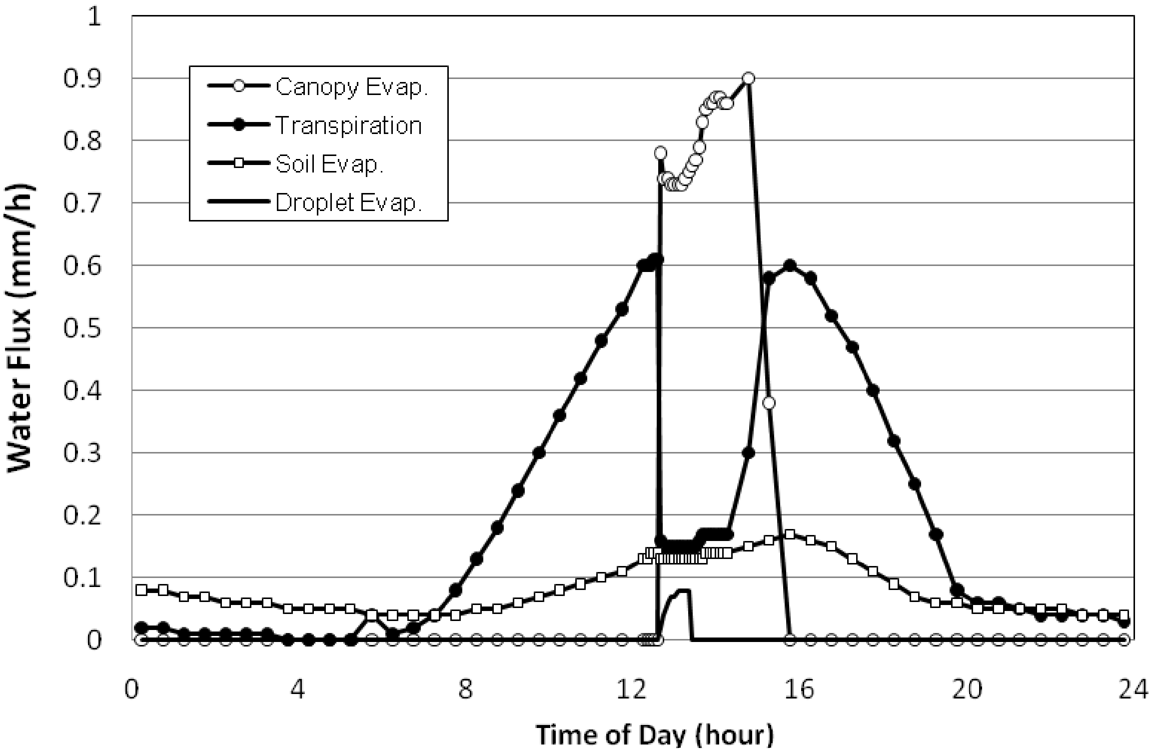


Figure 3. Water use for the rotator sprinkler placed on top the pivot lateral. (Martin et. al 2010).

with proper irrigation scheduling. The remaining irrigation losses as shown in Figure 4 occur either in the air, from the crop canopy, or from the soil. These losses occur as evaporation to the atmosphere, so the irrigation water is consumed just as the water used in the crop transpiration process. The implication of this discussion on water losses for a single irrigation event during the growing season, assuming the system is properly designed and operated (i.e. no surface run off) and properly scheduled (i.e. no deep percolation), then essentially all the water applied would be used consumptively. This implication for a single irrigation event, however, can be different when viewed on a longer time scale, as will be discussed in a later section.

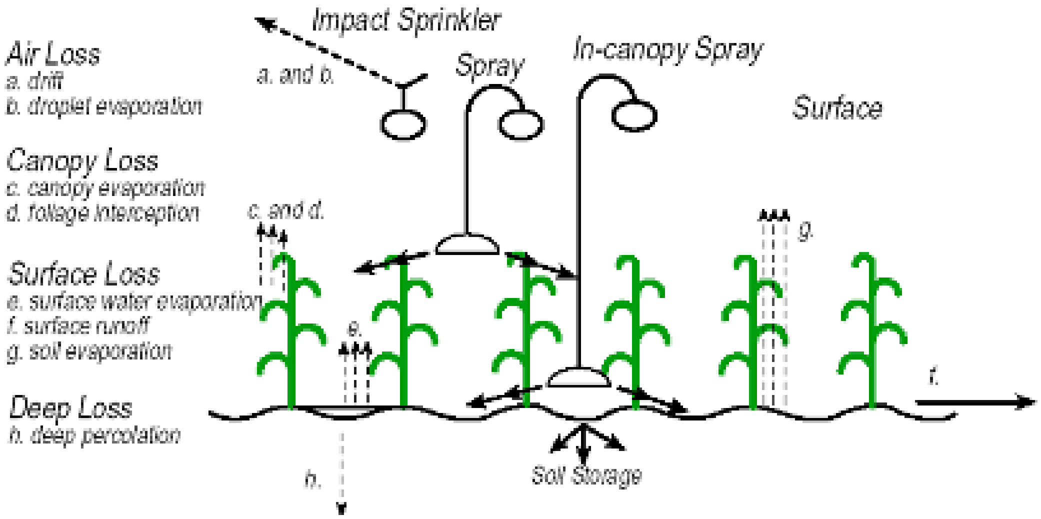


Figure 4: Illustration of where irrigation water losses can occur for a center pivot nozzle package (Rogers et al. 1997).

An example of how irrigation losses can be affected by design criteria is illustrated in Figure 5. Three water-use scenarios are shown for two irrigated conditions and a non-irrigated condition. Note for the non-irrigated condition, no losses of water occurred due to canopy or drop evaporation since no irrigation occurred. There was still some soil evaporation contribution, but there was a high level of transpiration. For the two irrigated conditions, a small sliver is shown to represent droplet evaporation, the evaporation that occurs while the water droplet is in flight. The soil evaporation was greater in the irrigated condition as compared to non-irrigated due to the recently-wetted soil surface from the irrigation. Between the two irrigated conditions, note that the spray just about the crop canopy had less canopy evaporation than the impact sprinkler. Spray nozzles would have a much smaller wetted diameter than the impact sprinkler, and therefore a specific location in a field would have been wetted for less time, resulting in less time for canopy evaporation to occur at that location.

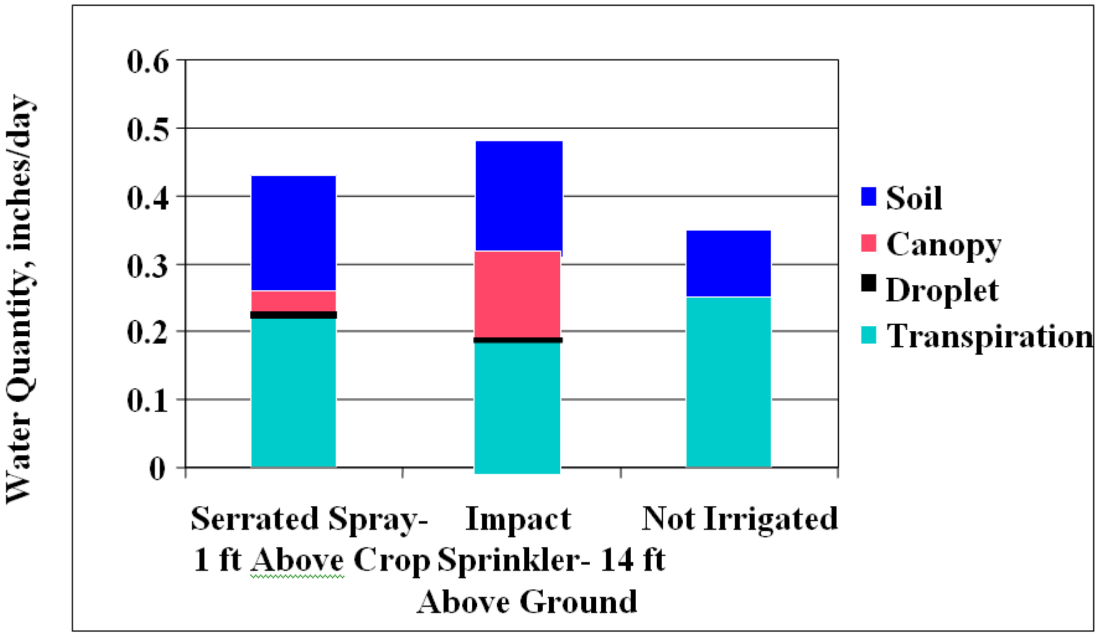


Figure 5: Evaporative losses for impact and spray nozzle devices (Thompson, et al. 1997) Data was collected at Bushland, TX; 90 F, 15-mph windspeed, and dry.

Example of a Center Pivot Uniformity Test

(Text and figure from KSU Bulletin L-908)

When designing sprinkler irrigation systems, it is important to provide as uniform of an application as possible. A non-uniform application will result in areas of under-watering as well as areas of over-watering. This will result in reduced yields as well as decreased system efficiency. The uniformity of the sprinkler nozzle package design is determined by package design. It is affected by the operating conditions, and environmental factors, especially wind. Figure 6 shows the results of a center-pivot uniformity test. Section A of the pivot illustrates a portion of the sprinkler package that was performing well. This area of the pivot has a coefficient of uniformity of almost 90 percent. In section B, a leaky boot connection between two spans was caught in one container. Section C represents the area covered by the outer two spans of the system that shows an area of over watering and under watering. Section D of Figure 6 demonstrates the effect of an improperly-operating end gun. In this case, the operation-angle of the end gun was improperly set and it was over spraying the nozzles of about one third of the last span and the overhang of the center pivot. In this example, all of the causes of the poor uniformity were easily and inexpensively correctable.

Uniformity is decreased if system pressure is not kept at the design pressure. Wear of nozzles and incrustation buildup can also affect the pattern. Canopy interference also affects distribution uniformity.

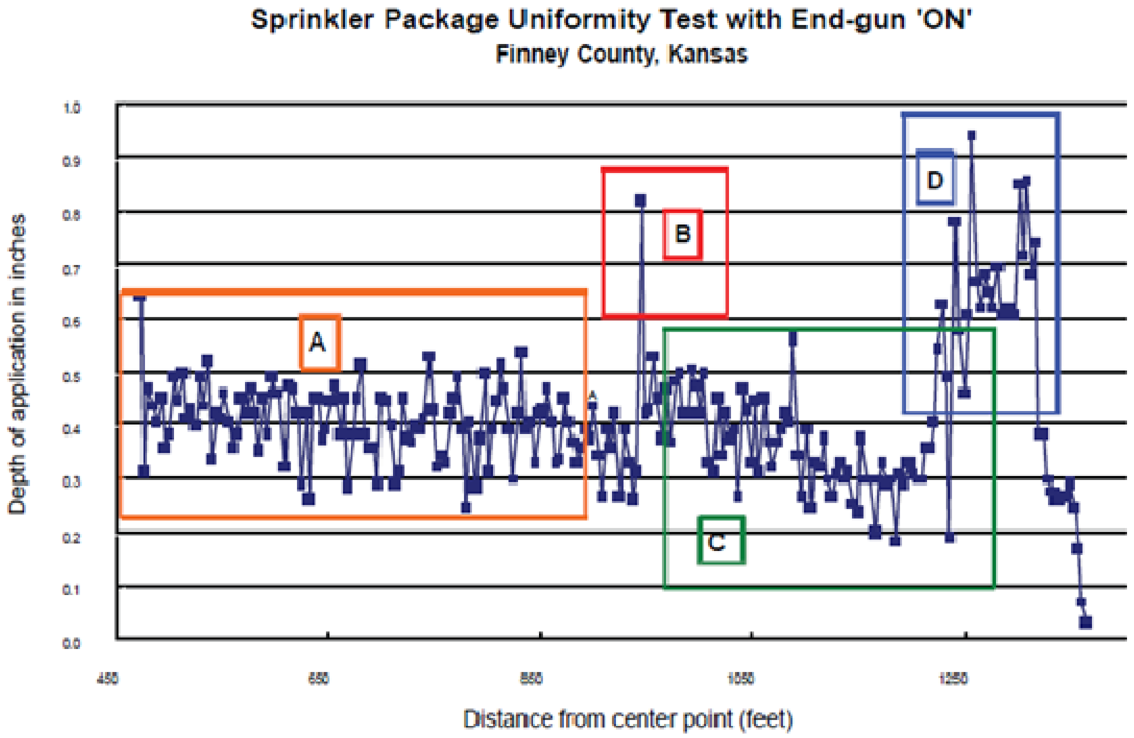


Figure 6: Uniformity test results for a Mobile Irrigation Lab uniformity evaluation (Rogers et al. 2008).

Irrigation Efficiency Impact on Irrigation Schedules and Crop Water Use

Table 1 illustrates the effect of improving irrigation efficiency on the water budget for an example year with average seasonal ET and rainfall for a corn crop. The water budgets were made using KanSched, an ET-based, irrigation-scheduling program (Rogers and Alam, 2008). While the rainfall was near normal for the growing season, it was less than normal early in the season and heavier than normal late in the season. The non-water-stressed ET for the year is 21.13 inches, which would be associated with “full” yield. Three water budgets are shown in Table 1 using a low-capacity irrigation system (1.00 inches/6 days). All field and crop characteristics were identical (118-day corn emerging May 1, loam soil with a 42-inch managed root zone). All irrigation water was scheduled whenever 1.00 inches of root-zone, soil-water deficit existed and the previous irrigation was completed. The only difference between schedules was irrigation efficiencies which were selected to be, 70 percent, 80 percent, or 90 percent.

At 70-percent irrigation efficiency, there were 5 days where the root-zone, soil-water content dropped below the recommended managed-allowable deficient (MAD) of 50 percent. Actual ET was 21.00 inches, which is only slightly suppressed, as compared to “full” ET of 21.13 inches; however, the most severe stress occurred during the pollination period which is the most water-sensitive stage of growth for corn. The lowest predicted root-zone, soil-water level was 39.7 percent of available water. But, since this occurred at pollination, grain yield reduction would likely occur. When irrigation efficiency was increased to 80 percent irrigation efficiency, there were 3 days below MAD and crop ET was increased to 21.09 inches. The lowest predicted root-zone, soil-water level was 46.7 percent of available water. This stress still occurred at pollination, so grain yield reduction might occur, but not to the degree of the previous example. The length and severity of the stress was not as great as the previous example. “Full” ET was still not achieved at 80-percent efficiency but the gross amount of irrigation water was reduced. For the 70- percent efficiency level, 11.00 inches of gross irrigation water was applied as compared to 10.00 inches for the 80-percent efficiency level.

When irrigation efficiency is improved to 90 percent, the crop ET increases to 21.13 inches, which is the maximum for the climatic conditions and maturity length of corn used in this example. This is indicated (Table 1) by noting zero days of soil-water levels below 50 percent MAD. The gross irrigation application dropped to 8.00 inches as compared to the 11.00 or 10.00 inches of the previous examples. It is possible, however, to have examples where increasing irrigation efficiency would not result in reduced gross irrigation application, but it would result in an increase in the amount of water used beneficially by the crop. The drop of 2.00 inches of gross irrigation pumping occurred in this example because the increase in efficiency resulted in more net irrigation water being available to the crop with each irrigation to such a degree that the crop’s full-water requirement was met with a lower gross-irrigation amount.

The data shown in Table 2 represents the case where an increase in irrigation efficiency did not result in a drop in gross irrigation application depth. It uses the same weather record as the example in Table 1; the only change is the soil type and rooting depth. At 70-percent irrigation efficiency, there were 9 days where root-zone, soil-water dropped below the recommended managed allowable deficient (MAD) of 50 percent and the gross irrigation application was 11.00 inches. Increasing efficiency to 80 percent still resulted in 11.00 inches of gross irrigation application, but the number of stress days was reduced to 5 and the level of stress was lower. There was not a reduction in gross irrigation application with an increase in efficiency since all the “saved” water went into meeting the crop-water-use demand.

When irrigation efficiency was increased to 90 percent, one day of crop-water stress was still predicted, even with high efficiency; however, recall the example system is a low-capacity system that can only apply 1.00 inches every six days which could not meet the crop water needs during the extended dry period of this actual weather record. For the entire season, however, more net irrigation water was available due to the higher efficiency resulting in less gross pumping for the season.

In Example 2, increasing irrigation efficiency did not result in a decrease in overall pumpage because both the 70-percent and 80-percent systems pumped 11.00 inches of water. However, the water-use efficiency or water used productively should be improved as the net irrigation application increased from 7.70 inches to 8.80 inches and reduced the number of days that the crop experienced stress. Since the irrigations were scheduled, meaning the water was not applied unless sufficient root zone storage was available, the applied irrigation water should not be lost to deep percolation. This means the loss would be associated with soil, canopy, or air losses which are evaporation processes and the water returned to the atmosphere. This would be "consumed" from the groundwater water source. In this sense, increasing irrigation efficiency did not change the amount of water consumed from the aquifer as the pumped water was either consumed (returned to the atmosphere) by the crop or consumed (lost by the evaporation due to irrigation water losses) by the inefficiencies of the irrigation system. Historically, when the majority of irrigation systems were surface (gravity-flow) irrigation systems, large application depths were required to advance the water across the field in the furrows to ensure the crop root zone was filled along the entire length of the field. This often resulted in deep percolation losses in the upper part of the field and a zone of deep percolation at the end of the field if excess water was diked at the bottom end. Deep percolation losses may have been eventually be returned to the groundwater aquifer. As irrigators in Kansas switched from gravity-flood to sprinkler systems (primarily center pivots), the losses associated with irrigation has switched from deep percolation to surface evaporation losses. These evaporative losses are now considered consumed since these evaporation processes transfer water to the atmosphere and not back to the original water source (aquifer).

Table 1: Effect of improving irrigation efficiency on gross irrigation requirement for corn under a low-capacity irrigation system.

Irrigation Efficiency %	Crop ET Inches	Effective Rain Inches	Gross Irrigation Inches	Net Irrigation Inches	Number of days < 50% MAD	Lowest Soil Water Value
No Irr	17.23	12.57	0.00	0.00	51	16.1%
70	21.00	11.60	11.00	7.70	5	39.7%
80	21.09	11.49	10.00	8.00	3	46.7%
90	21.13	11.52	8.00	7.20	0	52.2%

Table 2: Effect of improving irrigation efficiency on gross irrigation requirement for corn under a low-capacity irrigation system.

Irrigation Efficiency %	Crop ET Inches	Effective Rain Inches	Gross Irrigation Inches	Net Irrigation Inches	Number of days < 50% MAD	Lowest Soil Water Value
70	20.80	12.10	11.00	7.70	9	38.4
80	21.04	11.44	11.00	8.80	5	44.5
90	21.12	11.45	10.00	9.00	1	49.8

Analysis of irrigation consumptive use on an annual basis.

A simulation model was used to examine the effects of several irrigation schedules for two soil types. The average results using multiple years of actual weather data for each of the water-budget components on an annual basis are shown in Table 3. High water-holding capacity, silt-loam soils were used for the northwest Kansas location, while sandy soils were used for the south central Kansas location. The application amounts used for each site were selected as typical for the region. Irrigation was limited to the frequency shown, but it was scheduled based upon available soil moisture (ASM) of 50, 60, and 70 percent, so a range of the total irrigation application amount was applied. A base-line crop was needed to be able to determine how the different water-budget components would change with the addition of irrigation water and what portion of the irrigation water was associated with each change.

For the northwest Kansas location (19.24 inches of average annual precipitation), the average ET for the simulation period was 14.40 inches for the base-line dry-land corn crop. The average amount of runoff for dry-land corn was estimated to be 0.94 inches, with zero predicted percolation and 3.90 inches of interception. As irrigation is added, water budget components increase. Using the three irrigation schedules, irrigation amounts ranged from 13.90 to 16.71 inches and ET values increased according in various amounts above the baseline dry-land value of 14.40 inches. The dry-land water budget components were then subtracted from the corresponding irrigated-condition, water-budget component and are shown in the lower portion of Table 3. For example, for the 50-percent schedule, run off was estimated to be 1.42 inches, however 0.94 inches occurred under dry-land conditions, therefore the increased runoff contribution due to irrigation is 0.48 inches. In the same example, ET increased by 12.34 inches due to the 13.90 inches of irrigation. Dividing these two numbers would be an estimate of the seasonal irrigation efficiency; calculated, in this case, to be 89 percent. The amount of water consumed is estimated by adding ET and interception, since these two amounts are returned to the atmosphere. Percolation could be returned to groundwater. The fate of runoff is less certain, it still might be lost to evaporation, but it was not consumed within the field.

Dividing the amount consumed by the irrigation amount would be an estimate of consumptive use (CU) efficiency, in this example the value is 94 percent.

As additional irrigation water added, both seasonal irrigation efficiency and CU efficiency decrease. Since soil-water levels in the crop root zone are increased, the likelihood of losses to runoff and percolation increase due to occasional large precipitation events within the irrigation season and during the non-irrigation portion of the year.

The results for the south central location (26.08 inches of annual precipitation) on sandy soil follow the same trend as the silt loam example for both seasonal irrigation efficiency and CU efficiency, but the efficiencies are considerably lower. Sandy soils have less water storage capacity and therefore are more prone to have deep percolation losses. Also, the greater annual precipitation south central Kansas provides more opportunities for percolation losses.

Table 3: Water budget comparisons using POTYLDR (Koelliker, 2010) comparisons for two soil types.

	Silt Loam Soil in Northwest Kansas					**Sandy Soil in South Central Kansas**			
Application Amount (inches)	1.00	1.00	1.00	**Dry-land Corn**		0.75	0.75	0.75	**Dry-land Corn**
Frequency in days, if needed	*3*	*3*	*3*			*2*	*2*	*2*	
@ ASM, %	*50*	*60*	*70*			*50*	*60*	*70*	
Irrigation, in.	13.90	15.69	16.71	None		9.39	10.99	12.24	None
Runoff, in.	1.42	1.45	1.52	0.94		1.20	1.27	1.33	1.05
Percolation, in.	0.22	0.44	1.21	0.00		6.38	7.12	8.02	4.05
Intercept., in.	4.68	4.77	4.85	3.90		3.51	3.65	3.74	2.64
ET, inches	26.74	28.18	28.26	14.40		24.33	24.98	25.18	18.34
	Additional amounts as compared to Dry-land Corn								
	Amount of Gross Irrigation Lost					**Amount of Gross Irrigation Lost**			
Runoff, in.	0.48	0.51	0.58			0.15	0.22	0.28	
Percolation, in.	0.22	0.44	1.21			2.33	3.07	3.97	
Interception, in.	0.78	0.87	0.95			0.87	1.01	1.10	
ET	12.34	13.78	13.86			6.03	6.68	6.88	
Eff., % (ET/Irr)	89	88	83			64	61	56	
CU (ET+Intc)	13.12	14.65	14.81			7.77	7.69	7.98	
CU eff, %	94	93	89			73	70	65	

Summary

Center pivot irrigation systems can be equipped with a variety of nozzle packages that can effectively deliver irrigation water to crops. Proper design and operation of the systems are essential for high efficiency and good distribution uniformity. Irrigation application depths, total seasonal application amount, soil type, and precipitation all have an effect on seasonal irrigation efficiency and consumptive use of water.

