PROCEEDINGS OF THE 2012 CENTRAL PLAINS IRRIGATION CONFERENCE

February, 21-22, 2012, Colby Kansas

TABLE OF CONTENTS

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N. Thompson, Colby, Kansas

KANSAS IRRIGATION TRENDS

Danny H. Rogers
Professor and Extension Agricultural Engineer
Kansas State Research and Extension
Department of Biological and Agricultural Engineering
Manhattan, Kansas
Voice: 785-532-2933 Fax: 785-532-5825
Email: drogers@ksu.edu

Freddie R. Lamm
Professor and Research Agricultural Engineer
Kansas State Research and Extension
Northwest Research and Extension Center
Colby, Kansas
Voice: 785-462-6281 Email: flamm@ksu.edu

INTRODUCTION

Initial irrigation practices in Kansas emerged around 1650 in a Taos Indian village in what is currently the Scott County State Park. The “modern” era of irrigation began in the 1880’s with the organization of irrigation ditch companies which built diversion works and canal systems along the Ark River (Erhart, 1969). Following World War II, Kansas irrigation rapidly expanded due to political/societal will, technology and readily available energy (Figure 1). The1945 Water Appropriation Act, which provides the basis of current Kansas water law, was designed to encourage the development of water resources. The development of the Hugoton natural gas well field and improved irrigation well drilling and pumping equipment following WWII contributed to the rapid increase in the irrigated area of Kansas, particularly over the Ogallala Aquifer.

IRRIGATION TRENDS

Irrigation System Type

Irrigation system types have evolved from primarily surface flood irrigation to predominately sprinkler irrigation (Figure 2). In 1970, approximately 18 percent of the 1.8 million irrigated acres were sprinkler irrigated. In 1989, there was a change in the water use reporting procedures (i.e., change from total authorized area to the actual area being irrigated within the given year) and this is responsible for the abrupt change in total irrigated area in that year.

The rapid increase of an irrigated land area (approximately 1 million acres) during the 1970's was a result of the adoption of center pivot irrigation. By 1990, approximately 50% of the total area used center pivot sprinkler irrigation and that percentage has increased to nearly 92% today, though the total irrigated area has remained relatively stable at approximately 3 million acres.

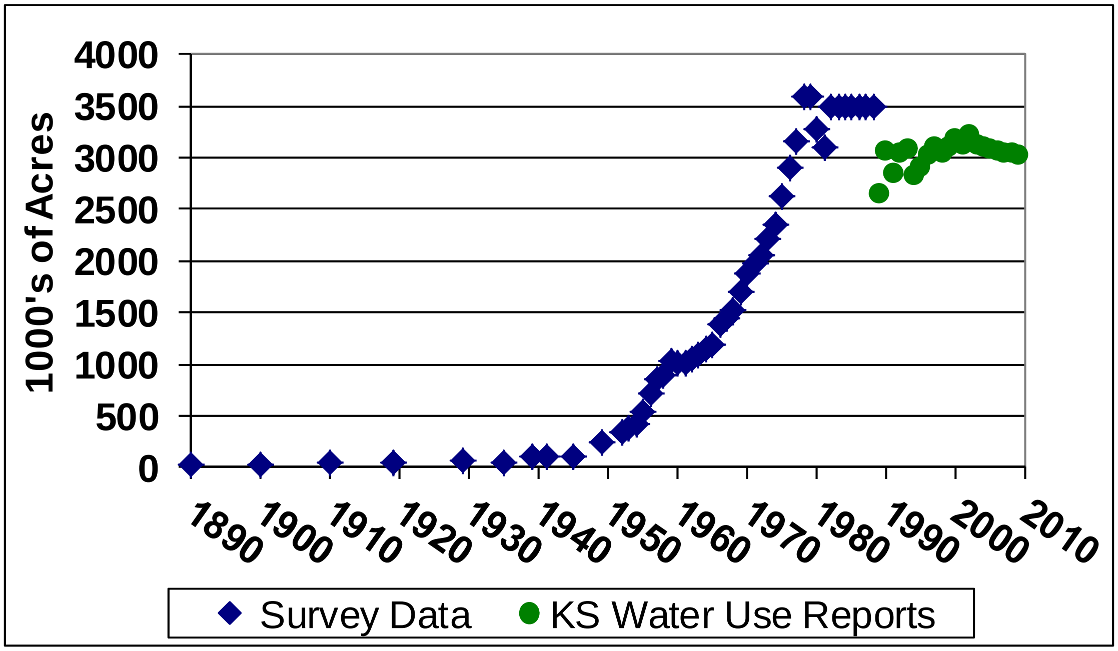


Figure 1. Progression of irrigated land area through time for Kansas. Early estimates are based on various surveys. Since 1989, the actual irrigated land area has been reported on annual water use reports submitted to the Kansas Department of Agriculture.

In 1989, subsurface drip irrigation (SDI) research plots were developed at the Northwest Research and Extension Center of K-State in Colby, Kansas (Lamm and Trooien, 2003). Surveys for SDI systems began in 1992 with an initial estimate of the existing systems of approximately 5,000 acres (Figure 3) and small, steady increases for each year thereafter. Concerns with the accuracy of these estimates led to a review of the annual water use reports in 2003, resulting in SDI estimates of just over 14,000 acres. In 2004, the DWR/KWO Annual Water Use Report began reporting SDI land area and systems combining multiple irrigation system types (i.e., in this case, SDI systems and another system type). A typical example would be SDI being used in the corners of a field irrigated with center pivot sprinkler system. In 2008 and 2009, SDI data include both SDI and SDI combo acres. SDI systems continue to be installed in Kansas but still represent less than 1 percent of the total irrigated land area.

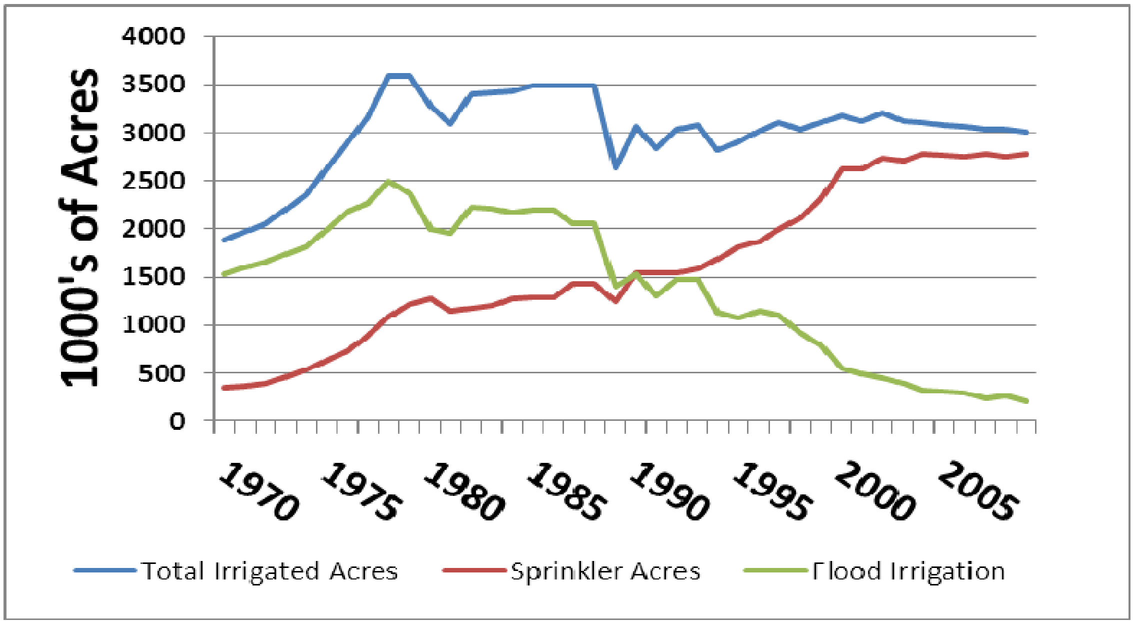


Figure 2. Progression of total irrigated land area, sprinkler systems, and flood Irrigation system Kansas.

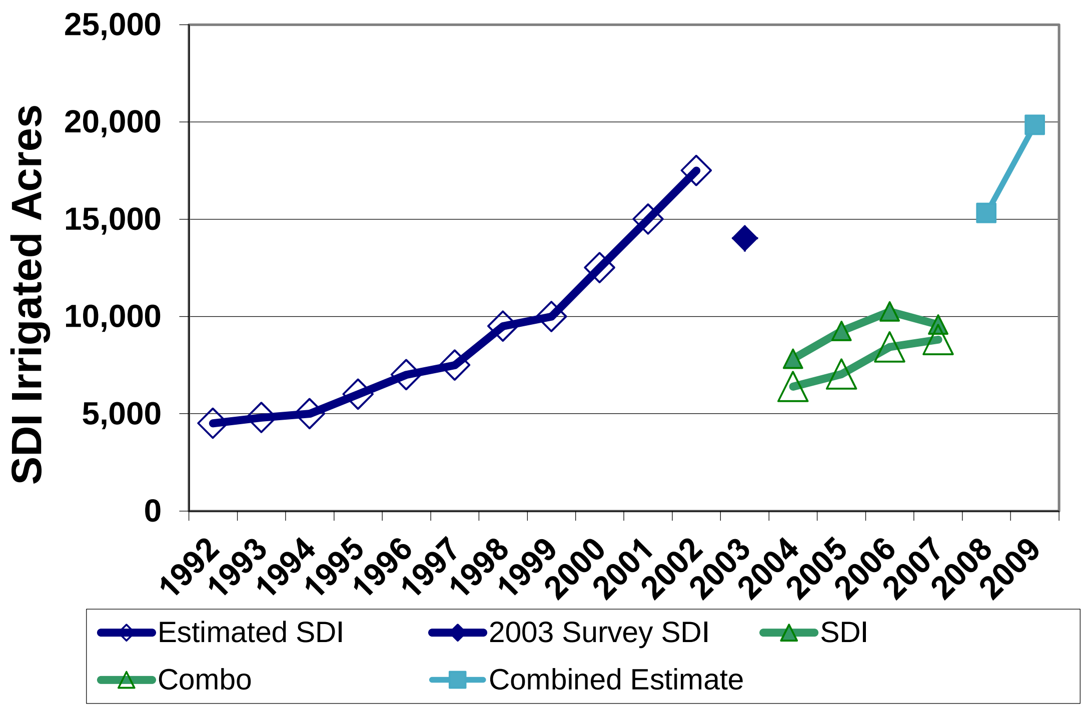


Figure 3. Increase in subsurface drip irrigation systems in Kansas. The abrupt changes in SDI area are due to survey and reporting methods and not due to abandonment of SDI systems. SDI has been increasing steadily in Kansas.

Irrigated Crops

Corn is currently produced on nearly 50% of the irrigated land in Kansas (Figure 4) with a peak land area of about 1.7 million acres in 1999 (Note: data beyond 2008 is not yet available). The area in corn production trended downward during the droughty and low crop price years of the early 2000's, but has rebounded beginning in 2005.

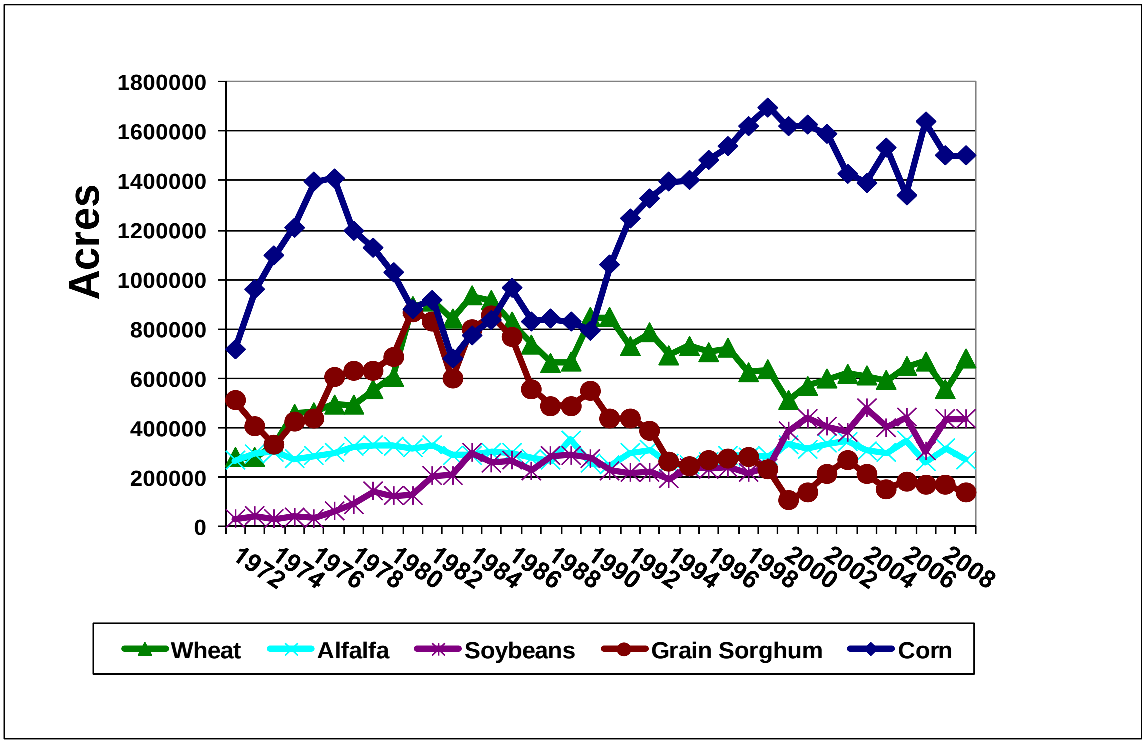


Figure 4. Irrigated area devoted to the five major irrigated crops in Kansas.

Irrigation Water Use

The total amount of annual water diversions and also the amount of water pumped on a given land area has decreased over time (Figure 5) although there are annual fluctuations caused by differences in precipitation and crop water use needs. For example, the 1990's were relatively wet years, while the early 2000's were extremely dry. Crop year 1993 was one of the highest rainfall years on record, while 2002 was one of the lowest and this is reflected in the corresponding valley and peak in water use, respectively (Note: Drought year 2011 data is not available at this time). Part of the rationale for the decrease in water use may be more accurate reporting, but the conversion of flood irrigated land to center pivot sprinklers was also rapid during this time period, changing from roughly 50 percent to 90 percent center pivot sprinkler irrigated land. When appropriately managed, center pivot sprinkler systems typically have greater application efficiency than surface flood irrigation systems.

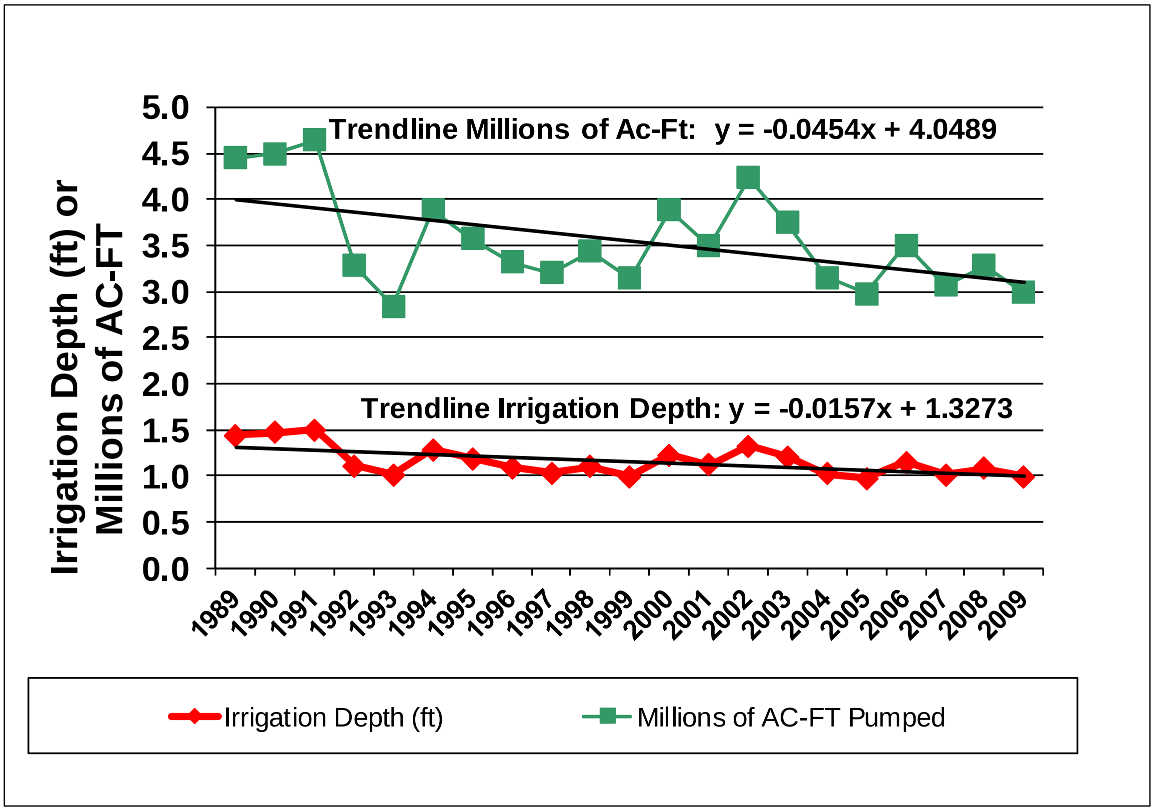


Figure 5. Total irrigation water diverted and average application depth by year for Kansas.

Reduced total water diversion can also be attributed to the continuing decline of water table levels and the subsequent decrease in well yield, and to the shifting of tillage practices (i.e., reduced and no-till tillage systems). Reduced tillage also enhances precipitation capture and reduces soil water losses that are caused by disturbance of the soil surface layers. Greater residue also reduces early-season soil evaporation losses. Increase pumping costs and the adoption of improved irrigation management practices, such as irrigation scheduling, also contribute to less overall water diversions.

Application depth varies (Figure 6) considerably across Kansas (Region 1, 2, and 3 represent the western, middle, and eastern one-third of the state respectively). Since, the majority of the irrigated acres are located in Region 1 and because it has the largest net irrigation requirements, the state total and Region 1 values are very similar.

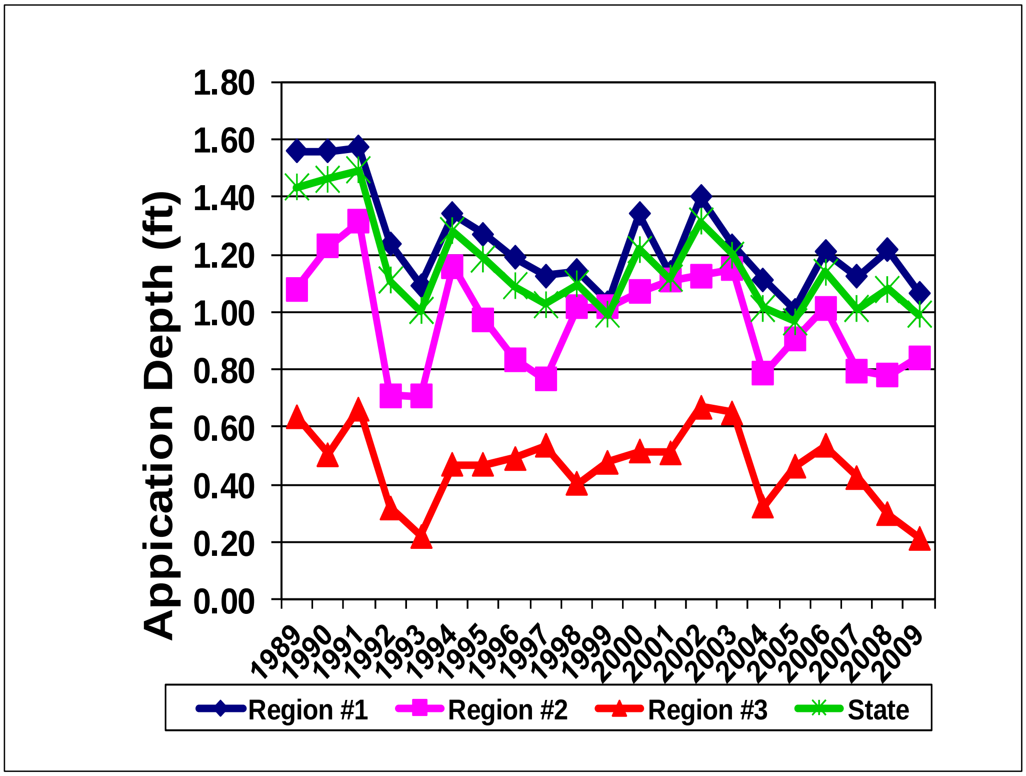


Figure 6. Regional average irrigation application depths by year for Kansas

Crop Yield

The four major grain crops grown in Kansas (corn, soybean, grain sorghum and wheat) have experienced upward trends in yield (Figures 7 – 10). Corn yield has had the most dramatic increase for both irrigated and dryland production with irrigated corn yield improvements of approximately 2.5 bushels/acre for the each year of record, This result is more than twice the dryland rate of 1.1 bushels/acre. The average irrigated yield increase is 0.59 bu/ac, 0.60 bu/ac and 0.31 bu/ac for soybean, grain sorghum and wheat respectfully. Irrigated yield increase trends have been larger than for dryland.

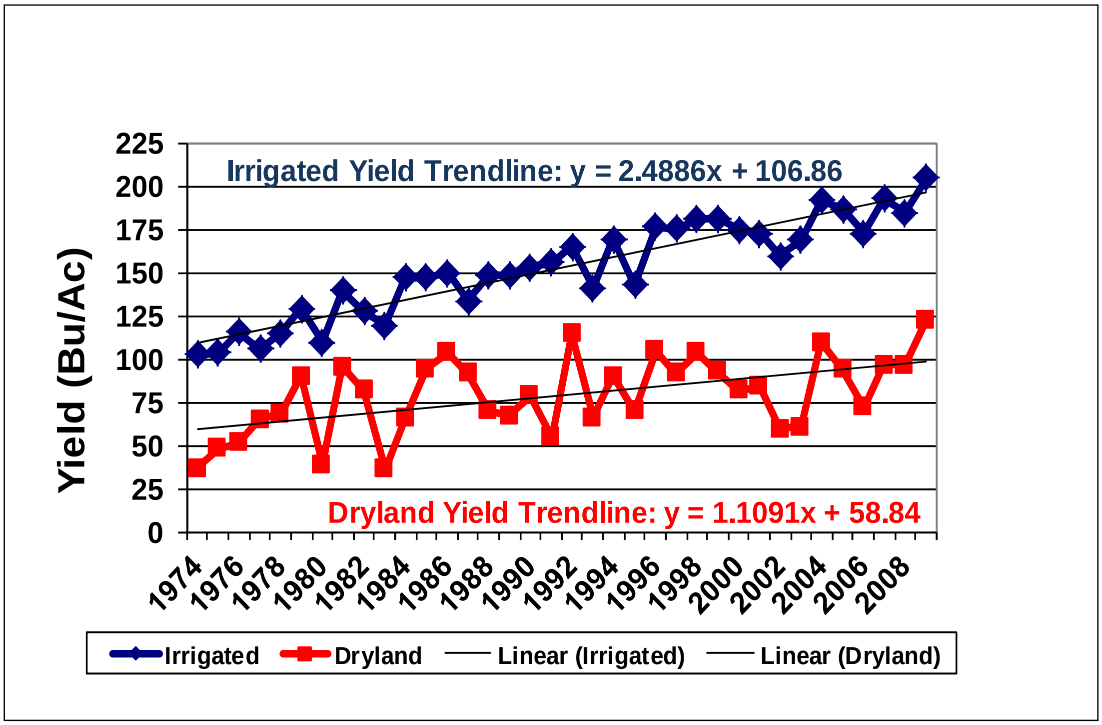


Figure 7. Kansas corn yield trends since 1974 (KDA Kansas Farm Facts).

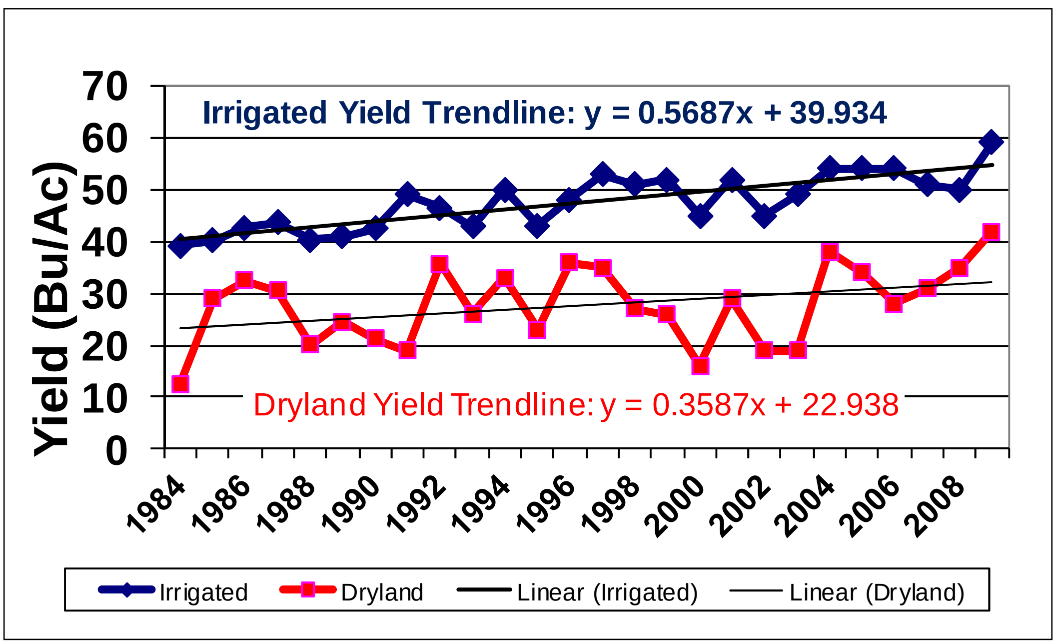


Figure 8. Kansas soybean yield trends since 1984 (KDA Kansas Farm Facts).

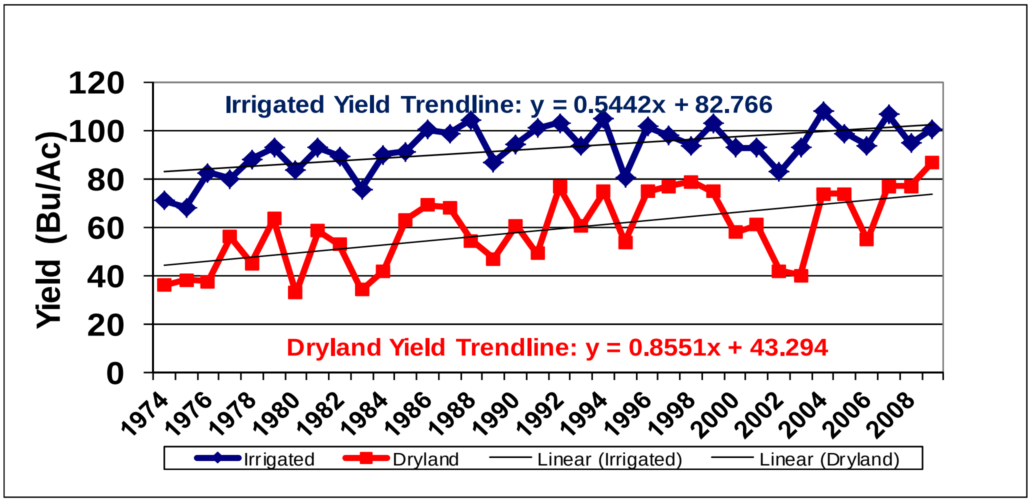


Figure 9. Kansas grain sorghum yield trends since 1974 (KDA Kansas Farm Facts).

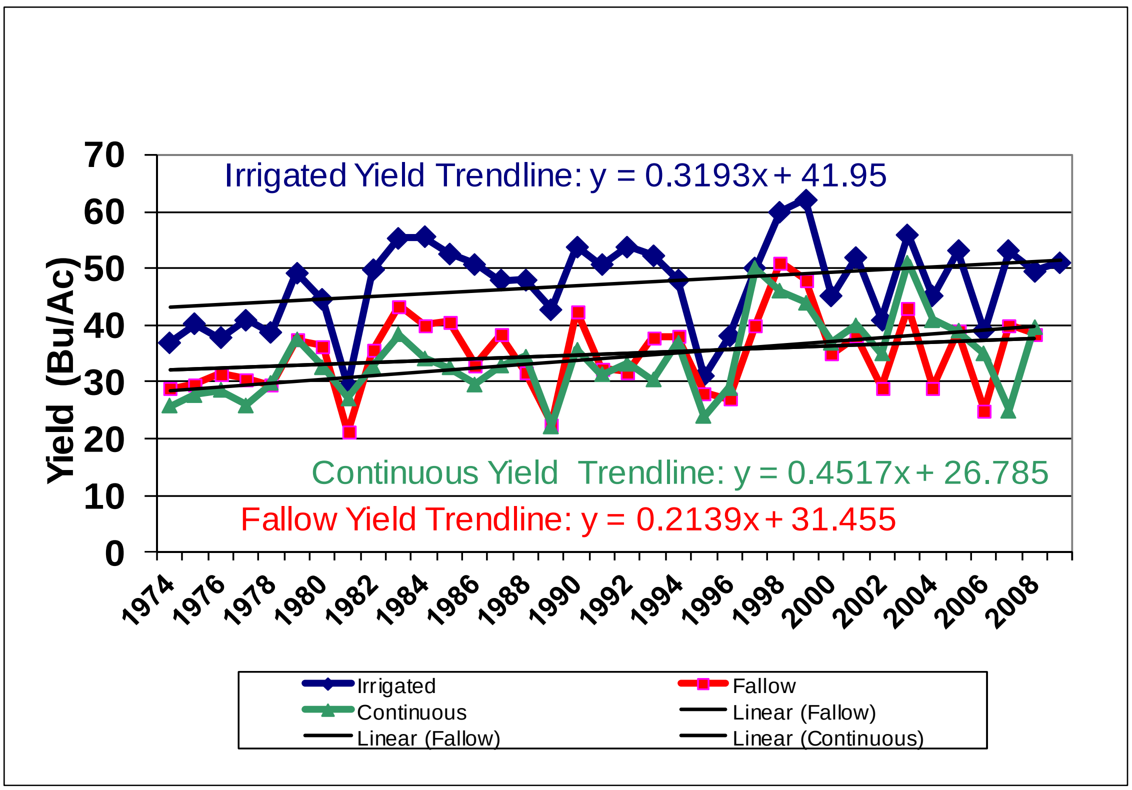


Figure 10. Kansas wheat yield trends since 1974 (KDA Kansas Farm Facts).

IRRIGATION WATER USE EFFICIENCY

Irrigation water use efficiency (IWUE) has sometimes been defined as the yield of a crop divided by the amount of irrigation water applied. Because yield has increased over time (Figures 7 -10) and the average application depth has been trending downward (Figure 6), IWUE has been increasing. Southwest Kansas yield, irrigation application, and IWUE for corn are shown in Figure 11. IWUE has increased by 0.16 bushels/inch for each year of record, although there is considerable year-to-year variability.