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VARIABLE RATE IRRIGATION 2010 FIELD RESULTS FOR CENTER PLAINS CONFERENCE

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BACKGROUND

Historically, the center pivot has been used by a farmer/operator to apply a selected depth of water uniformly across the entire field. Changes in technology have occurred that give growers the ability to apply differing amounts of water and products carried in the water to different zones along the pivot and sectors around the field (Perry 2005). This paper will discuss results from the summer of 2010 of a commercial center pivot equipped with the Valley Variable Rate Zone Control package. The paper will also review potential payback. It will close with a discussion of future needs for variable rate irrigation.

INTRODUCTION

Since the introduction of the center pivot in the mid-1950s, the mechanical move industry has continued to improve and develop products to better meet the needs of production agriculture. The overall goal has been to provide cost-effective, uniform irrigation across the field with a specific application depth .

With the introduction and acceptance of precision agriculture, suddenly more information has become available for a particular field and areas in the field, including yield, soil and gird sampled fertility maps. Farmers now have data indicating the variability across the field, which was already suspected but not proven. The challenge then became how to use this data and how to make changes that would impact different areas of the field.

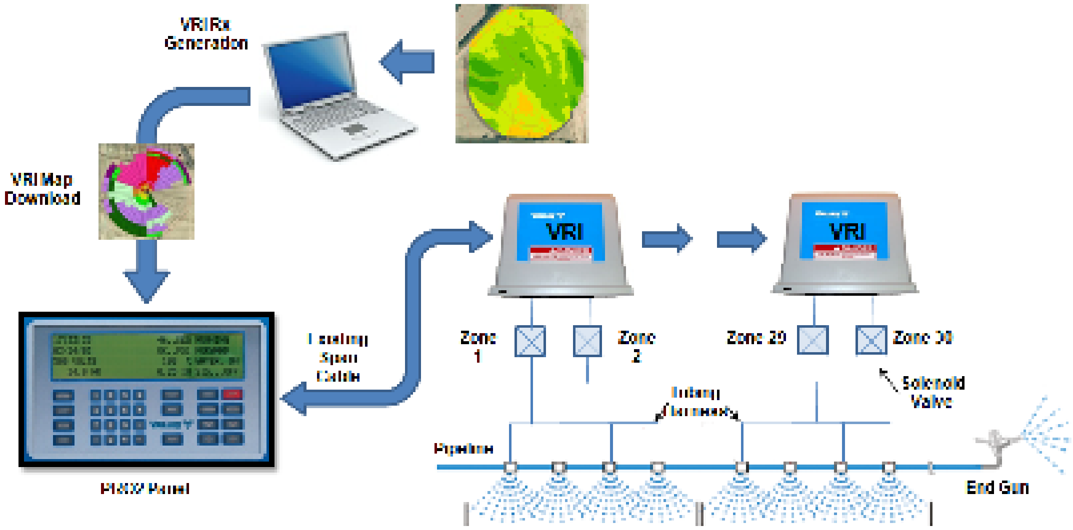
Fertilizer and chemical application equipment, as well as planters, have been equipped to make changes in rates or volumes across the field. Research into variable rate, or “site specific,” irrigation has been conducted at a number of locations across the United States by both Universities and USDA-ARS. These include, but are not limited to Universities of Georgia, Idaho, Nebraska and Texas A&M, and the USDA-ARS at Florence, SC, Ft. Collins, CO and Sidney, MT (King 2005, Marek 2004). The first commercial, marketed variable rate irrigation package was jointly developed by the University of Georgia, FarmScan and Hobbs and Holder (Hobbs & Holder 2006). These units have primarily been installed in the southeastern United States.

OBJECTIVE

The goal of this project was to demonstrate on a commercial field the viability of using a Valley Variable Rate Irrigation (VRI) Zone Control package to solve a farmer's challenges while maximizing returns from a center pivot irrigated field.

DISCUSSION

The VRI Zone Control package consists of a Valley Pro2 control panel, VRI tower boxes and a sprinkler control valve package. Information is sent between the control panel and the VRI tower boxes using a power line carrier (PLC) through the existing center pivot span cable. No additional control wires are required to use the product. Due to durability, reliability and experience, the sprinkler control valve used is the AquaMatic® brand, which has been used for more than thirty years on corner machines for sprinkler control. A tubing harness connects the AquaMatic valve to the solenoid on the VRI tower box. This hardware allows the center pivot to be broken into a maximum of thirty Pivot Zones. Below is a conceptual drawing of the Valley VRI Zone Control package components.



A prescription that is specific for the field is created with the VRI Prescription Software, which resides on an external computer. The prescription is then loaded into the Pro2 control panel. The VRI Prescription Software allows prescriptions to have up to 180 sectors around the field, each sector as small as two degrees.

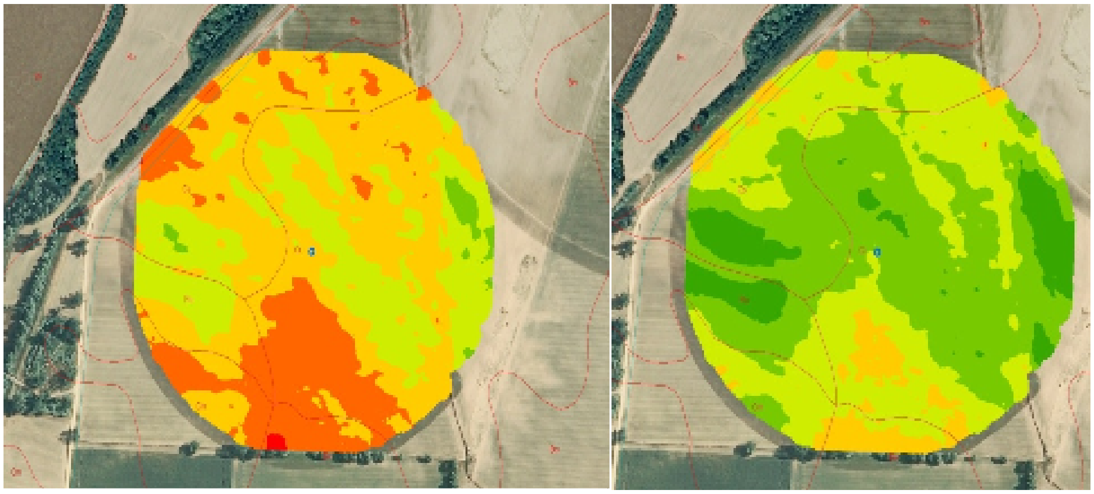
In the spring of 2010, Valmont Irrigation began to review commercial field sites to validate the lab and field testing that had been done with the Valley VRI Zone Control package. A possible field was identified near Dyersburg, Tennessee, owned by Jimmy Moody; the center pivot was a Valley Model 8000 that was installed in 1997. The machine's configuration was a total length of 1,148 ft: five spans of 180 ft and one span of 185 ft with a 64 ft overhang. The flow rate was 800 gpm and pipeline coupler spacing was 108 in. The control panel was mechanical. The sprinklers were fixed-pad sprays with a medium groove pad and regulator. End pressure was 10 psi at the nozzle; the center pivot had pressure regulators. The drive train was high speed with 14.9x24 tires. The pump was a deep well turbine with a fixed-speed motor. Based on the manufacturer's data, it was determined that the flow rate should not drop below 450 gpm to maintain good efficiency and minimal pressure rise.

Mr. Moody described his challenges with this field. Parts of the field were either being overwatered or under watered, and uniform crop production was not being achieved across the field. His goal was to have more uniform crop production across the field. To accomplish, this he believed he needed to be able to adequately water the light soils without flooding the heavy soils. To evaluate the field to determine both the number of Pivot Zones needed along the pivot and sectors around the field, the NRCS soil maps (Figure 1) were reviewed; however, they did not seem to match the situation Mr. Moody had described.

Bw – Bowdre clay
CM – Commerce loam
CR – Crevasse loamy sand
CS – Crevasse sandy loam
Ro – Robinsonville fine sandy loam

Figure 1

Mr. Moody did not have a series of annual yield maps to average in order to help define the appropriate VRI package. Mr. Moody had done grid soil sampling, but, while this data was valuable and interesting, it did not help to lay out the VRI package. In a conversation with Dr. Earl Vories of USDA-ARS about VRI and how to determine the layout of Management Zones, it was suggested by Dr. Vories that apparent electrical conductivity (EC_a) of the soil profile be used (Vories 2008). EC_a is a sensor-based measurement that provides an indirect indicator of important soil physical and chemical properties. Dual EM was used to determine EC_a, as shown on the map below in Figure 2.



Deep EC_a Figure 2 Shallow EC_a

This data seemed to match Mr. Moody's perception of the field's characteristics. The decision was thus made to use this information as a starting point to help define the VRI Zone Control package. Rice was the crop for the 2010 growing season. Based on the shallow root system of rice, it was decided to use the shallow EC_a information to both define the VRI Zone Control hardware and to develop the initial prescription.

A decision was made to maintain the same area in the zones in order to simplify management decisions and to make it easier to determine the impact on the hydraulics, as each Pivot Zone along the center pivot would have the same flow rate. The center pivot was split into ten Pivot Zones with the length of the Pivot Zones and number of sprinklers as:

Zone 1 – 363 feet – 40 sprinklers
Zone 2 – 150 feet – 17 sprinklers
Zone 3 – 115 feet – 13 sprinklers
Zone 4 – 97 feet – 11 sprinklers
Zone 5 - 86 feet – 10 sprinklers
Zone 6 – 78 feet – 9 sprinklers
Zone 7 – 71 feet – 8 sprinklers
Zone 8 – 66 feet – 7 sprinklers
Zone 9 – 62 feet – 7 sprinklers
Zone 10 – 59 feet – 7 sprinklers

Each Pivot Zone along the center pivot represents 9 ½ acres and had a flow of 80 gpm. The sectors around the field were in four-degree increments, which totaled 900 Management Zones, or "blocks." Figure 3 below illustrates the initial prescription used.

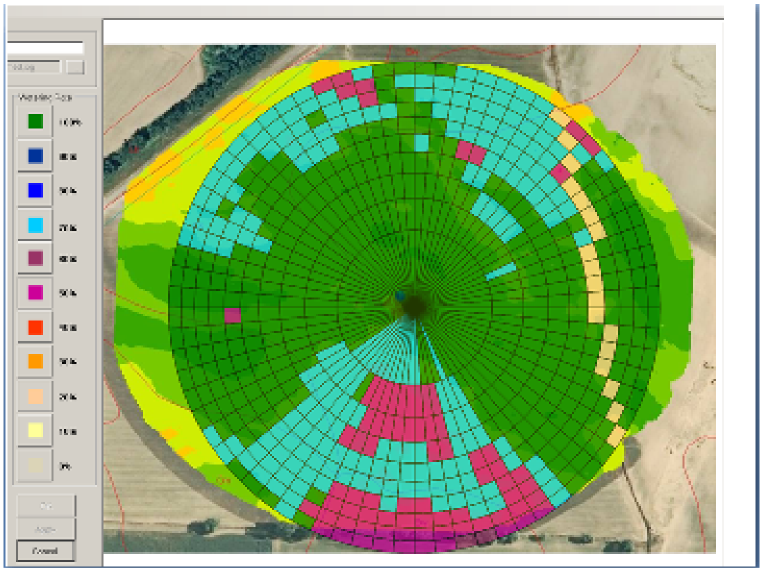


Figure 3

The VRI Zone Control hardware was installed along with a new sprinkler package, pressure regulators and sprinkler control valves. One AquaMatic valve was used for each hose drop. Once the hardware was installed and the VRI software was uploaded to the Pro2 control panel, the constants for the VRI Zone Control were entered and the prescription uploaded. The pivot was then run to test the package. During the growing season, base application depths ranged from 0.25 in to 0.45 in. A significant portion of the nitrogen for the rice crop was applied through the center pivot with an Inject-O-Meter pump. The nitrogen was liquid with an analysis of either 32-0-0-0 or 28-0-0-5. The VRI Zone Control package was used as the heavier soils had much better fertility than the lighter textured areas, so the nitrogen application amounts were cut back based on the EM map. Since the injector pump was a fixed speed, a separate prescription was created to compensate as much as possible for the fixed pump. The goal was to reduce nitrogen as in the areas that received less irrigation.

One area of particular interest was how to validate the performance of the VRI Zone Control during the growing season, while not just waiting for the yield results. The VRI Zone Control package “pulses,” or cycles, the valves off and on, which then turns the sprinklers off and on to achieve the desired change to the base application depth. The problem was approached in three ways:

- Visual observation of the Pivot Zones and Management Zones
- Soil moisture monitoring in one of the areas with the light textured soils where the prescription always called for 100% of the base application depth, and in heavy soils area where the base depth was reduced by up to 40%. For example, if the base application depth was 1.00 in, then an area of 40% reduction would only apply 0.60 in
- Aerial imagery– infrared and color spectrum

One of the first observations was the cycle time was too long when a Pivot Zone was operating in an area where there was to be a reduction in the application depth. It was observed the drive unit was moving so far during a pulse that sufficient overlap of the sprinkler package in the direction of travel was not being achieved. To correct this, the cycle time was changed in the constants – something easily done at the control panel.

The soil moisture data was tracked remotely; it looked for drying trends in the area where the prescription called for a reduced application depth. Below is an example of the data sets for a sample time period (Figure 4).

Figure 4

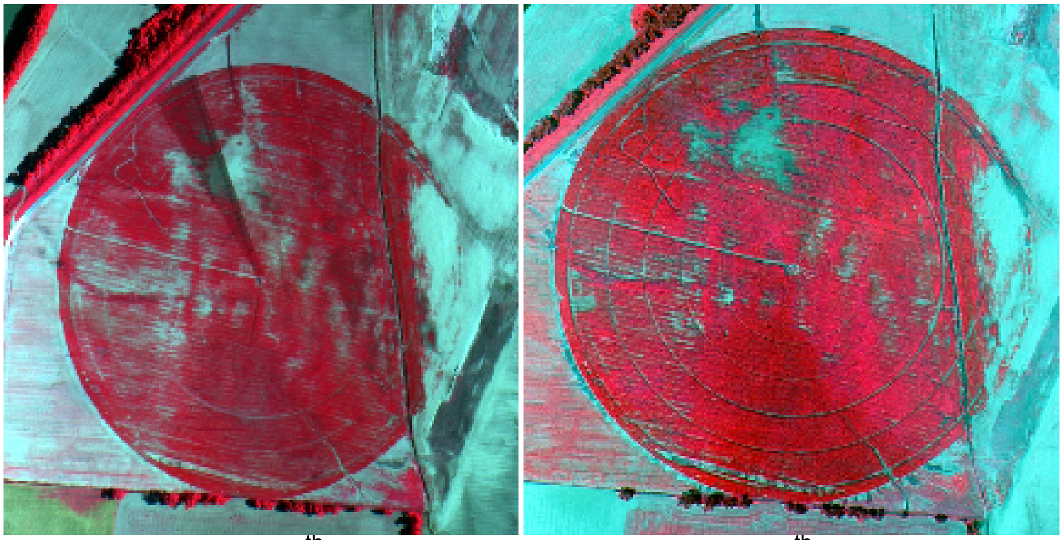
The top set of data is an area with clay loam soil that received 60% of the base application depth.

The bottom data set is an area of fine sand that always received 100% of the base depth.

Along the x axis is time, from June 15th to September 28th. The y axis is in centibars, which ranges from 0 to 100.

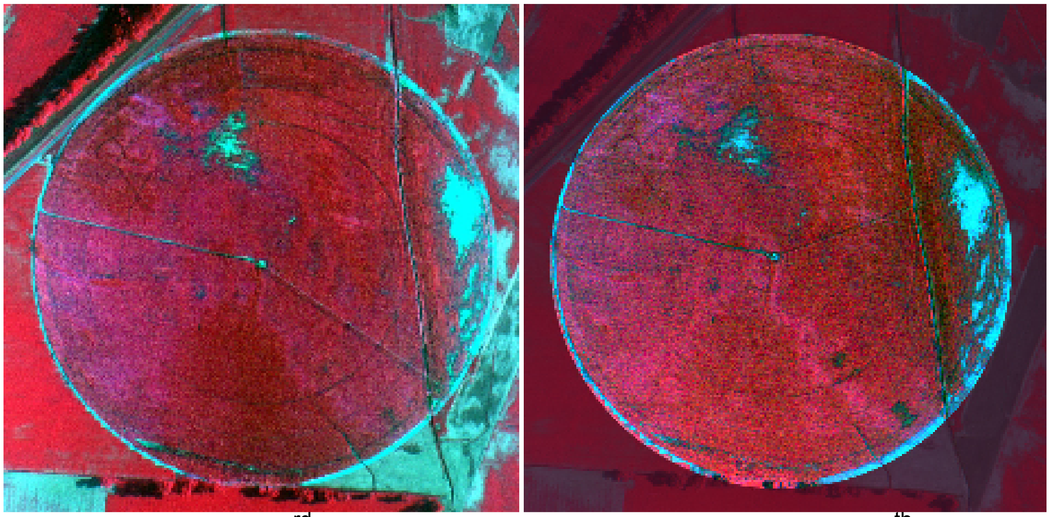
Most important from this data is that over time, the top graph did not show a drying trend; for most of the crop season it paralleled the soil moisture status of the area that received 100% of the base application depth. In addition, visual observations and use of a soil probe indicated the soil moisture was adequate in the area receiving 60% of the base application depth.

The following were a series of infrared images taken during the growing season (Figure 5).



June 16th June 30th

Figure 5



July 23rd August 6th

In the images above, there was gradual improvement in the ground cover and, in general, the crop appeared “good” across the field with no particular weak areas except for the areas where the crop was blown out by wind in the early season.

RESULTS

Harvest was a challenge due to a wind storm part-way through harvest that lodged the crop badly in the south-central part of the field, which traditionally was believed by Mr. Moody to have the best yields. Overall, the field variability was significantly reduced and the light textured soils yielded well in a very dry year; a total of 19.4 in per acre were applied to the crop in 61 passes of the center pivot.

19.4 in was calculated based on the hours of center pivot operation and the flowrate. This is interesting because it is incorrect – if there had been no VRI, then it would have been correct. Some sections of the field received 19.4 in because they had a prescription of 100% of the base application depth. However, the areas with a 60% prescription (40% reduction from the base depth) received 11.6 in per acre. Applying the prescription across the field to the total pumped inches indicates that, overall, 12% less irrigation was actually applied, which illustrates a significant water and energy savings. (Another VRI Zone Control pivot in western Nebraska monitored in 2010 had an overall reduction of 13% in the amount of water pumped.)

Total applied nitrogen was also reduced by using the VRI prescription. The reduction in nitrogen was 15% - another significant amount. The farmer was pleased with the performance, and based on savings and overall yield increase estimates the payback for the unit to be just over three years.

CONCLUSIONS

Historically, center pivot irrigation has treated the entire irrigated field the same and the goal has been to make uniform applications across the field. With variable rate irrigation, the farmer now has the ability to apply specific amounts of water to specific locations within the field. Based on the information collected in 2010, there are a number of areas requiring additional work and evaluation:

- Better tools to determine economic number and size of Management Zones. With the recent cooperation developed with CropMetrics^{TM}, this is one solution to overcome this.
- Better tools to determine prescriptions. This is now easy with the CropMetrics solution.
- Methods to obtain easy feedback from the Management Zones and to incorporate into the farmer's decision-making tools.
- Validation of VRI Zone Control performance
- Quantify possible benefits, such as water savings, yields increase and nitrogen use, and impact on the payback.
- Explore sprinkler package performance and how it relates to VRI.
- Management of the hydraulic issues associated with a fixed-speed pump.
- Use of variable rate chemigation pumps.

Another factor is how one thinks of center pivot irrigation. The overall goal may not be to achieve general field uniformity, but rather to apply specific amounts of water and other crop inputs to particular areas of the field.

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MONITORING IRRIGATION WATER APPLICATION WITH COMPUTERIZED CONTROLLERS

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INTRODUCTION

In the Central Plains area of Colorado, Kansas and Nebraska, approximately 10.6 million acres of cropland are irrigated by center pivot irrigation systems (USDA-NASS 2007 Census of Agriculture). Existing systems span the generations of center pivot technology evolution from water to electric and hydraulically driven machines. Standard sprinkler system designs seek to apply water as uniformly as possible. Due to their operating flexibility, center pivots are operating on varying topography, and often have a range in soil textures present under a single machine. Field anomalies such as perched water tables, surface drains, and rock outcroppings challenge managers of standard machines with the need to deliver different depths of water to specific areas of the field. Each of these factors provides some justification for using a monitor and control system to manage water applications based upon a predetermined management scheme.

On a more basic front, farming operations often include an average of 3 center pivot systems with some operations including 15 or more. Without a controller, the producer must physically be on site to determine the status of the center pivot. With new technology, producers can obtain knowledge of whether the system is operating on a real-time basis by communicating with the machine to determine operating status. The purpose of this article is to present some of the research that has been conducted to evaluate system controllers for use in monitoring and controlling center pivots and discuss how these systems could be used in a site-specific irrigation system.

CONTROLLERS

Center pivot manufacturers have developed proprietary means of monitoring and controlling center pivots using a variety of technologies. Computerized control panels provide center pivot operators with the potential to monitor and control center pivots using telephones, radio telemetry, internet connections and satellite communication. In addition, there are a few private venture monitor and/or controllers that are available under the trade names: FarmScan, AgSense, and PivoTrac. Table 1 provides a summary of the current monitor and control capability of programmable panels marketed by the four major center pivot manufacturers.

The first requirement of a controller is to know the system position. If a producer queries the control panel during the course of an irrigation event, knowledge of where the system is lets the producer determine if problems have occurred and also how soon the system will reach stop-in-slot (SIS) positions. Standard machines utilize a resolver located at the pivot point to report the position of the first tower. In nearly all cases, the main component of new controllers is a Wide Area Augmentation System (WAAS) enabled GPS unit that is mounted near the last tower of the center pivot. The WAAS is a publicly available GPS system that provides a differentially corrected signal to increase the accuracy of the unit at a relatively low cost. With the WAAS system, the position of the last tower is provided with ± 11foot accuracy. However, due to the pivot speed of travel and stop-start motion of the machine, ± 3 foot accuracy is possible.

Part two includes monitoring the center pivot control circuitry. This is accomplished directly at the main pivot panel. The main panel houses control circuitry for the end gun, system speed of travel and direction, and on/off controls. Since most of this circuitry terminates at the end tower, some after-market center pivot monitors and controllers are mounted near the last tower control box.

At the pivot point additional components can be monitored and/or controlled such as auxiliary chemical injection pumps, system operating pressure and flow rate. Likewise, weather sensors can be monitored to provide wind speed and direction, temperature and rainfall information if desired. Options also exist to continuously monitor soil water sensors in the field. Recent field research is aimed at developing decision support tools for using center pivot mounted infrared thermometer (IRT) or spectral sensors to help manage irrigation water, fertilizer, and pesticide applications.

Part three of the system includes a communication link between the controller and the end user whether that be cell phone, land line phone, radio or internet connection. Cell phone links are accomplished using an on-board modem. This arrangement requires cell phone service from the pivot location and from the user location. Despite the addition of many cell towers, there are still a few locations in the Central Plains where communications are not possible.

Some systems transmit GPS coordinates and system monitor information via radio to a satellite which is transmitted back to a ground-based facility where it is distributed via the internet and made accessible by phone using IVR solutions developed specifically for center pivot controls.

Table 1. Monitor, control, communication, and data reporting capability of center pivot control panels.

	Reinke	**T-L**	**Valmont**	**Zimmatic**
Monitors				
Position in field and travel direction	Y	Y	Y	Y
Speed of travel	Y	Y	Y	Y
Wet or dry operation	Y	Y	Y	Y
Pipeline pressure	Y	Y	Y	Y
Pump status	Y	Y	Y	Y
Auxiliary components[β]	Y (7)	Y (2)	Y (6)	Y (3)
Stop-in-slot and auto restart	Y	Y	Y	Y
Wind speed	Y	N	Y	Y
Controls				
Start and Stop	Y	Y	Y	Y
Speed of travel	Y	Y	Y	Y
Auto restart and auto reverse	Y	Y	Y	Y
End gun	Y	Y	Y	Y
High and Low pressure shutdown	Y	Y	Y	Y
High and Low voltage shutdown[£]	N/Y	N/Y	Y/Y	N/Y
System stall shutdown	Y	Y	Y	Y
Auxiliary components[β]	Y(7)	Y(2)	Y(6)	Y(3)
System guidance[§]	Y	Y	Y	Y
Maximum control points per circle[¶]	3600	360	180	180
Sprinkler application zones[£]	2	3	30	NL
Remote Communications				
Cell phone	Y	Y	Y	Y
Radio	Y	Y	Y	Y
Computer	Y	Y	Y	Y
Subscription required	Y	Y	Y	Y
Data Collection and Reports				
Soil water content	Y	Y	Y	N
Precipitation per season	Y	Y	Y	Y
Application date and depth	Y	Y	Y	Y
Irrigation events per season	Y	Y	Y	N
Chemical application rate	N	N	N	Y
Chemical application per season	N	N	Y	Y
System position by date	Y	Y	Y	Y

[£] *N/Y indicates no automatic shutdown for high voltage is provided but the panel does provide automatic shutdown for low voltage.*

[β] *Y(7) indicates that up to 7 auxiliary components (injection pumps, end guns, etc.) can be controlled by the panel.*

[§] *System guidance provided by above ground cable, below ground cable, furrow or GPS.*

[¶] *Number of positions in a revolution where set points may be changed.*

[£] Number of banks of sprinklers that can be controlled along the pivot pipeline.

Line-of-sight radio telemetry is another means of transmitting information from the field to the office or phone. However, since the radios are line-of-sight buildings, trees, and hills impede communications over long distances. Most radio communication links employ radios operating in the 900 MHz range to communicate over distance less than 15 miles. For longer distances, a bridge or repeater is positioned on a tower or other structure to communicate over longer distances.

Recent developments in the center pivot industry have resulted in contractual arrangements with developers of after-market control and monitor systems. These additions to the existing onboard control capabilities of center pivot panels make site-specific irrigation a reality for irrigation zones of 1000 ft^2 or larger. The main considerations remaining include the development of decision support systems that maximize the value of the applied water or chemical based on field-based information, the cost recovery potential of the cropping system, and the verification of water savings and/or improved productivity when there are a large number of management zones within the field area.

SITE SPECIFIC IRRIGATION

Precision agriculture technologies are based upon the premise that crop growth and/or yield is not uniform across a field. It further assumes that the field average yield would increase if inputs of water and/or nutrients could be differentially applied to small field areas based upon a predefined management scheme. Site-specific water application technologies make it possible to vary both water and chemicals to meet the specific needs of a crop in each unique zone within a field. The hypothesis is that the total water and nutrients applied could potentially be reduced on a per field basis and/or crop yield or quality will be greater. One project comparing site-specific irrigation to conventional uniform irrigation was conducted in Idaho on potatoes (King, et al., 2006). They found that while statistical differences in yield were not recorded, a trend toward greater yield using site-specific irrigation was noted. The mean yield increase would allow the equipment costs to be recovered in a 2-3 year time frame.

With a uniform application, the questions are '*when'* to irrigate and '*how much'* to apply. The implementation of site-specific irrigation adds a third question of '*where'* to the irrigation scheduling decision. Answering the question about where requires that specific management zones be identified in some fashion. Early efforts to develop methods for identifying where zones should be located and why included using soil survey maps, field topography, landscape position, and bulk soil electrical conductivity (Jaynes et al.,1995; Jones, et al., 1989; Sudduth et al.,1997). Missouri research concluded that the number of zones necessary in each field is dependent of the availability of water and the type of crop planted in the field (Fraisse, et al., 2001).

Over the last two decades research has been conducted by public and private groups seeking to development methodology and decision support tools necessary for application of water and plant nutrients based upon the physical limitations of a tract of land. In essence this work has added center pivot irrigation systems to the list of variable rate applicators. As the technology has evolved so has the list of terminology used to help lay claim to unique ways that standard center pivot controls are replaced and/or enhanced to allow variation in the center pivot's application depth and/or water application rate. Definitions for some of the terminology are included at the end of this paper.

Initial steps to define decision making tools used for site-specific irrigation began in the early 1980's. Sadler, et al (2005) stated one of the issues with site-specific irrigation is that *"most of these technologies have been developed without considering the knowledge levels, skills and abilities of farmers and service providers to effectively and economically manage these tools. In addition, the equipment is often expensive and the economic returns from adopting these technologies have not been easy to consistently demonstrate. Nevertheless, the economics are improving and there is little doubt that at least some of the emerging precision agriculture technologies will be part of future crop production systems in American agriculture"*. Technologies such as Low Energy Precision Application (LEPA) were developed based on the early efforts to define optimum flow rates for sprinkler heads operating within inches of the soil surface (Lyle and Bordovsky, 1981). A series of control manifolds were used to deliver different flow rates. Later work by Roth and Gardner (1989) sought to use the irrigation system to apply different amounts of nitrogen fertilizer with irrigation water.

Fully site-specific irrigation research was initiated in earnest in the early 1990's at four USDA-ARS research lab locations across the US. Reports of this work were published beginning in 1992 based upon work conducted the USDA-ARS researchers located in Fort Collins, CO (Fraisse, et al., 1992), Moscow, ID (McCann and Stark, 1993), Florence, SC (Camp and Sadler, 1994), and Pullman, WA (Evans et al., 1996). These efforts have helped to shape the technologies used to control moving sprinkler systems and individual sprinklers.

The major addition needed to convert center pivot irrigation systems to allow site-specific water application is a means of controlling water flow to individual sprinklers. Individual sprinkler flow control can be accomplished by using a series of on-off cycles or as it has become known as 'pulsing' the sprinkler (Karmeli and Peri, 1974). Changing the sprinkler on time is effective at reducing both the application depth and the water application rate. This is accomplished using either direct-acting or pilot-operated solenoid valves. Direct acting valves have a linkage between the plunger and the valve disc while the pilot-operated solenoid uses irrigation pipeline pressure to activate the valve.

A second method for controlling irrigation water application was developed by King and Kincaid (2004) at Kimberly, ID. The variable flow sprinkler uses a mechanically-activated needle to alter the nozzle outlet area which can adjust the sprinkler flow rate over the range of 35 to 100% of its rated flow rate based upon operating pressure. The needle can be controlled using electrical and hydraulic actuators. The main issue is that the wetted pattern and water droplet size distribution of the sprinkler changes with flow rate which creates potential water application uniformity issues due to a change in sprinkler pattern overlap.

A third method of controlling irrigation water application is to include multiple manifolds with different sized sprinkler nozzles. In this case, activation of more than one sprinkler manifold can serve to increase the water application rate and depth above that for a single sprinkler package. Control of each manifold is accomplished using solenoid valves similar to those described for the pulsing sprinkler option above.

These new systems have been installed in various locations across the country, but few site-specific systems have been installed in the northern High Plains area. As with any new technology, there are positives and negatives associated with each of these three methods of controlling sprinkler flow rates. Certainly long term maintenance could be an issue. Water flow rates to 13 water application zones were monitored on a center pivot with results indicating most were within 10% of the target flow rate (Stone, et al., 2006). Application uniformity of sprinkler pulsing type site-specific systems has been addressed by Dukes, et al., (2006) who found coefficient of uniformities in excess of 90% regardless of the system travel speed and cycling rate. An additional concern is verification of results which can be difficult since it requires that comparable areas of the field where site-specific irrigation and uniform irrigation methods have been employed over a series of years.

SYSTEM REQUIREMENTS

Selecting the method of sprinkler control may be the easiest decision to make since the main factor of concern is: Will it pay to install the controls? However, once the decision is made to use a variable rate sprinkler application system and the management zones have been defined, design of the remaining portions of the irrigation system becomes interdependent.

How will the pumping plant respond to changes is system flow rate requirements? And how much additional pressure can the distribution system safely take before a pipeline breaks? As sprinklers turn on and off, the flow rate required by the system varies. The response of a standard pumping plant is that the pump output will follow the pump curve to the right or left depending on whether more or fewer sprinklers are operating. More significant is that sprinklers near the end gun have flow rates that are significantly greater than sprinklers near the pivot point. Consequently, turning off sprinklers on the third span of the system will have much less effect than turning off the sixth span. The correct design response is to install a pumping plant with variable revolutions per minute (RPM) so that as more sprinklers are added, the pumping RPM is increased and visa versa. In this way the pumping plant can supply water at the design pressure regardless whether 50 or 150 sprinklers are in operation.

The difficulty arises when the motor used to supply power to the pump is the same one used to supply power to the center pivot. Changes is pump RPM require changes in engine RPM. Engines operating at too high of an RPM will provide too much power to the center pivot while engines with too low of an RPM will not deliver enough power to the pivot. So a separate energy supply may be required for the center pivot should the system be converted to site-specific irrigation applications. New installations would be best served by installing a variable frequency drive electric motor with a pressure sensor to control the motor RPM.

How do I adjust the chemical injection system to apply different chemical amounts (fertilizer or pesticides)? Application of variable chemical rates can be achieved by simply maintaining a design injection rate and let the difference in water application depth control the chemical application rate. However, we have a problem if our management decisions require high application of a plant nutrient to an area that is to receive little or no water? A second factor is that the time of travel for chemicals to be transported from the pivot point to a position on the pivot lateral varies with the velocity of water in the pipeline. As the number of sprinklers in operation changes so does the water flow velocity. Thus, chemical could enter the system with a velocity of 6 feet per second when all sprinklers are on and 3 feet per second when a large number of sprinklers are turned off. This factor will determine when a change in injection rate will reach different positions along the pivot pipeline.

How accurately can I determine system position if application rate changes are desired? Center pivot position on most systems (without special equipment) is determined by the resolver that is located at the pivot point. Alignment systems typically have an accuracy of $\pm 1.5^{o}$ of where the first tower is located. Thus, at a distance of 1320 feet from the pivot point, the position of the last sprinkler could be off by 34 feet or more. Research conducted by Peters and Evett (2005) found that resolver determined position errors could be up to 5 degrees or over 100 feet on a 1320 foot long center pivot. Installation of a WAAS enabled digital GPS system is needed to ensure water and chemical are applied accurately. The net effect of the WAAS system is that management zone size can be reduced without increasing the potential for a misapplication.

From an engineering perspective these are not trivial questions particularly if changes in water, nutrient and energy use efficiency are to be accomplished simultaneously. In the end, it is the accuracy of the data used to make decisions that is critical. And so another question must be answered: *Will the increase in water application to **Management Zone 25** increase yields enough to pay for the application?*

Information Requirements

To make full use of site specific irrigation techniques, site-specific field information is needed for variables that will be used in making irrigation management decisions. Field soil texture and fertility will be needed to help isolate field areas where plant available water is indeed the single most important factor. Yield maps could show areas with reduced yields that are due more to soil nutrient levels than plant available water or a combination of the two. The difficult factor is to have production functions that give accurate information about what will happen to yield if water or plant nutrients are altered. Acquiring this information may require a 3-5 years of in-field testing while harvesting with a yield monitor. Private companies are becoming more active in providing a service of collecting and summarizing the field data.

Field maps of each of these variables (field slope and soil texture, fertility level, grain or forage yield) represent information that make up levels in a Graphic Information System (GIS) analysis. It is important that these maps provide information with enough resolution to delineate the desired number of management zones. Limitations in the ability to collect point measurements due to cost or response time of sensors all impact the spatial resolution of the application map. For example, an 8-row combine operating at 6 mph and collecting yield estimates every 3-seconds provides a different spatial resolution than a center pivot with control of banks of 5 sprinkler heads. Consequently, variable rate irrigation controls will typically be at a lower resolution than any of the other crop production inputs. Ultimately, mathematical models will be needed to utilize the different sources of information to produce a water application map (Fraisse, et al., 2001; Fridgen, et al., 2004).

SUMMARY

Center pivot controllers and monitors are available to help producers manage water application on a whole or part of field basis. The combination of knowledge of current system status and location in the field help ascertain if the irrigation application is proceeding as planned. By recording other field based information water applications can be adjusted due to different crops, field topography, soils and productivity levels. Ultimately, the complete control of crop water inputs on an IMZ basis could save between 10-20% of the water applied per season. Lower installation costs and further development of decision support systems for use by producers are needed before site-specific technology will receive widespread use by row crop producers in the Central Plains area.

TERMINOLOGY

Listed below are general definitions for the acronyms that are used in the discussion of center pivot monitors and controls.

GIS Geographic Information Systems is a system that allows for sets of geo-referenced variables (layers) to be analyzed, managed, displayed, and used to develop site-specific maps for the application of water, pesticides, or plant nutrients.

GPS Global Position Systems is a satellite system means of determining field positions, speed of travel, and time with sufficient precision to allow site specific application of irrigation water, pesticides, or plant nutrients in response to productivity indices.

IMZ Individual Management Zone is an individual area of an irrigated field for which the technology exists to alter the application of water, pesticides, or plant nutrients in response to productivity indices.

IRT Infra-Red Thermometry is the use of an infrared thermometer to record plant leaf temperature as an indicator of plant stress.

IVR Interactive Voice Response is technology that enables users to retrieve or deliver information on time critical events and activities from any telephone.

LEPA Low Energy Precision Application is a water, soil, and plant management system for uniformly applying small frequent irrigations near the soil surface to field areas planted in a circular fashion and accompanied by soil-tillage to increase soil surface water storage.

PA Precision Agriculture, or site-specific farming is the precise delivery of water, pesticides and plant nutrients based upon suspected deficiencies in or need for water, pesticides, or plant nutrients.

PLC Programmable Logic Controller is a digital computer used for automation of electromechanical processes and is designed for multiple inputs and outputs, and is not affected by temperature, electrical noise, or vibration.

VRI Variable Rate Irrigation is the delivery of irrigation water to match the needs of individual management zones within an irrigated field.

VRT Variable Rate Technology is the process of applying irrigation water, pesticides, or plant nutrients at rates which are based on defined crop production indices.

WAAS Wide Area Augmentation System is a navigation aid developed by the Federal Aviation Administration to augment the accuracy, integrity and availability of the GPS for use in aircraft flight monitoring and control.

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SELECTING SPRINKLER PACKAGES TO MINIMIZE POTENTIAL RUNOFF

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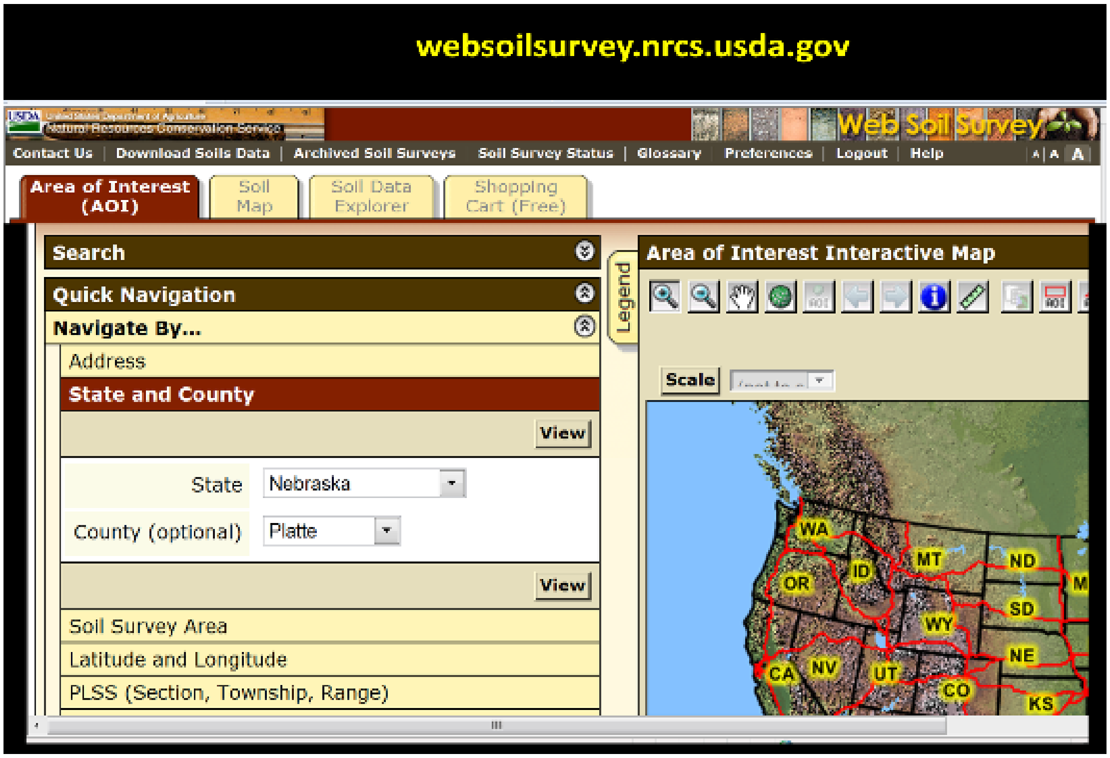
INTRODUCTION

Avoiding runoff requires assessment of soil properties across the field of concern along with the characteristics of the center pivot and the attributes of available sprinkler devices. The assessment begins with obtaining soil properties of the field. These data can be obtained from printed soil surveys for your county, or, you can use the relatively new electronic tool provided by the USDA Natural Resources Conservation Service. The tool is called the web soil survey and is available on the internet at http://websoilsurvey.nrcs.usda.gov . The following example illustrates the application of the web soil survey to a center pivot located in Platte County Nebraska.

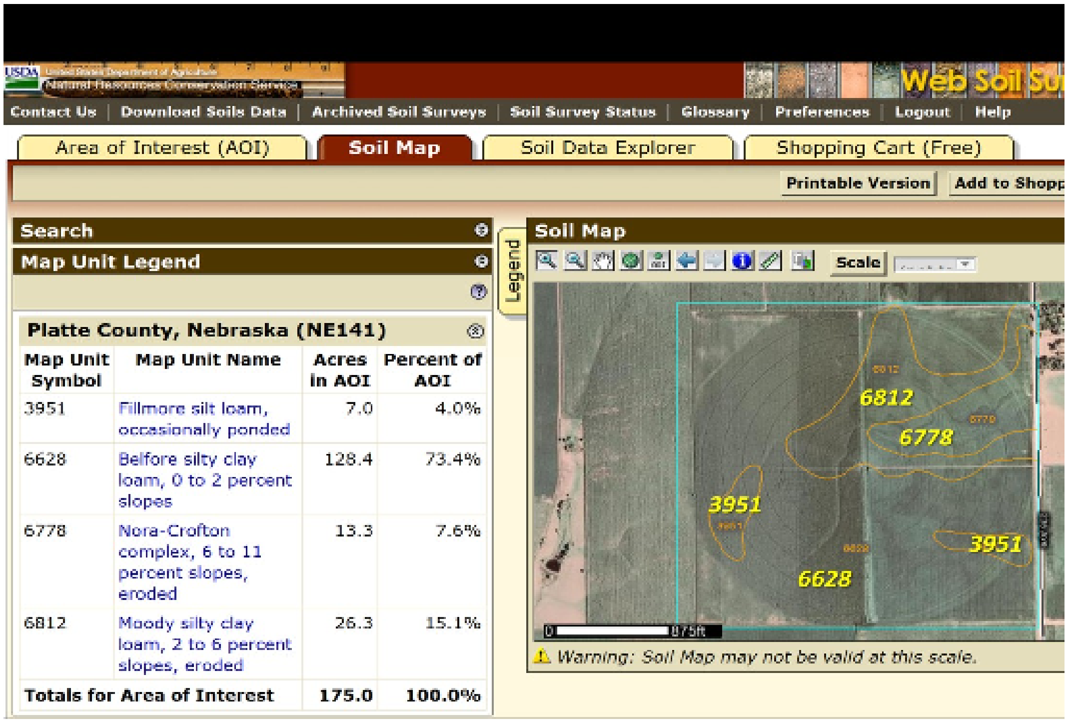
The state and county were selected in his example. You can also directly enter the legal description of the field (*i.e.,* township, range, and section). You can then zoom to your field using the magnifying glass icon. Once you have zoomed so that the field is visible in the map you then need to use the **area of interest** icon (AOI) to draw a rectangle around your field. After you have defined the area of interest you can then click on the **Soil Map** tab. This will bring up the soil map for your field as illustrated in the second figure below. The **Soil Map** includes information about the soil series in the field along with the fraction of the field represented by each mapping unit. This is the information that will be used to help select appropriate sprinkler devices for the conditions in your field. The important characteristics for the mapping units are the general soil texture (such as silty clay loam in this example for the Belfore soil). We also need the slope for the mapping unit. While the slope is only a generalization of slope categories it helps classify the soil. If you have better slope information you should certainly use that data.



State: Nebraska

County (optional): Platte

Figure 1 Selection of general area of interest in Web Soil Survey.



Platte County, Nebraska (NE141)

Map Unit Symbol	Map Unit Name	Acres in AOI	Percent of AOI
3951	Fillmore silt loam, occasionally ponded	7.0	4.0%
6628	Belfore silty clay loam, 0 to 2 percent slopes	128.4	73.4%
6778	Nora-Crofton complex, 6 to 11 percent slopes, eroded	13.3	7.6%
6812	Moody silty clay loam, 2 to 6 percent slopes, eroded	26.3	15.1%
Totals for Area of Interest		175.0	100.0%

Figure 2. Soil map produced for the area of interest selected for your field.