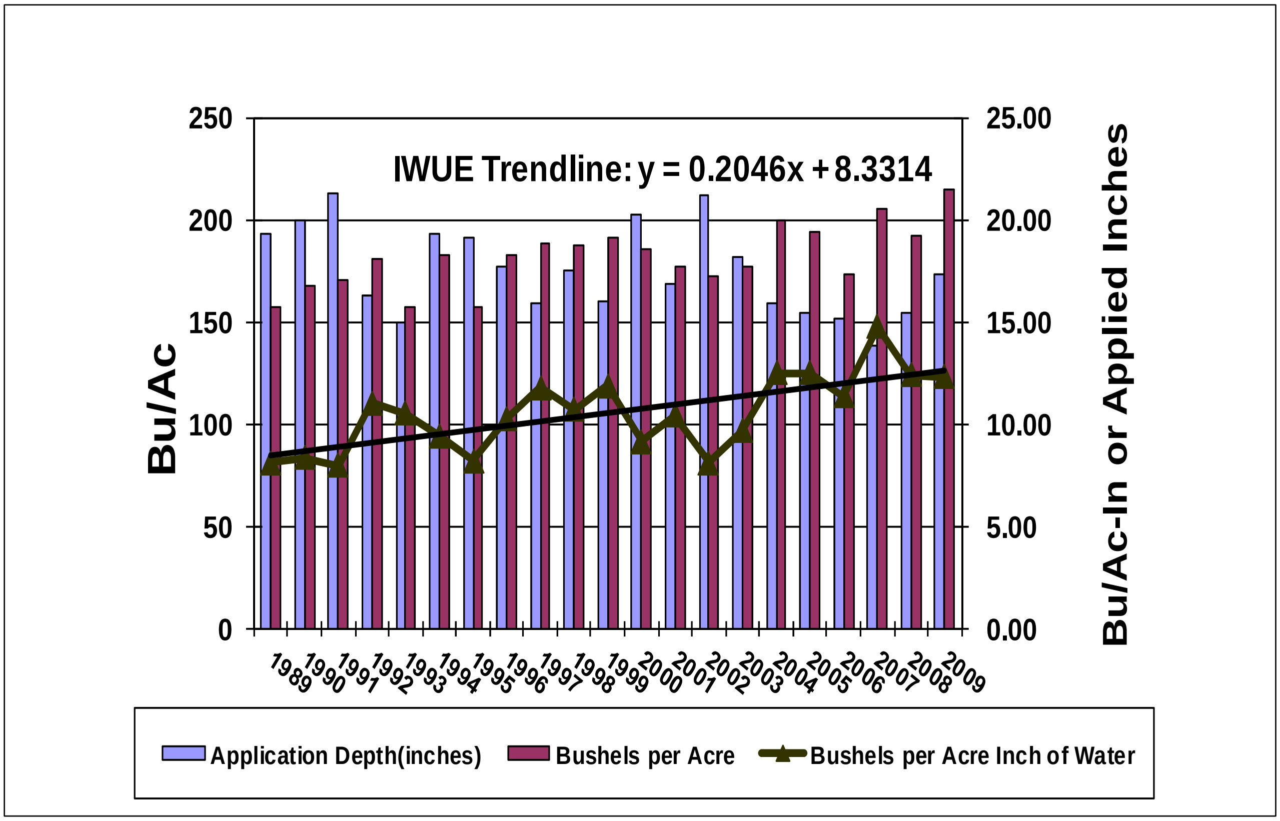


Figure 11. Corn yield, irrigation application depth, and irrigation water use efficiency trends for Southwest Kansas.

KANSAS IRRIGATION ENERGY

The four major energy sources for pumping irrigation water in Kansas are natural gas, electricity, diesel and propane (LP) with natural gas being the most common energy source (Figure 12). The use of electricity has been increasing since the mid 1990s (Figure 12) partially because its costs compared to the other sources has become more competitive (Figure 13).

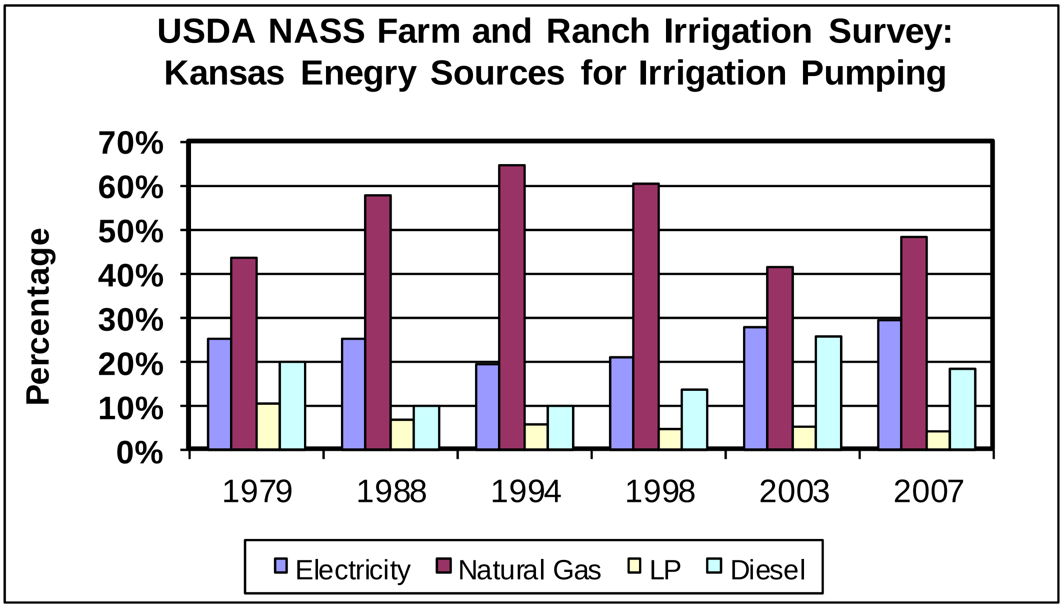


Figure 12. Kansas irrigation pumping plant energy source (USDA NASS Farm and Ranch Irrigation Survey).

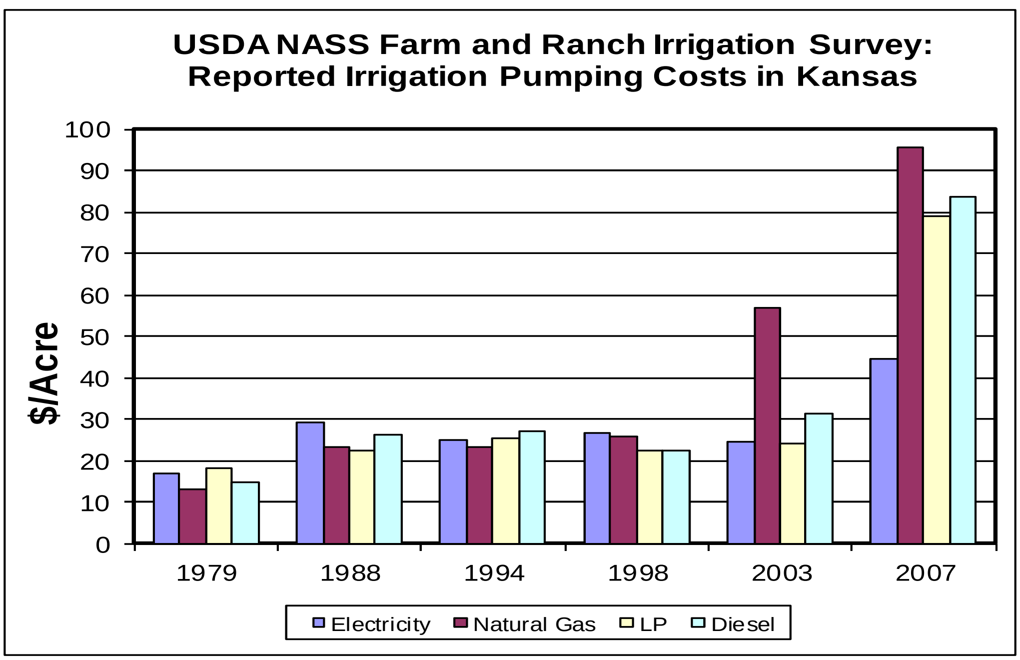


Figure 13. Kansas irrigation pumping costs by energy source (USDA NASS Farm and Ranch Irrigation Survey).

IRRIGATION ECONOMIC IMPACT

According to the 2007 Census of Agriculture (USDA, NASS), the First Congressional District of Kansas ranked as the leading Congressional district in the U.S. for the market value of agricultural products sold (total sales). All of western Kansas and much of the irrigated region in South Central Kansas are part of this Congressional district. Approximately 15 percent of Kansas' cropland area harvested each year is irrigated but contributes about 30 percent of the total value of crops produced (Figure 14 and Table 1). Kansas irrigated land area and irrigation water usage for three selected years, 1993 (wet year), 2000 (normal year), and 2002 (dry year) are shown in Table 1. The area irrigated is relatively stable as compared to the value of production share produced by irrigation. In general, a higher percentage from irrigation is associated with dry conditions resulting in loss of dryland yield productivity.

The total crop value is dependent on both the yield and crop price. Table 2 shows total production, value, and price for the major crops of Kansas in 2000 and 2009. On a percentage basis, irrigated agriculture for Western Kansas produced about 25 percent of the total Kansas crop value in both years, even though the value of total production was nearly twice as high in 2009 as compared to 2000.

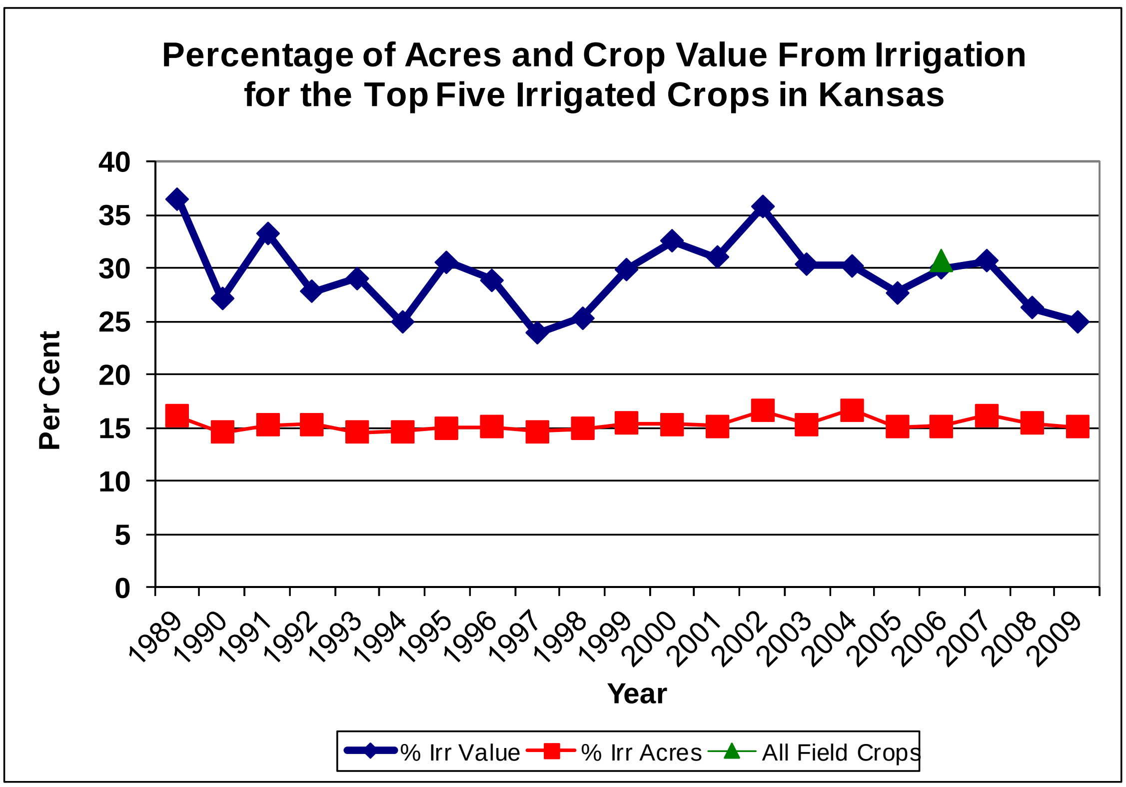


Figure 14: Kansas irrigation percentage of cropland harvested acres and total crop value for the five major crops.

Table 1. Selected example years of Kansas cropland, irrigated acreage, and irrigation water use (Kansas Farm Facts and DWR/KWO Kansas Irrigation Water Use Report).

Year	Total Cropland (Harvested) Acres	Total Irrigated Acres	Irrigation Percentage of Total Cropland	Irrigation Water Use (Acre-Ft)
1993	20,454,400	2,841,000	13.9%	2,828,973
2000	21,656,900	3,183,983	14.7%	3,885,805
2002	20,230,400	3,211,859	15.9%	4,228,410

Table 2. Irrigated crop production and value for Kansas in 2000 and 2009 (Kansas Farm Facts).

Crop	Production (million bu)		Farm value (billions $)		Crop price	
	2000	2009	2000	2009	2000	2009
Alfalfa	1.45**	0.96**	0.1414	0.1041	$97/ton	$108/ton
Wheat	19.9	28.5	0.0681	0.1382	$3.42/bu	$4.85/bu
Grain Sorghum	16.5	13.6	0.0393	0.0434	$2.38/bu	$3.19/bu
Corn	233.0	310.0	0.5778	1.1166	$2.48/bu	$3.60/bu
Soybean	17.0	25.6	0.0935	0.2368	$5.49/bu	$9.25/bu
Total farm value			0.9202	1.639		
Total farm value of all Kansas crops			3.6233	6.5430		
Irrigation percentage of total farm value*			**25.4%**	**25.1%**		

* Irrigation values only include the three Western Kansas crop reporting districts.
** Alfalfa yields in millions of tons, all other crops in millions of bushels.

Kansas irrigation is concentrated primarily in the Ogallala region of Western Kansas, thus resulting in increased economic impact. Harvested cropland acres, crop value produced and the irrigation percentage for 2002 and 2009 is shown in Table 3 for western Kansas. As compared to 2009, dryland crop failures resulted in fewer harvested acres in 2002. Consequently, the percentage of acres harvested and crop value produced by irrigation was much higher. Table 3 also shows 2009 data for Southwest Kansas and demonstrates the high concentration of irrigated agriculture in the region since over 70 percent of the crop value produced came from irrigated acres. The impact of irrigation in a single county in Table 3 shows 2002 and 2007 county data for Haskell County in Southwest Kansas. In 2002, a dry year, almost 95 per cent of all crop value came from irrigated land, while in 2007 still over 80 percent of the crop value comes from irrigated agriculture. Haskell County is used as an example as the county has been part of several social/economic studies that were initiated in the early

1940's (Williams and Bloomquist, 1996). Six communities across the US were selected originally to study issues of social and economic instability. Williams and Bloomquist (1996) noted that irrigated agriculture had played a key role in providing the foundation of stability for the county.

Table 3. Western Kansas crop production statistics for wheat, grain sorghum, corn, soybeans, and alfalfa* (Kansas Farm Facts).

Location	Total of Irrigated and Dryland (1000s of acres)		Total Value of Irrigated and Dryland Production (1000s of $)		Irrigation Percentage of Total Area		Irrigation Percentage of Total Value	
	2002	2009	2002	2009	2002	2009	2002	2009
Western KS	5,372	6,899	905,163	2,333,500	36.7%	28.3%	70.2%	48.3%
Southwest KS	2,532	3,042	565,555	1,120733	53.5%	44.0%	85.8%	70.4%
	2000	**2007**	**2000**	**2007**	**2000**	**2007**	**2000**	**2007**
Haskell County	224.2	274	63,783	134,174	74.9%	62.0%	94.3%	81.6%
* Other crops not included are silage, sunflower, cotton, and dry beans.								

IRRIGATION WATER WITHDRAWAL IMPACT

While some areas of the Ogallala have substantial water in storage (Figure 16), many areas have been depleted to levels that make large scale irrigation no longer possible. Using a minimum threshold criterion of the aquifer being able to support a well with a 400 gpm pumping rate for a 90 day pumping season, some areas have been depleted and other areas have a projected lifespan of less than 25 years (Figure 17). New technologies and cropping systems have allowed producers to adapt to declining well yield associated with the declining aquifer water table, but the irrigated land area in Kansas will eventually decrease.

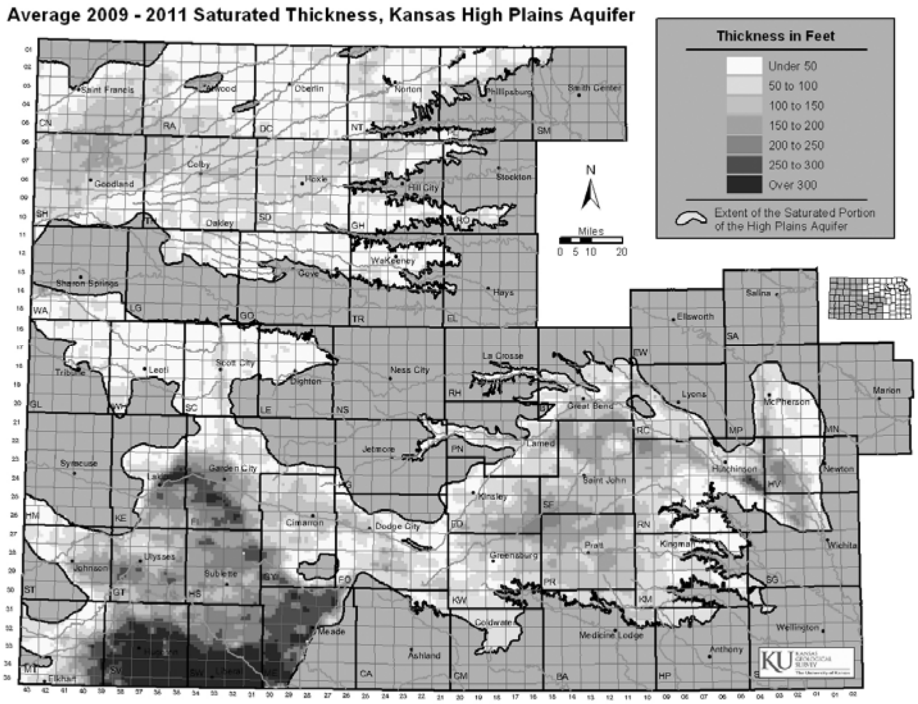


Figure 16. Average saturated thickness for the High Plains Aquifer in Kansas (Kansas Geological Survey, 2012).

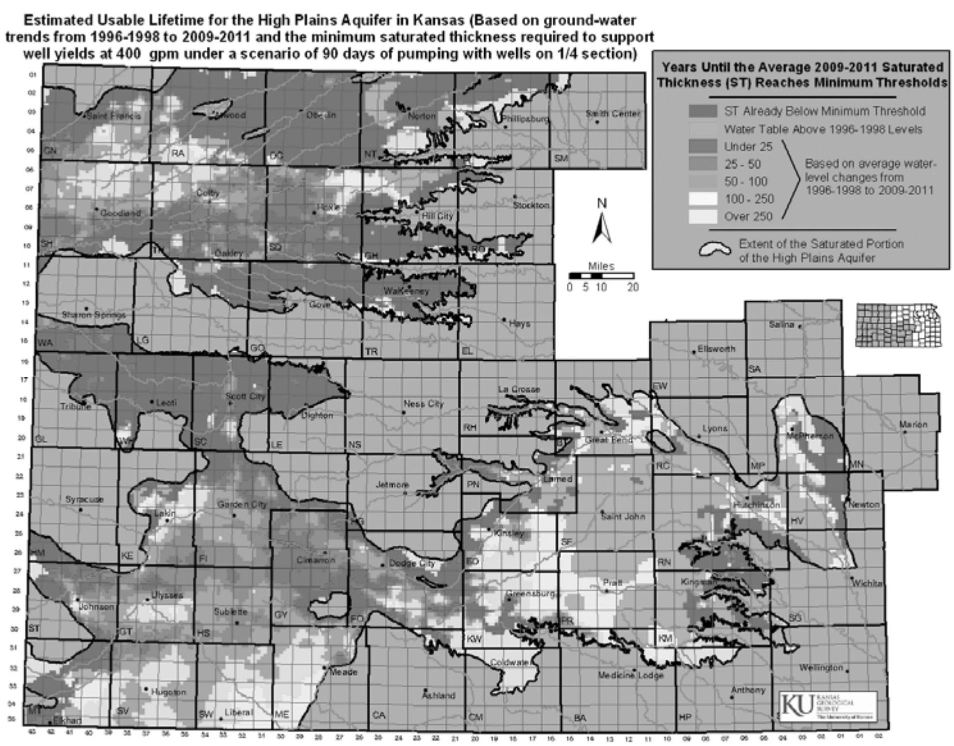


Figure 17. Estimated usable lifetime for the High Plains Aquifer in Kansas (Kansas Geological Survey, 2012)

SUMMARY

Irrigated agriculture initially developed using surface flood irrigation systems but has shifted to using center pivot irrigation systems. The land area irrigated has been relatively. Crop yield and irrigation water use efficiency have continued to improve even as average application depths have declined. Unfortunately, improvements in systems, irrigation management, and cultural practices have not been sufficient to overcome excess water withdrawals in many areas of the High Plains aquifer system, especially the Ogallala. The economic impact is considerable for the state of Kansas, in general, and is dramatic in areas of high irrigation concentration.

ACKNOWLEDGEMENTS

This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

Contribution no. 12-313-A from the Kansas Agricultural Experiment Station.

REFERENCES

Erhart, A. 1969. Early Kansas Irrigation. One of three article series, “A page out of Irrigation History”. Irrigation Age Magazine. Feb 1969. 4 pp.

Lamm, F. R. and T. P. Trooien. 2003. Subsurface drip irrigation for corn production: A review of 10 years of research in Kansas. Irrig. Sci. 22(3-4):195-200.

USDA NASS. Various Years. Kansas Farm Facts. In cooperation with Kansas Department of Agriculture.

Kansas Irrigation Water Use Report. Various Years. Prepared in cooperation by the Kansas Water Office and the KDA, Division of Water Resources.

Kansas Geological Service. 2012. Gray scale maps provided by request for conference proceedings.

Williams, D. D. and L. E. Bloomquist. 1996. From Dust Bowl to green circles: A case study of Haskell, County, Kansas. Bulletin 662. Kansas Ag. Expt. Station, Manhattan, Kansas. 44 pp.

This paper was first presented at the Central Plains Irrigation Conference, February 21-22, 2012, Colby, Kansas. It can be cited as

Rogers, D.H. and F.R. Lamm. 2012. Kansas irrigation trends. In: Proc. 24th annual Central Plains Irrigation Conference Feb. 21-22, 2012, Colby, Kansas. Available from CPIA, 760 N. Thompson, Colby, Kansas. pp. 1-15.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

TILLAGE PRACTICES IN KANSAS: 2010 SURVEY RESULTS

DeAnn Presley
Extension Specialist, Soil and Water Management
Department of Agronomy, Kansas State University
Manhattan, Kansas
Voice:785-532-1218   Fax: 785-532-6315
Email:deann@ksu.edu

INTRODUCTION

Between 1989 and 2004, crop tillage and residue management surveys were conducted on a county-level basis for all counties in Kansas (and in many other states) as part of the Conservation Technology Information Center's Crop Residue Management Survey (CTIC-CRM).

Since 2004, changing input prices (including fuel, fertilizer, equipment, etc.) are thought to have caused increases in reduced tillage practices, especially no-till. Anecdotal information from producers, extension agents, and other agricultural professionals suggest that no-till acreage has increased greatly in some counties (such as those in northeast and north central Kansas), and lagged behind in other counties (the south-central portion of Kansas is often mentioned).

Other than the 1989-2004 CTIC CRM survey data, there is no other comprehensive, current data source for this information. From 1989-2004 USDA-NRCS personnel completed these driving transects, however, neither the USDA-NRCS, USDA-Farm Service Agency, or the Kansas Agricultural Statistics Service collects this type of information. Therefore, there is no current source of information available to describe on a crop-by-crop, county-by-county, or state-wide basis, which tillage practices are being utilized by Kansas producers.

OBJECTIVE

To quantify tillage and residue management practices in Kansas on a crop-by crop, county-level basis through the use of driving transects for nine selected counties in Kansas.

METHODS

Kansas State University secured $10,000 in funds from SCC, and $20,000 from KDHE Clean Water Neighbor Grant. Twenty-two counties were selected, and each county was paid $750.00 to collect data. The counties were identified by targeting areas of interest in watersheds above Kanopolis, Tuttle, Perry, John Redmond, and Clinton Reservoirs(KDHE funds) while SCC funds were used to select for representative counties throughout the remainder of the state. Counties were selected carefully in order to capture information from counties that are predominantly cropland, and representative of the climate/soils/cropping systems that occur in a geographic area. Once the potential counties were selected, volunteers were recruited from among extension agents, Conservation District employees, WRAPS staff/volunteers, etc. Kansas State University Research and Extension Watershed Specialists also played a vital role in collecting data in their work areas, particularly due to their efficient use of tablet computers to collect the information in GIS-ready formats.

Volunteers were trained to collect the data, and completed driving tours of the selected counties in Fall 2009 (to observe the wheat crop) and spring 2010 (for row crops). Data was collected for a minimum of 460 fields in both the fall of 2009 (wheat) and spring of 2010 (row crops) and the tillage practice and crop was recorded for each point. Data was collected and compiled and presented in multiple formats, including tabular, spatial maps, and formats viewable in Google Earth. Calculations were made using the data points collected by the volunteers, and using 2010 Farm Services Agency data for planted acres in each county.

RESULTS

All data and outputs are posted on the KSU Agronomy Extension website at: http://www.agronomy.ksu.edu/extension/tillage The data available on the website and on the data CDs is presented in multiple formats. For example, for any given county, the user can observe the tillage practices observed for each crop, and we also added up the points observed for each tillage practice and divided by the total number of points observed, and reported as % acres for each tillage practice per county. In addition, we used the 2010 FSA acreage planted per county to extrapolate the % values into acres.

Data from Sherman County, Kansas is presented on the following pages. The data is presented separately for irrigated and dryland. Reduced tillage (15-30% residue) was the most common practice for most crops on the 119 irrigated fields surveyed, while conventional tillage (<15% residue) was the most common practice on dryland. For row crops, no-till was the most common tillage practice, while wheat was dominated by conventional tillage.

2010 Growing Season - Sherman County, Kansas
Irrigated Tillage by Land Cover Summary

	Number of Fields	Percent Tillage of Crop
CORN	**74**	
No Till	12	16.2%
Reduced Till	46	62.2%
Conventional Till	16	21.6%
FALLOW	**5**	
No Till	4	80.0%
Reduced Till	1	20.0%
GRAIN SORGHUM	**6**	
No Till	1	16.7%
Reduced Till	3	50.0%
Conventional Till	2	33.3%
SOYBEAN	**9**	
No Till	4	44.5%
Reduced Till	3	33.3%
Conventional Till	2	22.2%
SUNFLOWER	**12**	
No Till	3	25.0%
Reduced Till	5	41.7%
Conventional Till	3	25.0%
Strip Till	1	8.3%
WHEAT	**10**	
Reduced Till	5	50.0%
Conventional Till	5	50.0%
OTHER CROPS (Total)	**3**	
Dry Beans	**2**	
Reduced Till	1	50.0%
Conventional Till	1	50.0%
Oats	**1**	
Reduced Till	1	100.0%
TOTAL FIELDS	**119**	

2010 Growing Season - Sherman County, Kansas
Irrigated Tillage Summary

	Number of Fields	Percent of Tillage Fields
NO TILL (Greater than 30% Residue)	24	20.2%
REDUCED TILL (15-30% Residue)	65	54.6%
CONVENTIONAL TILL (Less than 15% Residue)	29	24.4%
OTHER METHODS (TOTAL)	1	0.8%
Continuous No Till	-	-
Burn	-	-
Mulch Till	-	-
Ridge Till	-	-
Strip Till	1	1%
TOTALTILLAGE FIELDS	**119**	

2010 Growing Season - Sherman County, Kansas
Dryland Tillage by Land Cover Summary

	Number of Fields	Percent Tillage of Crop
CORN	**37**	
No Till	30	81.1%
Reduced Till	6	16.2%
Conventional Till	1	2.7%
CRP	**19**	
Not Applicable	19	100.0%
FALLOW	**91**	
No Till	29	31.9%
Reduced Till	33	36.2%
Conventional Till	29	31.9%
GRAIN SORGHUM	**5**	
No Till	4	80.0%
Conventional Till	1	20.0%
PASTURE	**38**	
Not Applicable	38	100.0%
SOYBEAN	**1**	
No Till	1	100.0%
SUNFLOWER	**5**	
No Till	5	100.0%
WHEAT	**104**	
No Till	1	1.0%
Reduced Till	19	18.3%
Conventional Till	84	80.7%
OTHER (Total)	**2**	
Dry Beans	**1**	
Conventional Till	1	100.0%
Oats	**1**	
Conventional Till	1	100.0%
TOTAL FIELDS	**302**	

2010 Growing Season - Sherman County, Kansas
Dryland Tillage Summary

	Number of Fields	Percent of Tillage Fields
NO TILL (Greater than 30% Residue)	70	28.6%
REDUCED TILL (15-30% Residue)	58	23.7%
CONVENTIONAL TILL (Less than 15% Residue)	117	47.8%
OTHER METHODS (TOTAL)	-	-
Continuous No Till	-	-
Burn	-	-
Mulch Till	-	-
Ridge Till	-	-
Strip Till	-	-
TOTALTILLAGE FIELDS	**245**	

Proceedings of the 24st Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

Tillage and Crop Residue Removal Effects on Evaporation, Irrigation Requirements, and Yield

Simon J. van Donk
Assistant Professor, Biological Systems Engineering
University of Nebraska
West Central Research and Extension Center
North Platte, Nebraska
Voice: 308-696-6709 Fax: 308-696-6780
Email: svandonk2@unl.edu

Norman L. Klocke
Professor, Water Resources Engineering
Kansas State University
Southwest Research and Extension Center
Garden City, Kansas
Voice: 620-276-8286 Fax: 620-276-6028
Email: nklocke@ksu.edu

Irrigators in the western Great Plains and other irrigated regions face water restrictions caused by decreased well capacity, water allocations imposed by water policy, and/or rising energy costs. These growers require water management practices that optimize grain production. When not enough water is available to produce full yields, the goal for water management is to maximize transpiration and minimize nonessential water losses such evaporation of soil water.

It is generally believed that increasing crop residue levels leads to reduced evaporation. However, crop residue that is removed from the field after harvest is gaining value for use in livestock rations and bedding, and as a source of cellulose for ethanol production. It is important to know the water conservation value of crop residue so crop producers can evaluate whether to sell the residue or keep it on their fields.

Tillage also greatly affects the amount of residue on the soil surface. The effects of no-till and conventional tillage on soil and water dynamics are controversial. Producers have expressed concerns about production practices where high levels of crop residue are present on the soil surface. These concerns include the increased use of chemicals, and wetter soil and lower soil temperatures delaying planting and retarding plant development during early vegetative growth, and less uniform germination and emergence using planting equipment that cannot operate adequately in the residue.

However, in the semi-arid climate of the western Great Plains, vegetative growth of crops under no-till management can catch up to the growth of crops under tilled management by the reproductive growth stage. In the hot and dry summers of this environment, reduced soil temperatures and increased soil water under crop residue during and after the reproductive stage benefit the crop and outweigh the drawbacks experienced earlier in the cropping season.

INFILTRATION AND RUNOFF

Crop residue reduces the energy of water droplets impacting the soil surface and reduces the detachment of fine soil particles that tend to seal the surface, leading to crust formation. This sealing and crusting process can be enhanced by subsequent soil surface drying. It reduces infiltration and promotes runoff because precipitation or irrigation rates may be greater than the rates at which the soil is able to absorb water. Residue also increases surface storage of rain or irrigation water. In addition, it slows the velocity of runoff water across the soil surface, allowing more time for infiltration. University of Nebraska-Lincoln (UNL) researchers used a rainfall simulator at Sidney, Nebraska, to demonstrate differences in infiltration and runoff from no-till wheat stubble and plowed soils. In the experiment, 3.0 inches of water was applied, resulting in 1.7 inches of runoff on the plowed soil and only 0.2 inches on the no-till soil.

Standing residue helps to conserve water by causing snow to settle, rather than blow to field boundaries, by slowing the wind velocity just above the residue. Subsequent melting snow is more likely to infiltrate into the soil because the stubble slows runoff, enhancing soil water storage. This water can then be used for crop production in the subsequent growing season.

EVAPORATION OF WATER FROM THE SOIL

When the soil surface is wet from a recent irrigation or precipitation event, evaporation from bare soil will occur at a rate controlled by atmospheric demand (Figure 1). The evaporation rate decreases as the soil surface dries over time because water that is deeper in the soil is not transported to the surface quickly enough to maintain the rate of wet-soil evaporation; the drying surface soil starts to act as a barrier to water transport (Figure 1).

If the soil surface is covered with residue, it is shielded from solar radiation, and air movement just above the soil surface is reduced. This reduces the evaporation rate from a residue-covered surface compared to bare soil. Surface moisture under the residue will continue to evaporate slowly, but a number of days after the wetting event, the evaporation rate from the residue-covered surface can exceed that of the bare surface (Figure 1).