We use the information from the USDA-NRCS to estimate the amount of surface storage that is available in a field. Their method depends on the general slope in the field and the amount of residue cover in the field. The USDA-NRCS presents typical values as listed in Table 1 below. You can estimate the amount of residue in the field using the method described by Shelton and Jasa (2009, *Estimating Percent Residue Cover Using the Line-Transect Method,* available at http://www.ianrpubs.unl.edu/sendIt/g1931.pdf). This table shows that soils with the slope that average about 2% produces surface storage of 0.30 inches when there is no crop residue and up to 0.65 inches when residue cover is about 70%.

We have developed some general guidelines for some typical sprinkler devices that commonly used. Table 2 shows the amount of surface storage that is required to avoid runoff for general soil textures when one inch of water is applied with the pivot. Results in Table 2 for the silty clay loam texture class shows that about 0.49 to 0.62 inches of surface storage for any devices suspended on drops while storage would have to be from 0.38 to 0.53 inches for devices installed on top of the center pivot lateral. Clearly, the silty clay loam soil will require significant residue cover to avoid runoff for even mild soil slopes.

Applying smaller applications per irrigation can help reduce the runoff potential. Results in Table 3 are for an application of 0.75 inches per irrigation. As the table illustrates the amount of surface storage required to avoid runoff for applications of 0.75 inches drops to a range from 0.37 to 0.47 inches for devices installed on drops and from 0.29 to 0.40 inches for installation on top of the pivot lateral. Thus smaller applications may allow for steeper slopes and less residue.

Table 1. Surface storage available due to residue and slope (from NRCS).

Percent Residue Cover	Storage Due to Residue, inches	Field Slope, %								
		0.5	1	1.5	2	2.5	3	3.5	4	5
0	0.00	0.50	0.44	0.38	0.30	0.26	0.20	0.16	0.10	0.00
10	0.01	0.51	0.45	0.39	0.31	0.27	0.21	0.17	0.11	0.01
20	0.03	0.53	0.47	0.41	0.33	0.29	0.23	0.19	0.13	0.03
30	0.07	0.57	0.51	0.45	0.37	0.33	0.27	0.23	0.17	0.07
40	0.12	0.62	0.56	0.5	0.42	0.38	0.32	0.28	0.22	0.12
50	0.18	0.68	0.62	0.56	0.48	0.44	0.38	0.34	0.28	0.18
60	0.24	0.74	0.68	0.62	0.54	0.5	0.44	0.4	0.34	0.24
70	0.35	0.85	0.79	0.73	0.65	0.61	0.55	0.51	0.45	0.35

http://efotg.sc.egov.usda.gov//references/public/NE/NE_Irrig_Guide_Index.pdf

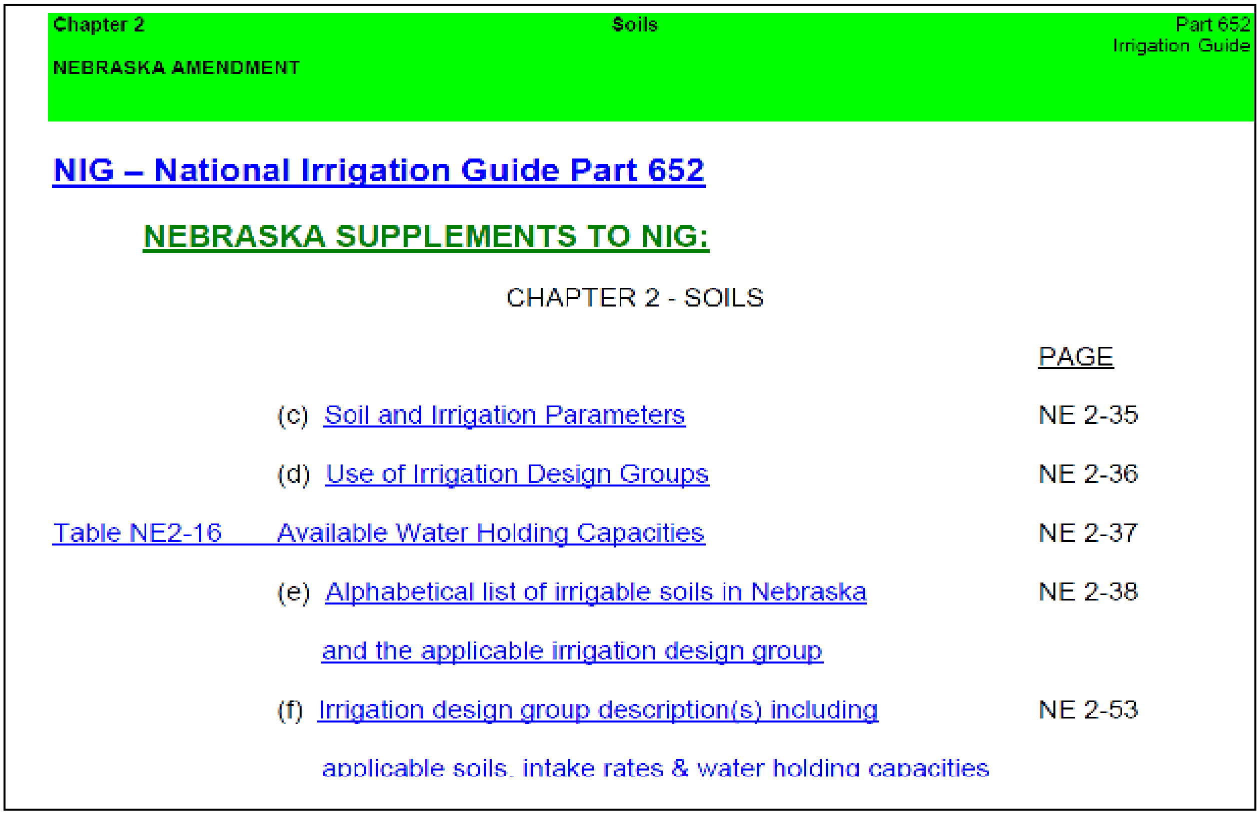
Table 2. General guidelines of surface storage (inches) needed to avoid runoff for 1-inch application for common sprinkler devices.

Texture Class	Device Installed on Top of Lateral			Device Suspended on Drops				
	Xi-Wob @ 10 psi White Pad	Rotator @ 20 psi White Pad	Impact with Vane	Spray @ 10 psi - Multi Trajectory	LDN @ 10 psi - Concave	Spinner @ 15 psi	I-Wob @ 10 psi	Rotator @ 15 psi Multi Trajectory
Sand	NR	NR	NR	NR	NR	NR	NR	NR
Loamy Sand	NR	NR	NR	NR	NR	NR	NR	NR
Sandy Loam	NR	NR	NR	NR	NR	NR	NR	NR
Loam	0.07	NR	NR	0.22	0.17	0.10	0.10	0.01
Silt Loam	0.11	0.00	NR	0.25	0.22	0.15	0.15	0.05
Sandy Clay Loam	0.40	0.28	0.21	0.52	0.49	0.43	0.43	0.34
Clay Loam	0.54	0.44	0.38	0.63	0.60	0.56	0.56	0.49
Silty Clay Loam	0.53	0.44	0.38	0.62	0.60	0.56	0.56	0.49
Sandy Clay	0.67	0.60	0.56	0.74	0.72	0.69	0.69	0.64
Silty Clay	0.70	0.64	0.59	0.76	0.74	0.72	0.72	0.67
Clay	0.77	0.72	0.68	0.81	0.80	0.78	0.78	0.74

Table 3. Guidelines of surface storage (inches) needed to avoid runoff for 0.75-inch application for common sprinkler devices.

	Device Installed on Top of Lateral			Device Suspended on Drops				
Texture Class	Xi-Wob @ 10 psi White Pad	Rotator @ 20 psi White Pad	Impact with Vane	Spray @ 10 psi - Multi Trajectory	LDN @ 10 psi - Concave	Spinner @ 15 psi	I-Wob @ 10 psi	Rotator @ 15 psi Multi Trajectory
Sand	NR	NR	NR	NR	NR	NR	NR	NR
Loamy Sand	NR	NR	NR	NR	NR	NR	NR	NR
Sandy Loam	NR	NR	NR	NR	NR	NR	NR	NR
Loam	0.05	NR	NR	0.16	0.13	0.08	0.08	0.01
Silt Loam	0.08	0.00	NR	0.19	0.16	0.11	0.11	0.03
Sandy Clay Loam	0.30	0.21	0.16	0.39	0.37	0.32	0.32	0.26
Clay Loam	0.40	0.33	0.29	0.47	0.45	0.42	0.42	0.37
Silty Clay Loam	0.40	0.33	0.29	0.47	0.45	0.42	0.42	0.37
Sandy Clay	0.50	0.45	0.42	0.55	0.54	0.52	0.52	0.48
Silty Clay	0.53	0.48	0.45	0.57	0.56	0.54	0.54	0.50
Clay	0.57	0.54	0.51	0.61	0.60	0.58	0.58	0.56

The USDA-NRCS uses a computer program that we developed called CPNozzle to develop guidelines based on designation of soils into intake families. The procedure is available at: http://efotg.sc.egov.usda.gov//references/public/NE/NE_Irrig_Guide_Index.pdf. A portion of the table of contents for the Nebraska Irrigation Guide is listed below.



Chapter 2 **Soils** Part 652 Irrigation Guide

NEBRASKA AMENDMENT

NIG – National Irrigation Guide Part 652

NEBRASKA SUPPLEMENTS TO NIG:

CHAPTER 2 - SOILS

Figure 3. Copy of a portion of the table of contents for Nebraska Irrigation Guide.

The USDA-NRCS has categorized soil series as shown in the Soils Map above into general soil intake families. We generally find that three intake familes (0.3, 0.5, and 1.0) are appropriate for many soils. Generally these intake families represent most soils that pivots are adapted to and that express some runoff potential. You can refer to the file from the NRCS if your soil is not listed on the following tables.

Table 4. Soil Series in the INTAKE FAMILY 0.3

Deep soils with a clay loam, silty clay loam, or sandy clay loam surface layer and moderate or moderately slow permeability in the subsoil.

- Aksarben Silt clay loam
- Alcester Silt clay loam
- Bazile Silt clay loam
- Belfore Silt clay loam
- Betts Clay loam
- Blake Silt clay loam
- Blyburg Silt clay loam
- Boel Silt clay loam
- Buffington Silt clay loam
- Bufton Clay loam
- Bufton Silt clay loam
- Burchard Clay loam
- Coleridge Silt clay loam
- Colo Silt clay loam
- Cortland Loam
- Cozad Silt clay loam
- Deroin Silt clay loam
- Geary Silt clay loam
- Geary variant Silt clay loam
- Gibbon Silt clay loam
- Gibbon Variant Silt clay loam
- Gymer Silt clay loam
- Hall Silt clay loam
- Hastings Silt clay loam
- Hastings variant Silt clay loam
- Haverson Silt clay loam
- Hobbs Sandy loam
- Holder Silt clay loam
- Holder variant Silt clay loam
- Holdrege Silt clay loam
- Holdrege variant Silt clay loam
- Hord Silt clay loam
- Judson Silt clay loam
- Kanorado Silt clay loam
- Kennebec Silt clay loam
- Kenridge Silt clay loam
- Lamo Clay loam
- Lamo Silt clay loam
- Lawet Silt clay loam
- Lohmiller Silt clay loam
- Manvel Silt clay loam
- Marshall Silt clay loam
- McCook Silt clay loam
- Merrick Sandy clay loam
- Minnequa Silt clay loam
- Moody Silt clay loam
- Morrill Clay loam
- Muir Silt clay loam
- Nodaway Silt clay loam
- Nora Silt clay loam
- Nora variant Silt clay loam
- Norrest Clay loam
- Norrest Silt clay loam
- Nuckolls variant Silt clay loam
- Onita Silt clay loam
- Paka Sandy clay loam
- Pohocco Silt clay loam
- Ponca Silt clay loam
- Reliance Silt clay loam
- Roxbury Silt clay loam
- Rusco Silt clay loam
- Rusco variant Silt clay loam
- Salix Silt clay loam
- Salmo Silt clay loam
- Saltine Silt clay loam
- Savo Silt clay loam
- Sharpsburg variant Silt clay loam
- Shelby Clay loam
- Shell Silt clay loam
- Shell Variant Silt clay loam
- Skilak Silt clay loam
- Steinauer Clay loam
- Steinauer Loam
- Trent Silt clay loam
- Uly variant Silt clay loam
- Yutan Silt clay loam

Table 5. Soil Series in the Intake Family 0.5

Deep soils with a silt loam or loam surface layer and moderate or moderately slow permeability in the subsoil.

Alliance Loam
Alliance Silt loam
Belfore Silt loam
Betts Loam
Burchard Loam
Burchard Silt loam
Calco Silt clay loam
Calco Silt loam
Calco Sandy loam
Caruso Loam
Caruso variant Loam
Clarno Loam
Coleridge Silt loam
Colo Silt loam
Geary Silt loam
Goshen Loam
Goshen Silt loam
Hall Silt loam
Harney Silt loam
Hastings Silt loam
Hastings variant Silt loam
Hemingford Loam
Holder Loam
Holder Silt loam
Holdrege Silt loam
Humbarger Loam
Humbarger variant Silt loam
Janise Loam
Janise Silt loam
Johnstown Loam
Judson Silt loam
Kadoka Silt loam
Keith Loam
Keith Silt loam
Keya Loam
Kuma Loam
Kuma Silt loam
Lamo Loam
Lamo Silt loam
Lamo Variant Loam
Lawet Loam Lawet
Silt loam Lawet
variant Loam Leisy
Loam
Loretto Loam
Mace Silt loam
Marshall Silt loam
Maskell Loam
Moody Loam
Moody Silt loam
Nuckolls Silt loam
Nuckolls variant Silt loam
Nunn Silt loam
Onita Silt loam
Ord Variant Silt loam
Paka Loam
Ree Loam
Ree Silt loam
Reliance Silt loam
Richfield Loam
Richfield Silt loam
Rusco Silt loam
Salix Silt loam
Salmo Silt loam
Satanta Loam
Satanta Very fine sandy loam
Thirtynine Loam
Thirtynine Silt loam
Tomek Silt loam

Table 6. Soil Series in the Irrigation Intake Family 1.0

Deep soils with a silt loam, loam, or very fine sandy loam surface layer and a moderately permeable, medium-textured subsoil.

- Ackmore Silt loam
- Alcester Silt loam
- Angora Very fine sandy loam
- Aowa Silt loam
- Benkelman Very fine sandy loam
- Bigbend Loam
- Blackwood Loam
- Blackwood Silt loam
- Blyburg Silt loam
- Bridget Loam
- Bridget Silt loam
- Bridget Very fine sandy loam
- Bushman Very fine sandy loam
- Colby Loam
- Colby Silt loam
- Coly Silt loam
- Cozad Loam
- Cozad Silt loam
- Cozad variant Loam
- Cozad variant Silt loam
- Craft Loam
- Craft Very fine sandy loam
- Creighton Very fine sandy loam
- Crofton Silt loam
- Duroc Loam
- Duroc Silt loam
- Duroc Very fine sandy loam
- Eltree Silt loam
- Eudora Loam
- Eudora Silt loam
- Gates Silt loam
- Gates Very fine sandy loam
- Gibbon Loam
- Gibbon Silt loam
- Gosper Loam
- Grable Silt loam
- Grable Very fine sandy loam
- Grable variant Silt loam
- Graybert Very fine sandy loam
- Grigston Silt loam
- Haverson Loam
- Haverson Silt loam
- Haynie Silt loam
- Haynie Very fine sandy loam
- Haynie variant Silt loam
- Hobbs Silt loam
- Hobbs Sandy loam
- Hord Silt loam
- Hord Very fine sandy loam
- Ida Silt loam
- Janude Loam
- Kenesaw Silt loam
- Kennebec Silt loam
- Kezan Silt loam
- Laird Fine sandy loam
- Leshara Silt loam
- Malcolm Silt loam
- McCash Very fine sandy loam
- McConaughy Loam
- McCook Loam
- McCook Silt loam
- McCook variant Loam
- McPaul Silt loam
- Merrick Loam
- Merrick variant Loam
- Mitchell Silt loam
- Mitchell Very fine sandy loam
- Mitchell variant Silt loam
- Modale Silt loam
- Modale Very fine sandy loam
- Monona Silt loam
- Morrill Loam
- Moville Silt loam
- Muir Silt loam
- Munjor Loam
- Napier Silt loam
- Nimbro Silt loam
- Nodaway Silt loam
- Nodaway variant Silt loam
- Nora Silt loam
- Nora variant Silt loam
- Norwest Loam
- Oglala Loam
- Oglala Very fine sandy loam
- Olmitz Loam
- Olney Loam
- Omadi Silt loam
- Pohocco Silt loam
- Ponca Silt loam
- Ralton Loam
- Roxbury Silt loam
- Rushcreek Loam
- Saltine Loam
- Saltine Silt loam
- Shell Silt loam
- Sidney Loam
- Sulco Loam
- Sulco Silt loam
- Sulco Very fine sandy loam
- Sully Loam
- Sully Silt loam
- Trent Silt loam
- Tripp Loam
- Tripp Very fine sandy loam
- Uly Silt loam
- Ulysses Loam
- Ulysses Silt loam
- Yockey Fine sandy loam
- Yockey Loam
- Yockey Silt loam
- Yockey Very fine sandy loam

Sandy soils that are classified into soil intake families with larger infiltration rates such as Intake Family 1.5 or higher seldom have serious runoff problems with most sprinkler devices.

We have developed a graphical procedure to estimate the required wetted diameter of a sprinkler packages for selected application depths, available surface storage and system capacity expressed as the system flow rate divided by the size of the field (*i.e.,* gpm/acre). To use the chart you should determine which intake family for the most runoff prone areas in the field. Those soils should include enough area to be significant and should be located at the outer end of the pivot lateral where the water application rate is the highest.

The next step is to select your typical application depth per irrigation and move horizontally across the chart until the horizontal line intersects the available surface storage for your field. Move vertically downward to the lower portion of the graph until the vertical line intersects the system capacity of your system. Move horizontally to the right from that intersection point to read the required wetted diameter for sprinkler devices located near the end of a traditional center pivot with a lateral that is about 1300 feet long. You can then compare the required wetted diameter to the value produced by an array of sprinkler devices that are installed at various heights above the crop. You can obtain sprinkler performance data directly from the web page for most sprinkler manufacturers.

The analysis is illustrated in Figures 4-6 for the three soils when the available surface storage is 0.3 inches and the system capacity is 6 gallons per minute per acres. The results in Figure 4 show that sprinkler devices at the end of a traditional lateral would need to produce a wetted diameter of about 70 feet for the 0.3 Intake Family such as found in the Soil Map for the field in Platte County. The required wetted diameter drops to about 45 feet for the 0.5 Intake Family Soils and to about 25 feet for the 1.0 Intake Family Soils. Obviously, the correct sprinkler choice will vary a great deal for these conditions. Choices are fairly limited for the 0.3 Intake Family and efforts to increase residue cover and enhance the infiltration rate would be strongly recommended.

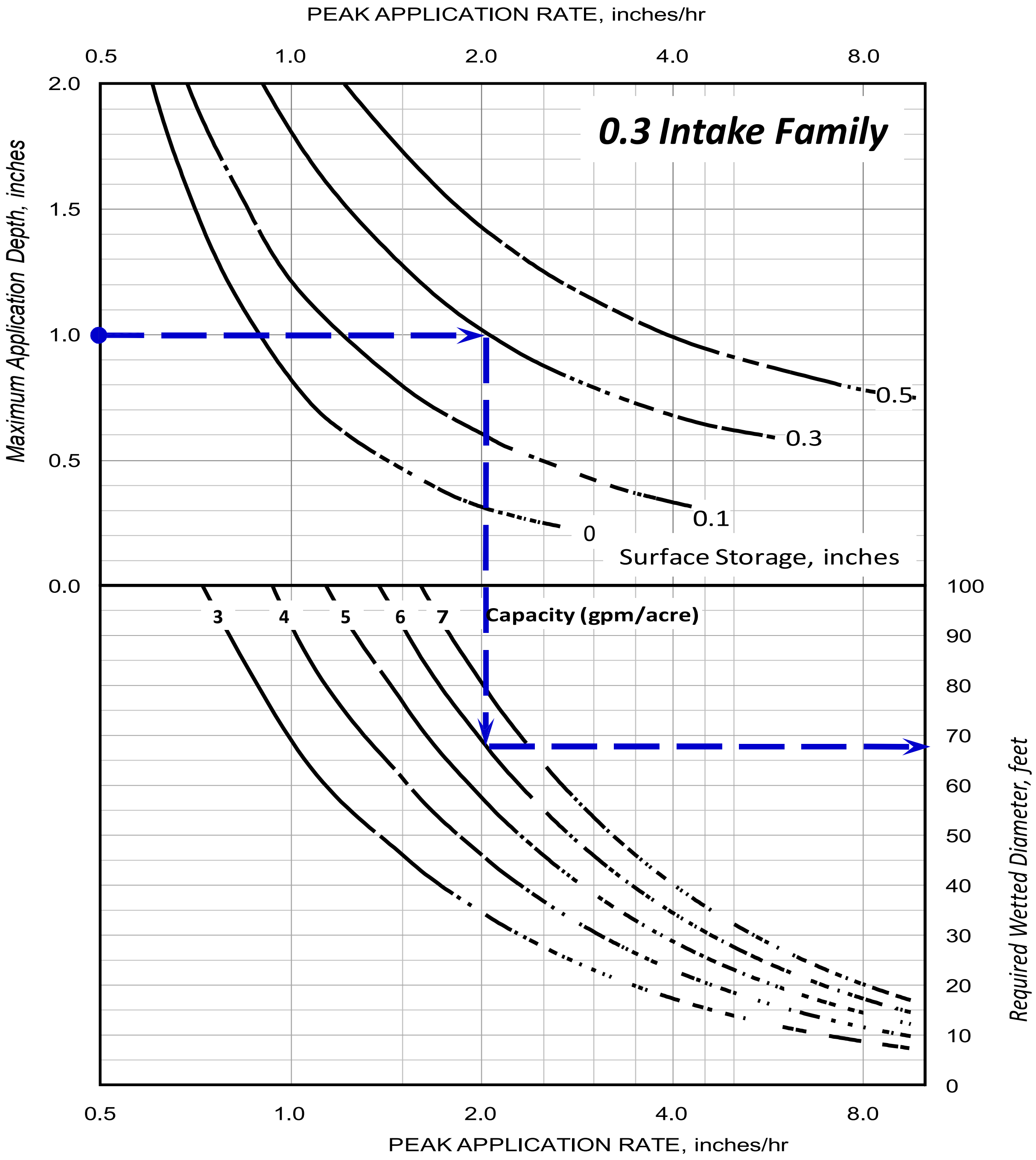


Figure 4. Graphical procedure to estimate the wetted diameter of the sprinkler devices to avoid runoff at the end of a traditional pivot that is 1300 feet long for soils that are categorized in the 0.3 Intake Family.