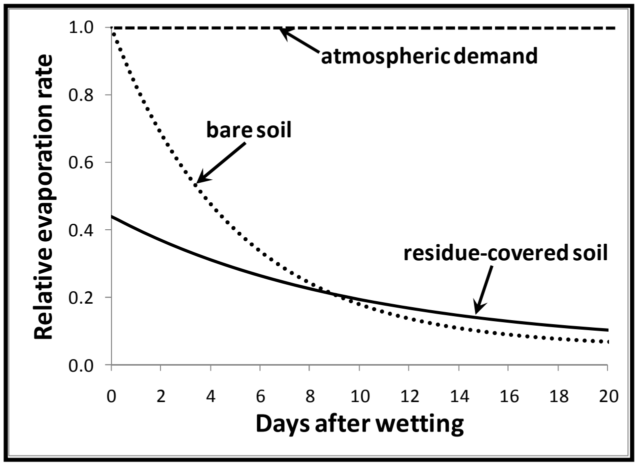


Figure 1. Evaporation rates, relative to atmospheric demand, from bare and residue-covered soil after a single wetting event (irrigation or rainfall) – conceptual diagram.

Eventually, after many days without rain or irrigation, the cumulative evaporation from the bare and residue-covered soils will be the same. In the conceptual diagram in Figure 1, this point has not yet been reached after 20 days. In reality, this point is seldom reached because more frequent wetting events result in more days with higher evaporation rates from bare soil than from residue-covered soil. The net effect over a season is that total evaporation is expected to be greater from bare soil.

Crop residue does not eliminate evaporation entirely. It still takes place from the crop canopy, the residue itself, and the soil every time they are wet. This loss is fairly constant for each wetting event, no matter how light or heavy the wetting event is. Therefore, light, frequent rains or irrigations are less effective than heavy, infrequent ones. Some center pivot irrigators experience runoff on tilled soils so they apply small amounts frequently, typically only 0.5 inches each time. Percent wise, the evaporation losses are relatively large when applying such small amounts. When adopting continuous no-till, a pivot can apply a greater amount of water before runoff occurs. With more water applied per event, but less often, the evaporation losses are reduced.

Also, when soils are tilled, they often dry to the depth of tillage. With multiple tillage events, soil water may not be adequate in the seed zone for uniform germination and emergence, resulting in lower yields, even though there may be sufficient soil water the rest of the year.

EXPERIMENTS AT GARDEN CITY, KANSAS

Field Study Under Corn Canopy

A study was conducted to find the effect of crop residue on soil water evaporation at Kansas State University's Research and Extension Center near Garden City, Kansas (Klocke et al., 2009). Soil water evaporation (E) was measured from a soil surface covered with no residue, corn stover, or wheat stubble under a corn canopy during the summers of 2004, 2005, and 2006. Mini-lysimeters**,** 12 inches in diameter and 5.5 inches deep were used for the E measurements. The mini-lysimeters were filled by pressing PVC cylinders into undisturbed crop residue and soil following corn or wheat harvest the previous year. E was determined daily by weighing the lysimeters. Weighing precision was ± 1 gram producing E measurements with a resolution of ± 0.00006 in/day. Surface residue cover in the mini-lysimeters was greater than 90% when they were placed in the field (Table 1).

Average daily E from June 12 through September 16 was significantly different among the surface cover treatments for all years (Table 1). Corn stover surface cover was more than wheat stubble cover in 2005 and 2006 which led to significantly less E from the corn stover. The trend in E was reversed in 2004, primarily because the wheat stubble amount (mass) was more that the corn stover amount. The crop residue decreased bare soil E by approximately 50%. Corn evapotranspiration (ETc) was different among the years, but the residue significantly reduced E/ETc. Even though there were differences in peak leaf area index (LAI) among years, E was nearly the same all years indicating that crop residue influenced E more than shading by the corn crop. For the entire measurement period between June 12 and September 16, there was about 3 inches more E from the bare soil compared to the residue-covered surfaces.

Table 1. Evaporation of water from soil shaded by a corn canopy at Garden City, Kansas.

	Residue Type	Surface Cover %	Residue Amount (tons/ac)	Avg E[1] (in/day)	ETc[2] (in/day)	E/ETc	Peak LAI[3]
2004	Bare	0	0	0.07 a[4]	0.21	0.37 a	4.4
	Corn	97	7.3	0.04 b	0.21	0.19 b	4.4
	Wheat	98	9.8	0.03 c	0.21	0.18 c	4.4
	$LSD_{.05}$			0.003		0.006	
2005	Bare	0	0	0.06 a	0.27	0.23 a	3.4
	Corn	100	9.5	0.03 c	0.27	0.12 c	3.4
	Wheat	91	6.3	0.04 b	0.27	0.14 b	3.4
2006	$LSD_{.05}$			0.002		0.01	
	Bare	0	0	0.06 a	0.22	0.30 a	3.7
	Corn	100	7.5	0.03 c	0.22	0.14 c	3.7
	Wheat	92	4.3	0.04 b	0.22	0.18 b	3.7
	$LSD_{.05}$			0.002		0.02	

[1] Average daily evaporation from June 12 through September 16.
[2] Average daily evapotranspiration of corn shading soil surface.
[3] Peak leaf area index (leaf upper surface area/ground surface area) of corn shading soil surface.
[4] Values in the same column for the same year followed by different letters are significantly different for p=0.05

Study with Partial Residue Cover and no Crop Canopy

Evaporation was measured with mini-lysimeters that had soil surfaces fully or partially covered with corn stover or wheat stubble with no crop canopy (Figure 2). This study was conducted at Kansas State University's Research and Extension Center near Garden City, Kansas (Klocke et al., 2009). High and low irrigation frequencies of wetting events were achieved by applying water either once or twice per week for six weeks. Translucent shelters on steel tracks were rolled over the mini-lysimeters to exclude rain when needed. Otherwise, shelters were rolled away from the mini-lysimeter installation and the mini-lysimeters were exposed to ambient weather.

High and low irrigation frequency caused more E from bare soil than soil with 100% residue cover, but the differences in E due to high and low irrigation frequency decreased as residue cover increased (Figure 2). Evaporation from bare soil was 48% more from high frequency than from low frequency irrigation. The regressions of E with respect to residue cover showed that E depended more on residue cover with high frequency than low frequency irrigations, as indicated by the differences in R^2 (0.80 for high frequency and 0.54 for low frequency).

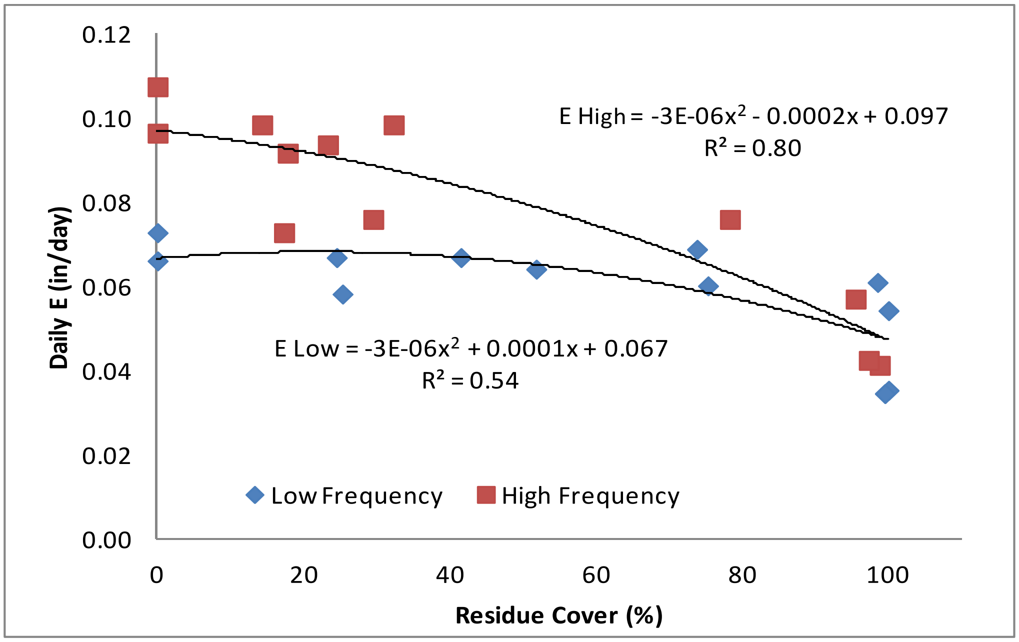


Figure 2. Daily soil water evaporation from soil surfaces that were partially to fully covered with corn stover or wheat stubble. Half of the mini-lysimeters were wetted once per week (low frequency). The other lysimeters were wetted twice per week (high frequency). There was no shading by a crop canopy.

FIELD EXPERIMENT AT NORTH PLATTE, NEBRASKA

A study was initiated in 2007 to find the effect of crop residue on evaporation, soil water content, and corn yield at the UNL West Central Research and Extension Center in North Platte, Nebraska (van Donk et al., 2010). The experiment was conducted on a Cozad silt loam soil with a set of plots planted to corn. There were two treatments: residue-covered soil and bare soil. In April 2007, bare-soil plots were created by using a dethatcher and subsequent hand-raking, removing most of the residue. Thus, the over-winter benefits of the residue were the same for both treatments. Residue removal was repeated the following three years (Table 2).

Table 2. Time table for planting corn and soybean crops and removing crop residue – field experiment at North Platte, Nebraska.

Year	Month	Event
2004	May	Plant corn
2005	May	Plant soybeans
2006	May	Plant soybeans
2007	April	Remove crop residue (mostly soybean residue) from four field plots
	May	Plant corn
2008	April	Remove crop residue (mostly corn residue) from four field plots
	May	Plant corn
2009	April	Remove crop residue (mostly corn residue) from four field plots
	May	Plant soybeans
2010	April	Remove crop residue (mostly soybean residue) from four field plots
	May	Plant soybeans

Crop residue was always removed from the same four field plots

The residue-covered plots were left undisturbed. The experiment consisted of eight plots (two treatments times four replications). Each plot was 40 by 40 ft. Winter and spring 2007 were very wet at North Platte and the corn was only irrigated three times with a total of 4.5 inches of water on all plots. The crop was purposely water-stressed, so that any water conservation in the residue-covered plots might translate into higher yields.

Differences in soil water content between the residue-covered and the bare-soil plots were small throughout the growing season. However, average corn yield was 197 bu/ac in the residue-covered plots and 172 bu/ac in the bare-soil plots (Figure 3, Table 3). An additional 3 inches of irrigation water on the bare-soil plots would be necessary to reach the same yield as obtained in the residue-covered plots.

In April 2008, residue was removed from the same four plots as in 2007. As in 2007, all plots were irrigated at the same time with the same amount of water, but the crop was again somewhat water-stressed. The average corn yield in 2008 was 186 bu/ac in the residue-covered plots and 169 bu/ac in the bare-soil plots (Table 3). It would take an additional 2 inches of irrigation water on the

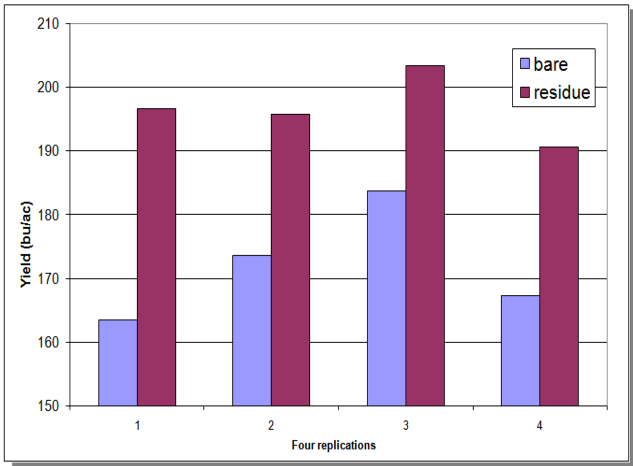


Figure 3. Corn yield on bare soil (avg. 172 bu/ac) and residue-covered soil (avg. 197 bu/ac) in 2007 at North Platte, Nebraska on small field plots.

bare-soil plots to reach the same yield as obtained in the residue-covered plots. In addition, the residue-covered plots held more water towards the end of the season (1.5 inches more than the bare-soil plots in the top 4 ft). Thus, the combined effect in 2008 is estimated to be a total of 3.5 inches of water savings on the residue-covered plots.

In April 2009 and 2010, residue was again removed from the same four plots as in the two previous years. As before, both the bare-soil and the residue-covered plots were irrigated at the same time with the same amount of water, but the crop (soybean in 2009 and 2010) was again somewhat water-stressed.

The average soybean yield in 2009 was 68 bu/ac in the residue-covered plots and 58 bu/ac in the bare-soil plots. An extra 3 inches of irrigation water would have been necessary on the bare-soil plots to produce the same yield as obtained in the residue-covered plots. In addition, the residue-covered plots held 2 inches more water towards the end of the 2009 growing season in the top 4 ft of soil (Table 3).

In 2010, the average soybean yield was 61 bu/ac in the residue-covered plots and 53 bu/ac in the bare-soil plots. An additional 2.5 inches of irrigation water would have been necessary on the bare-soil plots to produce the same yield as obtained in the residue-covered plots (Table 3).

Table 3. Crop yield and water savings for crops grown on residue-covered soil and on bare soil at North Platte, Nebraska.

		Yield			Water savings		
		Residue	Bare soil	Difference	Yield*	Soil**	Total
Year	Crop	Bu/ac	Bu/ac	Bu/ac	Inch	Inch	Inch
2007	Corn	197	172	25	3.0	0.0	3.0
2008	Corn	186	169	17	2.0	1.5	3.5
2009	Soybean	68	58	10	3.0	2.0	5.0
2010	Soybean	61	53	8	2.5	0.0	2.5

* Additional irrigation water needed to produce the same yield on the bare-soil plots as was obtained on the residue-covered plots
** Additional soil water (in the top 4 ft of soil, at the end of the growing season) in the residue-covered plots compared to the bare-soil plots

ECONOMIC ASPECTS

The economic benefits of the water savings discussed here can be calculated. Less irrigation water needs to be pumped when water is saved when retaining more residue on the soil surface. This translates into a savings in pumping cost. An example of pumping cost savings is shown in Table 4 for a 3-inch water savings on a 130-acre field.

Table 4. Pumping cost savings ($) for a dynamic pumping lift ranging between 0 and 400 ft and a cost of diesel fuel ranging between $2.00 and $5.00 per gallon.

Lift (ft)	$2.50	$3.00	$3.50	$4.00	$4.50	$5.00
0	1281	1538	1794	2050	2306	2563
50	1836	2203	2570	2937	3304	3672
100	2390	2868	3346	3824	4302	4781
150	2945	3534	4123	4712	5301	5890
200	3499	4199	4899	5599	6299	6999
250	4054	4865	5675	6486	7297	8108
300	4608	5530	6452	7373	8295	9217
350	5163	6195	7228	8260	9293	10326
400	5717	6861	8004	9148	10291	11435

This table is based on the following conditions:

- ✓ Water savings anticipated from more residue: 3 inches on a 130-acre field.
- ✓ Pump discharge pressure: 50 psi.
- ✓ Performance rating: 80%. This is a rating according to the Nebraska Pumping Plant Performance Criteria; 80% is an average rating for Nebraska.

For example, for a dynamic pumping lift of 200 ft and diesel at $3.50 per gallon, the pumping cost savings is $4899. A calculator has been developed to make the above calculations using your own input data. It is available at *http://water.unl.edu/web/cropswater/reduceneed*. Scroll down to the bottom of the page where you will find the calculator.

In a deficit-irrigation situation there are economic benefits because of higher yields associated with more residue and less tillage. For example, corn yield may be 25 bu/ac higher, as was the case in 2007 in the experiment at North Platte, described earlier. For corn at $6/bu, this would be $150/acre and almost $20,000 for a 130-acre field.

SUMMARY

With more residue cover, less solar energy reaches the soil surface and air movement is reduced near the soil surface, resulting in a reduction of evaporation of water from the soil beneath the residue cover. Research at Garden City, Kansas showed a 3-inch (50%) reduction in evaporation over a period of three summer months with a nearly 100% cover of wheat straw or no-till corn stover compared to bare soil. A full cover was needed to obtain the maximum reduction in evaporation. The study also showed that frequent rains or irrigations caused more evaporation losses than infrequent ones.

Another experiment was conducted from 2007-2010 at North Platte, Nebraska, to study the effect of crop residue on soil water content and crop yield. The crop on residue-covered and bare-soil plots was purposely water-stressed, so that any water conservation in the residue-covered plots might translate into higher yields. In all four years of the study, crop yield was greater in the residue-covered plots compared to the bare-soil plots. Also, in two of the four years, there was more water left in the root zone at the end of the growing season in the residue-covered plots. This four-year study showed a 2.5 - 5.0 in/year water savings when residue was left on the field. These results are very similar to the results of the Garden City experiments, which were obtained using a very different research approach.

In addition to reducing evaporation, higher residue levels and long-term no-till increase infiltration and reduce runoff, thus directing more water to where the crop can use it. Similarly, in the winter, more standing residue means that more snow stays where it falls, thus storing more water in the soil once the snow melts. The results from the Garden City and North Platte studies did not include these effects. Thus, on typical farm fields, water savings due to crop residue may be even greater than found in these studies.

Water conservation of the magnitudes discussed here will help reduce irrigation pumping cost significantly, which can amount to a savings of more than $5,000 on a typical 130-acre field. In a deficit-irrigation situation, the economic benefits due to higher yields associated with more residue and less evaporation can exceed $20,000 for a 130-acre field. But not only irrigators would benefit; more water would be available for competing needs including those of wildlife, endangered species, municipalities, hydroelectricity plants, and compacts with other states.

REFERENCES

Klocke, N.L., R.S. Currie, and R.M. Aiken. 2009. Soil water evaporation and crop residues. Transactions of the American Society of Agricultural and Biological Engineers 52(1): 103-110.

van Donk, S.J., D.L. Martin, S. Irmak, S.R. Melvin, J.L. Petersen, and D.R. Davison. 2010. Crop residue cover effects on evaporation, soil water content, and yield of deficit-irrigated corn in west-central Nebraska. Transactions of the American Society of Agricultural and Biological Engineers 53(6): 1787-1797.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N. Thompson, Colby, Kansas

OPTIMIZING CROPPING SYSTEMS UNDER LIMITED IRRIGATION CONDITIONS

Alan J. Schlegel
Research Agronomist
Kansas State University
Southwest Research-Extension Center
Tribune, Kansas
Voice: 620-376-4761 Fax: 620-376-2278
schlegel@ksu.edu

Loyd R. Stone
Research Soil Physicist
Kansas State University
Department of Agronomy
Manhattan, Kansas
Voice: 785-532-5732 Fax: 785-532-6094
stoner@ksu.edu

Troy J. Dumler
Extension Agricultural Economist
Kansas State University
Southwest Research-Extension Center
Garden City, Kansas
Voice: 620-275-9164 Fax 620-276-6028
Email: tdumler@ksu.edu

Freddie R. Lamm
Research Irrigation Engineer
Kansas State University
Northwest Research-Extension Center
Colby, Kansas
Voice: 785-462-6281 Fax: 785-462-2315
flamm@ksu.edu

ABSTRACT

Research was initiated in 2001 and conducted through 2010 under sprinkler irrigation at Tribune, Kansas to evaluate limited irrigation in several no-till crop rotations on grain yield, water use, and profitability. Crop rotations were 1) continuous corn, 2) corn-winter wheat, 3) corn-wheat-grain sorghum, and 4) corn-wheat-grain sorghum-soybean. Irrigation was limited to 10 inches annually with 5 inches applied to wheat, 15 inches to corn (when in rotation with wheat), and 10 inches to grain sorghum, soybean, and continuous corn. Crop water productivity and yield of corn was greater when grown in rotation than with continuous corn. The length of the rotation did not affect grain yield or crop water productivity of grain sorghum or winter wheat. Continuous corn was generally the most profitable cropping system. However, changes in prices or yields could result in multi-crop rotations being more profitable, indicating the potential for alternative crop rotations to reduce risk under limited irrigation.

INTRODUCTION

Irrigated crop production is an important component of agriculture in western Kansas. However, with declining water levels in the Ogallala Aquifer and high energy costs, optimal utilization of limited irrigation water is required. Precipitation is limited and sporadic in the region with annual precipitation supplying about 60-90% of the seasonal water requirement for grain sorghum and only 50-75% for corn (Doorenbos and Kassam, 1979). While crop rotations have been used extensively in many dryland systems, the most common crop grown under irrigation in western Kansas is corn (about 50% of the irrigated acres), often in a continuous corn system. While corn responds well to irrigation, it also requires substantial amounts of water to maximize production. 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]) with 57% applied to corn (Kansas Water Office, 1997). This amount of water withdrawal from the aquifer has reduced saturated thickness by as much as 150 ft. Although crops other than corn are grown under irrigation, they have not been grown as extensively because of relatively inexpensive water and a ready market for corn to the livestock feeding industry in the area. The trend in western Kansas during the 1990s has been towards increasing acreage of irrigated corn (665,000 acres in 1990 compared with 1.2 million acres in 2000) with corresponding reductions in grain sorghum (326,000 acres in 1990 compared with 71,000 acres in 2000) and winter wheat (692,000 acres in 1990 compared with 455,000 acres in 2000) (Kansas Farm Facts, 1991 and 2001). Although corn is expected to remain the dominant irrigated grain crop (especially in areas with abundant groundwater), the need exists to develop strategies to more effectively utilize limited irrigation water for corn. While there have been increases in irrigated soybean acreage (71,000 acres in 1990 compared with 134,000 acres in 2000), there has been limited research on its water use characteristics in western Kansas.

Alternative crop management practices are needed to reduce the amount of irrigation water required while striving to maintain economic returns sufficient for producer sustainability. To prepare for less water available for irrigation in the future, whether from physical constraints (lower well capacities and declining water tables) or from regulatory limitations, information on crop productivity and profitability with less irrigation water will be beneficial for agricultural sustainability.

MATERIALS AND METHODS

A field study was conducted at the Kansas State University Southwest Research-Extension Center near Tribune, Kansas from 2001 to 2010 on a deep silt loam soil (Ulysses silt loam [fine-silty, mixed, superactive, mesic Aridic Haplustolls]). Only data collected beginning in 2003 are presented to allow time for establishment of the crop rotations. The region is semi arid with a summer precipitation pattern and an average annual precipitation of 17.3 inches. The study consisted of four crop rotations; continuous corn (CC), corn-winter wheat (CW), corn-winter wheat-grain sorghum (CWS), and corn-winter wheat-grain-sorghum-soybean (CWSB). Each phase of each rotation was present each year and replicated four times. The plots were approximately 60 ft wide and 120 ft long. Irrigations were scheduled to supply water at the most critical stress periods (near flowering) for the specific crop and were limited to 1.5 inches per week. If precipitation was sufficient within a week, then irrigation was postponed. In some years, the maximum amount of irrigation was not applied because of above normal precipitation. The average first irrigation was 14 June for corn in rotation, 23 June for continuous corn, and 4 July for sorghum and soybean. The final irrigation averaged 28 August for corn in rotation, 15 August for continuous corn, and 22 August for sorghum and soybean. If needed to aid emergence of wheat, irrigation was initiated in the fall (four years) otherwise irrigation was reserved for spring application with average final irrigation on 6 June.

Average plantings dates were 3 May for corn, 20 May for soybean, and 27 May for grain sorghum. Winter wheat was planted after corn harvest (average of 1 October). Cultural practices (e.g., pesticides, tillage, and fertilization) typical for the region were used in all years of the study. The center portion of all plots was machine harvested with grain yields adjusted to 15.5% moisture (wet basis) for corn, 13% for soybean, and 12.5% for sorghum and wheat. Plant densities were determined along with the other yield components (kernels/ear and kernel mass).

The plots were irrigated with a linear move sprinkler irrigation system which had been modified to allow for water application from different span sections as needed to accomplish the randomization of plots. Soil water measurements (8-ft depth in 1-ft increments) were taken throughout the growing season using neutron attenuation. Available soil water was calculated by subtracting unavailable water from measured soil water. All water inputs, precipitation and irrigation, were measured. Crop water use was calculated by summing soil water depletion (soil water near emergence less soil water at harvest) plus in-season irrigation and precipitation. Non-growing season soil water accumulation was the increase in soil water from harvest to the amount at emergence the following year. Precipitation storage efficiency was calculated as non-growing season soil water accumulation divided by non-growing season precipitation. Crop water productivity (WP) was calculated as grain yield (bu/acre) divided by crop water use (inches).

Statistical analyses were performed using the GLM procedure from SAS version 9.1 (SAS Institute, Cary, North Carolina).

Local crop prices and input costs were used to perform an economic analysis to determine net return to land, management, and irrigation equipment for each treatment. Custom rates were used for all machine operations. Harvest prices and input costs were kept uniform for all years based on 2010 prices.

The objectives of this research were to determine the effect of limited irrigation on crop yield, water use, and profitability in several crop rotations.

RESULTS AND DISCUSSION

All rotations were limited to an average of 10 inches of irrigation annually; however, corn following wheat received 15 inches because the wheat received only 5 inches. This extra 5 inches of irrigation water increased the level of irrigation to nearly full and increased corn yields about 40 bu/acre compared to continuous corn (Table 1). Thus, limited irrigated corn yielded about 80% of full irrigation. These results are similar to those reported by Klocke et al. (2007) that found limited irrigation (no more than 6 in water) corn yields were 80 to 90% of fully irrigated yields at a location in Nebraska with average annual precipitation of 20 inches. In a simulation study using weather data from Northwest, Kansas, Lamm et al. (2007) found a 38% reduction in applied irrigation from nearly ful irrigation (i.e., when irrigation capacity was limited to not more than 1 inch/4 days) only reduced yields about 21 %. Corn grain yields averaged across different tillage treatments and plant densities were only reduced 9% (23 bu/acre) for a 25 % reduction in applied irrigation amount (13.75 vs. 10.25 inches) in a field study at Colby, Kansas (Lamm et al., 2009).

Corn yields in the multi-crop rotations were similar regardless of length of rotation. Wheat and grain sorghum yields were similar in all rotations.

Table 1. Average grain yields of four crops as affected by crop rotation, KSU Southwest Research-Extension Center, Tribune, Kansas, 2003-2010.

	Crop rotation†			
Crop	CC	CW	CWS	CWSB
	----------------------------- bu/acre-----------------------------			
Corn	163 b‡	203 a	202 a	203 a
Wheat	—	35 a	36 a	37 a
Sorghum	—	—	134 a	138 a
Soybean	—	—	—	43

† CC = continuous corn; CW = corn-wheat; CWS = corn-wheat-grain sorghum; CWSB = corn-wheat-grain sorghum-soybean.

‡ Means within a row with different letters are significantly different ($P \leq 0.05$). Statistical analysis was not completed for column means.

Crop water productivity was ranked in the order of corn > sorghum > wheat = soybean (Table 2). Crop water productivity of corn was increased when irrigation was increased to 15 inches and grown in rotation with other crops. Grain sorghum grown in 4-yr rotations had slightly greater crop water productivity than grown in 3-yr rotations. The length of rotation had no effect on crop water productivity of wheat.

Table 2. Average crop water productivity of four crops as affected by crop rotation, KSU Southwest Research-Extension Center, Tribune, Kansas, 2003-2010.

	Crop rotation†			
Crop	CC	CW	CWGS	CWSB
	----------lb/acre-inch----------			
Corn	377 b‡	411 a	398 a	410 a
Wheat	—	115 a	125 a	122 a
Sorghum	—	—	314 b	326 a
Soybean	—	—	—	110

† CC = continuous corn; CW = corn-wheat; CWS = corn-wheat-grain sorghum; CWSB = corn-wheat-grain sorghum-soybean.

‡ Means within a row with different letters are significantly different ($P \leq 0.05$). Statistical analysis was not completed for column means.

An economic analysis (based on grain prices and input costs in 2010 with average crop yields) found that the most profitable crop was corn in rotation with other crops (Table 3). Profitability was similar for grain sorghum and soybean in the 3- and 4-yr rotations. The least profitable crop was wheat, primarily because of reduced yields caused by hail and spring freeze injury in about 50% of the years. However, the most profitable crop rotation was continuous corn. All multi-crop rotations had net returns of \$57-69 acre^{-1} less than CC. Lower returns in the multi-crop rotations were due to low returns from wheat.

Table 3. Net return to land, irrigation equipment, and management from four crop rotations, KSU Southwest Research-Extension Center, Tribune, Kansas, 2003-2010.

	Crop rotation†			
Crop	CC	CW	CWS	CWSB
	---------- $/acre ----------			
Corn	237	332	326	321
Wheat	—	4	1	5
Sorghum	—	—	189	198
Soybean	—	—	—	198
Net for rotation	237	168	172	180

† CC = continuous corn; CW = corn-wheat; CWS = corn-wheat-grain sorghum; CWSB = corn-wheat-grain sorghum-soybean.

CONCLUSIONS

With limited irrigation (10 inches annually), continuous corn has been more profitable than multi-crop rotations including wheat, sorghum, and soybean primarily because of spring freeze and hail damage to wheat in the multi-crop rotations. In multi-crop rotations, relatively poor results with one crop (in this case wheat) can reduce profitability compared with a monoculture, especially when the monoculture crop does well. However, the multi-crop rotation can reduce economic risk when the monoculture crop does not perform as well. All multi-crop rotations had net returns \$57-69 acre^{-1} less than continuous corn. However, changes in prices or yields could result in any of the rotations being more profitable than continuous corn, indicating the potential for alternative crop rotations under limited irrigation.

ACKNOWLEDGEMENTS

This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

Contribution no. 12-314-A from the Kansas Agricultural Experiment Station.

This paper was originally presented at Innovations in Irrigation Conference, San Diego, CA, 6 Nov. 2011.

REFERENCES

Doorenbos, J., and A.H. Kassam. 1979. Yield response to water. Irrig. and Drain. Pap. 33. FAO, Rome.

Kansas Department of Agriculture. 1997. Kansas reported water use summary, calendar year 1995. State of Kansas, Topeka, Kansas.

Kansas Farm Facts. 1991 and 2001. Kansas Agricultural Statistics. Kansas Dept. of Agriculture and U.S. Dept. of Agriculture, Topeka, Kansas.

Kansas Water Office. 1997. 1995 Kansas irrigation water use. State of Kansas, Topeka, Kansas.

Lamm, F. R., R. M. Aiken, and A. A. Aboukheira. 2009. Corn yield and water use characteristics as affected by tillage, plant density and irrigation. Trans ASAE: 52(1):133-143.

Lamm, F. R., L. R. Stone, and D. M. O'Brien. 2007. Crop production and economics in Northwest Kansas as related to irrigation capacity. Appl. Engr in Agric. 23(6):737-745.

Klocke, N.L., J.O. Payero, and J.P. Schneekloth. 2007. Long-term response of corn to limited irrigation and crop rotations. Trans. ASABE 50:2117-2124.

ASSESSMENT OF PLANT AVAILABLE SOIL WATER ON PRODUCER FIELDS IN WESTERN KANSAS

Freddie R. Lamm
Research Irrigation Engineer
Kansas State University
Colby, Kansas
Voice: 785-462-6281
Fax: 785-462-2315
flamm@ksu.edu

Danny H. Rogers
Extension Irrigation Engineer
Kansas State University
Manhattan, KS
Voice: 785-532-2933
Fax: 785-532-5825
drogers@ksu.edu

Alan J. Schlegel
Research Soil Scientist
Kansas State University
Tribune, Kansas
Voice: 620-376-4761
Fax: 620-376-2278
schlegel@ksu.edu

Norman L. Klocke
Water Resources Engineer
Kansas State University,
Garden City, Kansas
Voice: 620-276-8286
Fax: 620-276-6028
nklocke@ksu.edu.

Loyd R. Stone
Research Soil Physicist
Kansas State University
Manhattan, Kansas
Voice: 785-532-5732
Fax: 785-532-6094
stoner@ksu.edu

Rob M. Aiken
Research Crop Scientist
Kansas State University
Colby, Kansas
Voice: 785-462-6281
Fax: 785-462-2315
raiken@ksu.edu

L. Kent Shaw
Extension Irrigation Assistant
Kansas State University,
Garden City, Kansas
Voice: 620-276-8286
Fax: 620-276-6028
lkshaw@ksu.edu

INTRODUCTION

Water shortage is the primary factor limiting crop production in the USA's west-central Great Plains, and agricultural sustainability depends on efficient use of water resources. Precipitation is limited and sporadic with mean annual precipitation ranging from 16 to 20 inches across the region, which is only 60-80% of the seasonal water use for corn. Yields of dryland crops are limited and variable and some producers have used irrigation to mitigate these effects. Continued declines within the Ogallala Aquifer will result in a further shift from fully irrigated to deficit or limited irrigation or even dryland production in some areas. As this occurs, producers will desire to maintain crop production levels as great as possible while balancing crop production risks imposed by constraints on water available for production. Efficient utilization of plant available soil water (PASW) reserves is important for both dryland and irrigated summer crop production systems.