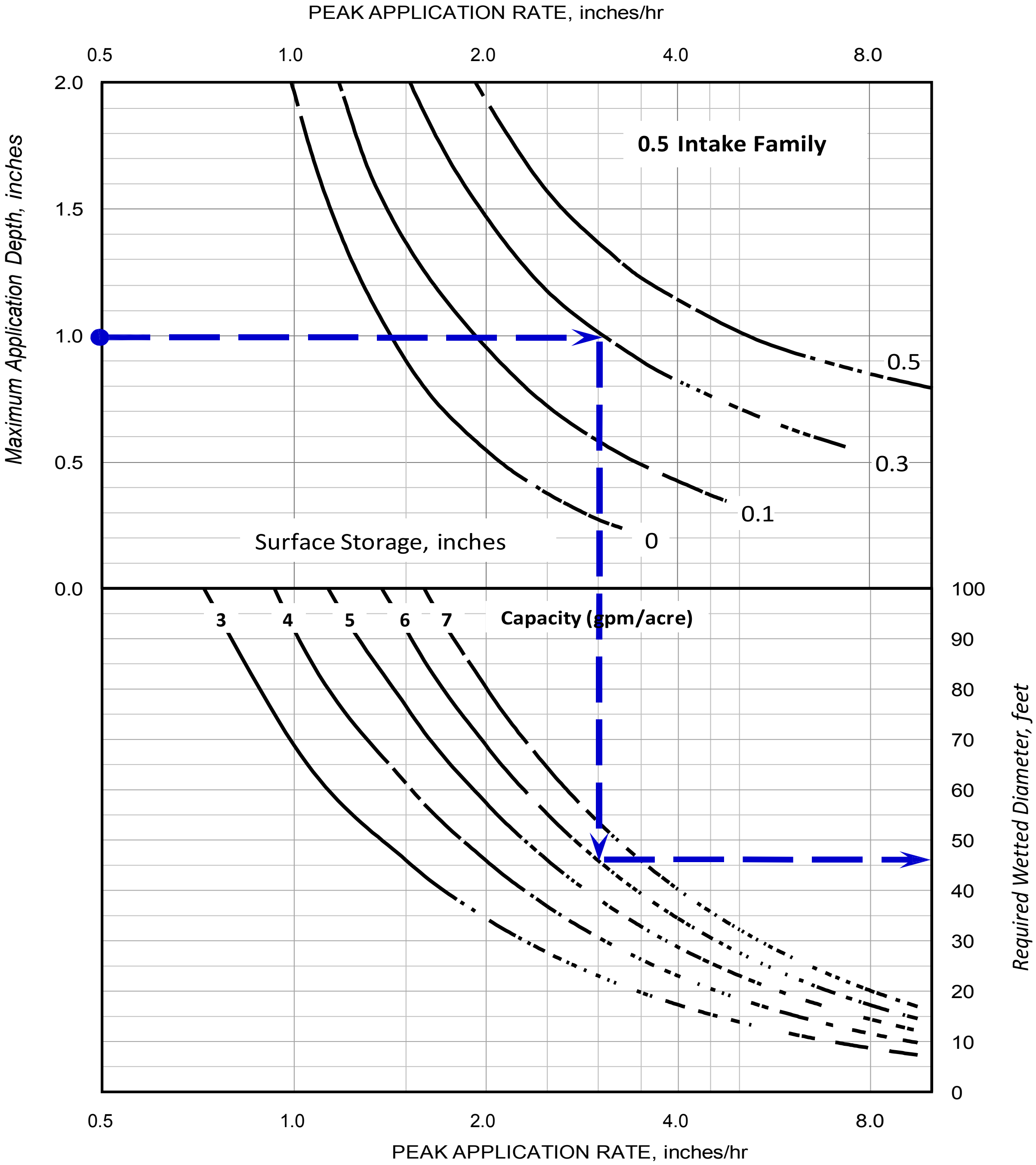


Figure 5. Graphical procedure to estimate the wetted diameter of the sprinkler devices to avoid runoff at the end of a traditional pivot that is 1300 feet long for soils that are categorized in the 0.5 Intake Family.

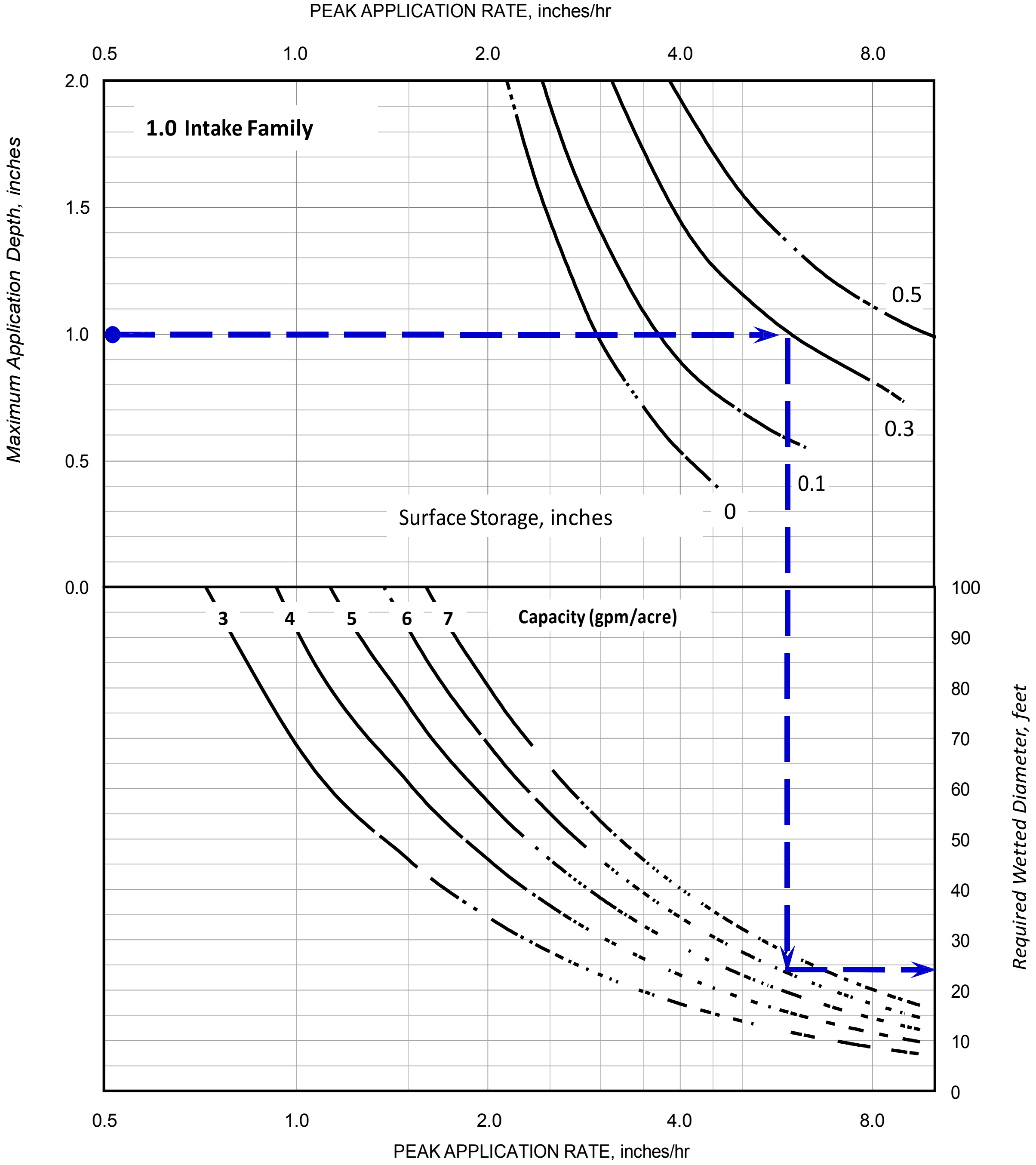


Figure 6. Graphical procedure to estimate the wetted diameter of the sprinkler devices to avoid runoff at the end of a traditional pivot that is 1300 feet long for soils that are categorized in the 1.0 Intake Family.

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IRRIGATION RESEARCH WITH SUNFLOWERS IN KANSAS

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INTRODUCTION

Sunflower is a crop of interest in the Ogallala Aquifer region because of its shorter growing season and thus lower overall irrigation needs. Sunflowers are thought to better withstand short periods of crop water stress than corn and soybeans and the timing of critical sunflower water needs is also displaced from those of corn and soybeans. Thus, sunflowers might be a good choice for marginal sprinkler systems and for situations where the crop types are split within the center pivot sprinkler land area.

CURRENT IRRIGATED SUNFLOWER STUDY AT KSU-NWREC

Procedures

A study was conducted in 2009 and 2010 at the KSU Northwest Research-Extension Center in Colby, Kansas to examine the effect of three in-season irrigation capacities (limited to 1 inch every 4, 8, or 12 d) with and without a preseason irrigation application (5 inches applied in early May) on sunflower yield and water use parameters. All in-season irrigation events were scheduled using a weather-based water budget, so the irrigation capacities represent limits on irrigation not the actual applied amounts. Volumetric soil water content was measured in each subplot to a depth of 8 ft in one-foot increments on a weekly to biweekly basis throughout the crop production seasons.

Additionally, the irrigation treatments were superimposed with three target seeding rates of plant populations (18,000, 23,000 or 28,000 seeds/acre). A short stature hybrid (Triumph hybrid S671) was planted on June 18, 2009 and June 16, 2010 and the crop emerged on June 25, 2009 and June 24, 2010, respectively.

Sunflower yield and yield components (plant population, heads/plant, seeds/head and seed mass) seed oil quality, irrigation, total crop water use and crop water productivity (aka WUE and defined as Yield/Water Use) were determined for each subplot. The data was analyzed using statistical procedures from PC-SAS.

Results

Crop year 2009

The crop year 2009 was very cool and wet and irrigation needs were very low. In 2009, wet weather resulted in no irrigation being required before July 27, 2009. Irrigation amounts for the 1 inch every 4 and 8 days treatments were identical in 2009 at 2.88 inches (3 irrigation events) because the climatic water budget did not require the 1 inch every 4 days frequency to be used at maximum capacity. The 1 inch every 12 days had two irrigation events for a total of 1.92 inches over the course of the season. During the period April through October every month had above normal precipitation and between crop emergence and crop maturity the total precipitation was 10.18 inches.

There was a significant interaction of in-season irrigation capacity and plant population in 2009. The general trend was for greatest yields at the lowest and intermediate plant population (target plant populations of 18 and 23 K plants/acre) when in-season irrigation capacity was at intermediate or the greatest levels (1inch/8 days or 1 inch/4 days). At the lowest irrigation level, the trend was for the greatest yields at the intermediate and greatest plant population (Table 1). There were no other significant irrigation treatment effects on any yield component or water use parameter in 2009 (Table 1).

In 2009, plant population significantly affected all of the water use parameters and all of the sunflower yield components except seed yield and heads/plant (Table 1). The number of seeds/head and seed mass compensated for differences in plant population to achieve similar yield levels.

Crop year 2010

The early portion of the crop year 2010 was wet and irrigation needs were lower than normal. However, later in season, it was extremely dry with only 1.08 inches of precipitation occurring between August 4 and crop maturity on October 11. Wet weather resulted in no irrigation being required before July 25, 2010. In-season irrigation amounts were 11.52, 6.72, and 4.8 inches for the irrigation capacities limited to 1 inch/4 days, 1 inch/8 days and 1 inch/12 days, respectively. The 2010 sunflower irrigation amounts appear to be approximately 1 inch less than normal as estimated from long term (1972-2010) irrigation scheduling simulations conducted at Colby, Kansas.

There were no significant differences attributable to preseason irrigation on any yield component or water use parameter with the exception of plant population which was slightly decreased when preseason irrigation was performed (5 inches applied in late April) as shown in Table 2. The cause of this effect is unknown and perhaps should not be a concern at this time. So, preseason irrigation was an uneconomical practice in 2010 with the 5 inches of application costing approximately $17.50/acre (assuming a pumping cost of $3.50/acre-inch).

There were significant differences in yield and oil content with significantly lower yield and oil content occurring for the lowest irrigation capacity (limited to 1 inch/12 days for a total of 4.8 inches in 2010). Greatest yields and seed mass were obtained by the lowest target plant population (18,000 plants/acre) and at the greatest irrigation capacity (Table 2 and Figure 1). Oil content followed a different trend with greatest oil content occurring for the greatest target plant population (Table 2 and Figure 1). Oil yield for the 18,000 plants/acre population was 1357, 1361 and 1314 lbs/acre for the 1 inch/4 days, 1 inch/8 days and 1 inch/12 days irrigation capacities, respectively. Assuming a sunflower seed yield value of $0.213/lb and a pumping cost of 3.50/acre-inch, the 1 inch/8 days irrigation capacity would obtain $12.73 and $17.18 greater economic returns than the 1 inch/4 days and 1 inch/12 days irrigation capacities, respectively. Increases in plant population significantly decreased the seeds/head and seed mass as might be anticipated. Water use was increased by increased irrigation capacity as might be anticipated but was not affected by increases in plant population (Table 1). Water productivity (yield/water use) was significantly greater with decreases in irrigation capacity which is often the case, but must be balanced with the effect on overall economic productivity. The smallest plant population had significantly greater water productivity due to having a greater sunflower yield.

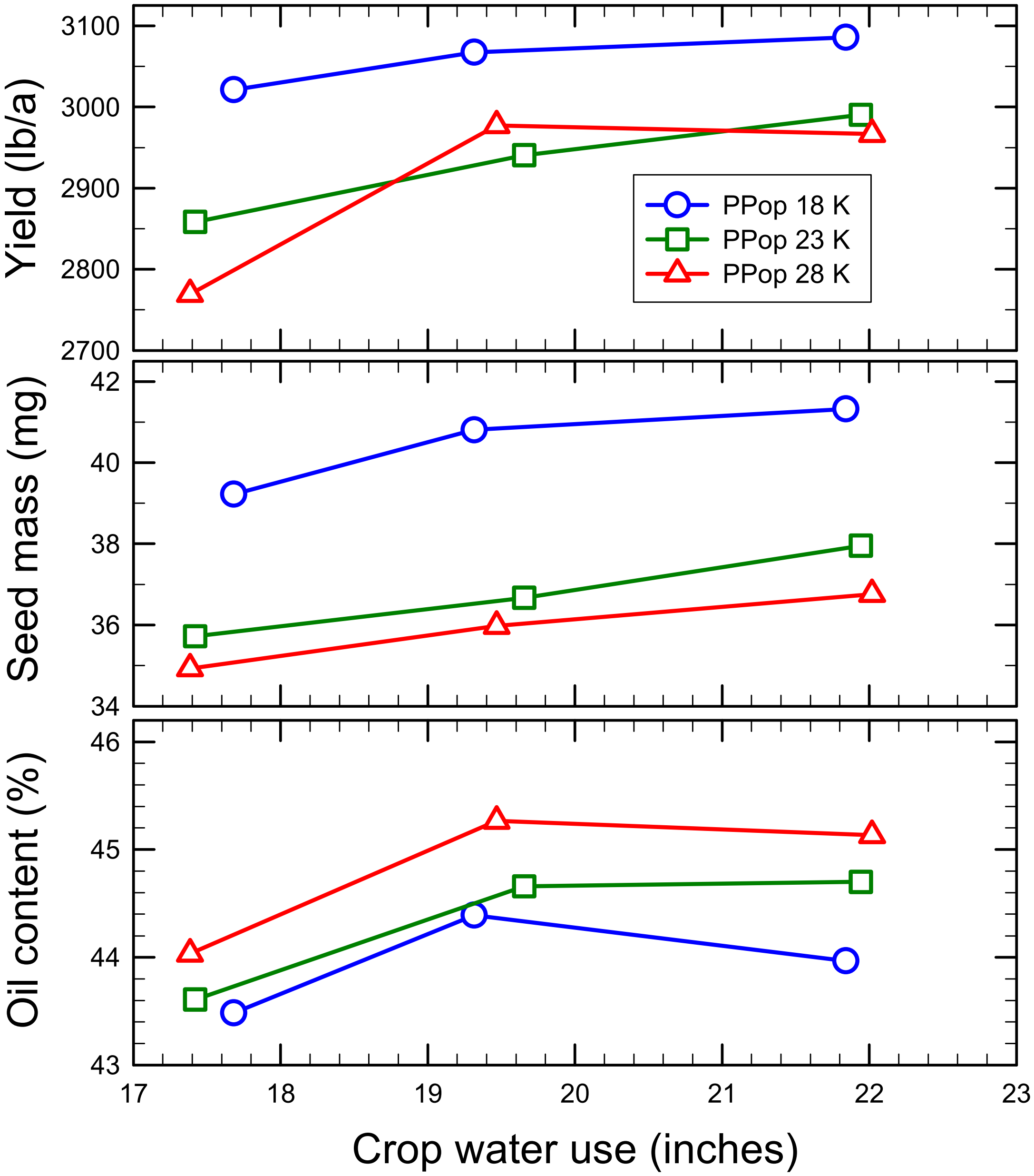

Figure 1. Sunflower yield, seed mass and oil content as related to total crop water use and the targeted plant population at KSU Northwest Research-Extension Center, Colby, Kansas in 2010. The three clusters of data points from left to right represent irrigation capacities of 1 inch/12 days (4.80 inches), 1 inch/8 days (6.72 inches) and 1 inch/4 days (11.52 inches), respectively.

Table 1. Summary of sunflower yield components and water use parameters for a sprinkler irrigated study, 2009, KSU Northwest Research-Extension Center, Colby Kansas.

Irrigation capacity	Preseason irrigation	Targeted plant pop (1000 p/a)	Yield (lb/a)	Harvest plant pop (p/a)	Heads /plant	Seeds /head	Seed mass (mg)	Seed Oil%	Water use (in)	Water productivity (lb/a-in)
1 in/4 d (2.88 in)	None	18	3266	16262	0.94	2114	46.6	45.6	17.14	191
		23	3324	20183	0.92	2043	40.2	46.2	17.69	189
		28	3109	23813	0.93	1720	37.2	46.6	17.30	180
		Mean	3233	20086	0.93	1959	41.3	46.2	17.38	186
	5 inches	18	3229	16553	0.94	2155	44.3	45.7	17.26	187
		23	3326	20328	0.93	1919	42.0	46.3	17.44	191
		28	3246	22942	0.99	1728	39.3	46.8	18.16	179
		Mean	3267	19941	0.95	1934	41.9	46.2	17.62	186
Mean 1 inch/4 days			**3250**	**20013**	**0.94**	**1947**	**41.6**	**46.2**	**17.50**	**186**
1 in/8 d (2.88 in)	None	18	3376	16698	0.95	2259	43.4	45.7	17.24	197
		23	3189	20183	0.95	1893	40.4	46.0	17.45	183
		28	3081	22506	0.96	1790	37.5	46.5	18.05	171
		Mean	3215	19796	0.95	1981	40.4	46.1	17.58	184
	5 inches	18	3427	16553	0.99	2214	42.8	45.0	17.72	193
		23	3208	19312	0.96	1934	40.6	46.1	17.37	185
		28	3332	22506	1.01	1766	38.4	46.6	18.17	184
		Mean	3322	19457	0.99	1971	40.6	45.9	17.76	188
Mean 1 inch/8 days			**3269**	**19626**	**0.97**	**1976**	**40.5**	**46.0**	**17.67**	**186**
1 in/12 d (1.92 in)	None	18	3158	16408	0.93	2198	42.8	45.7	17.50	181
		23	3186	19457	0.96	1923	40.3	45.9	17.87	178
		28	3168	24103	0.91	1728	38.3	46.5	17.87	178
		Mean	3171	19989	0.93	1950	40.5	46.0	17.75	179
	5 inches	18	3100	16117	0.97	2127	42.3	46.1	17.48	177
		23	3345	19166	0.96	1985	41.9	45.6	17.53	191
		28	3279	23522	0.94	1758	38.4	46.2	17.80	184
		Mean	3241	19602	0.96	1957	40.8	45.9	17.60	184
Mean 1 inch/12 days			**3206**	**19796**	**0.95**	**1953**	**40.7**	**46.0**	**17.68**	**182**
Study-Wide Mean			**3242**	**19812**	**0.95**	**1959**	**40.9**	**46.0**	**17.61**	**184**
Preseason Irrigation	None		**3206**	**19957**	**0.94**	**1963**	**40.7**	**46.1**	**17.57**	**183**
	5 inches		**3277**	**19667**	**0.97**	**1954**	**41.1**	**46.0**	**17.66**	**186**
Target plant population (1000 p/a)		18	**3260**	**16432 c**	**0.95**	**2178 a**	**43.7 a**	**45.6 c**	**17.39 b**	**188 a**
		23	**3263**	**19771 b**	**0.95**	**1950 b**	**40.9 b**	**46.0 b**	**17.56 b**	**186 a**
		28	**3203**	**23232 a**	**0.96**	**1748 c**	**38.2 c**	**46.5 a**	**17.89 a**	**179 b**

Values within the same shaded column are significantly different at P<0.05 when followed by a different lower-cased letter.

Table 2. Summary of sunflower yield components and water use parameters for a sprinkler irrigated study, 2010, KSU Northwest Research-Extension Center, Colby Kansas.

Irrigation capacity	Preseason irrigation	Targeted plant pop (1000 p/a)	Yield (lb/a)	Harvest plant pop (p/a)	Heads /plant	Seeds /head	Seed mass (mg)	Seed Oil%	Water use (in)	Water productivity (lb/a-in)
1 in/4 d (11.52 in)	None	18	3172	20038	0.94	1916	40.4	44.2	22.69	141
		23	2919	23668	0.89	1631	38.6	44.7	22.74	128
		28	2946	27007	0.85	1570	37.4	45.0	23.32	127
		Mean	3012	23571	0.90	1706	38.8	44.6	22.92	132
	5 inches	18	3000	19166	0.93	1845	42.3	43.8	20.99	143
		23	3062	23958	0.95	1646	37.3	44.7	21.15	146
		28	2987	25265	0.95	1597	36.1	45.3	20.72	145
		Mean	3172	20038	0.94	1916	40.4	44.2	22.69	141
Mean 1 inch/4 days			**3014 a**	**23184**	**0.92**	**1701**	**38.7**	**44.6 a**	**21.93 a**	**138 c**
1 in/8 d (6.72 in)	None	18	3043	19602	0.92	1893	41.0	44.5	19.63	157
		23	2989	23377	0.98	1668	36.1	44.6	20.01	150
		28	3004	25700	0.97	1563	35.7	45.3	19.36	156
		Mean	3012	22893	0.96	1708	37.6	44.8	19.66	154
	5 inches	18	3091	18440	0.98	1912	40.6	44.3	19.01	164
		23	2892	23087	0.93	1647	37.2	44.7	19.31	151
		28	2951	25410	0.98	1506	36.3	45.3	19.58	152
		Mean	3043	19602	0.92	1893	41.0	44.5	19.63	157
Mean 1 inch/8 days			**2995 a**	**22603**	**0.96**	**1698**	**37.8**	**44.8 a**	**19.48 b**	**155 b**
1 in/12 d (4.80 in)	None	18	2983	19312	0.96	1868	39.4	43.2	17.25	175
		23	2886	23522	0.96	1715	34.4	43.6	16.85	175
		28	2705	27588	0.88	1480	34.4	44.0	17.10	159
		Mean	2858	23474	0.93	1688	36.1	43.6	17.07	170
	5 inches	18	3059	19021	0.95	1983	39.0	43.7	18.12	170
		23	2831	22942	0.94	1613	37.0	43.6	17.99	158
		28	2833	26572	0.91	1511	35.5	44.1	17.67	162
		Mean	2908	22845	0.93	1702	37.2	43.8	17.93	163
Mean 1 inch/12 days			**2883 b**	**23159**	**0.93**	**1695**	**36.6**	**43.7 b**	**17.50 c**	**167 a**
Study-Wide Mean			**2964**	**22982**	**0.94**	**1698**	**37.7**	**44.4**	**19.64**	**153**
Preseason Irrigation	None		**2961**	**23313 a**	**0.93**	**1700**	**37.5**	**44.3**	**19.88**	**152**
	5 inches		**2967**	**22651 b**	**0.95**	**1695**	**37.9**	**44.4**	**19.39**	**155**
Target plant population (1000 p/a)		18	**3058 a**	**19263 c**	**0.94**	**1903 a**	**40.5 a**	**43.9 c**	**19.61**	**158 a**
		23	**2930 b**	**23426 b**	**0.94**	**1653 b**	**36.8 b**	**44.3 b**	**19.67**	**151 b**
		28	**2904 b**	**26257 a**	**0.92**	**1538 c**	**35.9 b**	**44.8 a**	**19.62**	**150 b**

Values within the same shaded column are significantly different at P<0.05 when followed by a different lower-cased letter.

Summary of Current Field Study

The crop year 2009 was too wet to gain much information on response of sunflower to irrigation, but there was the general trend of greater yields for lower or intermediate plant populations (target populations of 18,000 to 23,000 plants/acre and actual harvest populations of 16,500 to 19,800 plants/acre) under intermediate or higher irrigation capacities. In contrast, sunflower yield increased with greater plant population at the lowest irrigation level.

In 2010, a year that was wet in the early portion of the season, but very dry after August 4, sunflower seed yield increased with in-season irrigation capacity up until a capacity of 1 inch/8 days (6.72 inches total irrigation). The lowest plant population (target of 18,000 plants/acre and actual plant population of 19,300 plants/acre) gave the greatest yield (significant at $P<0.05$) and also had significantly greater seeds/head and seed mass.

Crop water use was slightly, but significantly greater ($P<0.05$) for the highest plant population in 2009 but was not affected in 2010. Crop water productivity was not affected by irrigation in 2009 but increased with decreased levels of irrigation in 2010. Increased plant population tended to decrease crop water productively primarily because of seed yield reduction.

The field study will be continued in 2011 because of the wetter than normal conditions experienced in 2009 and 2010.

RESULTS FROM EARLIER STUDIES AT KSU-NWREC

Irrigation studies with sunflower have been conducted periodically at the KSU Northwest Research-Extension Center since 1986. These irrigation treatments in these studies varied with some studies applying various percentages of well-water crop water use (ET), some studies applying water at specific sunflower growth stages, and some studies using water budget irrigation scheduling under various irrigation system capacities. Yield response varied some from year to year and some between studies as might be anticipated, but on the average 154 lbs of sunflower seed was obtained for each acre-inch of water use above a yield threshold of approximately 3 inches (Figure 2).

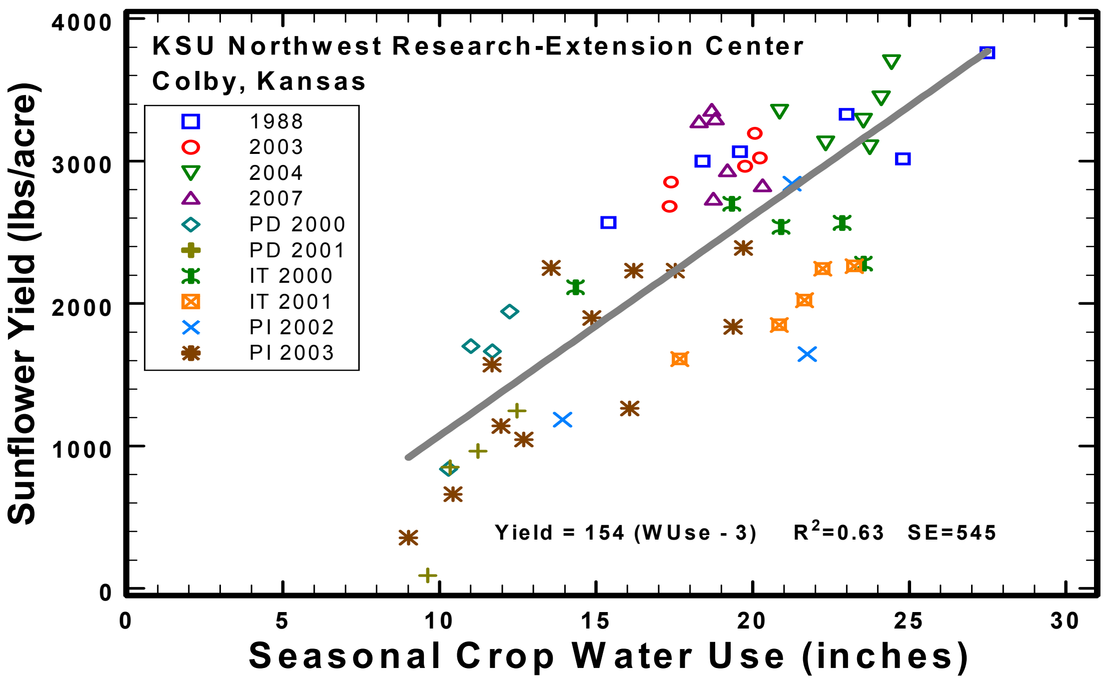

Figure 2. Sunflower yield response to total seasonal crop water use for selected studies conducted at the KSU Northwest Research-Extension Center, Colby Kansas, 1986-2007. The PD data from 2000 and 2001 was from dryland studies. The IT data from 2000 and 2001 was from studies scheduled by stage of growth. The data from the PI studies had irrigation applied at various growth periods throughout the summer. All other studies presented here were scheduled according to various percentages of crop water use.

RESULTS FROM SIMULATION MODELING

Thirty-nine years (1972-2010) of weather data was used to create simulated irrigation schedules for sunflower and also corn for a comparison crop. These irrigation schedules were also coupled with a crop yield model to estimate crop yield at various irrigation capacities (limited to 1 inch every 3, 4, 5, 6, 8, or 10 days) and under dryland production.

Although corn has greater crop water use (ET) and requires more irrigation (Figure 3) than sunflower, their peak water use rates and peak irrigation rates are very similar (Figure 4). Under full irrigation (a capacity not less than 1 inch every 4 days if needed), corn uses approximately 4.3 inches more water than sunflower during the season but only requires approximately 2.3 inches of additional irrigation because of its growth period encompasses some months of greater rainfall. Although peak ET and peak irrigation needs are similar between the two crops, sunflower’s needs are for a much shorter duration and occur at a time when corn’s needs are about to start declining.

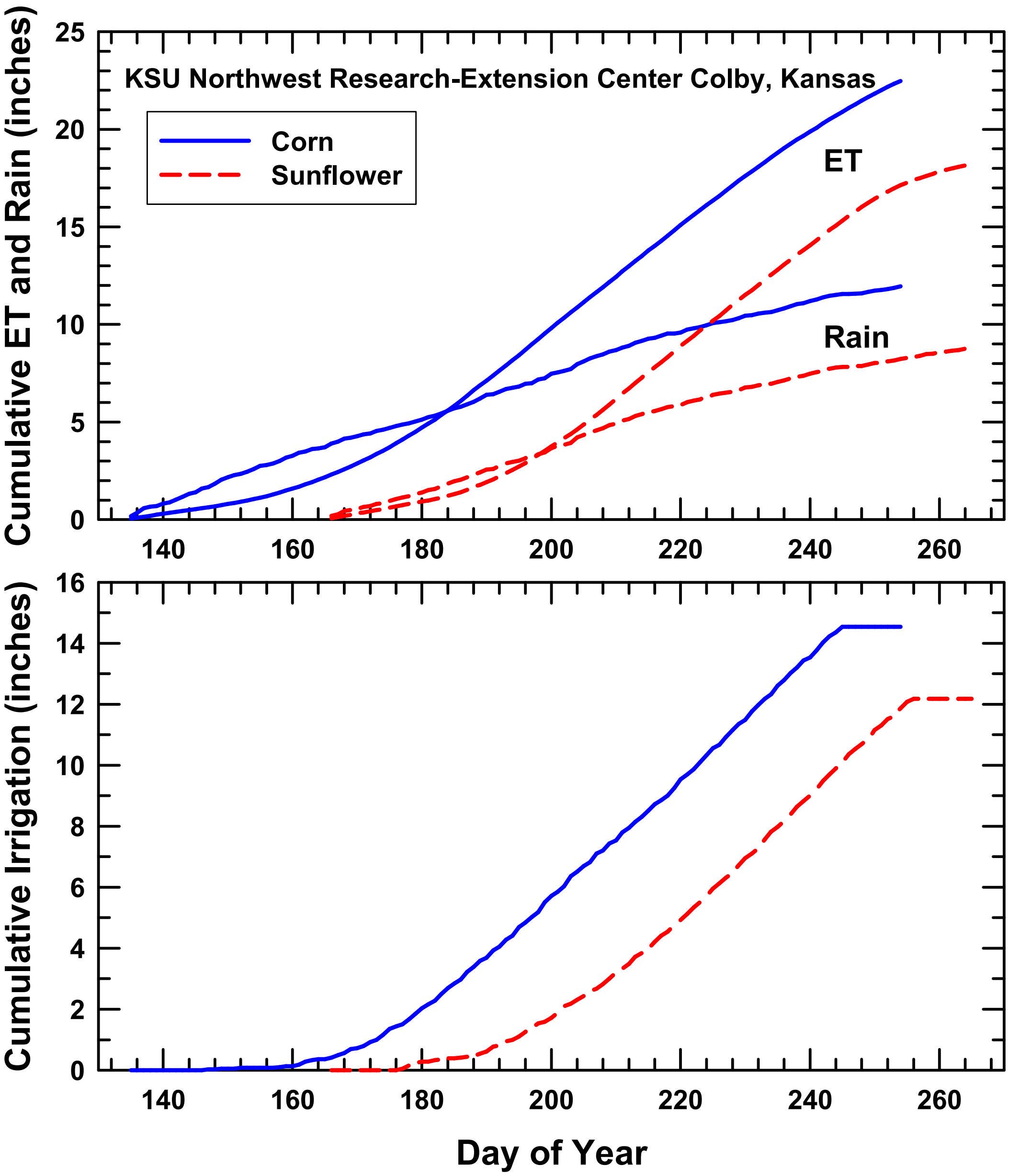

Figure 3. Simulated average cumulative crop water use (ET), rainfall and gross irrigation requirement for sunflower and corn for the 39 year period 1972 through 2010 at Colby, Kansas. Irrigation scheduling simulations were performed for sprinkler irrigation amounts of 1 inch at an application efficiency of 95%.

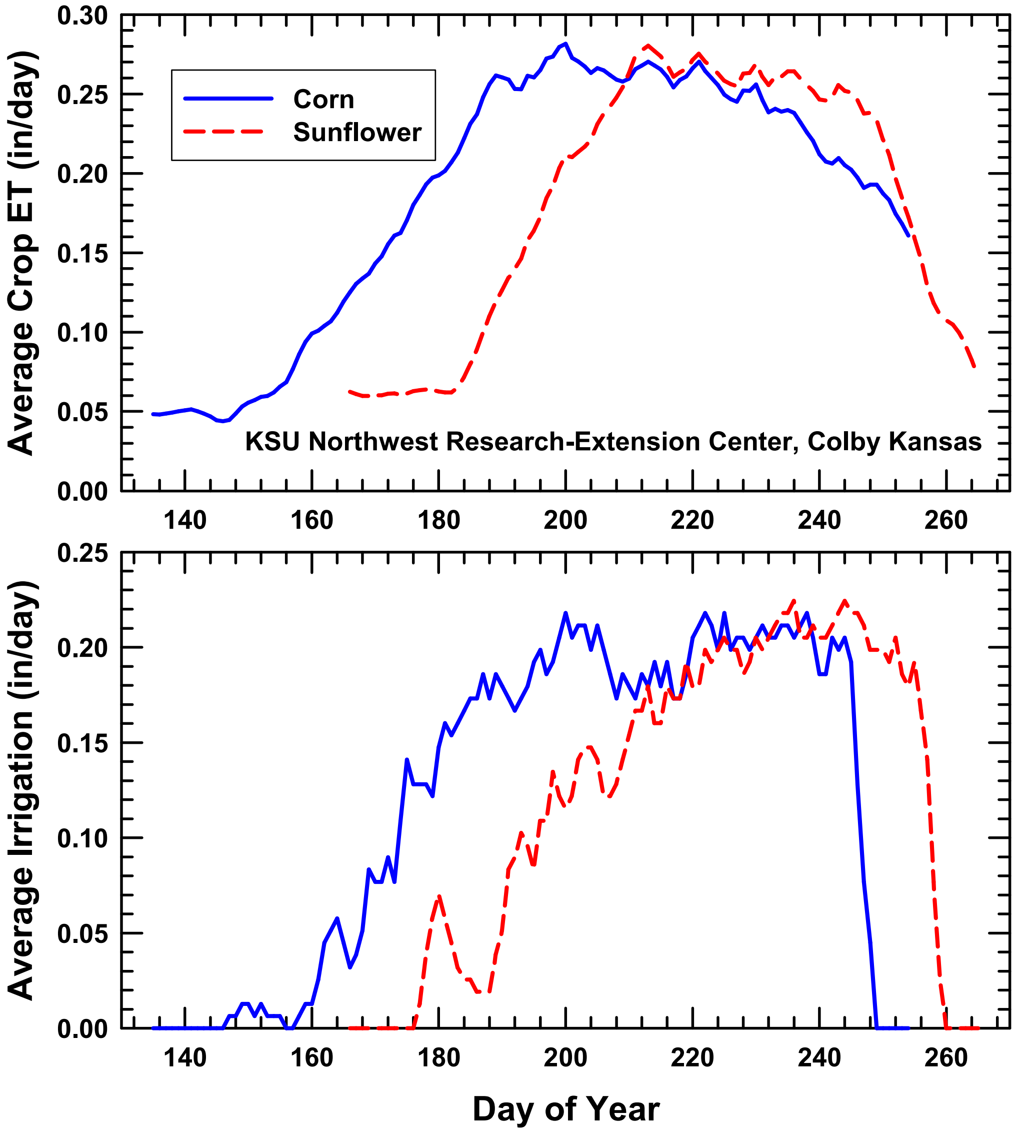

Figure 4. Simulated average daily crop water use (ET) and gross irrigation requirements for sunflower and corn for the 39-year period 1972 through 2010 at Colby, Kansas. Irrigation scheduling simulations were performed for sprinkler irrigation amounts of 1 inch at an application efficiency of 95%. The data are presented as a 4 day moving average.

The shorter duration of peak ET and irrigation needs for sunflower and their occurrence at a time when peak needs for corn are about to decline open up some opportunities to shift irrigation allocations between crops. Additionally, the yield decline with just slightly deficit irrigation is usually very small with sunflowers compared to corn (Figure 5). Under the right economics, sunflower can be a good candidate for deficit irrigation.

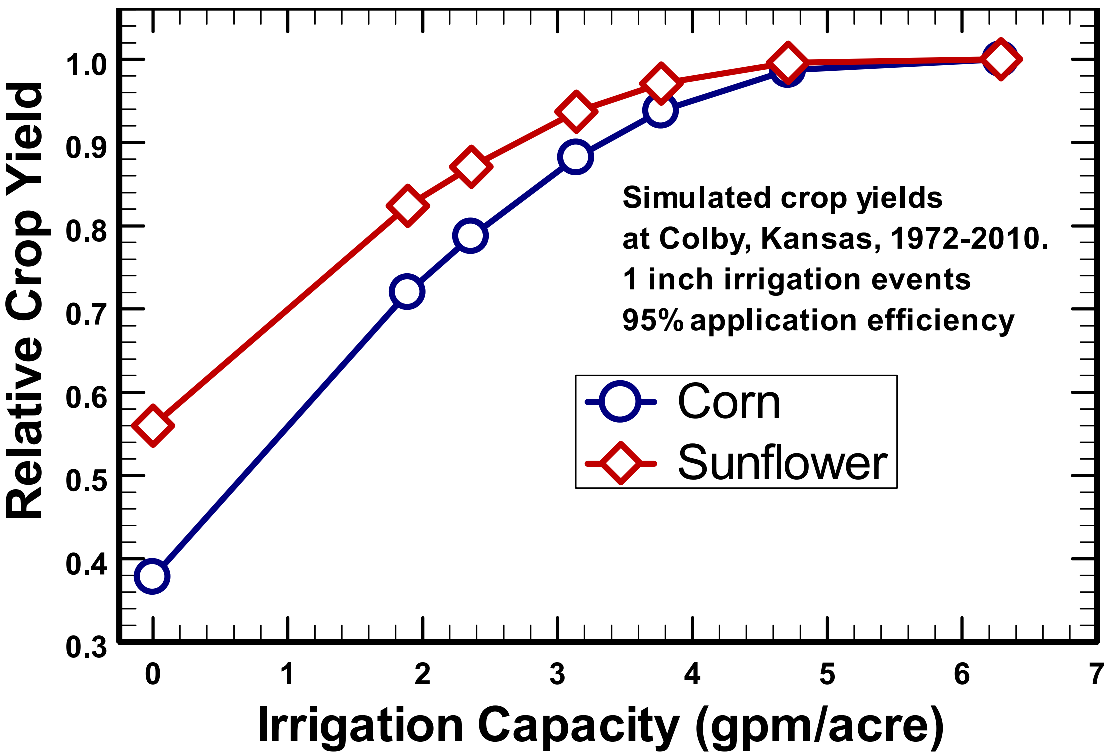

Figure 5. Simulated average relative crop yield of sunflower and corn as affected by irrigation capacity at Colby, Kansas for the 39-year period 1972-2010. Irrigation capacity data points left to right are dryland, 1 inch every 10, 8, 6, 5, 4 or 3 days, respectively. A capacity of 1 inch/4 days is equivalent to an irrigation capacity of 589 gpm/125 acre center pivot irrigation system.

As stated earlier, under full irrigation sunflower uses about 2.3 inches less irrigation than corn. However, because relative yield reductions are less for sunflower than with corn, many producers choose to deficit irrigate sunflowers and the annual irrigation difference may be 4 to 5 inches. Irrigation needs are greatest in August for sunflowers while the need is greatest in July for corn Figure 6. Some producers may want to plant a portion of their production area to sunflower to better manage their risk on lower capacity irrigation systems. However, they would be advised to estimate the economics of such a decision prior to the season. The Crop Water Allocator program (available at http://mobileirrigationlab.com/) developed by N.L Klocke and others at KSU can help with those decisions.

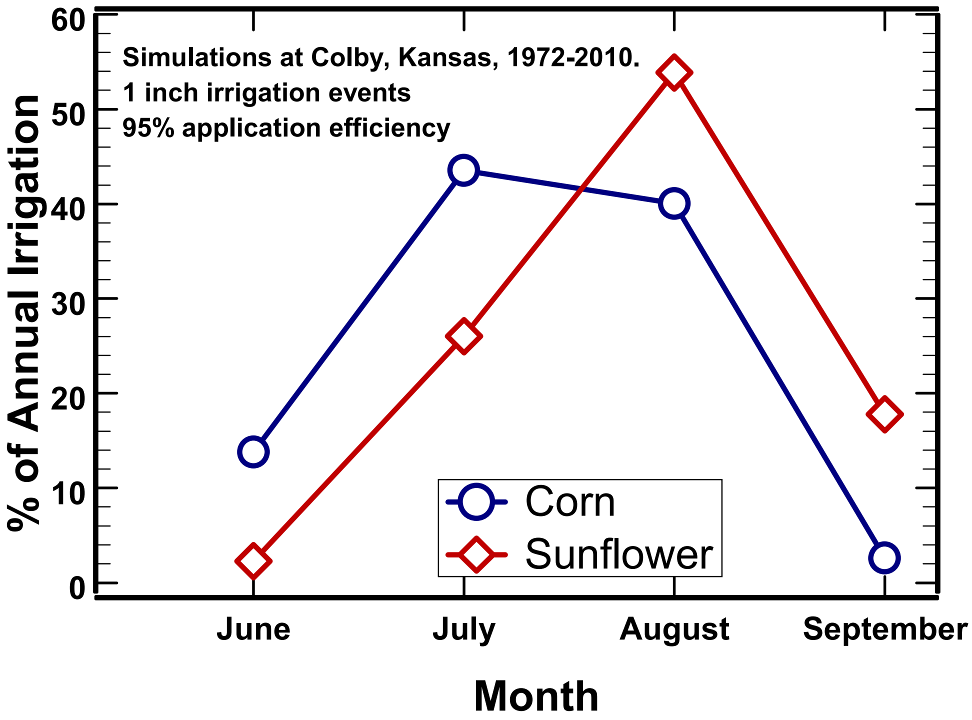

Figure 6. Average monthly distribution of irrigation needs of sunflower and corn at Colby, Kansas for the 39-year period 1972-2010 as determine from simulated irrigation schedules.

Summary

Research continues with developing irrigation strategies with sunflower in western Kansas. Declines in sunflower yield with deficit irrigation are less drastic than with corn, so producers may wish to consider sunflower when irrigation system capacities are marginal. Sunflower and corn have similar peak ET and irrigation rate requirements for full irrigation, but sunflower requires about 2.3 inches less irrigation and its peak needs began at about the time corn needs are starting to decline. Average full irrigation of sunflowers would be approximately 12 inches, but often producers will apply between 8 and 10 inches of irrigation because the amount of yield decline is only a few percentage points.

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WATER USE OF OILSEED CROPS

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INTRODUCTION

Water use of a crop, with adequate available soil water supply, is primarily affected by its canopy and weather conditions (Tanner and Sinclair, 1983; Albrizio and Steduto. 2005; Suyker and Verma, 2010). These effects are represented by seasonal crop coefficients and the potential evaporative demand (ETp) of the atmosphere (Allen et al., 2005). The crop coefficient indicates the fraction of potential ET which the crop is expected to utilize on a given day. The crop coefficient value typically changes with crop stage. Crop water productivity (also known as water use efficiency) refers to the amount of biomass or economic yield produced with a given amount of water use. This article will present oilseed crop water use and crop water productivity field results from the U.S. central High Plains. Also, we review findings of environmental and management factors which can improve the water productivity of oilseed crops in this region.