In western Kansas, dryland grain sorghum yield was linearly related to PASW at emergence and sorghum yields increased 501 lbs/acre for each additional inch of PASW (Stone and Schlegel, 2006). When the experimental effects of tillage were considered, grain sorghum yield response to water supply (PASW at planting plus cropping season precipitation) was greater with no-tillage than with conventional tillage (417 vs. 292 lbs/acre-inch). With conventional tillage at

Bushland, Texas, grain sorghum yield increased 385 lbs/acre-inch of PASW at planting (Jones and Hauser, 1974). Evaporative demands increase from north to south (i.e., decreasing latitude) in the Great Plains and this can reduce overall yield response to water (Musick et al., 1994; Nielsen et al., 2002). Precipitation increases from west to east in the Great Plains and in Kansas the average increase is approximately 1 inch for each 18 miles (Flora, 1948). Research is needed to characterize the amounts of PASW available to producers in the spring before planting of summer crops. The research results can be used to develop better cropping recommendations for producers based on their geographical location within western Kansas when used with information about their anticipated summer precipitation.

Preseason irrigation (also referred to as preplant, dormant-season, off-season, or winter irrigation) is a common practice in central and southern sections of the western Great Plains on the deep soils with large water-holding capacity that are prevalent. The residual soil water left in irrigated corn fields has a strong effect on the amount of preseason irrigation and precipitation that can be stored during the dormant period (Lamm and Rogers, 1985). Although preseason irrigation is common, research has shown it is often an inefficient water management practice (Stone et al., 1987; Lamm and Rogers 1985; Musick and Lamm, 1990). Measured water losses from marginal preseason irrigation capacities during the 30-45 day period prior to planting in a Texas study were extremely high, ranging from 45 to 70% (Bordovsky and Porter, 2003). While several reasons are given by producers for the use of preseason irrigation, Musick et al. (1971) stated its primary purpose is to replenish soil water stored in the plant root zone.

From an analysis of soil water data from producer fields with silt loam soils near Colby, Kansas, Rogers and Lamm (1994) concluded that irrigation above the amount required to bring soil water to 50% PASW water would have a high probability of being lost or wasted. They found in a three-year study (1989-1991) of 82 different fields that on average producers were leaving residual PASW in the top 5 ft of the soil profile at 70% of field capacity. Since that time, groundwater levels have continued to decline and more irrigation systems have marginal capacity. Research is needed to both assess the current amounts of residual PASW producers are leaving in the field after irrigated corn harvest and how much PASW is replenished during the period before spring planting of the next corn crop.

The primary objectives of this project were to characterize the fall residual profile PASW after irrigated corn production and the PASW in dryland wheat stubble following the winter period and prior to dryland summer crop production in producer fields in three distinct regions of western Kansas [southwest (SW), west central (WC) and northwest (NW)]. Secondary objectives were to characterize aspects of the overwinter precipitation storage for the two crop residues (i.e., irrigated corn and dryland wheat).

PROCEDURES

The ongoing study was initiated in the fall of 2010 on the deep silt loam soils in western Kansas. Fifteen fields from each of the three regions (SW, WC and NW) were sought for each crop residue type (dryland wheat and irrigated corn) for sampling of PASW. In general five fields of each residue type were selected in each county (Figure 1). In a few cases, additional fields (generally 1 or 2) were selected when it was deemed useful in gaining a better geographical distribution. Another selection criterion for the irrigated corn fields was irrigation system capacity. Attempts were made to find one or two fields in each county with capacities equivalent to less than 400, 400 to 600, and over 600 gpm for a 125 acre field.

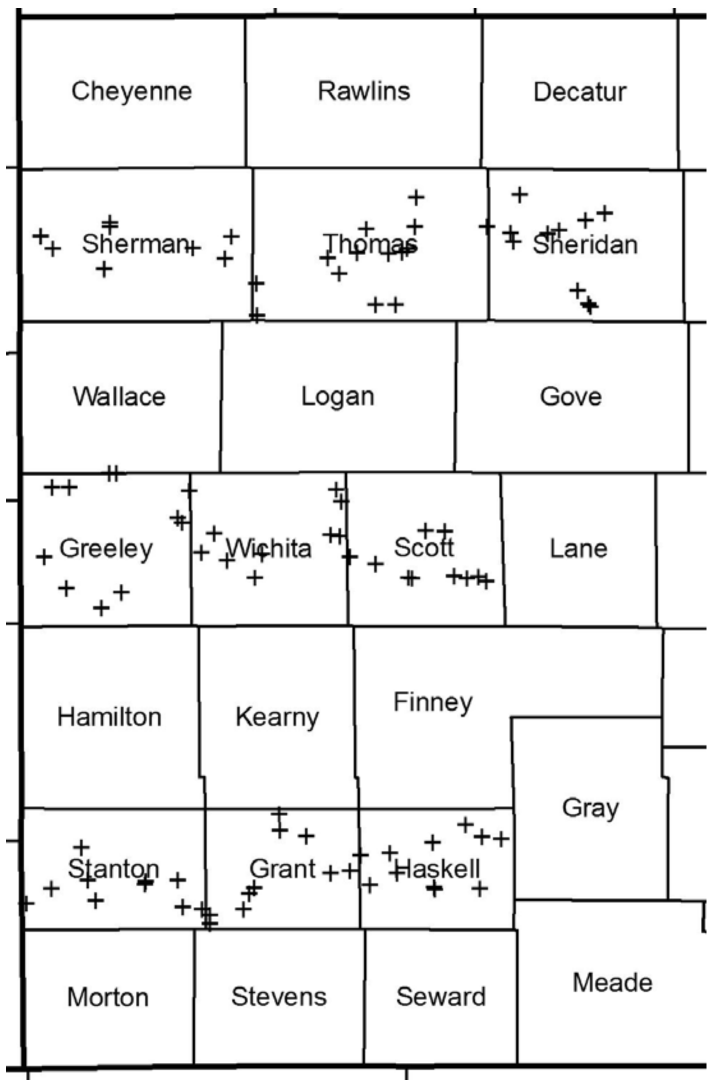


Figure 1. Geographical distribution of soil water measurements in producer fields in western Kansas, 2010. Each symbol represents a GPS-referenced producer field.

Although a broad geographical representation was a primary desire (Figure 1), an attempt was made to select producers using good management practices and for which realistic weather conditions could be obtained from public sources. Fields in NW Kansas were selected in Sheridan, Thomas and Sherman counties (east to west counties). Fields in WC Kansas were selected in Scott, Wichita and Greeley counties (east to west counties). There was increased difficulty finding producers with continuous (year-after-year) irrigated corn fields in WC Kansas, particularly in Wichita and Greeley Counties. The Ogallala aquifer in this region of Kansas is more marginal and severely depleted, so producers appear to be using more crop rotation to utilize residual soil water better, thus conserving more aquifer water for future years. Fields in SW Kansas were selected in Haskell, Grant and Stanton counties (east to west counties). There were 96 total fields in 2010 fall sampling and 91 fields in 2011.

The GPS-referenced neutron access tubes (3 per field) were installed in an equilateral triangular-shaped pattern (50-foot sides). Initial volumetric soil water content was determined in these fields after installation of tubes and again in late spring prior to summer crop initiation in one-foot increments to a depth of 8 feet. Published soil type and soil characteristics were used to estimate PASW within the profile. The data from the three sampling points was examined for uniformity between readings and to remove any anomalies. A few tubes were lost due to damage by producer field operations between the fall and spring measurement periods. Less than 1% of the data was lost due to measurement anomalies or damaged tubes.

RESULTS AND DISCUSSION

The study is ongoing and some of the more complex interrelationships of producer practices with residual soil water have not been quantified or evaluated yet. Although it should be noted that the results may vary widely from what may be occurring on your or other fields located within these counties, the soil water results may still be indicative of some of the irrigation capacities and practices, climatic, soil, and cropping conditions of these three distinct regions of western Kansas.

Weather Conditions

Weather conditions in nearly all of western Kansas were excessively dry from early August 2010 through mid-April of 2011. The western portion of WC and NW Kansas began to get more normal precipitation in late April 2011 and ended the cropping season with normal amounts of precipitation or greater. However, SW Kansas remained under severe drought conditions through the summer and much of the fall. For example, Grant County received less than 30% of normal annual precipitation for the period September 1, 2010 through September 1, 2011. In SW Kansas, dryland summer crops resulted in almost total failure and even many of the irrigated crops were severely stressed. The western edge of WC Kansas (Greeley County) and for nearly all of NW Kansas experienced near-to above-normal precipitation for most of the summer period. A particularly wet weather multi-day period in early October 2011 that tracked across some counties in WC Kansas and the eastern half of NW Kansas with those areas receiving between 2 and 4 inches of precipitation. Because of the multi-day nature of this precipitation, much of the water infiltrated into the soil profile.

Soil Water as Affected by Location and Residue Type

In general, sprinkler irrigated corn fields had greater PASW than the dryland wheat fields (Tables 1 – 3) as might be anticipated. Additionally, it should be noted that in many cases in SW Kansas, some fall dormant season irrigation (both 2010 and 2011) had been practiced prior to the soil water measurements to facilitate easier strip tillage operations.

Fall 2010 results

In 2010, NW Kansas had slightly more PASW (7.39 inches) in wheat fields (Table 1) than in the other two regions (WC, 5.43 inches and SW, 6.57 inches, respectively). The coefficient of variation (CV) of PASW in wheat fields was least in NW Kansas and greatest in SW Kansas, probably reflecting the higher evaporative demand and worse drought conditions affecting SW Kansas.

The irrigated corn fields residual PASW averaged 160% that of the dryland wheat fields (Table 1) and also had less variability (CV of 0.30 and 0.43 for corn and wheat, respectively). The average PASW in irrigated corn fields for the three regions only varied about 1 inch (range of 9.99 in NW to 10.90 inches in SW) and with an average value of 10.30 inches would approximate a profile at 60% of field capacity, which would suggest overall adequate irrigation management. However, there was a large amount of field to field variation. The maximum PASW for the irrigated corn fields averaged nearly 16.4 inches which would be very wet unless there was considerable late season precipitation or fall dormant season irrigation. At the other end of the spectrum, the minimum average PASW was approximately 4.3 inches, which would be only about 25% of field capacity.

Spring 2011 results

There was on average slight losses or very small accumulations in the dryland wheat residue fields by late spring 2011 (Table 2), with the exception of NW Kansas which saw an average increase of 2.05 inches of PASW. This reflects some appreciable late April 2011 precipitation events in NW Kansas that the other regions had missed or had lesser amounts.

In contrast, NW Kansas had only minimal increase in PASW in the irrigated corn fields while PASW in the WC and SW Kansas fields increased approximately 2 inches (Table 2). This reflects that many of the WC and SW Kansas fields had received additional dormant season irrigation to better cope with the drought before spring planting. The maximum PASW for the sprinkler irrigated corn fields averaged 12.15, 20.06, and 18.65 inches for NW, WC and SW Kansas, respectively. These values in WC and SW Kansas would be considered extremely wet (i.e., above field capacity) and would be subject to high deep percolation rates. Close examination of the individual field data revealed that these high maximum values in the spring 2011 also were very high on the same fields in the fall of 2010, suggesting that these irrigators should cut back on late and/or dormant season irrigation. In contrast, the minimum values of PASW in the spring of 2011, on the producer fields averaged only 5.51 inches in the 8 ft profile (approximately 30% of field capacity). These producers with such low values of PASW might have greatly benefited had they used more dormant season irrigation, particularly in such a dry summer.

The irrigated corn fields had approximately 160% of the PASW of the wheat fields, similar to the results from the fall of 2010 and again with less variability in PASW.

Fall 2011 results

In fall of 2011, because of the continuing drought in SW Kansas, it was anticipated that producer fields would be much drier than in 2010 (Tables 3 and 1, respectively). Although this turned out to be true for SW Kansas for dryland wheat fields (nearly 1.5 inches drier), overall the irrigated corn fields were wetter (approximately 11% wetter) in 2011, with only SW Kansas having slightly drier irrigated fields in fall 2011 (approximately 7% drier). The wetter summer period in portions of WC Kansas (Greeley County) and NW Kansas no doubt had some effects on the amounts of residual PASW.

The October 2011 multi-day wet period resulted in some very wet wheat residue fields in Thomas and Sheridan Counties in northwest Kansas (Table 3).

Discussion of Annual Differences in Corn Residual PASW

Although record or near-record drought conditions existed in southwest Kansas for the entire period from the middle of the summer of 2010 through the fall of 2011, there were only minimal differences in fall irrigated corn PASW for the 31 fields that were available for PASW measurements in both years (Figure 2). Part of the rationale might be that drought conditions were similar between the two years. However, the irrigated corn residual soil water is still relatively high on the average for SW Kansas (approximately 60% of field capacity). So, the presence of severe drought may not be a good indicator of the amounts of residual soil water left after irrigated corn harvest. Sometimes, crop damage is caused by system capacity (gpm/acre) at the critical stages, rather than what irrigation amounts can be applied during the total season. Insect damage such as spider mites is exacerbated by high canopy temperatures and drought. Producers recognizing the drought and crop damage may continue to irrigate hoping to mitigate further crop damage and this sometimes increases profile PASW as the damaged crop is no longer transpiring typical amounts of water. One caveat, in some cases the PASW results are probably reflecting the effects of some fall dormant season irrigation that occurred before the PASW sampling. However, in most cases the fall irrigation amounts were not large.

Table 1. Plant available soil water (inches/8ft) in producer fields in western Kansas in fall 2010 (October through December).

Residue Type	County and number of fields	Average	Maximum	Minimum	CV*
Northwest Kansas, Sheridan, Thomas and Sherman Counties					
Dryland Wheat	Sheridan (5)	7.64	11.40	4.49	0.33
	Thomas (7)	8.58	11.08	6.16	0.19
	Sherman (5)	5.48	8.26	3.86	0.31
	All 3 Ctys (17)	7.39	11.40	3.86	0.30
Irrigated Corn	Sheridan (5)	10.50	11.10	8.57	0.06
	Thomas (7)	10.79	15.55	6.76	0.22
	Sherman (5)	8.35	11.64	6.56	0.24
	All 3 Ctys (17)	9.99	15.55	6.56	0.24
Irrigated to Dryland Ratio	Sheridan	1.37	0.97	1.91	0.19
	Thomas	1.26	1.40	1.10	1.12
	Sherman	1.52	1.41	1.70	0.77
	All 3 Ctys	1.35	1.36	1.70	0.79
West Central Kansas, Scott, Wichita and Greeley Counties					
Dryland Wheat	Scott (5)	5.11	8.97	2.48	0.50
	Wichita (6)	5.10	9.31	3.03	0.48
	Greeley (5)	6.13	11.08	2.07	0.53
	All 3 Ctys (16)	5.43	11.08	2.07	0.48
Irrigated Corn	Scott (5)	11.98	16.57	8.20	0.27
	Wichita (5)	9.31	11.78	6.54	0.20
	Greeley (5)	8.78	10.63	3.96	0.32
	All 3 Ctys (15)	10.02	16.57	3.96	0.29
Irrigated to Dryland Ratio	Scott	2.34	1.85	3.31	0.54
	Wichita	1.83	1.27	2.16	0.42
	Greeley	1.43	0.96	1.91	0.60
	All 3 Ctys	1.85	1.50	1.91	0.60
Southwest Kansas, Haskell, Grant and Stanton Counties					
Dryland Wheat	Haskell (5)	5.39	10.19	1.50	0.72
	Grant (5)	3.43	6.08	1.70	0.50
	Stanton (5)	10.88	14.41	7.39	0.29
	All 3 Ctys (15)	6.57	14.41	1.50	0.66
Irrigated Corn	Haskell (6)	9.82	17.06	2.37	0.61
	Grant (5)	9.06	13.86	6.28	0.37
	Stanton (5)	13.83	16.71	11.50	0.14
	All 3 Ctys (16)	10.84	17.06	2.37	0.41
Irrigated to Dryland Ratio	Haskell	1.82	1.67	1.58	0.84
	Grant	2.64	2.28	3.69	0.74
	Stanton	1.27	1.16	1.56	0.47
	All 3 Ctys	1.65	1.18	1.58	0.62

** Coefficient of variation is defined as the standard deviation of PASW divided by the mean PASW.*

Table 2. Plant available soil water (inches/8ft) in producer fields in western Kansas in spring 2011 (March through May).

Residue Type	County and number of fields	Average	Maximum	Minimum	CV*
Northwest Kansas, Sheridan, Thomas and Sherman Counties					
Dryland Wheat	Sheridan (5)	9.66	12.55	7.78	0.19
	Thomas (7)	9.67	11.47	7.34	0.13
	Sherman (4)	8.77	10.80	7.07	0.20
	All 3 Ctys (16)	9.44	12.55	7.07	0.16
Irrigated Corn	Sheridan (5)	11.21	12.15	10.67	0.05
	Thomas (7)	11.02	15.69	8.23	0.22
	Sherman (5)	8.74	11.84	6.37	0.24
	All 3 Ctys (17)	10.41	15.69	6.37	0.21
Irrigated to Dryland Ratio	Sheridan	1.16	0.97	1.37	0.26
	Thomas	1.14	1.37	1.12	1.69
	Sherman	1.00	1.10	0.90	1.21
	All 3 Ctys	1.10	1.25	0.90	1.28
West Central Kansas, Scott, Wichita and Greeley Counties					
Dryland Wheat	Scott (5)	6.26	10.92	3.74	0.46
	Wichita (5)	5.06	7.22	3.63	0.30
	Greeley (5)	6.44	11.36	2.43	0.50
	All 3 Ctys (15)	5.92	11.36	2.43	0.43
Irrigated Corn	Scott (5)	14.51	20.06	9.70	0.27
	Wichita (5)	11.12	13.87	7.51	0.23
	Greeley (5)	10.60	13.60	4.47	0.34
	All 3 Ctys (15)	12.08	20.06	4.47	0.30
Irrigated to Dryland Ratio	Scott	2.32	1.84	2.59	0.58
	Wichita	2.20	1.92	2.07	0.78
	Greeley	1.65	1.20	1.84	0.67
	All 3 Ctys	2.04	1.77	1.84	0.70
Southwest Kansas, Haskell, Grant and Stanton Counties					
Dryland Wheat	Haskell (5)	6.25	11.03	2.09	0.64
	Grant (5)	4.02	6.91	2.28	0.45
	Stanton (5)	8.76	11.93	5.28	0.34
	All 3 Ctys (15)	6.34	11.93	2.09	0.54
Irrigated Corn	Haskell (5)	12.10	18.65	5.70	0.43
	Grant (5)	11.50	15.74	7.05	0.30
	Stanton (5)	13.64	16.13	10.24	0.18
	All 3 Ctys (15)	12.39	18.65	5.70	0.31
Irrigated to Dryland Ratio	Haskell	1.94	1.69	2.73	0.67
	Grant	2.86	2.28	3.10	0.67
	Stanton	1.56	1.35	1.94	0.53
	All 3 Ctys	1.95	1.56	2.73	0.56

** Coefficient of variation is defined as the standard deviation of PASW divided by the mean PASW.*

Table 3. Plant available soil water (inches/8ft) in producer fields in western Kansas in fall 2011 (September through December).

Residue Type	County and number of fields	Average	Maximum	Minimum	CV*
Northwest Kansas, Sheridan, Thomas and Sherman Counties					
Dryland Wheat	Sheridan (5)	13.95	17.81	7.03	0.29
	Thomas (5)	7.11	9.14	6.19	0.16
	Sherman (5)	6.85	8.70	3.76	0.31
	All 3 Ctys (15)	9.30	17.81	3.76	0.46
Irrigated Corn	Sheridan (6)	13.77	15.60	10.45	0.14
	Thomas (5)	13.07	16.86	8.94	0.22
	Sherman (5)	8.31	11.69	5.95	0.28
	All 3 Ctys (15)	11.85	16.86	5.95	0.28
Irrigated to Dryland Ratio	Sheridan	0.99	0.88	1.49	0.49
	Thomas	1.84	1.84	1.44	1.32
	Sherman	1.21	1.34	1.58	0.89
	All 3 Ctys	1.27	0.95	1.58	0.61
West Central Kansas, Scott, Wichita and Greeley Counties					
Dryland Wheat	Scott (5)	8.08	10.96	5.44	0.25
	Wichita (5)	8.36	10.05	6.46	0.20
	Greeley (5)	8.57	10.76	6.63	0.18
	All 3 Ctys (15)	8.34	10.96	5.44	0.20
Irrigated Corn	Scott (5)	13.00	17.85	9.75	0.23
	Wichita (5)	12.59	14.21	10.74	0.11
	Greeley (5)	11.73	12.25	10.98	0.04
	All 3 Ctys (15)	12.46	17.85	9.75	0.16
Irrigated to Dryland Ratio	Scott	1.61	1.63	1.79	0.90
	Wichita	1.50	1.41	1.66	0.57
	Greeley	1.37	1.14	1.66	0.22
	All 3 Ctys	1.49	1.63	1.79	0.80
Southwest Kansas, Haskell, Grant and Stanton Counties					
Dryland Wheat	Haskell (5)	5.98	10.30	2.73	0.46
	Grant (5)	3.26	6.74	0.16	0.90
	Stanton (5)	5.57	8.16	4.63	0.26
	All 3 Ctys (15)	4.94	10.30	0.16	0.52
Irrigated Corn	Haskell (5)	10.40	15.58	2.94	0.59
	Grant (5)	8.76	16.49	3.13	0.66
	Stanton (5)	11.11	14.30	8.65	0.20
	All 3 Ctys (15)	10.15	16.49	2.94	0.46
Irrigated to Dryland Ratio	Haskell	1.74	1.51	1.08	1.30
	Grant	2.69	2.45	19.02	0.74
	Stanton	2.00	1.75	1.87	0.76
	All 3 Ctys	2.06	1.60	17.84	0.88

** Coefficient of variation is defined as the standard deviation of PASW divided by the mean PASW.*

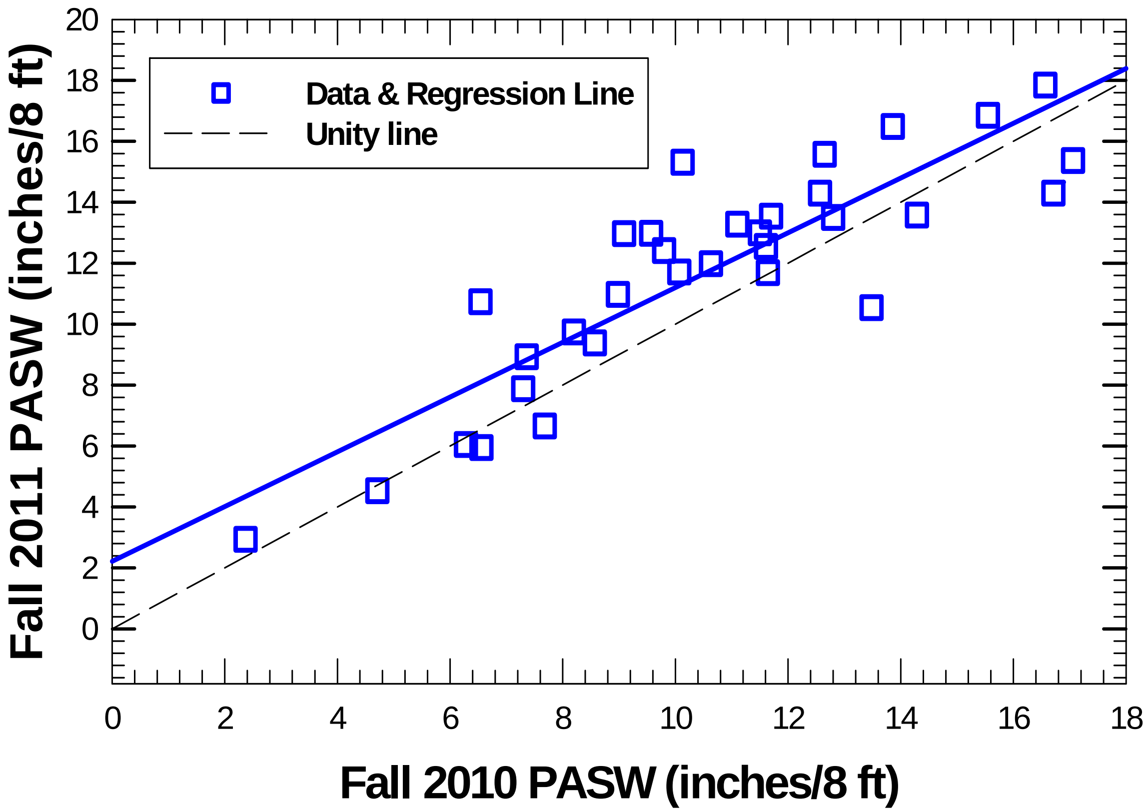


Figure 2. Similarity of plant available soil water (PASW) in the 8 ft soil profile in irrigated corn fields after harvest for the fall periods in 2010 and 2011 in western Kansas producer fields. These data represent 31 fields that producers made available for PASW measurements in both years.

Effect of Regional Characteristics on Corn Residual PASW

Although intuition might suggest that less saturated thickness of the Ogallala and more marginal irrigation system capacities (gpm/acre) would result in less residual PASW in the irrigated corn fields of WC Kansas, there was no strong evidence of that in the data from 2010 and 2011 (Figure 3). This might be because producers with lower capacity irrigation systems have adjusted to their limitation by using longer pumping periods. Their goal by pumping later into the crop season would be to minimize crop yield loss, but sometimes those later irrigation events also increase residual PASW.

Effect of Field Type on Overwinter Change in PASW

Overwinter accumulation or loss of PASW could be affected by precipitation, initial PASW, residue type, and any applied dormant season irrigation, so the following results are being discussed in terms of field type, rather than just crop residue type. The corn fields on average accumulated approximately 2 inches of soil water overwinter when the fall 2010 PASW was very low and only about 1 inch of accumulation when the PASW was high (Figure 4). In contrast, the wheat fields accumulated only about 1 inch of soil water overwinter when the fall 2010 PASW was very low and tended to lose up to 2 to 3 inches of PASW when PASW was higher (Figure 4). These differences are probably due to dormant season irrigation slightly increasing PASW in the corn fields while the drought conditions were not favorable for much overwinter accumulation in the dryland wheat fields.

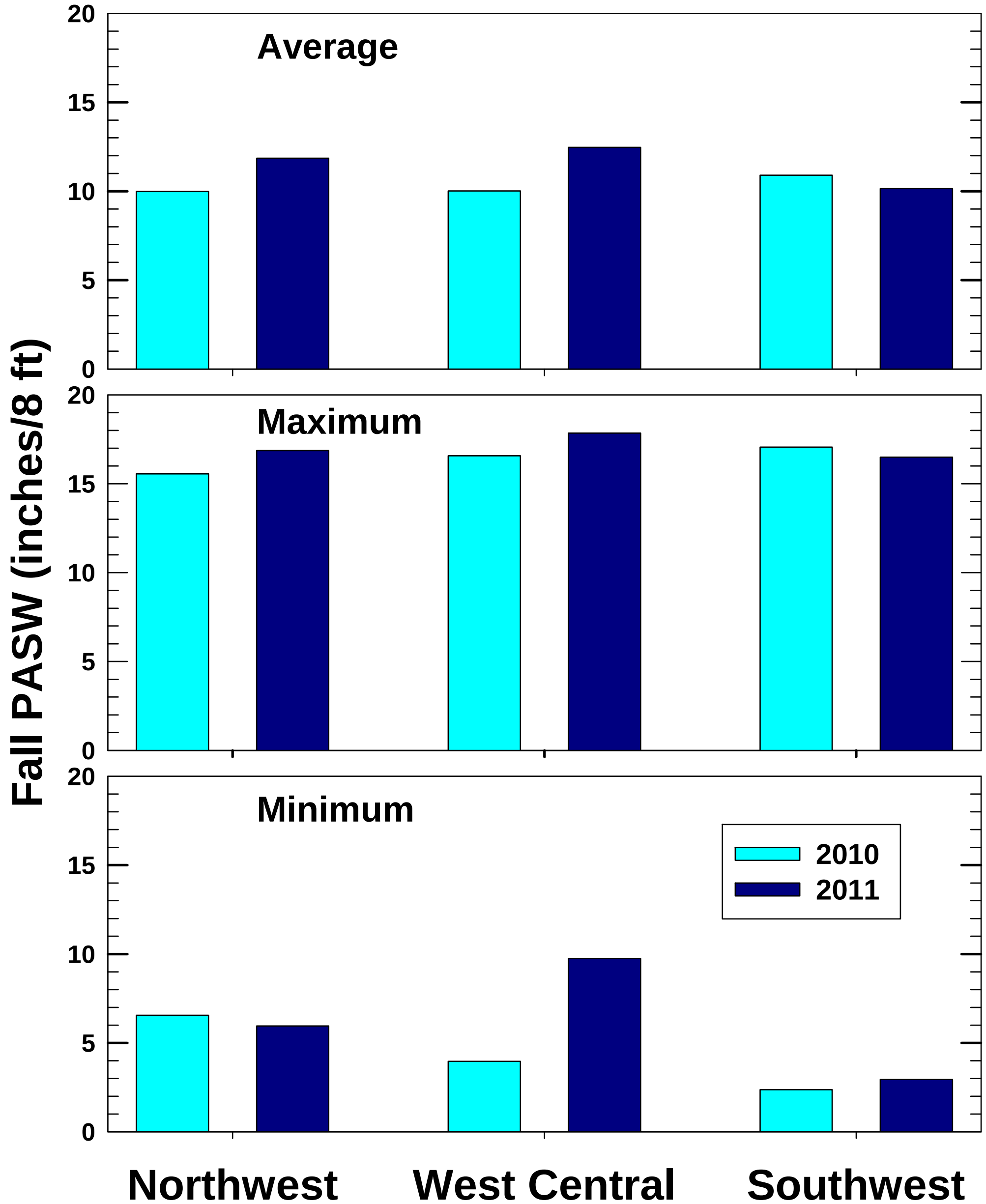


Figure 3. Effect of western Kansas region on average, maximum and minimum measured plant available soil water (PASW) in the 8 ft soil profile in irrigated corn fields after harvest for the fall periods in 2010 and 2011.

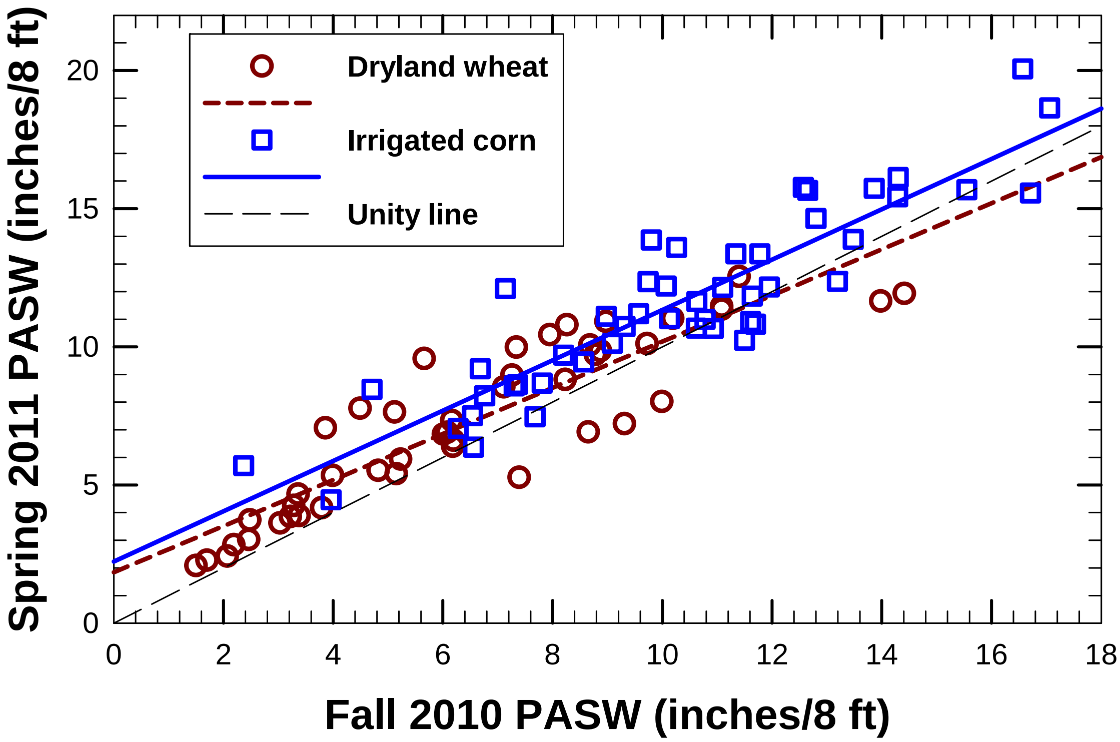


Figure 4. Effect of field type on accumulation of plant available soil water (PASW) in the 8 ft soil profile for the period fall 2010 through spring 2011 for producer fields in western Kansas.

Effect of System Capacity on Fall PASW in Irrigated Corn Fields

There were only small differences in PASW (less than 1 inch) as affected by low (less than 400 gpm/125 acres), medium (400 to 600 gpm/125 acres) or high (greater than 600 gpm/125 acres) irrigation system capacity (Figure 5) in 2011. Further analysis of the effect of capacity on fall PASW will be done by incorporating more precise information about system capacity and also from information to be provided by the producers about actual aspects of their irrigation cropping season and irrigation schedule.

SUMMARY

These results suggest a few very important aspects for irrigated crop production in western Kansas:

1. Irrigation not only increases the water available for crop production, but also reduces the variability in ASW in the field.

2. Average PASW may not be indicative of an individual field, so it is wise to check your each field after harvest.

3. Each year is different, so irrigating to average conditions is very risky and may be less profitable.

4. Science-based irrigation scheduling can help to better manage your water resources in-season and between seasons. Cost-sharing programs may be available to help individuals implement science-based irrigation scheduling.

ACKNOWLEDGEMENTS

This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

Contribution no. 12-311-A from the Kansas Agricultural Experiment Station.

REFERENCES

Bordovsky, J. P. and D. O. Porter. 2003. Cotton response to pre-plant irrigation level and irrigation capacity using spray, LEPA, and subsurface drip irrigation. Presented at the 2003 ASAE Annual International Meeting, July 27-30, Las Vegas NV. ASAE paper no. 032008. 11 pp.

Flora, S. D. 1948. The Climate of Kansas. Kansas State Board of Agriculture Report 67(285):1-320.

Jones, O.R., and V.L. Hauser. 1974. Runoff utilization for grain production. USDA-AR Series W-22, p. 277-283.

Lamm, F.R. and D.H. Rogers. 1985. Soil water recharge function as a decision tool for preseason irrigation. Trans. ASAE 28:1521-1525.

Musick, J.T. and F.R. Lamm. 1990. Preplant irrigation in the central and southern High Plains --- A review. Trans. ASAE 33:1834-1842.

Musick, J.T., W.H. Sletten, and D.A. Dusek. 1971. Preseason irrigation of grain sorghum in the southern High Plains. Trans. ASAE 14:93-97.

Musick, J.T., O.R. Jones, B.A. Stewart, and D.A. Dusek. 1994. Water-yield relationships for irrigated and dryland wheat in the U.S. Southern Plains. Agron. J. 86:980-986.

Nielsen, D.C., M.F. Vigil, R.L. Anderson, R.A. Bowman, J.G. Benjamin, and A.D. Halvorson. 2002. Cropping system influence on planting water content and yield of winter wheat. Agron. J. 94:962-967.

Rogers, D.H., and F.R. Lamm. 1994. Soil water survey after corn harvest in northwest Kansas. Appl. Eng. Agric. 10(1):37-40.

Stone, L.R., F.R. Lamm, A. J. Schlegel, and N. L. Klocke. 2008. Storage efficiency of off-season irrigation. Agron J. 100:1185–1192.

Stone, L.R., A.J. Schlegel, F.R. Lamm, and W.E. Spurgeon. 1994. Storage efficiency of preplant irrigation. J. Soil Water Conserv. 49:72-76.

Stone, L. R. and A. J. Schlegel. 2006. Yield-water supply relationships of grain sorghum and winter wheat. Agron. J. 98:1359-1366.

This paper was first presented at the Central Plains Irrigation Conference, February 21-22, 2012, Colby, Kansas. It can be cited as

Lamm, F.R., D.H. Rogers, A.J. Schlegel, N.L. Klocke, L.R. Stone, R. M. Aiken, and L.K. Shaw. 2012. Assessment of plant available soil water on producer fields in western Kansas. In: Proc. 24th annual Central Plains Irrigation Conference Feb. 21-22, 2012, Colby, Kansas. Available from CPIA, 760 N. Thompson, Colby, Kansas. pp. 37-50.

Soil water sampling process on producer fields in western Kansas, 2010-2011.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

A RETURN LOOK AT DORMANT SEASON IRRIGATION STRATEGIES

Alan J. Schlegel
Research Agronomist
Kansas State University
Southwest Research-Extension Center
Tribune, Kansas
Voice: 620-376-4761 Fax: 620-376-2278
schlegel@ksu.edu

Loyd R. Stone
Research Soil Physicist
Kansas State University
Department of Agronomy
Manhattan, Kansas
Voice: 785-532-5732 Fax: 785-532-6094
stoner@ksu.edu

Troy J. Dumler
Extension Agricultural Economist
Kansas State University
Southwest Research-Extension Center
Garden City, Kansas
Voice: 620-275-9164 Fax 620-276-6028
Email: tdumler@ksu.edu

Freddie R. Lamm
Research Irrigation Engineer
Kansas State University
Northwest Research-Extension Center
Colby, Kansas
Voice: 785-462-6281 Fax: 785-462-2315
flamm@ksu.edu

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, Kansas, 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 water productivity (CWP, grain yield divided by crop water use) 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. Lamm and Rogers (1985) developed a relationship between fall ASW and over-winter precipitation on spring ASW (Fig. 1). In a review of preplant irrigation, Musick and Lamm (1990) concluded that benefits of preplant irrigation are likely to be greatest when the soil profile is dry and growing season irrigation is reduced. With recent dry conditions in certain areas and diminished well capacities, this creates a situation where preplant irrigation may be beneficial. 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.

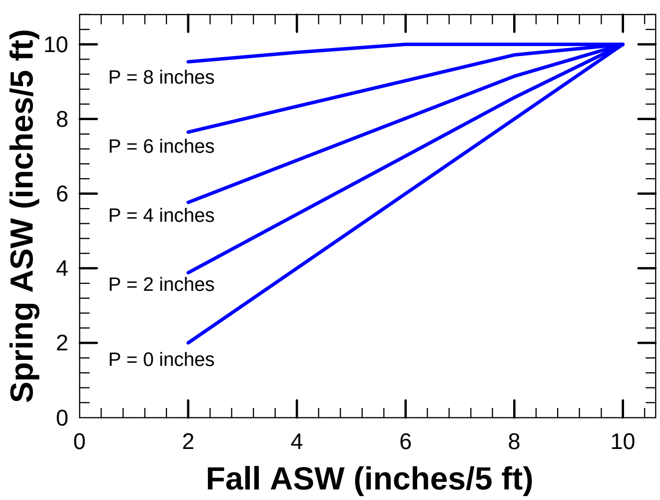


Figure 1. Available soil water in the 5 ft soil profile in the spring (May) as affected by available soil water in the fall (November) and overwinter precipitation (P). Results calculated using an equation from Lamm and Rogers, 1985.

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, Kansas 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 specified well capacities. Preseason irrigation was applied in early April and in-season irrigations were applied from about mid-June through 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 water productivity (CWP) 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 water productivity was not significantly affected by well capacity or preseason irrigation (Table 1), although the trend was for greater CWP 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 CWP. It was only at the highest well capacity that a higher seeding rate improved CWP.

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

This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

Contribution no. 12-315-A from the Kansas Agricultural Experiment Station.

This paper was originally presented at 5^{th} National Decennial Irrigation Conference, Phoenix, Arizona, 5 Dec. 2010.

REFERENCES

Lamm, F.R. and D.H. Rogers. 1985. Soil water recharge function as a decision tool for preseason irrigation. *Trans. ASAE* 28: 1521-1525.

Musick, J.T. and F.R. Lamm. 1990. Preplant irrigation in the central and southern High Plains - A review. *Trans. ASAE* 33: 1834-1842.

Rogers, D.H. and F.R. Lamm. 1994. Soil water survey after corn harvest in northwest Kansas. *Appl. Eng. Agric.* 10(1): 37-40.

Stone, L.R., C.G. Carlson, T.L. Hanson, R.E. Gwin, Jr., P. Gallagher, and M.L. Horton. 1983. Amount of profile water in early spring resulting from increased profile water in fall. *Soil Sci. Soc. Am. J.* 47: 305-309.

Stone, L.R., R.E. Gwin, Jr., P.J. Gallagher, and M.J. Hattendorf. 1987. Dormant-season irrigation: Grain yield, water use, and water loss. *Agron. J.* 79: 632-636.

Stone, L.R., F.R. Lamm, A. J. Schlegel, and N. L. Klocke. 2008. Storage efficiency of off-season irrigation. *Agron J.* 100: 1185–1192.

Stone, L.R., A.J. Schlegel, F.R. Lamm, and W.E. Spurgeon. 1994. Storage efficiency of preplant irrigation. *J. Soil Water Conserv.* 49: 72-76.

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

Well capacity	Pre-season irrigation	Seed rate	Grain yield	Crop water 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, Kansas, 2006 - 2009.

Well capacity	Pre-season irrigation	Seed rate	Available soil water: Planting	Available soil water: Harvest	Water use	Non-growing 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, Kansas 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

Corn research plots being irrigated with a lateral move sprinkler irrigation system at Kansas State University.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

NEBRASKA AGRICULTURAL WATER MANAGEMENT NETWORK (NAWMN) UPDATE

Gary L. Zoubek
Extension Educator

University of Nebraska-Lincoln
York, Nebraska
Voice: 402-362-5508
Email: gzoubek1@unl.edu

Suat Irmak
Soil and Water Resources and Irrigation Engineering
University of Nebraska-Lincoln
Lincoln, Nebraska
Voice: 402-472-4865
Email: sirmak2@unl.edu

Jenny M. Rees
Extension Educator
University of Nebraska-Lincoln
Clay Center, Nebraska
Voice: (402) 762-3644
Email: jrees2@unl.edu

Brandy VanDeWalle
Extension Educator
University of Nebraska-Lincoln
Geneva, Nebraska
Voice: (402) 759-3712
Email: bvandewalle2@unl.edu

Water is the life support of irrigated and rain-fed agriculture and economy of Nebraska and other Central Plains and mid-western states. Nebraska's approximately 8.5 million acres of irrigated lands are extremely vital to the state's economy with an approximate five billion dollars per year of revenue.

Withdrawal of fresh water resources for irrigation in Nebraska represents the largest of the state's water pumping demands. Irrigated agriculture consumes more than 90 percent of groundwater pumped in Nebraska (Irmak et al., 2010).Thus, *c*ollaborating to maximize the net benefits of irrigated crop production is of growing importance in Nebraska as we need to produce more food with less water. Many areas in the state are involved in significant management changes to conserve irrigation water (Irmak et al., 2010).

The Nebraska Agricultural Water Management Demonstration Network (NAWMDN) was established in early 2005 for testing cutting-edge irrigation management technologies. The Network includes growers, UNL Extension, Natural Resource Districts, the Natural Resource Conservation Service, crop consultants and other interested partners — all key to the adoption of water and energy efficiency measures.

From its inception thru 2011, the NAWMDN has grown from 15 to over 700 participants, so it is no longer a demonstration, it's a network (NAWMN)!

The NAWMN was designed to encourage farmers to adopt newer technologies associated with water and energy resources in irrigated crop production. Education and information about the use of appropriate technologies are delivered to agriculture professionals and irrigators through field demonstrations, the website, and educational meetings. Detailed descriptions of the goals and objectives of the Network, components, operational functions, and procedures used as well, as the quantitative impacts in terms of water and energy conservation, have been reported in (Irmak et al., 2010).

History and Goals….
The NAWMN partnership in 2005 between UNL Extension, the Upper Big Blue Natural Resources District, and 15 growers from south central Nebraska expanded to include the state Natural Resources Conservation District (NRCS) in 2006. The demonstration projects that started in the Upper Big Blue NRD were extended to other parts of the state and NRDs in 2007 and subsequent years.

The goal of the NAWMN is to transfer high quality information to Nebraska producers through a series of demonstration projects established in farmers' fields, and to implement newer tools and technologies to enhance crop water use efficiency and energy savings.

We believe that this interdisciplinary demonstration project:

- Increases the adoption of appropriate newer technologies and methods to obtain higher crop water use efficiency on a field scale.
- Enhances communication and information exchange between farmers, research faculty, academics, NRCS, UNL Extension, NRDs, and other state and federal agencies.
- Promotes water conservation.

The NAWMN is working hand-in-hand with growers and crop consultants on strategies on how to achieve efficiency through a series of field demonstrations, initiated in the Upper Big Blue NRD in south central Nebraska.

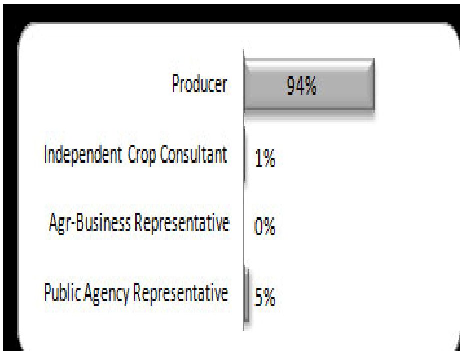
The demonstration project is supported by the extensive research projects conducted by Suat Irmak on newer technologies at the South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska where research on the accuracy, durability and other operational characteristics of ET-based ET gages and Watermark sensors and other type of soil moisture and ET measurement technologies have been investigated since April 2004.

Suat Irmak, UNL Irrigation Specialist, and Extension Educators from UNL Extension and Upper Big Blue NRD (UBBNRD) personnel developed a partnership to initiate the Network and install ETgages and Watermark sensors in producer's fields to teach producers strategies for water and energy conservation. Due to the success of the Network, the UBBNRD cost shared with producers and consultants for the equipment in 2006. This became the pattern in successive years as more partners joined with equipment cost-share coming from the local NRD's. A grant was obtained from the USDA to allow for expansion of the NAWMN statewide.

The two primary tools adopted initially in the Network are ETgages and Watermark sensors. The ETgage is used to estimate crop water use from reference evapotranspiration and crop coefficient information. The Watermark sensors are used to monitor available water in the crop root zone over time. The Network participants learn how to utilize these tools to make better-informed decisions in their irrigation management operations.

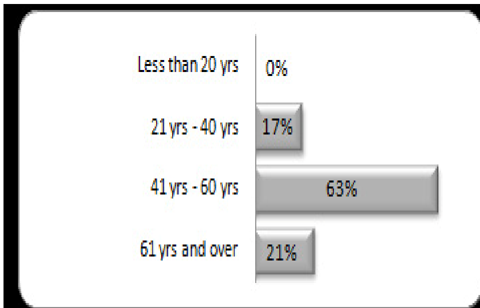
In addition to the demonstration projects, the information is shared and delivered to Network participants and others through field days, seminars, workshops, outreach publications, media reports, refereed journal articles, etc. A webpage was developed and producers were encouraged to post ETgage data on the website on a weekly basis to encourage the use of this information. In addition, High Plains Regional Climate Center automatic weather station data is also available.

Following the 2010 season, 506 NAWMN participants were surveyed to measure the Network's impact. Two hundred and eight participants or 41% responded and they reside in 36 counties across Nebraska. Several demographic questions were asked. Ninety four percent of the respondents were producers and 63% were in the 41-60 year age bracket and nearly 60% have been involved in the network for three or more years. See the following tables for some demographic information.



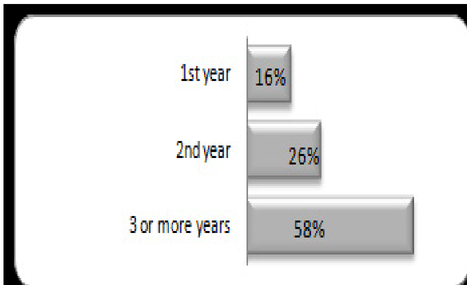
Which of the following do you consider your PRIMARY occupation?

	#	%
Producer	192	94%
Independent Crop Consultant	3	1%
Agr-Business Representative	0	0%
Public Agency Representative	10	5%
Total respondents to this question	205	99%



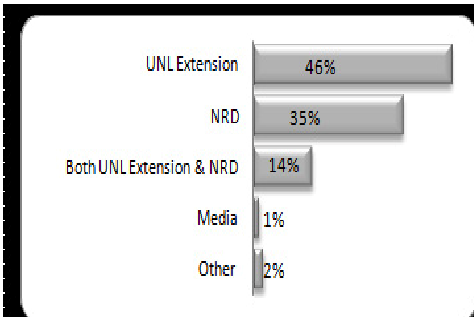
Which age category best describes you?

	#	%
Less than 20 yrs	0	0%
21 yrs - 40 yrs	34	17%
41 yrs - 60 yrs	128	63%
61 yrs and over	42	21%
Total respondents to this question	204	98%



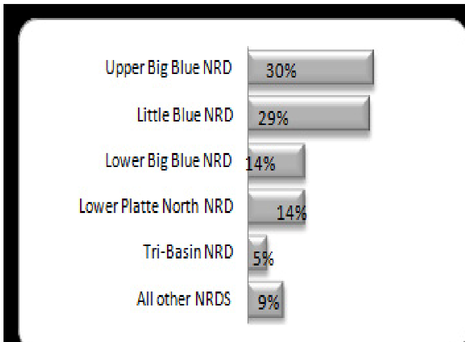
How many years have you been involved with the NAWMN?

	#	%
1st year	32	16%
2nd year	53	26%
3 or more years	119	58%
Total respondents to this question	204	98%



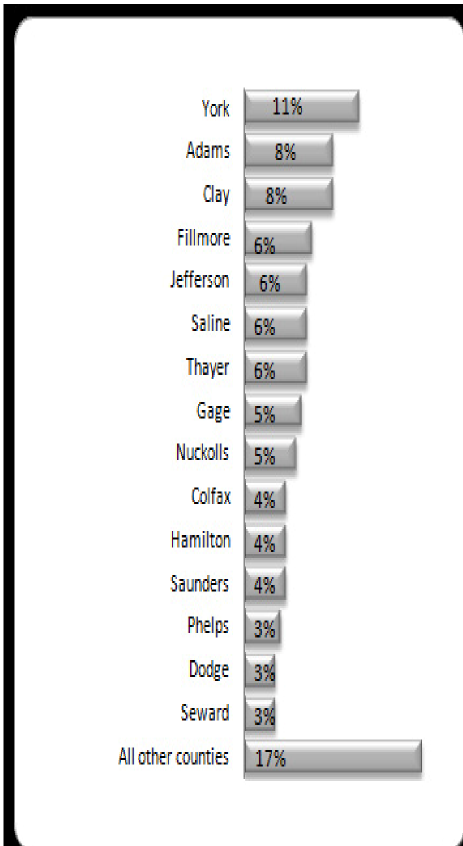
Where did you hear about this program?

	#	%
UNL Extension	94	46%
NRD	71	35%
Both UNL Extension & NRD	28	14%
Media	3	1%
Other	5	2%
Total respondents to this question	204	98%



What NRD do you reside in?
Responses from 36 counties were received.

	#	%
Upper Big Blue NRD	61	30%
Little Blue NRD	59	29%
Lower Big Blue NRD	28	14%
Lower Platte North NRD	28	14%
Tri-Basin NRD	10	5%
All other NRDS	18	9%
Total respondents to this question	204	98%



What County do you reside in?

	#	%
York	22	11%
Adams	17	8%
Clay	17	8%
Fillmore	13	6%
Jefferson	12	6%
Saline	12	6%
Thayer	12	6%
Gage	11	5%
Nuckolls	10	5%
Colfax	8	4%
Hamilton	8	4%
Saunders	8	4%
Phelps	7	3%
Dodge	6	3%
Seward	6	3%
All other counties	34	17%
Total respondents to this question	***203***	***98%***

The surveyed participants were asked to identify their interest in reducing inputs such as energy costs, water usage, improving irrigation efficiency, networking with other producers, practicing irrigation management and increasing knowledge of irrigation management technologies. Seventy one percent of the responses were to reduce energy input costs and to improve irrigation efficiency on their farm.

Participants were asked to estimate their water applications to both corn and soybean crops in 2010. Irrigation application amounts on corn and soybean crops varied from 0 to11 inches and averaged 5.4 inches on corn and 4.6 inches on soybeans. When asked to estimate their savings, the average response was 2.4 inches on corn and 2.1 inches on soybeans. Annual participant surveys showed average irrigation water savings of 2.0 inches for both corn and soybeans the past five years along with the associated energy savings.

As of 2011, the number of active growers who have joined the NAWMN has increased to more than 700. Irrigated acreage that were represented by the NAWMN producers has increased from 1,482 acres in 2005 to 342,500 acres in 2010. Due to the information and strategies taught in the NAWMN participants are changing their behaviors of how they manage irrigation and as a result, the NAWMN is having significant impacts.

When asked if using the equipment or the NAWMN information influenced the growers on the amount of irrigation water applied. 97% of the respondents indicated '**yes'.** The participants were asked if they planned to be involved in the NAWMN the following year and 98% indicated yes!

The NAWMN and technology is assisting growers to reducer inputs such as energy costs, water usage, improving irrigation efficiency, and networking with other producers practicing irrigation management and increasing knowledge of irrigation management technologies.

The NAWMN is continually working to increase its outreach, increasing by 200 members in 2011.

The NAWMN is striving to improve and expand and survey respondents share valuable insights and suggestions to help the program reach a larger audience. The 2010 survey respondents made the following suggestions when asked what did you like best about the NAWMN program?

Savings - 30 responses
- Saving both water and dollars!
- Saving fuel!
- Water conservation - more crop per drop!
- Most people know that underwatering a crop hurts, many don't realize the damage they do overwatering.

Confidence—19 responses
- Knowing!
- Taking the guesswork out.
- Piece of mind & dollars in my pocket!

Support - 22 responses
- Extension & NRD support!
- Assistance from Extension Educator.
- Help!
- One on one support!
- Guidance!
- Adopting at my pace.

New Technology - 22 responses
- Information on what's new.
- Another tool!

On my farm - 9 responses
- Gathering ET data on my farm!
- The large area involved & ET readings next to my crop.
- Bring the technology out to the farm and demonstrating it!
- Local ET.

Information & Training - 21 responses
- Hands on!
- A better source of information!
- Being able to use the work of others.
- Self help.
- My own field trials and experiences!

When asked how the NAWMN could be improved and expanded they responded:

Technology - 19 responses
- ***"Continue to monitor and try newer technologies to remain on the cutting edge."***
- Continue your research efforts.
- Look for more automated ways to collect the needed information.
- Look for ways to relay the information to the home computer/Ipad.
- Develop permanent sensor installation protocols.

Website Updates - 7 responses
- Daily Updates on website of ETgage readings.
- Have a different color on ETgages not reporting.
- More timely reporting of ETgage readings.
- Make the website more user friendly.

Training - 13 responses
- ***"Should be required for at least one field for every producer to realize the benefits - maybe incorporate into pesticide certification."***
- I'd like a good pocket-sized, laminated card with the readings on it.
- More than one training session per year.
- More training on tying atmometer with sensors and how to use the two.

Good Program - 14 responses
- ***"We are in a big growth year, we are doubling the numbers of our first three years. It's working for producers and the 1.5 - 2" of water saved is a significant cost item as well as a valuable resource."***
- Keep doing what you are and encourage more producers.
- Keep up the work and continue to refine the program.

Cost Share - 10 responses
- ***"Continue to cost share & provide technical support!"***
- Cost sharing on equipment is an excellent way to expand the program.
- Encourage more NRD involvement.

Other - 3 responses
- ***"Over come the "herd instinct" that everyone else is watering then I should too!"***
- Mandate all producers that farm 1,000 acres + use this system.

When asked to share any additional thoughts with the NAWMN team participants responded:

Great Program:
- "I feel that this program has saved us more irrigation water & fuel than anything! We are 150% sold on it. We use it on all our pivots!"
- "Could not trust the thing the first year. Now I have confidence in them."
- "This the best program ever for knowing when to irrigate and when not to!"
- "Really appreciated the knowledge gained utilizing this program. Thanks!"
- "Keep up the Great work -- This is a "Premier Irrigation Event"."
- "This is a well-run program and can save a lot of our water resources."
- "Great program, state wide would reduce water use."

Training:
- "The program allowed for learning and flexibility to change with conditions and schedule and I the producer had control."
- "I'm not much for meetings. I prefer short sit downs with local extension educator, NRCS and NRD staff."

Research/Technology:
- "Get the sensors compatible with pivot panels so we can check them from our computer."
- "Good concept, we need to go from Stone Age devices to what's available today!"
- "We need to continue to research the last watering!"

In General:

- “The NRD is requiring flow meters, but it might be more important to know when to irrigate rather than how much you pumped? A combination of both would be good.”
- “I've had some great Extension Educator support.”
- “For me the ETgage was easier to monitor and read making it a better choice for me.”
- “The ETgage doesn't know if I have 36,000 or 25,000 plants/acre, but Watermark sensors do!”

The goal of the NAWMN is to enable the transfer of high quality information to Nebraskans through a series of demonstration projects established in farmers' fields, and to implement newer tools and technologies to enhance crop water use efficiency and energy savings.

Growers, crop consultants, state and federal water regulatory agencies and other interested partners can contact any one of the members of the NAWMN if they would like to sign up to be a part of the network and efforts.

Contacts and additional information about the NAWMN can be found on the webpage: http://water.unl.edu/web/cropswater/nawmdn.

References

Irmak, S., J.M. Rees, G.L. Zoubek, B.S. VanDeWalle, W.R. Rathje, R. DeBuhr, D. Leininger, D.D. Siekman, J.W. Schneider, and A.P. Christiansen. 2010. Nebraska Agricultural Water Management Demonstration Network (NAWMDN): Integrating Research and Extension/Outreach. *Applied Engineering in Agriculture* 26(4):599-613.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

IRRIGATION CAPACITY IMPACT ON LIMITED IRRIGATION MANAGEMENT AND CROPPING SYSTEMS

Joel P. Schneekloth
Water Resource Specialist
Colorado State University
Akron, Colorado
(970) 345-0508
Joel.Schneekloth@Colostate.Edu

David C. Nielsen
Research Agronomist
USDA-ARS
Akron, Colorado
(970) 345-0507
david.nielsen@ars.usda.gov

Alan Schlegel
Agronomist
Kansas State University
SWREC-Tribune, KS
(620) 376-4761
schlegel@ksu.edu

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.

Lamm (2004) found that irrigation capacities of 50% of the amount 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 to 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 which coincides with the reproductive growth stages and lower precipitation during those weeks of the summer. 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 tasseling, silking and pollination.

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. It is an effective index for quantifying the degree of water stress that a crop is growing under.

METHODS

The system capacity research was conducted at the Central Great Plains Research Station near Akron, CO from 2009 to 2011 and at the KSU-SWREC near Tribune, KS from 2006 to 2009.

Akron

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 Limited, GSL). These 3 capacities represent full irrigation capacity, inadequate capacity and growth stage timing with reduced acres for an inadequate capacity well. Three varieties were tested with varying relative maturity (99, 101 and 103 days to maturity).

Corn was planted in mid to late May at populations of 28,000 plants acre^{-1} in 2009 and 33,000 plants acre^{-1} in 2010 and 2011. Fertility management was according to soil tests. Total nitrogen applied was 175 lbs acre^{-1} and phosphorus at 40 lbs acre^{-1}.

Irrigation was applied for the full and inadequate capacity treatments if there was allowable storage for the application. During the early growth stages, irrigation applications were 0.5 inch per irrigation event while later applications were 0.75 inch per irrigation. Irrigation for the GSL treatment was withheld until 2 weeks prior to tassel emergence. Irrigation applications for this treatment 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 producing 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 with a standard rain guage (NWS-type with 8” receiving orifice) in 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) in 2009 and 2010 and in each of the 48 plot (four hybrids, three irrigation treatments, four replications) in 2011. 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 (18 plots in 2009 and 2010, 24 plots in 2011). 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.

Tribune

The study was a factorial design of 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. 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). 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 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

Akron

Irrigation capacity significantly decreased grain yields compared to full irrigation (Table 1). Inadequate capacities resulted in yield reductions of 26% on average compared to full irrigation. Yield reductions were as much as 46% in 2011. When water was limited during the vegetative growth stage, yield reductions were not significant compared with full irrigation.

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 all three 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, 0.47 in 2010 and 0.70 in 2011, 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, 0.24 in 2010 and 0.09 in 2011, 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 or 2011 (CWSI = 0.09 during vegetative stages and 0.19 during reproductive stages in 2009 compared with CWSI = 0.32 during vegetative stages and 0.67 during reproductive stages in 2010 and 2011). There were no differences in CWSI due to hybrid. Yield was highly correlated with CWSI averaged over the reproductive period (Figure 1).

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 2011 with the inadequate capacity treatment, with ND4903 yielding highest (127 bu/a) and NE5321 yielding lowest (105 bu/a).

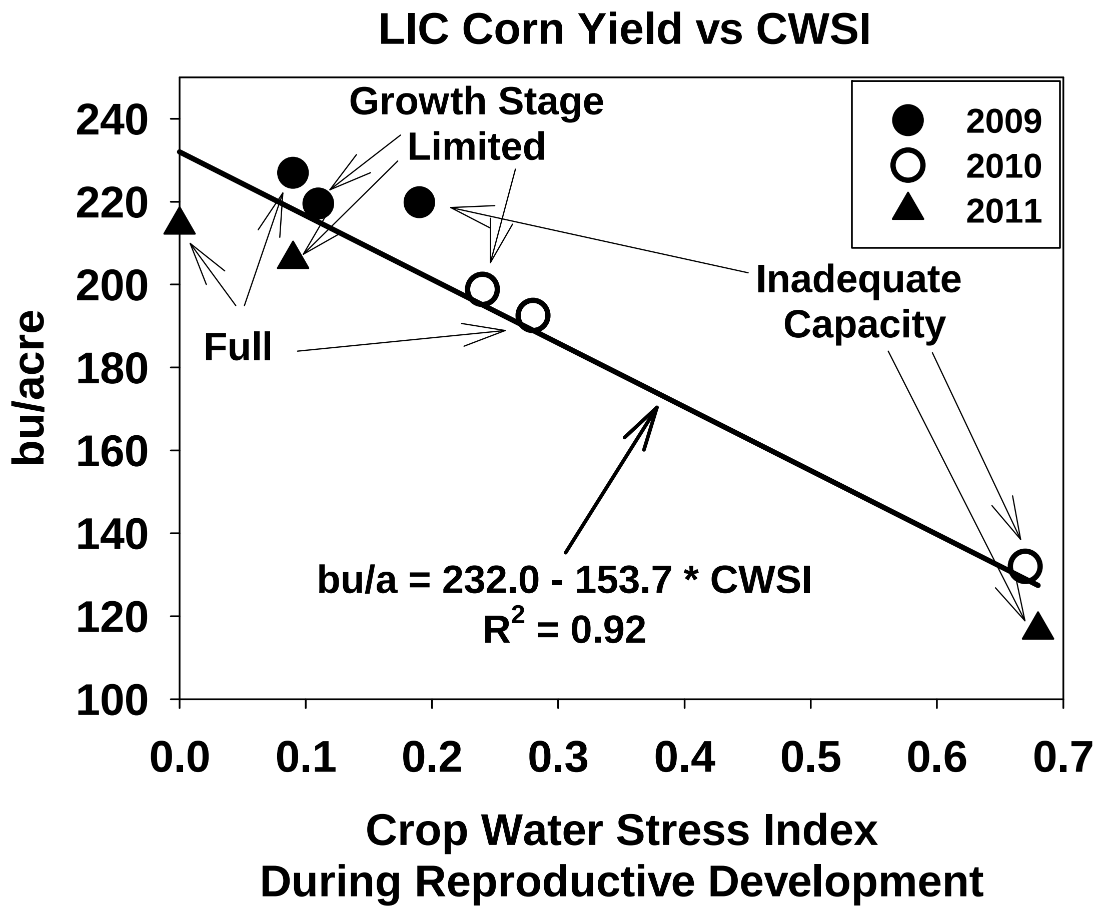


Figure 1. Corn yield vs crop water stress index.