Oilseed crops

The primary oilseed crops considered here are canola (winter or spring), soybean and sunflower. Limited information is available for other spring oilseed crops (Indian Brown Mustard, Baltensperger et al., 2004; Crambe, Nielsen, 1998) and summer oilseed crops (Safflower, Istanbulluoglu et al., 2009; Lesquerella, Puppala et al., 2005). In the U.S. central High Plains, winter canola is typically planted in mid-August, flowering in mid-May and matures in early July (Rife and Salgado, 1996); spring canola can be planted early March, flowering in late-May and maturing in mid-July (Aiken, 2010). Figure 1 shows expected water use and crop productivity for spring canola (Nielsen, 1998). Soybean can be planted in

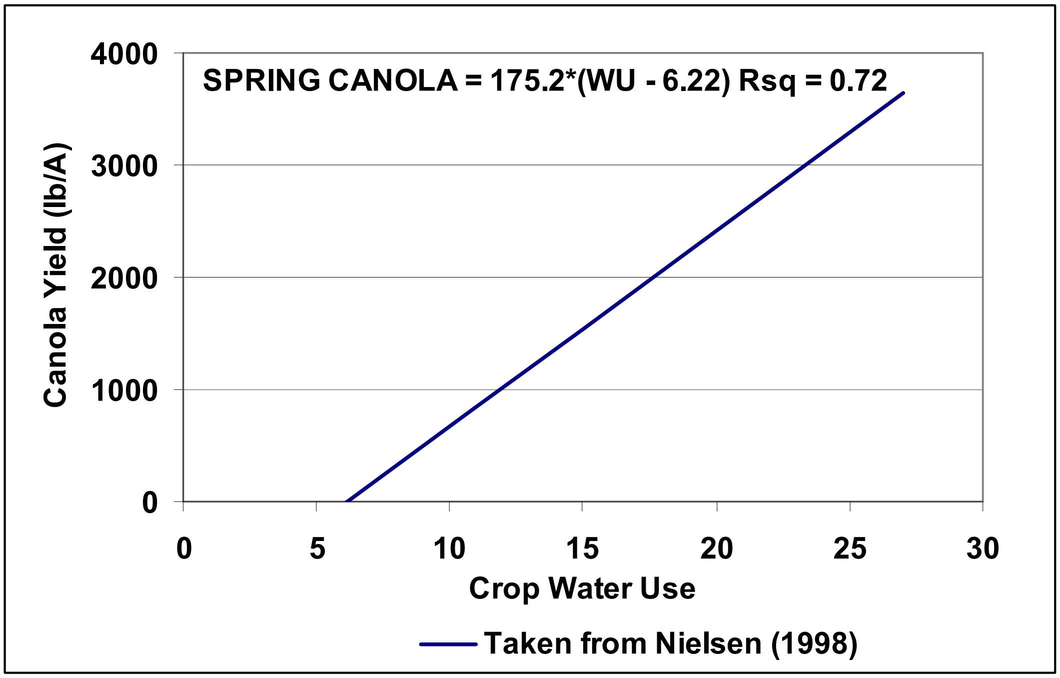

Figure 1. Expected oilseed yields of spring canola are presented, in relation to expected crop water use (soil water depletion plus precipitation and irrigation) in this crop water production function (taken from Nielsen, 1998).

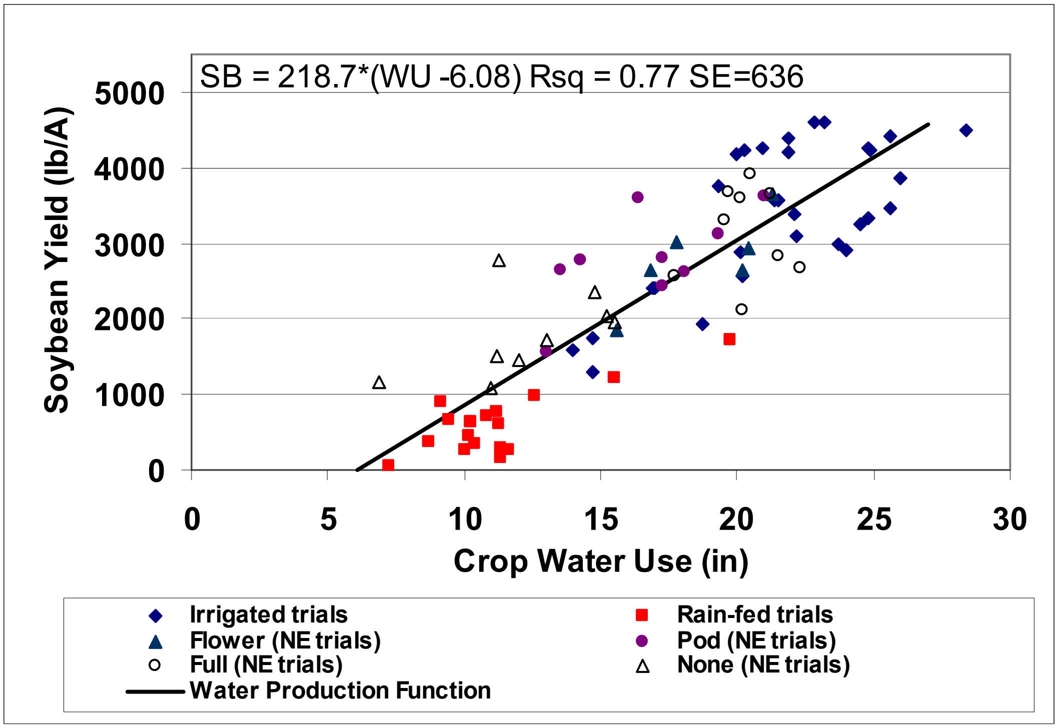

Figure 2. Expected oilseed yields and crop water use of soybean are derived from Colby, KS and Nebraska trials (NE trials indicate irrigation delayed to begin at flowering or pod development (Ellmore et al., 1988, Specht et al., 1989).

early May, flowering in mid-July for late-September harvest (Kranz et al., 2005). Sunflower is planted in mid-June to avoid pests, flowering in mid-August for harvest in late-September or early October (Rogers et al., 2005). Double-cropped soybean or sunflower can be planted after wheat harvest in early-July with flowering in late August and early October maturity. Figures 2 and 3 show expected crop productivity and water use for these summer oilseed crops. These spring and summer oilseed crops provide opportunities to shift irrigation applications among fields throughout the growing season (Klocke et al., 2006). Aiken and Lamm (2006) discussed crop development stages and yield sensitivities to water deficits for these crops.

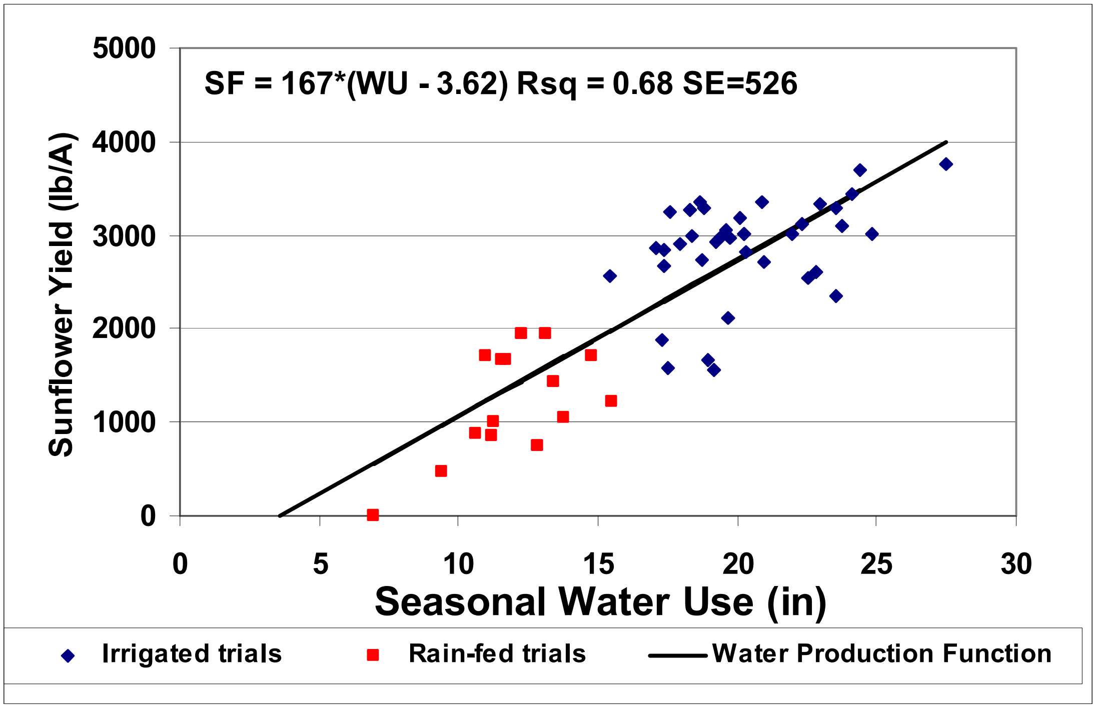

Figure 3. Expected oilseed yields and crop water use of sunflower are derived from Colby, KS trials.

WATER PRODUCTION FUNCTIONS

Crop Water Use

Oilseed yield is expected to increase with water use, up to a maximum yield potential (Anastasi et al., 2010; Demir et al., 2006; Payero et al., 2005). The oilseed yield-water use relationships (Fig. 1 - 3) show that a certain amount of water use (i.e. intercept of line with water use axis) is required before oilseed yield is expected. This apparent 'yield threshold' (6.2" for spring canola, 6.1" for soybean and 3.6" for sunflower) indicates the amount of water use required before the first unit of yield is obtained. The magnitude of this yield threshold can vary, to some extent, depending on early season soil water evaporation, prevailing humidity conditions and water used in vegetative growth. The rate of yield increase, relative to increased water use (slope of the yield response line), represents a measure of water productivity (175.2 lb/A-in for spring canola, 218.7 lb/A-in for soybean and 167.0 lb/A-in for sunflower). This factor is affected by inherent crop productivity, growing conditions (particularly amounts of sunshine and effects of atmospheric temperature and humidity) and harvest index (the fraction of biomass represented by economic yield). These water productivity functions have been developed from experimental data (e.g. Colby, KS, Tribune, KS, Akron, CO, North Platte, NE). The similarity in predicted yield responses to water use indicates applicability throughout the region.

Crop Water Productivity

A comparison of water productivity functions (Figure 4) for spring canola, soybean and sunflower (corn is also shown, for comparison) indicates the apparent yield threshold is least for sunflower, but largest for soybean (among oilseed crops). In contrast, the marginal water productivity (yield increase per additional unit of water use beyond the yield threshold) is largest for soybean and least for sunflower; water productivity for spring canola is intermediate. The inherent productivity of corn exceeds that of oilseed crops. Suyker and Verma (2010) reported that corn had 50% greater assimilation, 100% greater biomass productivity than soybean. Figure 4 indicates that relative corn productivity can exceed this rate. This difference is primarily due to the greater inherent

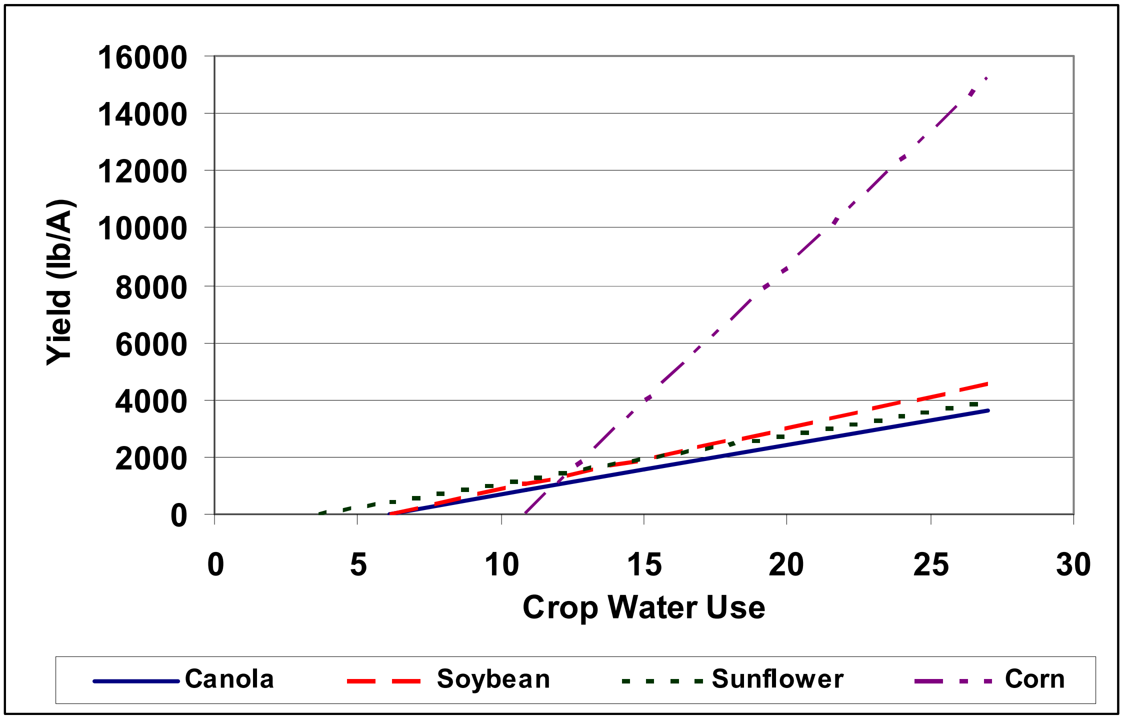

Figure 4. Crop water production functions for spring canola, soybean, sunflower and corn. The crop water production for corn was taken from Stone (2003); those for oilseeds are presented in Figures 1-3.

productivity[1] of warm-season grasses as well as the larger energy content of oilseeds, which require greater use of assimilates[2]. However, when oilseed yields are converted to a glucose equivalent, the water productivity of sunflower (~180 lb/A-in) is similar to that of cool-season crops (e.g. wheat, ~300 lb/A-in), which also rely on C3 physiology (Grassini et al., 2009). Further, the yield thresholds of oilseed crops appear to be less than that of corn; and the harvest price of oilseeds are typically greater than that of corn. As a result oilseeds may provide greater economic returns to water use than other crops at intermediate levels of irrigation.

An upper limit to water productivity of oilseed crops is likely constrained by the characteristics of C3 physiology and the large assimilation requirements for oil or protein biosynthesis. Crop water productivity may approach this upper limit when 1) irrigation is delayed (minimizing evaporation from soil surface) when available soil water is sufficient for vigorous canopy expansion to intercept radiation and increase the crop transpiration fraction of ET; 2) harvest index approaches the maximum potential; and 3) growing conditions are optimal, with minimal pest damage.

IMPROVING CROP WATER PRODUCTIVITY

Increase Transpiration Fraction

Delaying initial irrigation can reduce evaporation from the soil surface prior to canopy closure (Conner et al., 1985) and increase the crop transpiration fraction of ET. Specht et al. (1989) reported soybean yields equivalent to scheduled irrigation when irrigation was delayed to flowering or mid-pod stages. A similar response was reported by Lamm (1989a) with greater or equal soybean yields occurring with reduced irrigation during the vegetative period. However, maintaining sufficient soil moisture for vigorous canopy formation may require irrigation prior to canopy closure. Rapid canopy formation is vital to productivity as conversion of sunlight into biomass requires light interception by a healthy crop canopy (Albrizio and Steduto, 2005; Suyker and Verma, 2010).

Soybean and sunflower crops appear to differ in response to soil water deficits. Soybean exhibited tolerance of soil drying by maintaining non-stress photosynthetic rates when available soil water was 47% of full water-holding capacity (Wang et al., 2006). Also, soybean reduced crop transpiration by 67% under these deficit conditions. In contrast, sunflower maintained crop water use near non-stress rates when available soil water was 40% of water-holding

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[1] Plants with C4 physiology characteristically have greater CO_2-fixing efficiency than plants with C3 physiology--due to Kranz anatomy and PEP carboxylase which permit sequestration of the Rubisco enzyme in bundle sheath cells where O_2 concentrations are typically maintained at less than 2%.

[2] The fraction of a sugar molecule which results in oil (33%) or protein (40%) is substantially less than that for starch (83%); see Tanner and Sinclair (1983), p. 13.

capacity (Casadebaig et al, 2008). Also, sunflower reduced leaf expansion rates when available soil water was 60% of full capacity, indicating sunflower producivitity declines under water deficits while water use continues at rates near the expected maximum. These results indicate a potential advantage to soybean--maintaining productivity while reducing transpiration under vegetative water deficits. Lamm (1989b) demonstrated increased water productivity for soybean by reducing irrigation during vegetative development.

Spring oilseed crops such as spring canola avoid evaporative losses, as crop canopy is established under cool conditions with modest evaporative demand. Water productivity can be increased by minimizing evaporative losses from soil by delaying initial irrigation, seeking rapid canopy closure, or planting a early spring oilseed which forms canopy under conditions of low evaporative demand.

Managing Harvest Index

Increasing harvest index (the fraction of biomass represented by economic yield) can improve crop water productivity. Establishing yield potential involves components of yield (plant population, potential seeds per plant[3], actual seeds per plant and seed mass). Vega et al. (2001) showed that seeds per plant increased with plant growth rate during seed set for soybean and sunflower. The indeterminate growth of soybean permitted branching and continued flowering, for continued increase in seeds per plant for plants with large growth rates. In contrast, the rate of seed set for sunflower was smaller at the greatest growth rates, compared to rate of seed set at intermediate growth rates due to limits in the potential number of seeds per head. It follows that yield formation in sunflower is more sensitive to sub-optimal populations than indeterminant crops such as soybean. Likewise, the indeterminant spring oilseed crops, such as canola, should be able to compensate for low population with increased branching and flowering.

Maintaining vigorous growth during floral development and seed set is critical for all grain crops, but can depend on weather conditions as well as crop management. Grassini et al., (2009) found that harvest index in sunflower was reduced under cloudy or hot conditions (low photothermal quotient, ratio of photosynthetically-active radiation to temperature) during the flowering period. Andrade (1995) reported that soybean yield formation was most sensitive to water deficits during seed fill, while sunflower yield was sensitive to water deficits during flowering and seed fill stages; canola exhibits yield sensitivity during flowering and seed fill (Champolivier and Merrien, 1996; Istanbulluoglu et al., 2010). Increased harvest index can be favored by planting optimal populations, selecting appropriate planting dates, varieties or hybrids, and avoiding water deficits for vigorous growth during floral development and seed fill.

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[3] Components of yield for indeterminant crops, such as soybean and canola, include pods per plant and seeds per pod. Determinant crops, such as sunflower, typically have seeds arranged in a single head.

Genetic Advance

Genetic gain in crop water productivity may result from restricted transpiration, crop tolerance of soil water deficits and increased harvest index. Hufstetler et al., (2008) compared adapted soybean lines with non-adapted accessions; adapted lines had greater crop water productivity and lower transpiration rates at night than accessions. Lines also differed in sensitivity of transpiration to soil water deficit thresholds and in recovery upon re-wetting. Sinclair et al. (2000) screened 3,000 soybean lines and identified eight with substantial tolerance of N2 fixation to soil drying. This trait could enhance the growth response of soybean to a delayed irrigation strategy (see Increase Transpiration Fraction, above). Developing varietals and hybrids which maintain crop productivity and yield formation under water deficits and environmental stress can increase crop water productivity.

SUMMARY

Seasonal crop growth, in relation to crop water use, is known as a crop water productivity function; typically, these consist of a yield threshold (water use prior to expected economic yield) and a yield response (rate of yield increase per unit water use). Field studies in the U.S. central High Plains indicate sunflower has least yield threshold as well as least yield response; soybean has greatest yield threshold as well as greatest yield response. An upper limit to oilseed crop water productivity is primarily set by characteristics of the C3 physiology, which governs CO2 fixation by oilseed crops, and the large energy requirements for oil and protein biosynthesis. An adaptive management strategy can help growers achieve the maximum crop water productivity expected for oilseed crops. Components of this strategy include selecting crops and managing vegetative water supply to minimize the evaporative component of ET during vegetative growth, selecting seeding rates, planting dates and water management to ensure vigorous growth during flowering and seed-fill growth stages, and developing varieties and hybrids which tolerate water deficits to maximize harvest index.

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YIELDS AND ET OF DEFICIT TO FULLY IRRIGATED CANOLA AND CAMELINA

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BACKGROUND

In the past few years, many areas of Nebraska faced reduced irrigation amounts due to drought, low reservoir supplies or ground water allocations. The production of biofuel crops will compete for acres and irrigation water if there is an economic incentive to increase production. Nebraska is a large producer of ethanol from corn with 35% of the crop being used for biofuel in the state. This does not include the 26% of the crop that is exported and from which ethanol is also produced (http://www.nebraskacorn.org/main-navigation/corn-production-uses/use-stats/). The western portion of the Central Great Plains is defined as the northern High Plains region and has lower rainfall, sandier soils and higher elevation than the eastern portion. Biofuel crops that use less water and are adapted to the northern High Plains include canola, brown mustard, camelina, safflower, and sunflower. Oil-seed crops represent a good alternative for areas with limited water (Pavlista *et al*., 2011a). Due to their higher oil content, canola and camelina can produce over 110 gallons of oil per acre versus soybean that can produce 60 gal/ac (CAST, 2008). There is some information on water use for canola (Nielsen,1997), but the yield potential for canola and camelina under a range of soil, climatic and irrigation management regimes and the associated water use was needed. Spring planting of brown mustard, canola and camelina is viable in western NE (Pavlista*, et al*., 2011b). Growth curves for these crops in this region are currently being developed.

Deficit irrigation applies less water than is required to meet full ET. The goal is to manage irrigation timing such that the resulting water stress has less of a negative impact on grain yield. Previous NE research on limited irrigation (Garrity et al., 1982; Hergert et al, 1993; Klocke, et al., 1989; Maurer et al., 1979; Schneekloth et al., 1991) has looked at a range of crops but not canola and camelina.

Currently, a program for managing limited irrigation water (***Water Optimizer***), enables producers to evaluate what crops to grow, how many acres to irrigate and how much water to apply during a given year, field by field. However, this program did not include potential biofuel crops and deficit irrigation. Over a four-year period (2007-2010), University of Nebraska researchers, with funding from the USDA Risk Management Agency, conducted research to develop additional capabilities in ***Water Optimizer*** to expand its application to other crops and geographic areas. The focus of this report is to present results related to irrigation and water use production functions that will provide additional management tools for predicting spring- planted camelina and canola yields under limited and full irrigation for western NE.