Tribune

As expected, grain yields increased with increased well capacity. Grain yields (averaged across seeding rate) were 36% greater when well capacity was increased from 0.1 to 0.2 in day^{-1} as compared to 11% when well capacity was increased from 0.1 to 0.15 in day^{-1}. Yearly yield differences ranged from as low as 10% to as much as 75% when comparing 0.1 to 0.2 in day^{-1} showing that precipitation variability is important in determining yields.

The optimum seeding rate varied with irrigation level. With the two lowest well capacities, a seeding rate of 22,500 seeds a^{-1} was generally adequate. With a well capacity of 0.2 in day^{-1}, a seeding rate of 32,500 seeds a^{-1} provided greater yields.

Crop productivity was not significantly affected by well capacity or seeding rate (Table 2), 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 (not shown). 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. Average non-growing season precipitation was 9.3 in giving an average non-growing season precipitation storage efficiency of 29%. 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.

Overall

Yield compared to ET at Akron, CO and Tribune, KS was a linear response (Figure 2). The yield response at Akron was slightly greater than the yield response observed at Tribune. A linear response at both locations shows that as irrigation system capacity is diminished, yield reductions will occur.

Economics of irrigation with limited well capacities is important in determining the acreage of corn to be grown with a specific well capacity. At Akron and Tribune, a limited well capacity resulted in net returns to risk and management of 58% of adequate capacities (Table 3). When well capacities are such that only 50% of the irrigated acreage can be fully irrigated, total returns are only reduced by less than $6,000 when irrigating only 50% of the acres. However, during years of drought such as 2008 at Tribune and 2010 and 2011 at Akron, yield reductions by irrigating all the acres resulted in losses.

CONCLUSIONS

Timing and capacity had an impact on grain yield when precipitation was below average. With an inadequate capacity well a 25% reduction in grain yields as compared with a full irrigation capacity well was observed. Timing irrigation towards reproductive growth with a higher capacity well resulted in similar grain yields to full season irrigation with a high capacity well. 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 during reproductive development.

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 with irrigating the entire system with inadequate capacities. Variety selection is important as the yield potential can vary by water management.

REFERENCES

Gardner, B.R., D.C. Nielsen, and C.C. Shock. 1992. Infrared thermometry and the Crop Water Stress Index. I. History, Theory, and Baselines. J. Prod. Agric. 5:462-466.

Idso, S.B., R.D. Jackson, P.J. Pinter, Jr., R.J. Reginato, and J.L. Hatfield. 1981. Normalizing the stress-degree-day parameter for environmental variability. Agri. Meteorol. 24: 45-55.

Lamm, F.L., 2004. Corn production as related to sprinkler irrigation capacity. In Proceedings of the Central Plains Conference, Kearney, Nebraska, Feb 17-18, 2004. Available from CPIA 760 N. Thompson, Colby, Kansas. pp 23-36.

Li, L., D.C. Nielsen , Q. Yu., L. Ma, and L.R. Ahuja. 2010. Evaluating the Crop Water Stress Index and its correlation with latent heat and CO_2 fluxes over winter wheat and maize in the North China Plain. Agric. Water Manage. 97:1146-1155.

Nielsen, D.C., and R.L. Anderson. 1989. Infrared thermometry to measure single leaf temperatures for quantification of water stress in sunflowers. Agron. J. 81:840-842.

Nielsen, D.C., and B.R. Gardner. 1987. Scheduling irrigations for corn with the crop water stress index (CWSI). Appl. Agric. Res. 2:295-300.

Schneekloth, J.P., 2005. Response of irrigated sunflower to water timing. In Proceedings of the Central Plains Conference, Sterling, Colorado, Feb 17-18, 2005. Available from CPIA 760 N. Thompson, Colby, Kansas. pp 44-50.

Shaw, R.H. 1976. Climatic requirement. p. 591-623. *In* G.F. Sprague (ed.) Corn and corn improvement. Agron. Monogr. 18. ASA, CSSA, and SSSA, Madison, WI.

Sudar, R. A., K. E. Saxton, and R. G. Spomer. 1981. A predictive model of water stress in corn and soybeans. Transactions of ASAE, 24:97-102

Table 1. Evapotranspiration, yield, and crop water stress index for irrigation capacities and strategies for 2009, 2010, and 2011.

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
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
2011	Full	ND4903	21.05	223.1	0.02	0.03	0.01
		TXP151	22.13	221.4	0.03	0.03	0.03
		NE5321	21.63	202.4	0.04	0.08	-0.01
		NC5209	20.69	210.7	0.01	0.04	-0.03
	Growth Stage	ND4903	21.47	205.9	0.47	0.77	0.13
		TXP151	21.77	217.8	0.41	0.69	0.07
		NE5321	21.81	203.6	0.30	0.53	0.03
		NC5209	19.65	197.2	0.48	0.79	0.12
	Inadequate Capacity	ND4903	19.10	127.2	0.37	0.14	0.62
		TXP151	18.55	119.2	0.38	0.14	0.66
		NE5321	18.93	105.2	0.42	0.18	0.70
		NC5209	18.91	115.3	0.44	0.19	0.73
	Avg. by Irrigation	Full	21.37	214.4	0.02	0.04	0.00
		GSL	21.17	206.1	0.41	0.70	0.09
		Inad CP	18.87	116.7	0.40	0.16	0.68

†Averaged over all measurements taken: 7/1 to 9/8/2009, 6/29 to 8/31/2010, and 7/18 to 9/1/2011

‡Averaged over vegetative development

ζ Averaged over reproductive development

Table 2. Crop parameters of corn as affected by well capacity and seeding rate (without preseason irrigation), Tribune, KS, 2006 - 2009

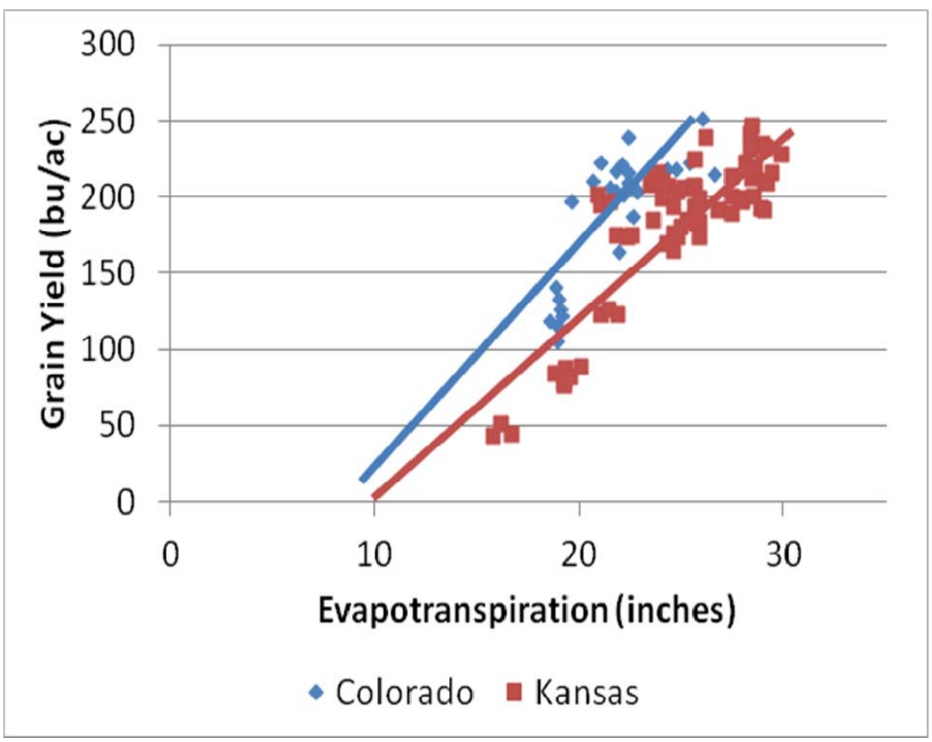
Well Capacity			Seed rate	Avg. Grain Yield	2006 Grain Yield	2007 Grain Yield	2008 Grain Yield	2009 Grain Yield	Avg Crop Prod.
in day^{-1}			10^3 a^{-1}	bu a^{-1}	bu a^{-1}	bu a^{-1}	bu a^{-1}	bu a^{-1}	lb ac-in^{-1}
0.1			22.5	150	175	197	44	183	379
			27.5	155	174	202	51	192	389
			32.5	152	175	195	45	194	382
0.15			22.5	169	181	207	89	197	381
			27.5	170	194	216	77	193	387
			32.5	167	176	204	79	211	375
0.2			22.5	196	201	214	170	197	395
			27.5	207	219	235	165	207	405
			32.5	218	223	242	185	222	430
MEANS	Well cap.	0.1		152	175	198	47	190	383
		0.15		169	184	209	82	200	381
		0.2		207	214	230	173	209	410
		$LSD_{0.05}$		20	26	20	39	15	43
	Seed rate	22,500		171	186	206	101	192	385
		27,500		177	196	218	98	197	394
		32,500		179	191	214	103	209	395
		$LSD_{0.05}$		10	12	7	11	7	26

Table 3. Net return to risk and management from three irrigation well capacities and three seeding rates at Tribune, KS and irrigation well capacity and management at Akron, CO.

Tribune			
Well capacity	Seeding rate (10^3 a^{-1})		
	22.5	27.5	32.5
in day^{-1}	Net return, \$ a^{-1} yr^{-1}		
0.1	\$346	\$359	\$334
0.15	\$419	\$414	\$389
0.2	\$533	\$575	\$620

Akron	
	Net return, \$ a^{-1} yr^{-1}
Inadequate	\$356
Growth Stage Limited (GSL)	\$599
Full	\$620

Figure 2. Yield vs Evapotranspiration for Akron, CO and Tribune, KS.



Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

WATER PRODUCTION FUNCTIONS FOR CENTRAL PLAINS CROPS

THOMAS J. TROUT and **WALTER C. BAUSCH**
USDA-ARS-Water Management Research
2150 Centre Ave., Bldg D, Fort Collins, CO 80526
970-492-7419 thomas.trout@ars.usda.gov

Abstract. *Sustaining irrigated agriculture with limited water supplies requires maximizing productivity per unit of water. Relationships between crop production and water consumed are basic information required to maximize productivity. This information can be used to determine if deficit irrigation is economically desirable and how to best manage limited water supplies. Field trials of corn, sunflower, dry bean, and wheat production with six levels of water application were used to develop water production functions based on consumptive use and to better understand water timing effects and crop responses to stress. Initial results indicate linear relationships between yield and crop ET. The field data are being used to improve and validate crop models so they can be used to generalize the field results for other climate and soil characteristics.*

INTRODUCTION

Irrigation water supplies in the Central Plains and much of the western U.S. are declining. Supplies originally developed for irrigated agriculture are being diverted to growing urban areas and for ecosystem restoration. Groundwater use in many areas must decrease if we are to reduce depletion of this valuable resource. Temperature increases due to climate change will likely reduce the mountain snowpack accumulation that is critical to surface water supplies. Irrigated agriculture will very likely have less water available in the future than it had in the past. Sustaining irrigated agriculture will require increasing the economic productivity per unit of water.

Past studies have shown that the reduction in yield is often less than the reduction in irrigation water applied - for example, a 30% reduction in irrigation may result in only a 10% reduction in yield (Zang, 2003). This means the marginal productivity of irrigation water applied tends to be low when water application is near full irrigation. However, as the water deficit increases, higher marginal productivity may result either from higher efficiency of water applications (less deep percolation, runoff, and evaporation losses from irrigation and better use of precipitation), or from a physiological response in plants that increases productivity per unit water consumed when water is limited. Increasing marginal productivity of water with deficit irrigation indicates that deficit irrigation may be a way to maximize economic returns per unit irrigation water.

Past studies have also shown that yield relationships based on water consumption or evapotranspiration are often linear (Doorenbos et al., 1986). This implies that the marginal productivity of the water is constant and deficit irrigation may be no more productive per unit water consumed than full irrigation. If this is the case, where deep percolation and runoff losses can be reused and have value, full irrigation on a reduced irrigated area may provide higher economic returns for the watershed. In many western watersheds, water is effectively reused, and in fact, reuse of irrigation water return flows is the legal water right of downstream users. For example, Colorado water law allows transfers to other uses only of the estimated consumptively used portion of a water supply; the return flows must be maintained for downstream users.

Thus, it is critical to understand the water balance and water law in a watershed to establish the value of water for crop production and means to maximize irrigation productivity. Improved irrigation efficiency is not likely to produce much “new” water because it results primarily in a reduction of return flows rather than a reduction in ET, and even deficit irrigation is economically viable only if the marginal productivity of consumed water increases substantially.

Although many limited irrigation studies have been carried out in the Central Plains and around the world, we feel there continues to be a need for more information on crop responses to deficit irrigation. So, in 2008, USDA-ARS began a field study of the water productivity of 4 common Central Plains crops under a wide range of irrigation levels from fully irrigated to about 40% of full irrigation. We are measuring ET of the crops under each of these conditions and seeking ways to maximize productivity per unit water consumed. We also strive to better understand and predict the responses of the crops to deficit irrigation so that limited irrigation water can be scheduled and managed to maximize yields.

METHODS

A 50 acre research farm northeast of Greeley, CO – the Limited Irrigation Research Farm, or LIRF - was developed to enable the precision water control and field measurements required to accurately measure ET of field crops. The predominately sandy-loam soils and good groundwater well are ideal for irrigation research.

Four crops – field corn, sunflower (oil), dry beans (pinto), and winter wheat were rotated through research fields on the farm. Crops are planted, fertilized, and managed for maximum production under fully-irrigated conditions, but are irrigated at 6 levels that range from fully irrigated to 40% of the fully irrigated amount. Deficit irrigations are timed to maximize production – usually by allowing relatively higher stress during mid-to-late vegetative and late maturity stages and applying extra water to reduce stress during reproductive stages.

Each crop field was divided into 4 replications in which the 6 irrigation treatments were randomized. Water was regulated, measured, and delivered to each 12 row (30 ft) x 140 ft plot. We applied irrigation water with drip irrigation tubes placed on the soil surface in each crop row to insure that the water was applied uniformly. This was essential to be able to complete the water balance. Figure 1 shows an aerial view of the research fields in 2008.

A CoAgMet (Colorado Agricultural Meteorological Network) automated weather station was installed on the farm in a 1 acre grass plot. Hourly weather data from the station were used to calculate ASCE Standardized Penman-Monteith alfalfa reference evapotranspiration (ETr). Soil water content between 6 inch and 7 ft depth was measured by a neutron probe from an access tube in the center of each plot. Soil water content in the surface 6 inches was measured with a portable TDR system (MiniTrase, SoilMoisture, Inc., Santa Barbara, CA)*****. Soil evaporation was estimated based on techniques described in Allen et al. (1998). Basal crop coefficients were adapted from Table 8.8 in Allen et al. (2007) based on full cover date. Irrigations were scheduled using both predicted soil water depletions based on ETr measurements, and measured soil water depletion.

Figure 1. Aerial view of the water productivity plots at LIRF in 2008. Crops from left to right are beans, wheat, sunflower, and corn. Lower fields contain Bowen Ratio instrumentation.

---

[*] Equipment brand names are provided for the benefit of the reader and do not imply endorsement of the product by USDA.

Plant measurements were taken periodically to determine crop responses to the water levels. We recorded plant growth stage and measured canopy cover with digital cameras. The digital camera along with spectral radiometers and an infrared thermometer were mounted on a "high boy" mobile platform and driven through the plots weekly (Figure 2). Indicators of crop water stress such as stomatal conductance and leaf water potential were measured periodically. Canopy temperature was measured continuously with stationary infrared thermometers and periodically with the mobile platform (Bausch et al., 2010). At the end of the season, seed yield and quality as well as total biomass were measured in each plot. On two fields on the farm, crop ET was measured with energy balance instruments (Bowen Ratio method) for well-watered crops. These measurements allow crop coefficients to be estimated for the crops.

An important part of the research is to extend the results beyond the climate and soils at LIRF. We are working with the ARS Agricultural Systems Research group to use this field data to improve and validate crop models. Once we have confidence in the models, we can estimate crop water use and yields over a wide range of conditions.

Figure 2. High Boy reflectance tractor measuring canopy reflectance and temperature.

RESULTS

We will summarize the four years of corn (Dekalb DKC52-59 (VT3)) results in this paper. Figure 3 shows the seasonal water balance for the 2011 corn crop for the 6 irrigation treatments. The irrigation applications varied from 6 to 19". Of the 8" of seasonal precipitation, about 1.2" was lost by deep percolation from the 100% treatment and none was lost from the lowest two irrigation treatments. All treatments ended the season will slightly increased soil water storage due to late season rainfall. With deep percolation and storage changes, the ET varied only between 13 to 24". In all years, ET of the fully-irrigated crop averaged 23" and of the most stressed crop, 14". Irrigations were timed such that plant water stress for the deficit irrigation levels was least between tasseling and soft dough (growth stages VT to R4).

The wide range of irrigation applications resulted in substantial differences in crop growth. Figures 4 and 5 show a comparison of plant height and ground cover in early August, 2008 as the corn was beginning to tassel.

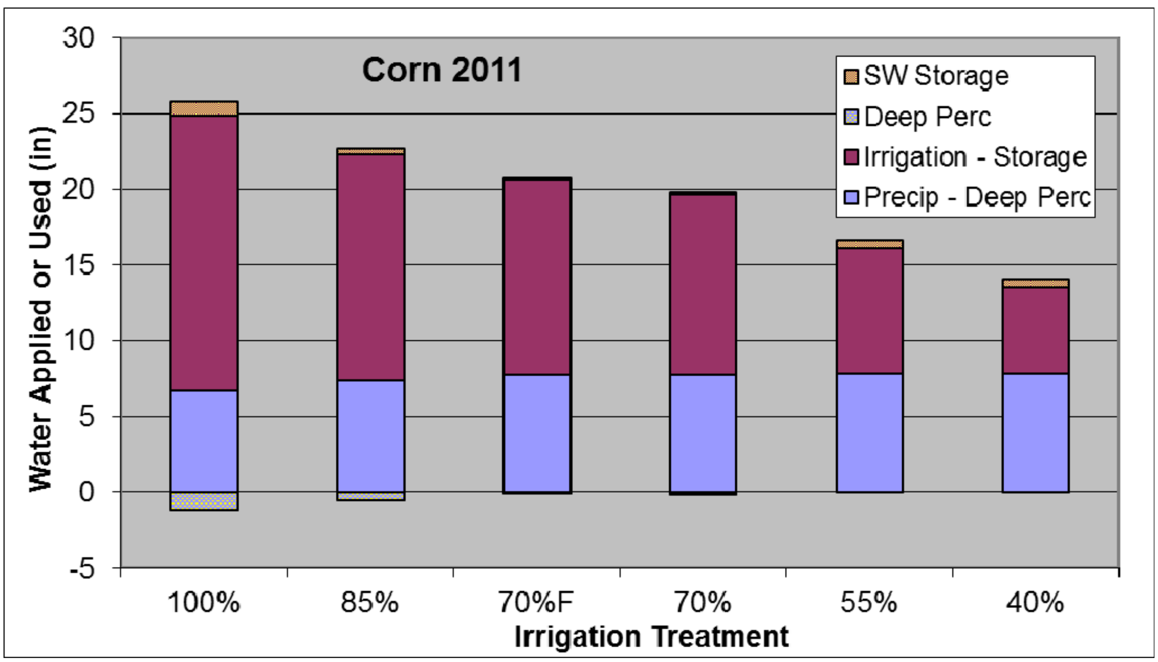


Figure 3. Water balance for the 2011 corn crop showing precipitation, irrigation, and seasonal soil water storage changes. Bars below zero represent deep percolation losses.

Figure 4. Comparison of corn growth condition on Aug 4, 2008 just before tasseling. Rows at the left and background were fully irrigated; rows at right were the lowest irrigation level.

(a) Full irrigation: 91% ground cover (b) Low irrigation: 63% ground cover

Figure 5. Overhead photos showing corn canopy on Aug 1, 2008.

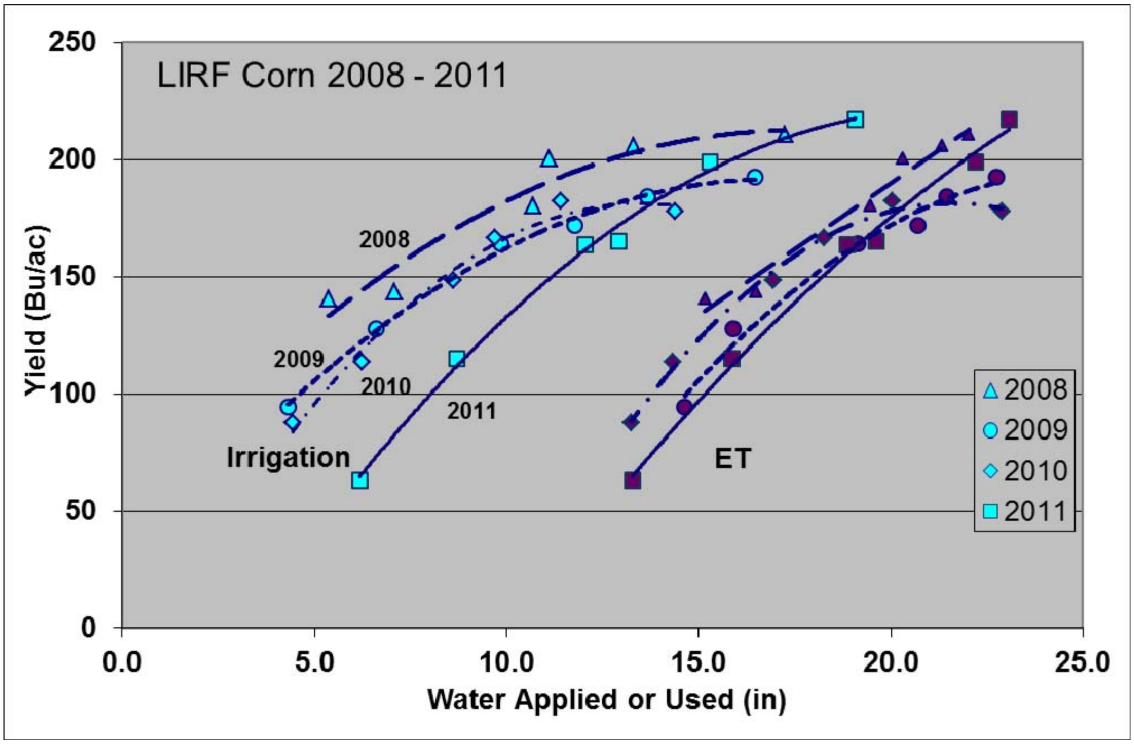


Figure 6. Water production functions for 2008 - 2011 corn at LIRF. Left curves are yield vs. irrigation water applied; right curves are yield vs ET.

Figure 6 shows the yield:water relationship for corn for each year. Grain yields varied from over 200 bu/ac at full irrigation to under 100 bu/ac at low irrigation. Hail damage in 2009 resulted in about 15% lower grain yields. The reason for the relatively low yield with full irrigation in 2010 is not known. Harvest index (the portion of total above-ground biomass that is grain) ranged from 50 – 60% and did not vary with irrigation level.

The water production function curves based on applied irrigation water tends to flatten (get horizontal) as the water application increases because the increase in yield for each unit increase in water applied tends to decrease as irrigation increases. This means that the marginal productivity of irrigation water (additional yield per unit additional water) is relatively low near full irrigation, showing the potential benefit to the farmer of deficit irrigating and using the water for higher-valued uses. The marginal value of water decreases from about 15 bu/ac-in. of irrigation water applied at the lowest irrigation level to less than 4 bu/ac-in. near full irrigation. The marginal value of irrigation above full irrigation requirements would be zero. Likewise, the water use efficiency (absolute yield per unit water applied), tends to increase with deficit irrigation. This shows a possible economic benefit to deficit irrigation.

However, the water production function for grain yield based on ET is relatively linear (straight line). This implies that, once sufficient water is available from rainfall or irrigation to produce grain (about 10 in.), the corn is equally efficient in its use of every additional unit of water consumed and the marginal value of the consumptively used water is fairly constant over the wide range of applications – about 15 bu/ac-in. Beyond full irrigation, the yield would not increase and line would be expected to be horizontal. Because of the initial water requirement to produce yield, the water use efficiency decreases with deficit irrigation from about 9 bu/ac-in. at full irrigation to about 8 bu/ac-in. at 16 in. of consumptive use and eventually to zero at about 10 in. of consumptive use.

For our highly uniform drip irrigation system, most of the increase in the marginal value of applied water with deficit irrigation results from more effective use of precipitation and increased use of stored soil water, or conversely, the lower marginal value of water near full irrigation is due to inefficient use of rainfall and irrigation water. The marginal value of applied water near full irrigation would be even smaller with less efficient irrigation systems since more of the applied water would be lost to runoff, deep percolation, and possibly surface evaporation.

These results imply that, based on consumptive use, there would be no yield benefit to deficit irrigation compared to fully irrigating only a portion of the land. Fully irrigating less land would likely provide higher economic return due to lower production costs of fallowed land compared to cropped land.

These results demonstrate the importance of developing water production functions based on the relevant unit of water. If water value is based on cost of the water supply (eg. pumping costs from a well), then productivity based on applied water is important and deficit irrigation might be a good economic practice. However, if water costs or value is based on consumptive use (eg. for the purpose of transferring consumptive use savings), the productivity would be based on water consumed and deficit irrigation based on consumptive use savings may not be beneficial. If the crop is efficient at converting increased consumptive use to yield, as was corn in these trials, there may be no economic benefit to limited irrigation. In areas with declining groundwater, if water that is not evapotranspired percolates to the groundwater and can be repumped, consumptive use, rather than amount pumped, may be the more important unit of water to consider.

CONCLUSION

Although the yield per unit of applied water will generally increase with deficit irrigation, the yield per unit of consumptive use for corn tends to decrease with deficit irrigation. Thus, in watersheds where return flows are effectively used downstream, deficit irrigation may not increase overall irrigated production in the watershed and may not be economically viable for farmers.

REFERENCES

Allen, R.G., L.S. Pereira, D.Raes, and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage paper # 56. FAO, Rome.

Allen, R.G., J.L Wright, W.O. Pruitt, L.S. Pereira, M.E. Jensen. 2007. Water Requirements. Ch 8 in G.J. Hoffman, R.G. Evans, M.E. Jensen, D.L. Martin, and R.L. Elliott (eds) *Design and Operation of Farm Irrigation Systems* (2^{nd} Ed). ASABE, St. Joseph, MI.

Bausch, W., T.J. Trout and G. Buchleiter. 2010. Evapotranspiration estimates for deficit irrigated crops. *In* Proceedings of the 5th Decennial National Irrigation Symposium. Phoenix, AZ. Dec 5 – 8, 2010. ASABE, St. Joseph, MI.

Doorenbos, J. and A.H. Kassam. 1986. Yield Response to Water. Irrigation and Drainage Paper #33, FAO, Rome.

Zang, H. 2003. Improving water productivity through deficit irrigation: examples from Syria, the North China Plain and Oregon. Ch 19 in Kinje, J.W., R. Barker, and D. Molden (eds). *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CABI Publishing. Wallingford, UK.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N. Thompson, Colby, Kansas

ERRATICITY OF SPRINKLER IRRIGATED CORN IN 2011

Freddie R. Lamm
Research Irrigation Engineer
Kansas State University
Colby, Kansas
Voice: 785-462-6281
Fax: 785-462-2315
flamm@ksu.edu

Terry A. Howell
Agricultural Engineer
USDA Agricultural Research Service
Bushland, Texas
Voice: 806-356-5746
Fax: 806-356-5750
terry.howell@ars.usda.gov

James P. Bordovsky
Agricultural Engineer
Texas AgriLife Research, Texas A&M
Lubbock / Halfway, Texas
Voice: 806-889-3315
Fax: 806-889-3416
j-bordovsky@tamu.edu

INTRODUCTION

A definition:

> erraticity (ĭr·ə·tĭs'·ĭ·tē) *n.* The quality or state of being erratic, characterized by the lack of consistency, regularity or uniformity.

That's correct, there is no such word, but you sure know it when you see it. Unfortunately, we saw a lot of it this past season in sprinkler irrigated corn.

Figure 1. Nonuniformity of sprinkler irrigated corn under extreme drought conditions in southwest Kansas in 2011.

These instances of erraticity resulted in low quality, low- or non-yielding corn production. Crop water stress caused by the extreme drought in portions of the central and southern Great Plains is ultimately responsible for the erraticity. However, there may be ways to reduce erraticity and its harmful effects by improvements in design and management of center pivot sprinklers for corn production that can minimize water losses.

SPRINKLER PACKAGE EFFECTS ON WATER LOSSES

Center pivot sprinkler management techniques to avoid water losses begin at the design and installation stages with selection of an appropriate sprinkler package. Typical sprinkler packages in use to today are medium and high pressure impacts which are located on top of the sprinkler span (approximately 12 to 15 ft height above soil surface), low pressure rotating spray nozzles which are typically located on the span or at least above the crop canopy, low pressure fixed spray applicators that are located above and within the crop canopy and LEPA (low energy precision application) that are located near the ground surface (usually 1 to 2 ft maximum height above soil surface). Commercial LEPA applicators often can apply water in multiple modes (e.g., bubble mode with little or no wetting of the canopy, fixed spray mode, and chemigation mode that sprays the undersides of the leaves). The popular low pressure fixed spray applicators have also been categorized by their location with respect to the canopy with the terms LESA (low elevation spray application, 1 to 2 ft maximum height) and MESA (mid elevation spray application, 5 to 10 ft maximum height) (Howell, 1997). Application with MESA is typically above the crop canopy for all or most of the crop season depending on the crop (e.g., MESA application occurs within top portions of corn canopy in last 30 to 40 days of irrigation season). There are numerous water loss pathways using center pivot sprinklers and each type of sprinkler package has advantages and disadvantages as outlined by Howell (2006) that must be balanced against the water loss hazards (Table 1).

Table 1. Water loss components associated with various sprinkler packages. Adapted from Howell (2006).

<table>
<tr><th rowspan="2">Water Loss Component</th><th colspan="4">Sprinkler Package</th></tr>
<tr><th>Overhead
(Impact sprinklers, rotating or fixed spray applicators)</th><th>MESA</th><th>LESA</th><th>LEPA</th></tr>
<tr><td>Droplet evaporation</td><td rowspan="3">Yes</td><td rowspan="5">Yes</td><td>Yes</td><td rowspan="2">No</td></tr>
<tr><td>Droplet drift</td><td>No</td></tr>
<tr><td>Canopy evaporation</td><td>Yes
(not major)</td><td>No
(chemigation mode only)</td></tr>
<tr><td>Impounded water evaporation</td><td>No</td><td>Yes</td><td>Yes
(major)</td></tr>
<tr><td>Wetted soil evaporation</td><td>Yes</td><td>Yes</td><td>Yes
(limited)</td></tr>
<tr><td>Surface water redistribution</td><td rowspan="2">No,
(but possible)</td><td>Yes,
(not major)</td><td>Yes</td><td rowspan="2">Yes
(not major unless surface storage is not used)</td></tr>
<tr><td>Runoff</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Percolation</td><td>No</td><td>No</td><td>No</td><td>No</td></tr>
</table>

Windy and hot conditions during the growing season affect center pivot sprinkler irrigation uniformity and evaporative losses. As a result many producers in the southern and central Great Plains have adopted sprinkler packages and methods that apply the water at a lower height within or near the crop canopy height, thus avoiding some application nonuniformity caused by wind and also droplet evaporative losses.

In-canopy and near-canopy sprinkler application can reduce evaporative losses by nearly 15% (Table 2), but introduce a much greater potential for irrigation nonuniformity. These sprinkler package systems are often adopted without appropriate understanding of the requirements for proper water management, and thus, other problems such as runoff and poor soil water redistribution occur.

Table 2. Partitioning of sprinkler irrigation evaporation losses with a typical 1 inch application for various sprinkler packages. (Adapted from Howell et al., 1991; Schneider and Howell, 1993).

Sprinkler package	Air loss, %	Canopy loss, %	Ground loss, %	Total loss,%	Application efficiency, %*
Impact sprinkler ≈ 14 ft height	3	12	--	15	85
MESA ≈ 5 ft height	1	7	--	8	92
LEPA ≈ 1 ft height	--	--	2	2	98

* Ground runoff and deep percolation are considered negligible in these data.