METHODS AND MATERIALS

Camelina (cv. Cheyenne) and Canola (cv. Hyola 357 RR) were planted under linear irrigation systems at the Panhandle Research and Extension Center, Scottsbluff, NE (SB) and the High Plains Ag Lab, Sidney, NE (HP). Canola was planted under a center pivot irrigation system on the Dan Laursen Farm, near Alliance, NE (AL). Camelina and canola were planted at rates of 3 and 5 pounds per acre (pure live seed), respectively. Soils were: Scottsbluff (Tripp very fine sandy loam, pH 8.1, 1.2% OM, root zone water holding capacity (5 ft) ~ 6 to 7 in); Alliance (Creighton fine sandy loam, pH 7.3, 1.8% OM, root zone water holding capacity (5 ft) ~ 5 to 6 in); and Sidney (Keith silt loam, pH 6.8, 2.4% OM, root zone water holding capacity (6 ft) ~ 9 to 11 in.).

Management and cultural practices for experimental plots were adapted from limited tillage/limited irrigation cropping systems and/or relevant research findings, including planting requirements, fertilization recommendations, herbicide/insecticide applications, and harvesting. Roundup®-ready canola was used. Plots were routinely scouted during the summer for insect problems. Helix seed treatment was required for canola to protect against flea beetle but no other insects were a problem. Because of the crop rotation there were no major insect problems in the other crops. During the wetter years of 2009 and 2010, there was a downy mildew problem on both canola and camelina that was treated with fungicide.

Cumulative irrigation treatments had targeted amounts of 0, 4, 8 and 12 inches of water; however, if insufficient soil moisture or soil crusting was present, all treatments received light irrigations (0.25 inches) to enhance and ensure uniform seed germination and plant emergence. Treatments were replicated three times in a randomized complete block design and applied to subplots within main plots of each crop. Irrigation was based on estimated crop use and/or critical growth stages.

Rain gauges were placed within plot areas to accurately record irrigation and rainfall amounts. Soil water content from 0-6 inches was determined gravimetrically, while water contents at soil depths of 1, 2, 3, 4 and 5 feet were determined from neutron probe measurements.

Cumulative water use (evapotranspiration) was calculated from the water balance equation. These calculations assume negligible rainfall and irrigation loss by deep percolation and runoff. However, observed runoff losses, resulting from significant/intense rainfall events, were estimated from differences in neutron probe readings taken prior to and after such events.

RESULTS AND DISCUSSION

Irrigation/seed yield production functions

Rainfall at the different sites was drastically different over the four years (Table 1). This provided an excellent range of conditions from drought to above average precipitation to develop production functions.

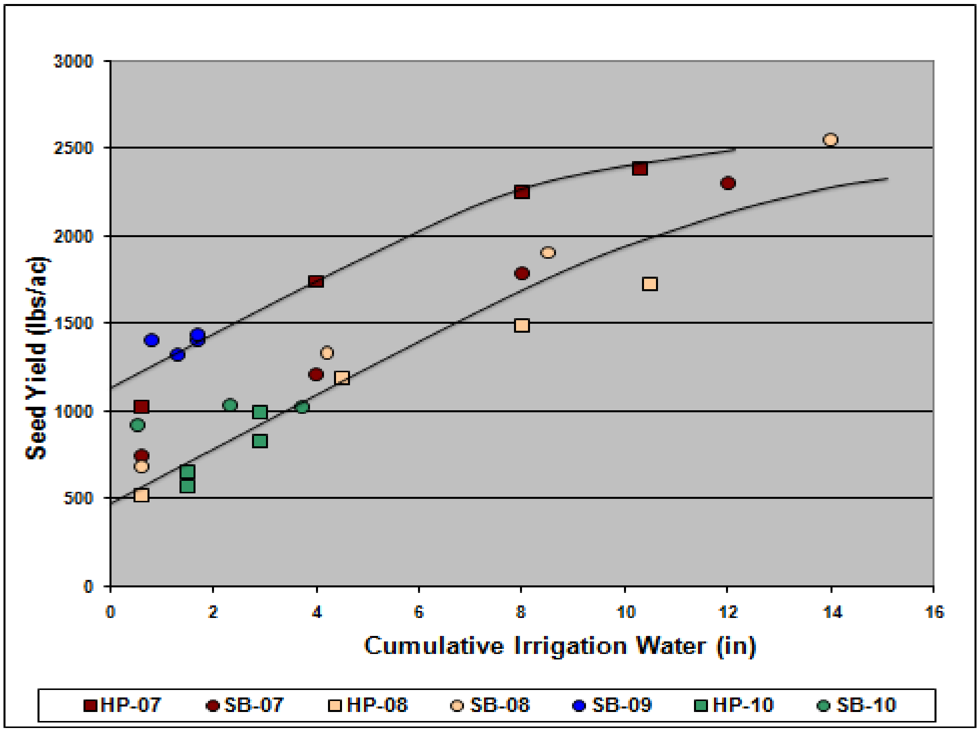
Table 1. Growing season precipitation (mid-April to harvest).

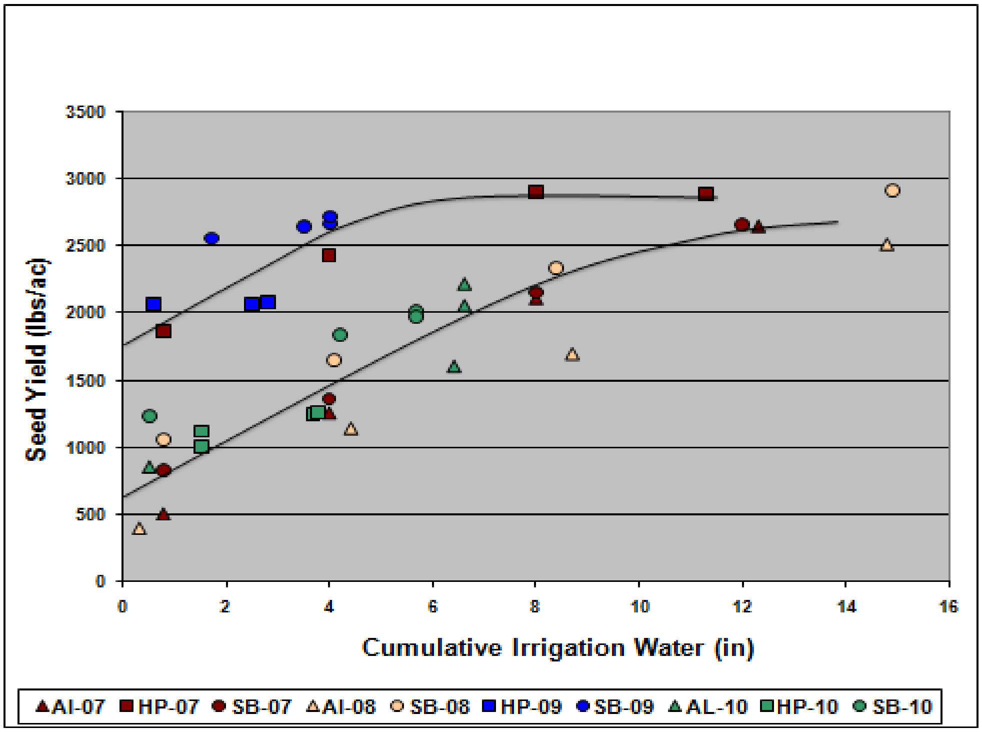
Location	2007	2008	2009	2010	30 yr avg.
	------------------------------inches------------------------------				
Alliance	5.7	6.6	---*	6.4	8.3
Scottsbluff	2.6	5.3	12.4	9.3	8.0
Sidney	10.5	7.5	15.1	9.6	8.6

*lost to hail.

Irrigation versus seed yield production functions for camelina and canola are depicted in Figures 1 and 2, respectively. Data for Sidney camelina (2009) and canola (2008) are not reported due to significant crop losses from downy mildew (*Peronosporaceae*) and adverse harvesting conditions, respectively. Data for Alliance canola (2009) is not reported due to severe crop loss from hail. Seed yield for both camelina (Fig.1) and canola (Fig. 2) increased curvilinearly in response to increases in cumulative irrigation. The data suggest that at least two (2) functions can be fitted to the data, herein referred to as upper and lower production functions. In general, for both crops, location years associated with the upper production functions are characterized by relatively high amounts of precipitation and/or stored soil moisture during the growing season whereas years associated with the lower production functions are characterized by relatively low precipitation and/or stored soil moisture.

Seed yields for the upper and lower camelina production functions increased linearly, at the rate of 150-160 pounds per acre per inch of irrigation, until cumulative irrigation amounts of approximately 8 to 10 inches were applied, respectively. Thereafter, the respective functions predict incremental seed yield increases of 50 to 70 and 80 to 100 pounds per acre for each additional inch of irrigation. Maximum seed yields of 2390 and 2560 pounds per acre were produced at the respective maximums of cumulative irrigation water for each function.


3000
2500
2000
1500
1000
500
0
Seed Yield (lbs/ac)
0
2
4
6
8
10
12
14
16
Cumulative Irrigation Water (in)
HP-07
SB-07
HP-08
SB-08
SB-09
HP-10
SB-10


3500
3000
2500
2000
1500
1000
500
0
Seed Yield (lbs/ac)
0
2
4
6
8
10
12
14
16
Cumulative Irrigation Water (in)
AI-07
HP-07
SB-07
AI-08
SB-08
HP-09
SB-09
AL-10
HP-10
SB-10

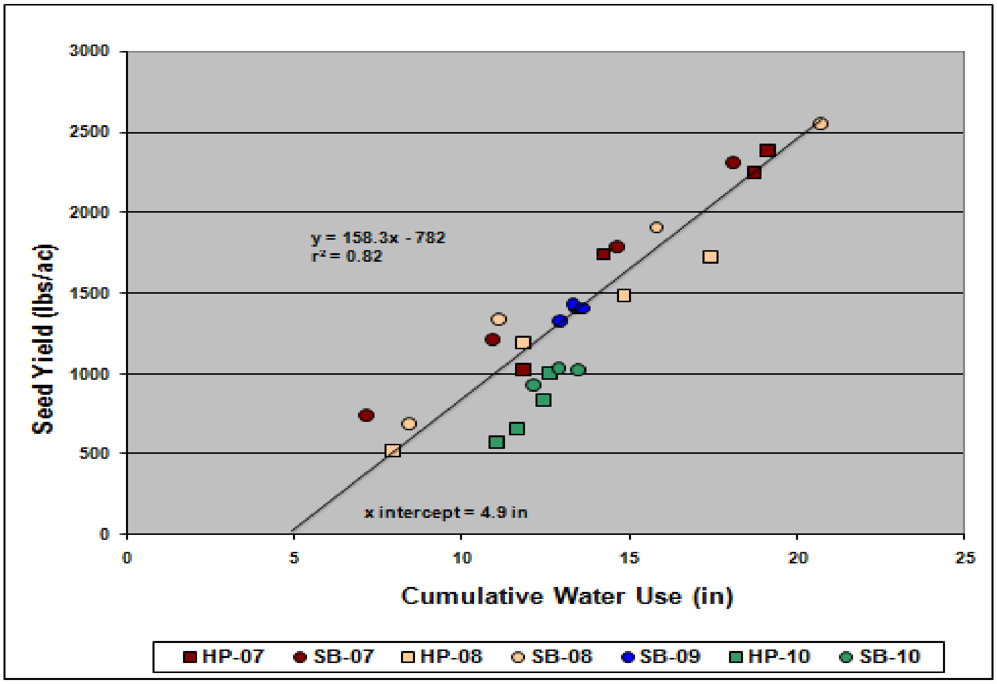
Data for both camelina functions exhibit “plateaus” in seed yield at or near the respective maximums of cumulative irrigation water. These “plateaus” are significant since they represent the cumulative irrigation water required to meet full evapotranspiration crop demand. Based on water use data (Figure 3) and phenology data (not shown), these “plateaus” correspond to a total water use of 18 to 20 inches when stored soil water, rainfall and irrigation are considered.

Seed yields for the upper and lower canola functions increased linearly, at the rate of 200 to 220 pounds per acre per inch of irrigation, until cumulative irrigation amounts of 4 and 8 inches were applied, respectively. Thereafter, corresponding incremental seed yield increases of 20 to 30 and 80 to 100 pounds per acre for each additional inch of irrigation are predicted. Maximum seed yields of 2900 and 2930 pounds per acre were produced at the respective maximums of cumulative irrigation water for each function.

As with camelina, “plateaus” exhibited by both canola production functions indicate that full evapotranspiration crop demand was attained at or near the respective maximums of cumulative irrigation water. Figure 4 shows these “plateaus” correspond to a total water use of 20 to 22 inches when stored soil water, rainfall and irrigation are considered.

Water Use/Seed Yield Production Functions

Figures 3 and 4 present water use versus seed yield functions for camelina and canola, respectively. Each function is described by a linear regression, the slope and x-intercept corresponds to a water use efficiency and threshold water use value.



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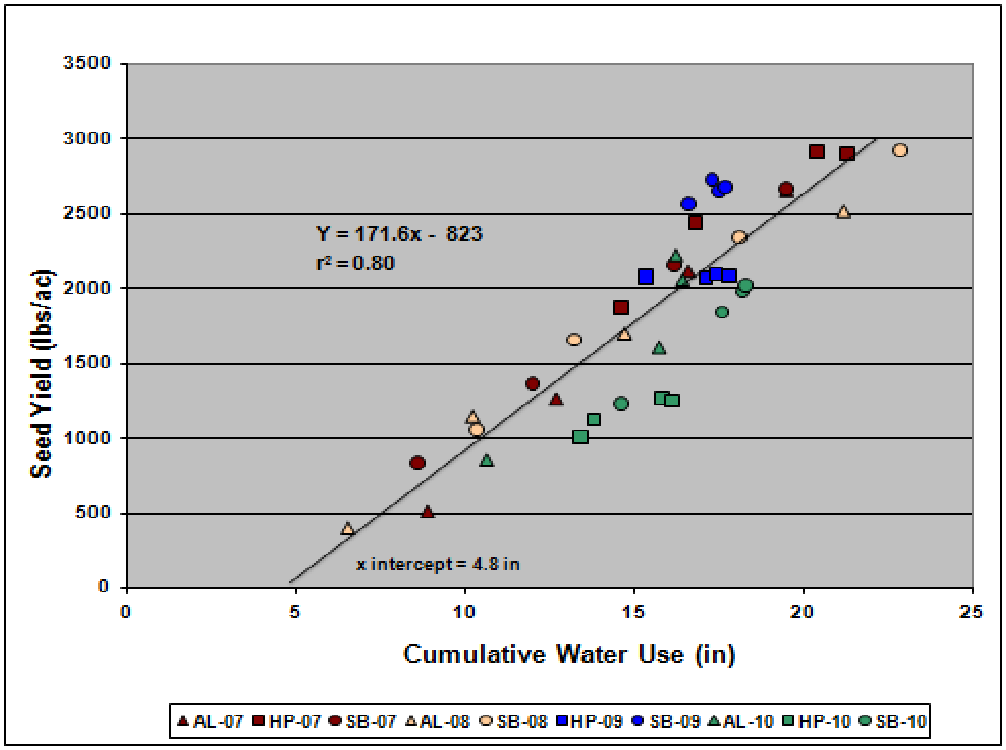


The water use/seed yield production functions for camelina and canola predict water use efficiencies of 158 and 172 pounds of seed for each inch of cumulative water use, respectively. In addition, the corresponding production functions predict threshold water use values of 4.8 and 4.9 inches or, in other words, approximately 5 inches of cumulative water would be required for any production of camelina or canola seed.

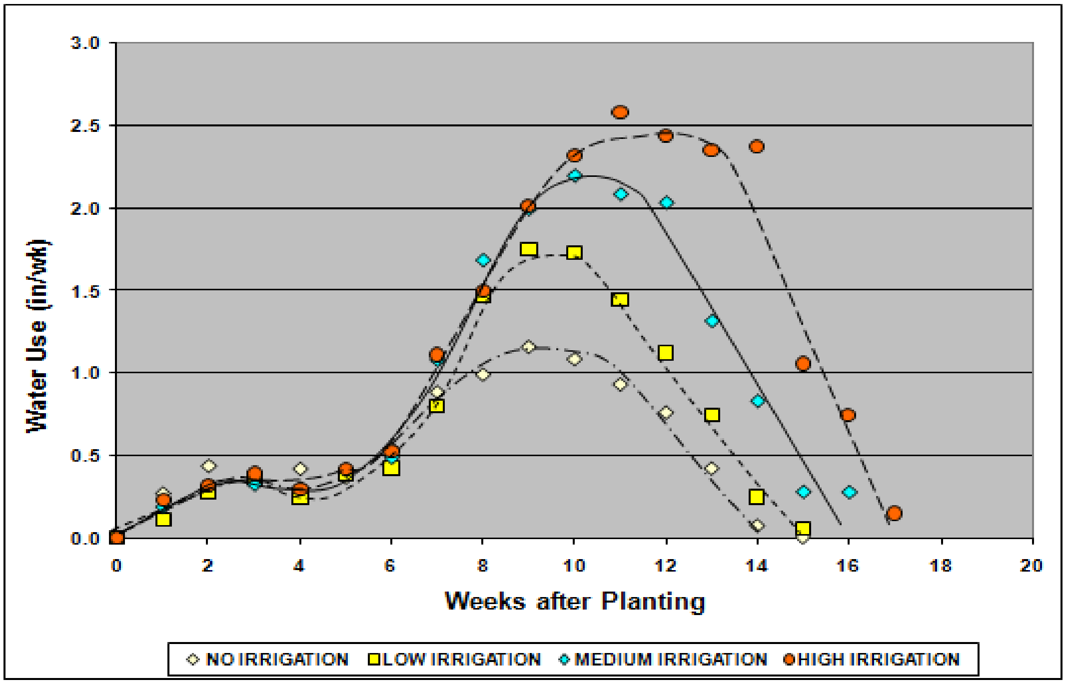
Camelina seed yields ranged from 520 to 2560 pounds per acre with 8.1 and 20.7 inches of cumulative water use, respectively. On the other hand, canola seed yields ranged from 400 to 2930 pounds per acre with 6.5 and 22.9 inches of cumulative water use, respectively.

Nielsen (1997) reported a water use/seed yield production function for canola that predicted a threshold water use of 6.2 inches and a water use efficiency of 175 pounds of seed per acre for each inch of water use. These reported values were based on soil moisture contents to a depth of 65 inches and a maximum water use of 20.5 inches.

Growing Season Water Use

The effect of the different irrigation levels was highlighted well for both canola and camelina during the 2008 (very dry) season. Figure 5 shows the effect of different irrigation levels on the extent and duration of crop ET as affected by water stress for camelina. The true dryland treatments advanced through flowering and seed fill more rapidly than well-watered treatments (data not shown) and the maximum water use varied considerably as did the time period of high water use. Maximum water use approached values for corn during the hot and dry conditions of 2008. Maturities were significantly different due to water effects.

In contrast, 2009 was an above average rainfall year and there was no significant difference between any of the irrigation levels for water use, crop development, maturity and yield (Figure 6). Disease did limit yields even though fungicide was applied to control downy mildew. Weekly water use was maximized near 1.7 inches per weeks versus a higher value in a dry year.



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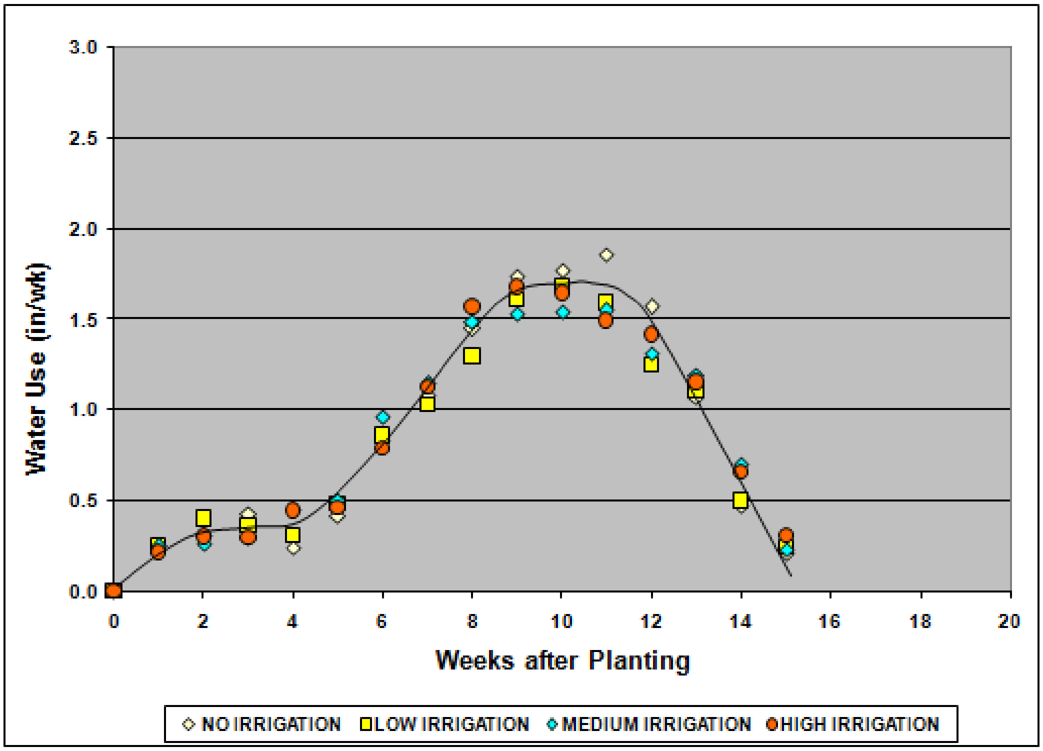

Conclusions

Camelina seed yields produced typical curvilinear responses to increasing irrigation. In drier years the full irrigation requirement ranged from 11 to 13 inches whereas 6 to 8 inches of irrigation produced optimum yields in wetter years. Maximum ET for fully irrigated camelina in dry years approached 2.4 inches per week for a total water use of 18-20 inches, when stored soil water, rainfall and irrigation are considered. Maximum seed yields of 2300 to 2500 lbs/ac are attainable with current cultivars. Non-irrigated yields ranged from 500 to 1200 lbs/acre. Soil water was extracted from at least 4 feet. Canola has a higher yield potential than camelina with maximum seed yields of 2900 to 3000 pounds per acre. This is likely a result of more years of genetic improvement in canola versus camelina. Non-irrigated yields ranged from 700 to 1900 lbs/acre. In drier years the full irrigation requirement ranged from 11 to 13 inches whereas 6 to 8 inches of irrigation produced optimum yields in wetter years. Maximum ET was similar to camelina, however, canola showed soil moisture extraction to at least the 5 foot level. Both crops required a minimum of 5 inches of ET to produce the first pound of seed. Our research did not show major differences in drought tolerance or water productivity (172 vs. 160 lbs/inch for canola vs.

camelina.) Both crops need sufficient soil moisture for germination and stand establishment. Stress during the reproductive stage can significantly reduce yield. Data suggest that spring camelina and canola would be suitable crops for biofuel production with limited water supplies in the northern High Plains.

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