Traditionally, center pivot sprinkler irrigation systems have been designed to uniformly apply water to the soil at a rate less than the soil intake rate to prevent runoff from occurring (Heermann and Kohl, 1983). These design guidelines need to be either followed or intentionally circumvented with appropriate design criteria when designing and managing an irrigation system that applies water within the canopy or near the canopy height where the full sprinkler wetted radius is not developed. Peak application rates for in-canopy sprinklers such as LESA (low elevation spray application) and LEPA (low energy precision application) might easily be 5 to 30 times greater than above-canopy sprinklers (Figure 2).

Runoff from LEPA sprinklers was negligible on 1% sloping silt loam soils in eastern Colorado but exceeded 30% when slopes increased to 3% (Buchleiter, 1991). Runoff from LEPA with basin tillage was approximately 22% of the total applied water and twice as great as MESA (mid elevation spray application at 5 foot applicator height) for grain sorghum production on a clay loam in Texas (Schneider and Howell, 2000). Basin tillage created by periodic diking of crop furrow (2 to 4 m spacing), rather than reservoir tillage created by pitting or digging small depressions (0.5 to 1 m), is often more effective at time averaging of LEPA application rates, and thus, preventing runoff (Schneider, 2000).

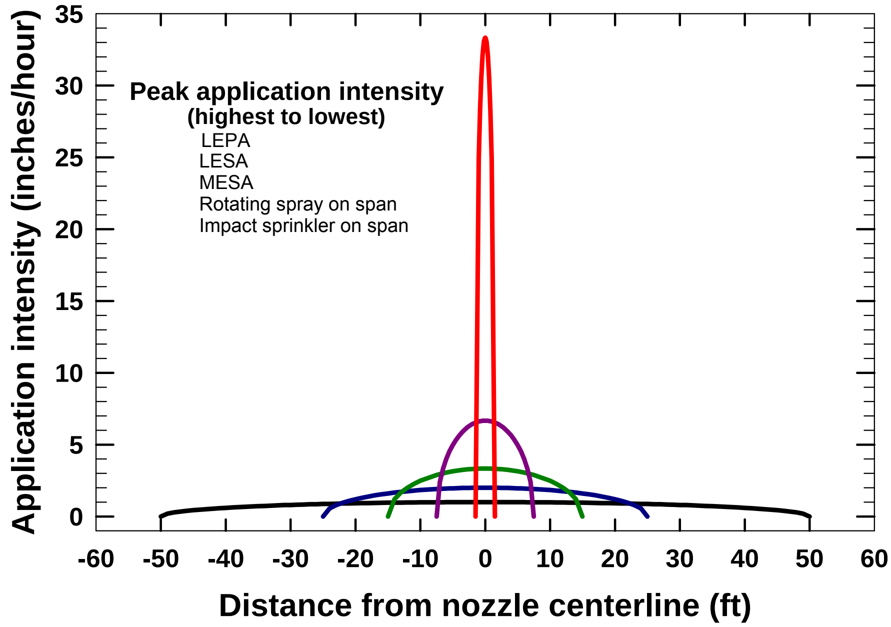


Figure 2. Application intensities for LEPA, LESA, MESA, rotating sprays on span and impact sprinklers on the span as related to the typical size of their wetting pattern.

Decreasing the application intensity is the most effective way to prevent irrigation field runoff losses and surface redistribution within the field (Figure 3.) When runoff and surface redistribution occurs using in-canopy sprinklers because of a reduced wetting pattern, one solution would be to raise the sprinkler height.

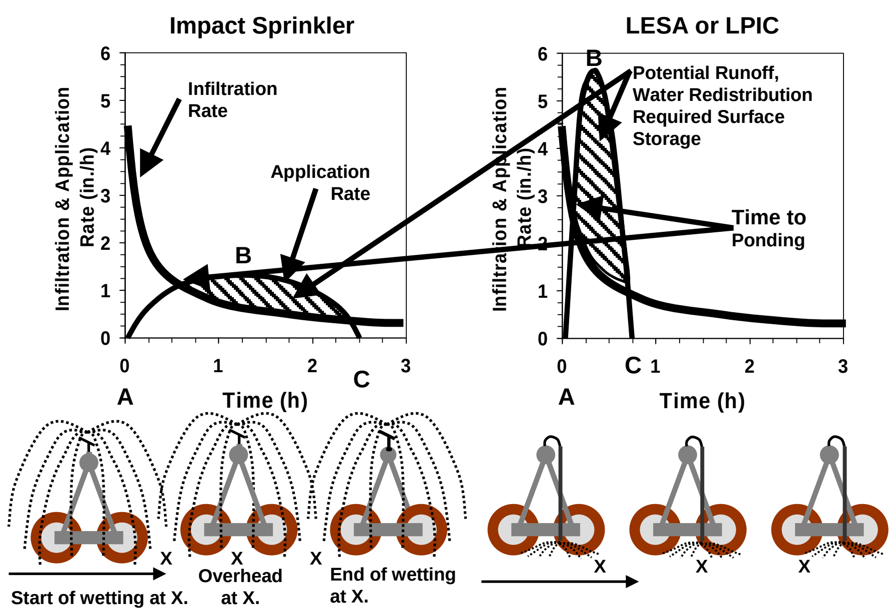


Figure. 3. Illustration of runoff or surface water redistribution potential for impact and LESA sprinkler application packages for an example soil. After Howell (2006).

One might assume that the erraticity observed in sprinkler irrigated fields in 2011 was primarily associated with the evaporative water loss components shown in Table 1, but that is probably not the case. When using fixed plate applicators near or within the canopy (MESA, LESA and LEPA), the magnitude of field runoff and particularly surface redistribution within the field may overwhelm the evaporative loss reductions possible with these packages. Surveys conducted by Kansas State University have indicated that approximately 90% of the center pivot sprinkler systems in western Kansas use fixed plate applicators and nearly 60% have sprinkler nozzle height less than 4 ft above the soil surface (Rogers et al. 2009). The erraticity can be caused by failure to follow appropriate guidelines for irrigation with near- and in-canopy sprinklers.

SOME GUIDING PRINCIPLES FOR IN-CANOPY APPLICATION

A prototype of the LEPA system was developed as early as 1976 by Bill Lyle with Texas A&M University. Jim Bordovsky joined the development effort in 1978 (McAlavy and Dillard, 2003) and the first scientific publication of their work was in 1981 (Lyle and Bordovsky, 1981). Although, originally LEPA was used in every furrow, subsequent research (Lyle and Bordovsky, 1983) demonstrated the superiority for alternate furrow LEPA. The reasons are not always evident, but they may result from the deeper irrigation penetration (twice the volume of water per unit wetted area compared with every furrow LEPA), possible improved crop rooting and deeper nutrient uptake, and less surface water evaporation (~30-40% of the soil is wetted). The seven guiding principles of LEPA were given by Lyle (1992) as:

1) *Use of a moving overhead tower supported pipe system (linear or center pivotal travel)*
2) *Capable of conveying and discharging water into a single crop furrow*
3) *Water discharge very near the soil surface to negate evaporation in the air*
4) *Operation with lateral end pressure no greater than 10 psi when the end tower is at the highest field elevation*
5) *Applicator devices are located so that each plant has equal opportunity to the water with the only acceptable deviation being where nonuniformity is caused by nozzle sizing and topographic changes*
6) *Zero runoff from the water application point*
7) *Rainfall retention which is demonstrably greater than conventionally tilled and managed systems.*

The other types of in-canopy and near-canopy sprinkler irrigation do not necessarily require adherence to all of these seven guidelines. However, it is unfortunate that there has been a lack of knowledge or lack of understanding of the importance of these principles because many of the problems associated with in-canopy and near-canopy sprinkler irrigation can be traced back to a failure to follow or effectively “work around” one of these principles. In-canopy and near-canopy application systems can definitely reduce evaporative losses

(Table 2), but these water savings must be balanced against runoff and within field water redistribution, deep percolation and other soil water nonuniformity problems that can occur when the systems are improperly designed and managed.

PROVIDING PLANTS EQUAL OPPORTUNITY TO ROOT-ZONE SOIL WATER

The No. 5 LEPA guiding principle listed earlier emphasizes the importance of plants having equal opportunity to root-zone soil water. Ensuring this equal opportunity requires sufficient uniformity of water application and/or soil water infiltration. Key issues that must be addressed are irrigation application symmetry, Crop row orientation with respect to center pivot sprinkler direction of travel, and the seasonal longevity of the sprinkler pattern distortion caused by crop canopy interference.

SYMMETRY OF SPRINKLER APPLICATION

Increased sprinkler application uniformity will often result in increased yields, decreased runoff, and decreased percolation (Seginer,1979). Improved sprinkler uniformity can be desirable from both economic and environmental standpoints (Duke et al., 1991). Their study indicated irrigation nonuniformity can result in nutrient leaching from over-irrigation and water stress from under-irrigation. Both problems can cause significant economic reductions.

Sprinkler irrigation does not necessarily have to be a uniform broadcast application to result in each plant having equal opportunity to the irrigation water. Equal opportunity can still be ensured using a LEPA nozzle in the furrow between adjacent pairs of crop rows provided runoff is controlled (Figure 4).

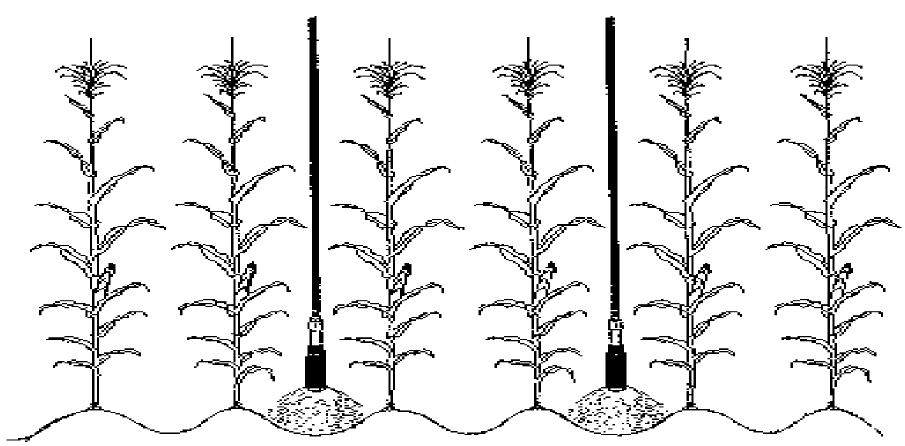


Figure 4. LEPA concept of equal opportunity of plants to applied water. LEPA heads are centered between adjacent pairs of corn rows. Using a 5–ft nozzle spacing with 30-inch spaced crop rows planted circularly results in plants being approximately 15 inches from the nearest sprinkler. After Lamm (1998).

Some sprinkler application nonuniformity can also be tolerated when the crop has an intensive root system (Seginer, 1979). When the crop has an extensive root system, the effective uniformity experienced by the crop can be high even though the actual resulting irrigation system uniformity within the soil may be quite low. Additionally, when irrigation is deficit or limited, a lower value of application uniformity can be acceptable in some cases (von Bernuth, 1983) as long as the crop economic yield threshold is met.

Many irrigators in the U.S. Great Plains are using wider in-canopy sprinkler spacings (e.g., 7.5, 10, 12.5, and even 15 ft) in an attempt to reduce investment costs (Yonts et al., 2005). Surveys from western Kansas in 2005 and 2006 indicated only 34% of all sprinkler systems with nozzle height of less than 4 ft had consistent nozzle spacing less than 8 ft (Rogers et al. 2009). Sprinkler nozzles operating within a fully developed corn canopy experience considerable pattern distortion and the uniformity is severely reduced as nozzle spacing increases (Figure 5).

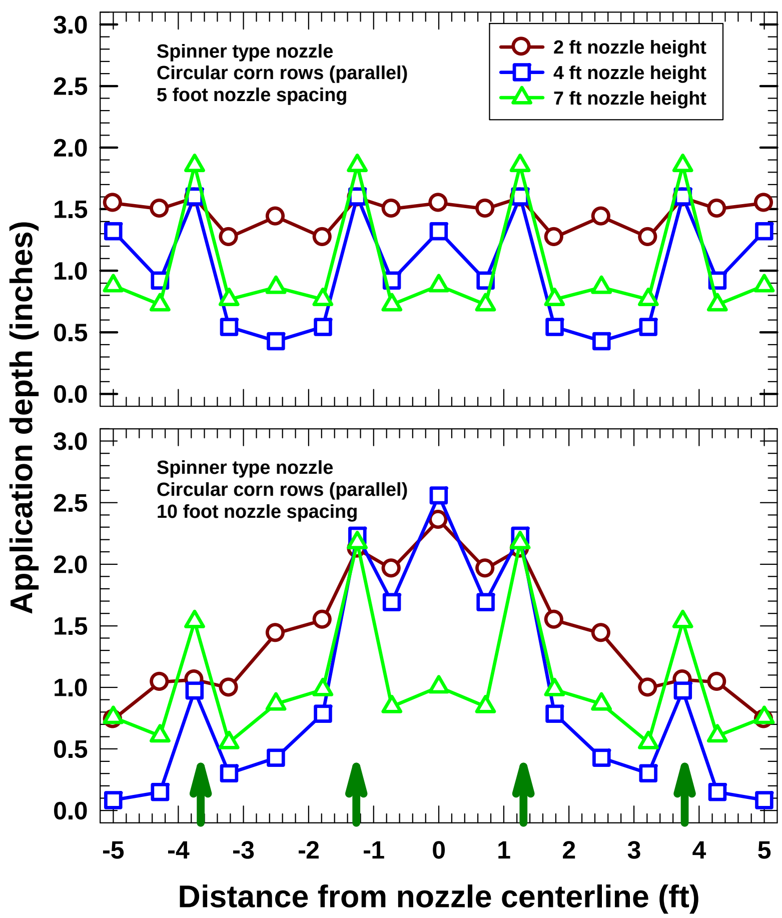


Figure 5. Differences in application amounts and application patterns as affected by sprinkler nozzle height and spacing. Center pivot sprinkler lateral is traversing parallel to the circular corn rows. Data are from a fully developed corn canopy, July 1996, KSU Northwest Research-Extension Center, Colby, Kansas. Data are mirrored about the nozzle centerline for display purposes. Arrows on X-axis represent location of corn rows and thus the location for higher stemflow amounts.

Although Figure 5 indicates large application nonuniformity, these differences may or may not always result in crop yield differences. Hart (1972) concluded from computer simulations that differences in irrigation water distribution occurring over a distance of approximately 3 ft were probably of little overall consequence and would be evened out through soil water redistribution.

Some irrigators in the Central Great Plains contend that their low capacity systems on nearly level fields restrict runoff to the general area of application. However, nearly every field has small changes in land slope and field depressions which do cause field runoff, in-field redistribution or deep percolation in ponded areas when the irrigation application rate exceeds the soil infiltration rate. In the extreme drought years of 2000 to 2003 that occurred in the U. S. Central Great Plains, even small amounts of surface water movement affected sprinkler-irrigated corn production (Figure 6). Similarly some of the worst erraticity in sprinkler-irrigated corn observed in the summer of 2011 was for sprinklers with 10 ft spaced in-canopy sprinkler packages (Figure 7).

Figure 6. Large differences in corn plant height and ear size for in-canopy sprinkler application over a short 10-ft. distance (4 crop rows) as caused by small field microrelief differences and the resulting surface water movement during an extreme drought year, Colby, Kansas, 2002. The upper stalk and leaves have been removed to emphasize the ear height and size differences.

Figure 7. Erraticity of sprinkler irrigated corn in southwest Kansas in 2011 under extreme drought conditions thought to be related to a nozzle spacing too wide (10 ft) for in-canopy application (2 ft nozzle height).

CROP ROW ORIENTATION
WITH RESPECT TO DIRECTION OF SPRINKLER TRAVEL

When using in-canopy sprinkler application, it has been recommended that crop rows be planted circularly so that the crop rows are always perpendicular to the center pivot sprinkler lateral. Matching the direction of sprinkler travel to the row orientation satisfies the important LEPA Principles 2 and 5 noted by Lyle (1992) concerning water delivery to one individual crop furrow and equal opportunity to water by for all plants. Producers are often reluctant to plant row crops in circular rows because of the cultivation and harvesting difficulties of narrow or wide "guess" rows. However, using in-canopy application for center pivot sprinkler systems in non-circular crop rows can pose two additional problems (Figure 8). In cases where the CP lateral is perpendicular to the crop rows and the sprinkler spacing exceeds twice the crop row spacing, there will be nonuniform water distribution because of pattern distortion. When the CP lateral is parallel to the crop rows there may be excessive runoff due to the great amount of water being applied in just one or a few crop furrows. There can be great differences in in-canopy application amounts and patterns between the two crop row orientations (Figure 9).

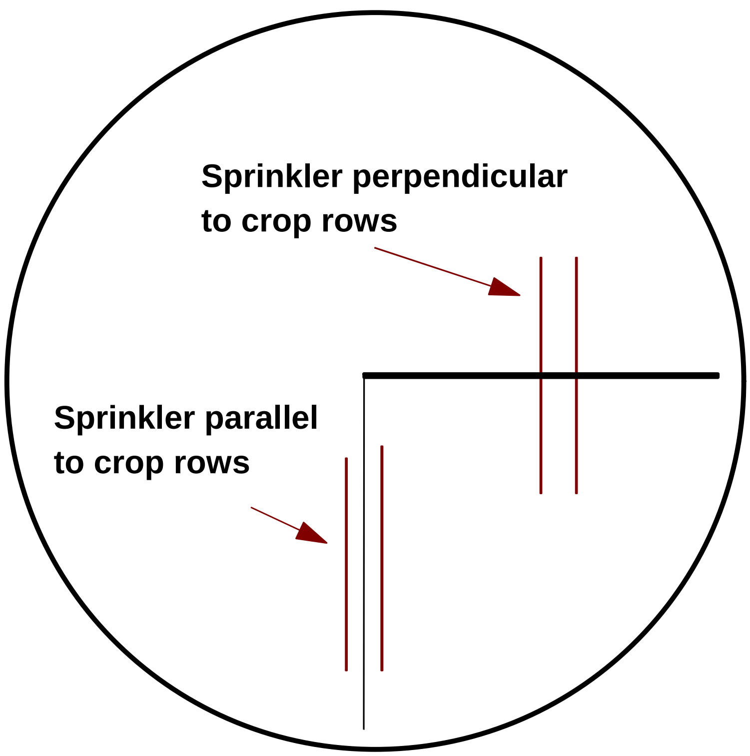


Figure 8. Two problematic orientations for in-canopy sprinklers when crops are not planted in circular rows.

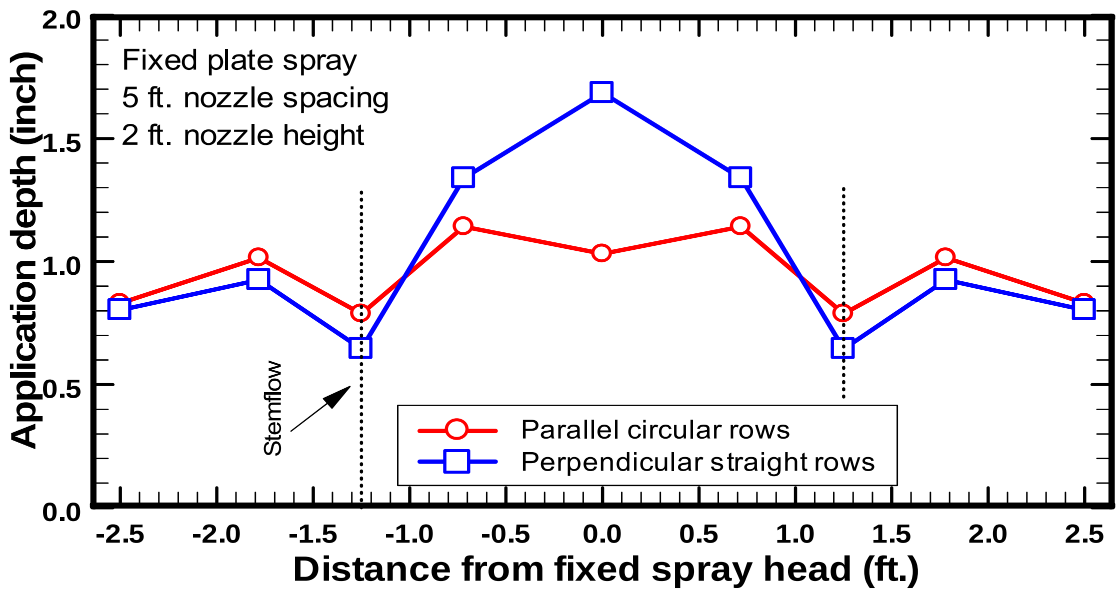


Figure 9. Differences in application amounts and application patterns as affected by corn row orientation with respect to the center pivot sprinkler lateral travel direction. Dotted lines indicate location of corn rows and stemflow measurements. Data are from a fully developed corn canopy, July 23-24, 1998, KSU Northwest Research-Extension Center, Colby, KS. Data are mirrored about the centerline of the nozzle.

PATTERN DISTORTION AND TIME OF SEASON

Drop spray nozzles just below the center pivot sprinkler lateral truss rods (approximately 7-10 ft height above the ground) have been used for over 30 years in northwest Kansas. This configuration rarely has had negative effects on corn yields although the irrigation pattern is distorted after corn tasseling. The reasons are that there is only a small amount of pattern distortion by the smaller upper leaves and tassels and this distortion only occurs during the last 30 to 40 days of the irrigation season. In essence, the irrigation season ends before a severe soil water deficit occurs. Compare this situation with spray heads at a height of 1 to 2 ft that may experience pattern distortion for more than 60 days of the irrigation season. Under dry and elevated evapotranspiration conditions in 1996, row-to-row corn height differences developed rapidly for 10-ft spaced sprinkler nozzles at a 4 ft nozzle height following a single one-inch irrigation event at the KSU Northwest Research-Extension Center, Colby Kansas (Figure 10). A long term study (1996-2001) at the same location on a deep silt loam soil found that lowering an acceptably spaced (10 ft) spinner head from 7 ft further into the crop canopy (e.g., 4 or 2 ft) caused significant row-to-row differences in corn yields (Figure 11).

Figure 10. Crop height difference that developed rapidly under a widely spaced (10 ft) in-canopy sprinkler (4 ft height) following a single 1 inch irrigation event at the KSU Northwest Research-Extension Center, Colby, Kansas. Photo taken on July 6, 1996.

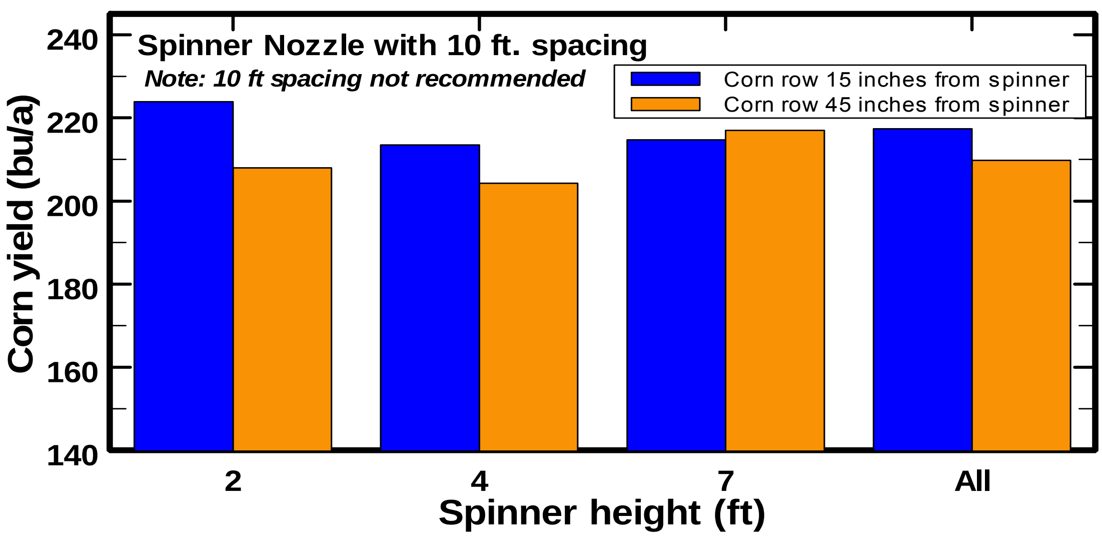


Figure 11. Row-to-row variations in corn yields as affected by sprinkler height for 10 ft. spaced in-canopy sprinklers. Sprinkler lateral travel direction was parallel to crop rows. Data was averaged from four irrigation levels for 1996 to 2001, KSU Northwest Research-Extension Center, Colby, Kansas.

COMBINATION OF EFFECTS CAN CAUSE ERRATICITY

Sometimes poor design, installation or maintenance problems can exist for years before they are visually observed as sprinkler irrigation erraticity. It may take severe drought conditions for some of these subtle effects to combine to such an extent to be noticeable erraticity. In addition, smaller row-to-row differences in crop yield cannot be measured with yield monitors on commercial-sized harvesters. An example of a combination several of these subtle effects was observed during the severe drought of 2002 in northwest Kansas (Figure 12). The small nozzle height difference on this sprinkler allowed at least three small effects to combine negatively to cause the sprinkler erraticity:

1. *Since there are no pressure regulators, the small height difference results in unequal flow rates for these low pressure spray nozzles.*
2. *There is a incorrect overlap of the sprinkler pattern due to the height difference with one sprinkler within the canopy while the other two nozzles are above the canopy.*
3. *Evaporative losses would be greater for the nozzles above the crop canopy.*

Figure 12. Erraticity of sprinkler-irrigated corn near Colby, Kansas during the extreme drought year of 2002.

CONCLUSIONS

The drought that southwest Kansas experienced in 2011 was devastating to production on many sprinkler irrigated corn fields, but the erraticity did highlight some design and management issues that producer might address before the next irrigation season:

1. *Does the selected sprinkler package strike the correct balance in reducing evaporative losses without increasing irrigation runoff or in-field water redistribution?*
2. *Does the sprinkler package and its installation characteristics provide the crop with equal opportunity to applied or infiltrated water?*
3. *Are the sprinkler nozzle heights and spacings appropriate for the intended cropping?*
4. *Should planting of taller row crops such as corn be in circular patterns if in-canopy sprinklers are used?*
5. *Are there subtle irrigation system characteristics (design, installation, or maintenance) that might combine negatively to reduce crop yields?*

These design and management improvements won't change the weather conditions, but they might change how the crop weathers future droughts.

ACKNOWLEDGEMENTS

This paper is the result of cooperative efforts of the authors through the Ogallala Aquifer Program, a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

This is a joint contribution from Kansas State University, USDA Agricultural Research Service and Texas A&M University. Contribution no. 12-309-A from the Kansas Agricultural Experiment Station.

REFERENCES

Buchleiter, G. W. 1991. Irrigation with LEPA. In: Proc. Central Plains Irrigation Shortcourse, North Platte, NE., Feb. 5-6, 1991. pp. 64-68.

Duke, H. R., D. F. Heermann, and L. J. Dawson. 1991. Selection of appropriate applied depth from center pivots. Presented at the Int'l. Summer Meeting of the ASAE. ASAE paper no. SW91-2052, ASAE, St. Joseph, MI. 18 pp.

Heermann, D. F. and R. A. Kohl. 1983. Fluid dynamics of sprinkler systems. Chapter 14 in Design and Operation of Farm Irrigation Systems, ASAE Monograph No. 3, pp. 583-618, ASAE, St. Joseph, MI.

Howell, T.A. 1997. What's in a name. Wetting Front 1(2);1-3. Also at http://www.cprl.ars.usda.gov/Wetting%20Front/WF-Vol1-No2.pdf

Howell, T. A. 2006. Water losses associated with center pivot nozzle packages. In: Proc. Central Plains Irrigation Conf., Colby, KS., Feb. 21-22, 2006. Available from CPIA, 760 N.Thompson, Colby, KS. pp. 12-24. Also at http://www.ksre.ksu.edu/irrigate/OOW/P06/Howell06.pdf

Howell, T. A., A. D. Schneider, and J. A. Tolk. 1991. Sprinkler evaporation losses and efficiency. In: Proc. Central Plains Irrigation Shortcourse, February, 5-6, 1991, North Platte, NE. pp. 69-89.

Lamm, F.R. 1998. Uniformity of in-canopy center pivot sprinkler irrigation. Presented at the Int'l. Meeting of the ASAE, July 12-16, 1998, Orlando FL. ASAE Paper No. 982069. ASAE, St. Joseph, MI. 7 pp. Also at http://www.ksre.ksu.edu/irrigate/UICCP98.html

Lyle, W. M. 1992. LEPA, concept and system. In: Proc. Central Plains Irrigation Short Course, Goodland, KS, Feb. 4-5, 1992. Available from KSU Extension Biological and Agricultural Engineering, Manhattan, KS. pp. 14-16.

Lyle, W. M., and J. P. Bordovsky. 1981. Low energy precision application (LEPA) irrigation system. Trans. ASAE 24(5):1241-1245

Lyle, W. M., and J. P. Bordovsky. 1983. LEPA irrigation system evaluation. Trans. ASAE 26(3):776-781.

McAlavy, T. and P. Dillard. 2003. LEPA leaps forward – A crop irrigation revolution born on the Texas Plains. Lifescapes Spring 2003. Texas A& M University, College Station, TX. 3 pp. Also at http://agcomwww.tamu.edu/lifescapes/spring03/lepa.htm

Rogers, D. H., M. Alam, and L. K. Shaw. 2009. Kansas center pivot survey. Kansas State Research and Extension. Irrigation Management Series MF-2870. April 2009. 8 pp. Also at http://www.ksre.ksu.edu/library/ageng2/mf2870.pdf

Seginer, I. 1979. Irrigation uniformity related to horizontal extent of root zone. Irrig. Science 1:89-96.

Schneider, A. D. 2000. Efficiency and uniformity of the LEPA and spray sprinkler methods: A review. Trans. ASAE 43(4):937-944. Also at http://www.cprl.ars.usda.gov/pdfs/SchneiderTrans2000.pdf

Schneider, A. D. and T. A. Howell. 1993. Reducing sprinkler water losses. In: Proc. Central Plains Irrigation Shortcourse, February, 2-3, 1993, Sterling, CO. pp. 43-46. methods: A review. Trans. ASAE 43(4):937-944. Also at http://www.cprl.ars.usda.gov/pdfs/Reducing%20Sprinkler%20Water%20Losses.pdf

Schneider, A. D. and T. A. Howell. 2000. Surface runoff due to LEPA and spray irrigation of a slowly permeable soil. Trans. ASAE 43(5):1089-1095. Also at http://www.cprl.ars.usda.gov/pdfs/SchneiderRunoffTrans2000.pdf

von Bernuth, R. D. 1983. Uniformity design criteria under limited water. Trans ASAE 26(5):1418-1421.

Yonts, C. D., F. R. Lamm, W. Kranz, J. Payero and D. Martin. 2005. Impact of wide drop spacing and sprinkler height for corn production. In: Proc. Central Plains Irrigation Conf., Sterling, CO, Feb. 16-17, 2005. Available from CPIA, 760 N.Thompson, Colby, KS. pp. 99-106. Also at http://www.ksret.ksu.edu/irrigate/OOW/P05/Yonts2.pdf

This paper was first presented at the Central Plains Irrigation Conference, February 21-22, 2012, Colby, Kansas. It can be cited as

Lamm, F.R., T.A Howell, and J.P. Bordovsky. 2012. Erraticity of sprinkler irrigated corn in 2011. In: Proc. 24th annual Central Plains Irrigation Conference Feb. 21-22, 2012, Colby, Kansas. Available from CPIA, 760 N. Thompson, Colby, Kansas. pp. 88-101.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N. Thompson, Colby, Kansas

CENTER PIVOT SPRINKLER NOZZLE REPLACEMENT AND MAINTENANCE

William Kranz
UNL Irrigation Specialist
Concord, NE
Voice: 402-584-3857 wkranz1@unl.edu

Ray Glaser
Senninger Irrigation
Voice: 308-381-8558
rglaser@senninger.biz

Gene Ross
Nelson Irrigation
Voice: 402-727-0378
Gene.Ross@nelsonirrigation.com

Danny Rogers
KSU Extension Ag Engineer
Manhattan, KS
Voice: 785-532-5813
drogers@ksu.edu

INTRODUCTION

Couched between the installation of a new center pivot and total system failure are a number of maintenance issues that can have a significant impact on economic returns. The original purpose of this paper was to highlight estimates of the expected life of a sprinkler package. However, during the course of our review of the available information it became clear that estimates vary greatly and in the end may not be very useful in ensuring that water application uniformity is maintained over the life of the sprinkler. This discussion will concentrate on a more important issue that is too often placed in the category of ‘If it ain’t broke don’t fix it’. Sprinkler package selection is a major topic when making the original purchase of the center pivot, but it is just the first decision related to managing the center pivot year-in, year-out. To be effective, the sprinklers must continue to run properly which means that when wear and tear causes the sprinkler to malfunction, repair or replacement is necessary.

SPRINKLER DISCHARGE

The design sprinkler flow rate out of each sprinkler orifice is based on the water pressure supplied to the sprinkler inlet as illustrated in Figure 1. Overall, the discharge delivered by a sprinkler also depends on the system capacity, the distance from the pivot point to a specific sprinkler, and the spacing between sprinklers at that location on the lateral. The goal of the sprinkler package selection or design process is select nozzles that would apply water with over 90% application uniformity.

The nozzle diameter has a big influence on the discharge from the nozzle since the discharge depends on the square of the nozzle diameter. For example, at a pressure of 40 psi the discharge for the $^1/_8$-inch nozzle is 2.8 gpm and discharge for a ¼-inch nozzle is 11.2 gpm. Therefore, doubling the nozzle diameter quadruples the discharge. Depending on the construction material of the nozzle and the quality of water being pumped, the nozzle opening could change. If the nozzle opening increases due to wear, the actual flow rate may be vastly different than the original design.

The effect of pressure is less significant than the nozzle diameter; since, in this case, the discharge varies as the square root of the pressure. For example, the discharge from the ¼-inch nozzle at 20 psi is 7.96 gpm while at 40 psi the discharge is about 11.2 gpm, an increase of 40% in the discharge rate. Normal wear on a pump impeller will result in a decrease in both flow rate and output pressure. Several years after the original installation, each nozzle will likely be supplied with less pressure and flow rate unless pressure regulators were installed and sufficient pressure is available to keep the regulators activated. Without pressure regulators, when nozzles become worn, field topography plays a major role in the flow rate delivered by each sprinkler. Thus uniformity depends on where in the field you look.

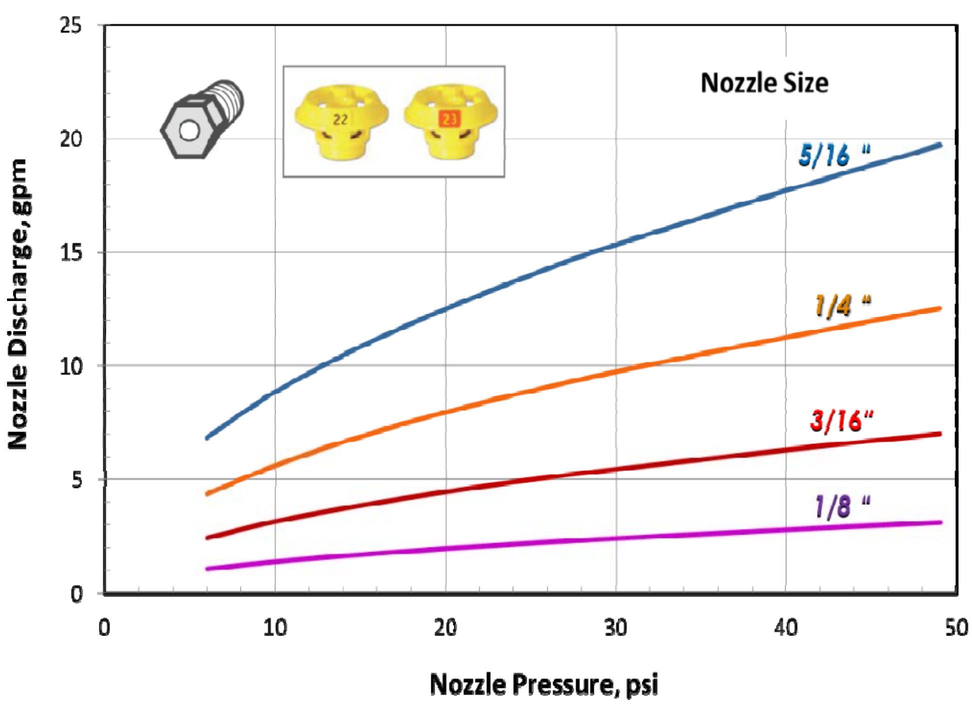


Figure 1. Performance of nozzles used in sprinkler devices

In the absence of the original sprinkler package printout, the approximate flow rate required from each sprinkler can be determined by collecting some information about the overall sprinkler operation. Figure 2 depicts a center pivot lateral showing the spacing between the sprinklers along the lateral and how to measure the distance from the pivot point to a sprinkler at some specific distance from the pivot point. The only other factor needed is the system capacity which is determined by dividing the total flow rate by the number of irrigated acres.

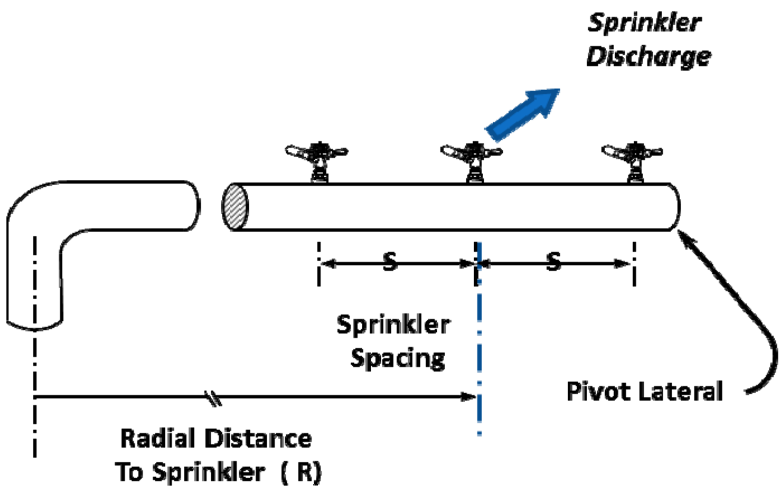


Figure 2. Information used to determine discharge required for a sprinkler along the center pivot lateral.

The following equation describes how to compute the required discharge from a sprinkler:

$$q_s = \frac{C_g \ R \ S}{6933}$$

where:

q_s is the discharge from a sprinkler (gpm),
C_g is the system capacity (gpm/acre),
R is the distance from the pivot point (feet),
S is the spacing between sprinklers along the lateral (feet), and
6933 is a conversion constant

For example, if a sprinkler is located 1000 feet from the pivot, the local spacing of sprinklers along the lateral is 9 feet and the system capacity is 6 gpm/acre, the required sprinkler discharge is:

$$q_s = \frac{6\,gpm\,/\,acre \times 1000\ \ feet \times 9\ \ feet}{6933} = 7.8\ \ gpm$$

The required nozzle size can be determined after computing the sprinkler discharge. To select the correct nozzle, the pressure available to the sprinkler must be determined. If pressure regulators are used, the available pressure is usually the pressure rating of the regulator. However, if regulators are not used then the pressure in the sprinkler lateral at the designated location must be determined based on pressure at the pivot point, pipeline friction loss and elevation difference between the pivot point and the position in question.

Though the goal is to apply water in a completely uniform manner, there is virtually no way to accomplish this even with a new system. Due to a limitation in available nozzle diameters, some nonuniformity of water application will occur in the design process. Table 1 presents information taken from a sprinkler design printout for a center pivot in Nebraska and depicts the point quite well. Note that the printout calls for 13.5 gpm at position 94, 912.5 feet from the pivot point (Row 5, Column 7) and the actual flow rate delivered is 13.9 gpm (Row 5, Column 8). This means that the water application depth will be slightly greater than desired at that location. This is because the nozzle diameters increase in 1/128" increments and the sprinkler package design requires a more precisely sized nozzle.

Similar things happen at each tower. Center pivot mainline pipe lengths and distance reserved for each tower can cause sprinkler spacing to change as noted for Position 100 in Table 1. Here the first sprinkler in the next span is located 23 feet from the previous sprinkler (23 feet vs. 19 feet). In this case there will be some nonuniformity that results due to constraints on sprinkler placement resulting from the pivot structure manufacturing specifications.

Table 1. Sprinkler package design printout for a center pivot in Nebraska.

Outlet		**Sprinkler**				**Flow Rate, gpm**		**Pressure**
No.	Loc.	No.	Sep.	Model	Nozzle	Req.	Del.	PSI
86	836.5	39	19	5006H2	RN-#14 x #14	12.4	12.4	61.5
88	855.5	40	19	5006H2	RN-#14 x #14	12.6	12.3	61.4
90	874.5	41	19	5006H2	RN-#15 x #14	13.1	13.1	61.3
92	893.5	42	19	5006H2	RN-#15 x #14	13.2	13.1	61.3
94	912.5	43	19	5006H2	RN-#15 x #15	13.5	13.9	61.2
96	931.5	44	19	5006H2	RN-#15 x #14	13.3	13.1	61.1
98	950.5	45	19	5006H2	RN-#17 x #16	15.7	16.0	61.0
100	973.5	46	23	5006H2	RN-#16 x #16	15.5	15.2	60.9

From a technical point of view, water application uniformity of a center pivot is determined by doing a catch-can test. Catch cans are placed in a ray outward from near the pivot point out to where the last sprinkler applies water. The cans are normally equally spaced at 10-15 foot intervals. Determination of the application uniformity is done by entering the catch amounts for each catch can into an equation that assigns each catch to a representative area of the field. Thus, catch cans near the distal end of the system are weighted more than catch cans near the pivot point. This process is both complicated and tedious to complete. Complications include the influence of the type, size, and spacing of catch cans, and climatic conditions like wind speed and air temperature. These factors most often render the test to one of identifying major water application issues such as improper operation of the sprinkler, missing low pressure drains, leaky tower boots, or improper endgun operation. Most of these same issues can be identified by a much more simple approach which will be outlined in the information provided below.

What are the problems associated with center pivot sprinkler operation?
The most obvious answer to this question is that over time various parts of the sprinkler can become worn to the point where it no longer distributes water over the same wetted area in a uniform manner. However, in some cases the original installation can be the issue. Figure 3 presents results from a catch-can test conducted in Kansas (Rogers, 2008).

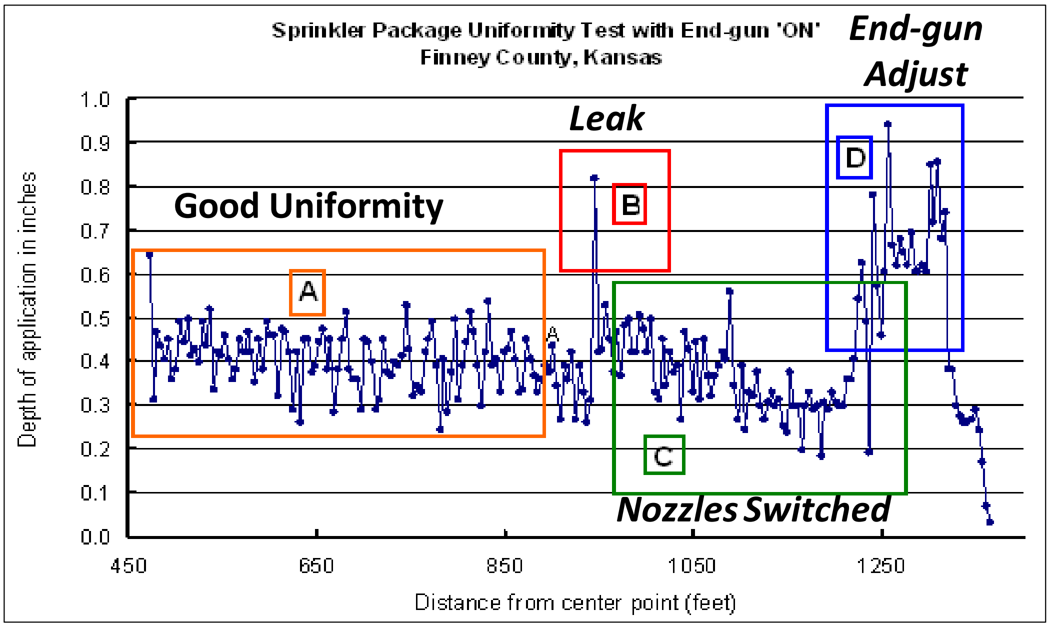


Figure 3. Results of a catch-can test of uniformity for a center pivot in Kansas.

The first 900 feet of this system has few application uniformity issues that are abnormal. Beginning at about 900 feet the catch-can test had several cans with elevated catch amounts. Upon inspection it was determined that the problem was a leak in a tower boot. This leak could have been identified by walking along the system while it was operating. Section C of the system provided some questions that could not be answered by simply walking along the system. However, when comparing the sprinkler package printout to the sprinklers installed it was determined that the sprinklers on two spans were installed in reverse order. The final item identify by the can test is depicted in Section D of the image. In this case, the end gun was set to irrigate a portion of the field located under the pipeline portion of the system. Thus, the field area starting at about 1200 feet was irrigated by the mainline sprinklers and the end gun when the original design was based solely on irrigation by the mainline sprinklers.

The water source can lead to two additional complications. If the water supply is a delivery canal or stream, suspended solids including moss, sand, decaying plant materials, and other solids can pass through the pump and be delivered to the center pivot where these materials can partially or completely plug the nozzle or pressure regulator. This issue can occur anywhere on the system but is often confined to the first couple of spans where nozzle openings are too small to pass the solids contained in the water.

The second water source factor deals with another water quality issue. Water pumped from surface water sources and from some irrigation wells can contain relatively large amounts of sand. When the water-borne sand contacts a stationary deflection pad it tends to wear the grooves out and over time can wear completely through the pad. Generally speaking moving deflection pads are less prone to this issue. In some cases, water containing excessive amounts of calcium and magnesium salts can cause the grooves in a stationary pad to become incrusted with calcium to the point where the grooves have little capacity to distribute water as they were originally designed to do.

Another possibility when the application water contains sand is that the sprinkler diameter may increase in diameter. One way to check to see if the nozzle diameter is greater than the manufactured size is to purchase a set of drill bits in 1/128” increments and based on the size of the nozzle (as shown in Figure 1) insert the correct sized drill bit into the nozzle opening. The drill bit should fit into the opening, but it should be snug so that the drill bit will not move side-to-side very easily. If the drill bit does move side-to-side easily, the nozzle is worn and should be replaced. In some cases, the only thing that needs to be replaced is the nozzle, the rest of the sprinkler and pressure regulator may be just fine.

With the constant introduction of new pesticides, insecticides and fertilizers over the last 25-30 years, end users should be aware that it may be a possible for these products or in combination with other ingredients could lead to deterioration or premature wear to sprinkler products. This sort of deterioration or wear is usually not easy to detect. Potential sites are generally associated with vegetable crop production where fungicides and insecticides are applied several times during the growing season.

The final item that we will discuss is damage to sprinklers caused by impact against the center pivot infrastructure. Sprinklers installed on long flexible drop tubes can be damaged when the wind is blowing at a sufficient enough velocity to cause the drop tubes to swing side-to-side. If the sprinkler impacts the truss rods, tower structure, or pipeline the sprinkler may be cracked or a piece of the sprinkler may be broken off. Sprinklers may also be damaged if the system is exposed to large wind-driven hail. When these kinds of damage occur, it may

not be easy to diagnose but over time broken sprinklers will not distribute water according to the original design.
It is always good to conduct the inspection just before sunrise and sunset as the angle of light from the sun makes it easier to identify water application problems. Each sprinkler should be operating and look very similar to the sprinkler next to it. If not, the regulator or nozzle opening could be partially plugged. Each of the issues described above could have been identified by a simple five part inspection which is best done in the spring before the crop canopy is present.

1) Verify that the system is supplied by the correct flow rate and operating pressure,
2) Compare the sprinklers sizes installed to the sprinkler design printout,
3) Verify that the last sprinkler is supplied with correct operating pressure when the end gun is on and the last tower is at its highest point.
4) Verify that the end gun is set to run according to the design sheets, and
5) Verify that the sprinkler is not cracked or broken and that the deflection pads are not worn excessively.

Why is water application uniformity important?
The original sprinkler package design will normally have a water application uniformity above 90% when operated under nowind conditions. Reduced water application uniformity means that some areas of the field are not receiving the correct amount of water. If any of the issues discussed above are present the nonuniformity can occur each time water is applied and the accumulative impact is that grain or forage yield can be less than expected. Often times small problems that impact only a few sprinklers may not be noticeable in yield maps while others can easily be seen from the air. Nonuniform water application can cause significant economic losses when corn is at $6/bu.

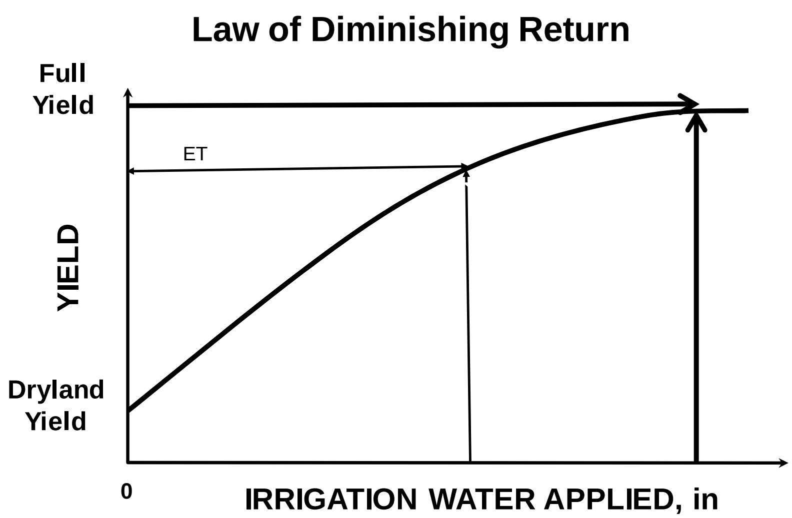


Figure 4. Graphical depiction of the Law of Diminishing Returns with respect to irrigation water application.

Grain and forage yield are dependent on irrigation water application uniformity due to the law of diminishing returns. Poor uniformity can lead to unnecessary water applications Figure 4 shows a grain yield response to irrigation water curve. Note that inside the small boxlike area, yield increases at a fairly constant rate. Recent yield trials would suggest the slope of the line in that segment would be approximately 15-16 bushels per inch of water. However, additional movement to the right on the curve shows that the slope of the curve decreases until on the far right it is flat. Research also suggests that while the plant may survive additional water application, excess water application would merely leach soluble nutrients out of the root zone and yields would begin to decline for each additional inch. This curve is a classic example of crop productivity known as the Law of Diminishing Returns.

One extreme example of nonuniform water application was exposed in Nebraska when aerial photographs indicated distinct rings in some center pivot fields in the western part of the state. The main issue was one of sprinkler spacing and to a lesser extent sprinkler positioning. Sampling of several of these fields identified the season-long impact of nonuniform water application. Hand harvest of each corn row between two sprinklers was conducted where the center pivot was oriented perpendicular to the crop row direction. Figure 5 shows the corn grain yield in bushels per acre for each row. Note that with a spacing of about 17.5 feet, grain yield varied from over 220 bu/ac to180 bu/ac. The economic impact of this outcome is obvious and with today's corn prices; installing at least one more sprinkler between the existing sprinklers was justified.

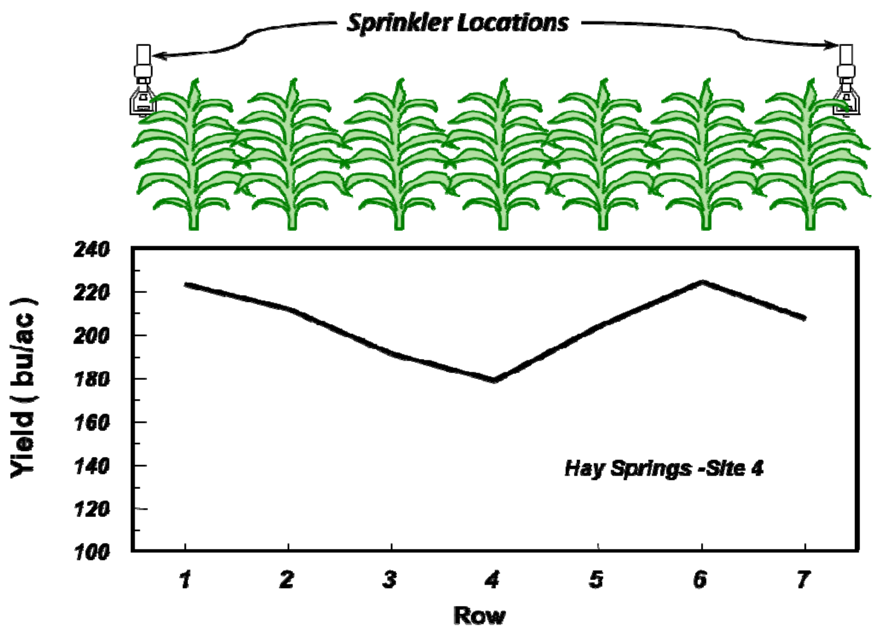


Figure 1. Variation of grain yield for individual corn rows where sprinkler spacing was too wide.

Figure 5 also depicts the situation that would occur if only one sprinkler of a center pivot were plugged or malfunctioning. Assume that there is a sprinkler located between the ones in Figure 5 but it is not functioning. Many of the potential problems discussed earlier in this paper could be included in this discussion. Looking at the graph the main impact of the wide sprinkler spacing is exhibited in rows 2-5 or a 7.5 foot wide strip. Extend a 7.5 foot wide strip along a full revolution and the importance depends on where on the lateral the sprinkler is located. A 7.5 foot wide strip located between 300 and 307.5 feet from the pivot point would represent only1/3 of an acre while the same sized strip located from1250 to 1257.5 feet from the pivot point would represent 1.4 acres. Either way there will be an impact of the malfunction of a single sprinkler on economic returns. Damage to or plugging of a sprinkler could happen during the first season of operation or not until the system has been in operation for 20 years. So delaying replacement of the sprinkler or waiting until the sprinkler package has been in operation for 10,000 hours will allow the problem to impact crop production for the entire period. Thus, one must fix this problem immediately.

The impact of wide sprinkler spacing would be exacerbated if the sprinklers were placed closer to the soil surface. Research conducted at Colby, KS and Alliance, NE clearly indicates that the corn canopy is quite adept at intercepting the water application pattern of most any sprinkler when positioned within the canopy. That work confirms that the water application pattern is narrowed to less than 7.5 feet when the sprinklers are operated in the corn crop canopy. Placing sprinklers at 6 feet from the soil surface would require a sprinkler spacing of 5 feet to ensure uniform water application.

SUMMARY

Selecting a sprinkler package is an important decision when purchasing a center pivot irrigation system. The original design seeks to deliver water with an application uniformity of over 90% unless the owner alters the sprinkler selection criteria due to the cost of the installation. Once installed, it is more important to ensure that each sprinkler continues to operate as it was designed. Field topography and pumping plant performance can have major impacts on the performance of a sprinkler package. Sprinklers may be damaged by a myriad of issues at any time after the original installation. Failure to replace damaged sprinklers or remove materials that may plug nozzle openings allow the water application to be affected in a negative manner for extended periods of time. Keeping good records on pumping plant performance and performing a simple sprinkler system check on a regular basis will help ensure that the system is operating efficiently regardless if it has been in operation for 100 or 10,000 hours.

REFERENCE

Rogers, Danny H., Maybub Alam, and L. Kent Shaw. 2008. Considerations for nozzle package selection for center pivots. KSU Irrigation Management Series No. L908. KSU Extension. pp. 8.

CONSIDERATIONS FOR VARIABLE RATE IRRIGATION

Jake LaRue
Director of R&D

Valmont Industries, Inc
Valley, Nebraska

Robert Evans
Supervisory Research
Agricultural Engineer
USDA-ARS
Sidney, Montana

ABSTRACT

The paper will focus on some items a grower, consultant and/or irrigation dealer should consider when contemplating the 'jump' into variable rate irrigation. A brief review of the status of commercially available variable rate products in the USA will begin the paper. Information on the processes used for considering variable rate irrigation will be presented. Then the discussion will move to specific information on fields' characteristics and VRI irrigation equipment. The paper will close with the conclusions and recommendations when planning for variable rate irrigation.

INTRODUCTION

Existing center pivot and linear irrigation technologies are well advanced and would conserve large amounts of water if fully implemented to the maximum extent of their capabilities. Adoption of advanced site-specific / variable rate technologies could potentially extend these water savings even more. Documented and proven water conservation strategies using variable rate irrigation (commonly referred to as VRI) are quite limited, and its cost-effectiveness has not been demonstrated by researchers (Evans 2011).

Various aspects of VRI technologies for general crop production are to beginning to gain acceptance; however, their uses are largely focused on non-irrigation of roads, ponds or rocky outcrops or addressing symptoms of poor design and less than optimal water and nutrient management. However, this significant underutilization of the potential of VRI technologies is still quite beneficial for crop production.

In the short term, adoption of these technologies will be enhanced by addressing equipment deficiencies and developing basic criteria and systems for defining management zones. The long term challenge will be to develop fully integrated management systems with supporting elements that accurately and inexpensively define dynamic management zones, sense within-field variability in real time, and then adaptively control site-specific, variable rate water applications.

Commercially available VRI choices are either speed control or zone control. Speed control varies the depth of application around the field in sectors (pie slices) by changing the speed of the center pivot in different sectors to try to meet the needs of the soil. The application depth remains uniform along the center pivot. Zone control, however, not only changes the application depth around the field but also along the length of the center pivot by pulsing sprinkler zones on and off. One caution is to not assume that by switching to VRI will automatically save water or reduce irrigation amounts. In addition currently there are no specific standards such as ASABE SW-436 for evaluating VRI systems. Manufacturers are offering ways to evaluate VRI performance.

DISCUSSION

In today's high cost environment, a grower cannot just look at overall farm income but must focus more and more on smaller areas at the field level or below. As a grower and his consultant analyze the profitability from a particular field, they have to discern all possible reasons why their yield or cost expectations may or may not have been met. Then they need to decide what changes need to made to their operation and at what scale. Often the discussion is driven by a yield maps and antidotal information to define areas requiring different management and if VRI is appropriate. More and more, growers are looking at determining management zones within a field that are relatively homogeneous with regard to at least one characteristic or factor (e.g., similar soils, topography, microclimate, harvested yields, pest pressures, plant response and field characteristics).

The first consideration would be to decide if VRI is being looked at as a tool to apply varying depths around the field based on soils or other factors or to control the application depth (anywhere from a reduction to none) to specific areas such as ditches, ponds, wetlands, non cropped or other physical features.

If the desire for VRI is based on the need to avoid water applications on a specific area, then a conventional aerial photograph or Google Earth map will generally be suffice to make a determination of how to proceed as shown in figure 1. This may be a VRI zone control package or utilization of the existing features if currently using a computerized control panel.

Figure 1

However, if the need is to apply varying depths of irrigation in different areas around the field then other analysis tools need to be found. In the spring of 2010, Valmont Irrigation began to validate the lab and field testing that had been done with the Valley VRI Zone Control package on a field near Dyersburg, Tennessee. The machine's configuration was a total length of 1,148 feet and six drive units. The flow rate was 800gpm with fixed-pad sprinklers with a medium groove pad and 15psi pressure regulator. The field challenge was that parts of the field were either being overwatered or under watered resulting in a very large variability in crop production across the field. Available data for the field included soil maps (figure 2), grid sampling (figure 3), yield maps and antidotal information. None of this data seemed to provide the guidance necessary to determine the VRI package because of providing either too little resolution, could not be tied to specific field properties or not providing information that could be readily used to evaluate the field.

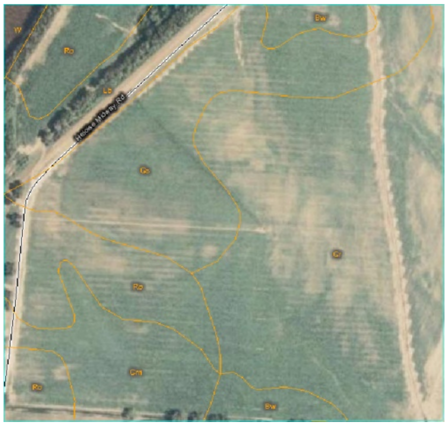


Figure 2, NRSC Soil Map

	Sample Number	P (lbs/A)	K (lbs/A)	Mg (lbs/A)	Ca (lbs/A)	S (lbs/A)	B (lbs/A)	Zn (lbs/A)	Mn (lbs/A)	SS (lbs/A)	Na (lbs/A)	NN (lbs/A)	OM (%)	pH	Buffer	ENR (meq)	CeC (meq)
FARM Hog Barn Pivot																	
FIELD 1 (116.10acres):																	
1.	5704																
2.	5705																
3.	5706																
4.	5707	62	334	648	2938	14	1.6	8	262		32		1.9	7.8	7.9		10.5
5.	5708	104	404	742	3894	16	2.2	12	290		44		2.4	7.7	7.9		13.4
6.	5709	96	340	696	3524	14	1.6	10	264		40		2.1	8.0	7.9		12.2
7.	5710	92	360	742	3414	12	1.6	10	268		34		2.2	7.8	7.9		12.2
8.	5711	96	326	482	2074	14	1.0	8	160		48		1.3	7.3	7.9		7.7
9.	5712	74	364	662	2886	16	1.4	9	236		44		3.7	7.7	7.9		10.5
10.	5713	90	408	650	3570	18	1.6	10	296		62		3.7	7.7	7.8		12.3
11.	5714	72	258	552	3198	16	1.8	8	250		44		2.9	7.8	7.9		10.7
12.	5715	62	340	536	2100	14	1.0	7	174		40		2.8	7.7	7.9		8.0
13.	5716	88	426	830	3444	16	1.6	10	334		50		2.5	7.8	7.9		12.7
14.	5717	66	348	646	2348	14	1.4	7	222		56		2.5	7.8	7.9		9.1
15.	5718	52	400	824	3492	16	2.0	9	332		58		2.0	7.7	7.9		12.8
16.	5719	56	442	700	2810	16	1.6	8	246		48		2.5	7.9	7.9		10.6
17.	5720	54	414	692	2536	16	1.4	8	216		46		2.9	7.8	7.9		9.9
18.	5721	72	376	582	2524	14	1.2	9	206		38		2.3	7.5	7.9		9.3
19.	5722	80	404	632	3538	18	1.6	10	272		92		2.5	7.8	7.9		12.2
20.	5723	60	358	568	2768	16	1.4	8	210		46		2.5	7.9	7.9		9.8
21.	5724	98	228	356	1596	12	0.6	8	142		40		2.1	7.4	7.9		5.9
22.	5725	88	200	298	1312	14	0.6	6	130		36		1.6	7.3	7.9		4.9
23.	5726	102	226	336	1510	14	0.8	7	132		40		2.3	7.3	7.9		5.6
24.	5727	64	344	674	2758	14	1.2	11	258		38		2.4	7.8	7.9		10.2
25.	5728	60	384	654	2440	14	1.2	9	210		46		2.1	7.9	7.9		9.4
26.	5729	70	296	558	2026	14	1.0	8	164		40		2.2	7.8	7.9		7.9

Figure 3, Grid Sampling Data

Following a discussion with Dr. Earl Vories at the Missouri Delta Center about VRI and how to determine the layout of management zones, it was decided that apparent electrical conductivity (EC_a) of the soil profile could be used to initially characterize field variability (Vories, 2008). EC_a is a sensor-based measurement that provides an indirect indicator of important soil physical and chemical properties. Figures 4 and 5 are ECa maps done with Dual EM unit looking at ECa with depth.

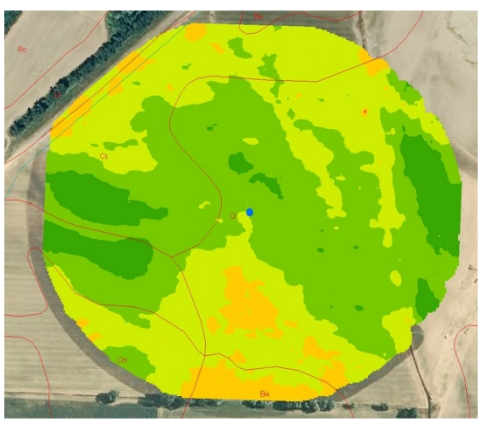


Figure 4, shallow DualME

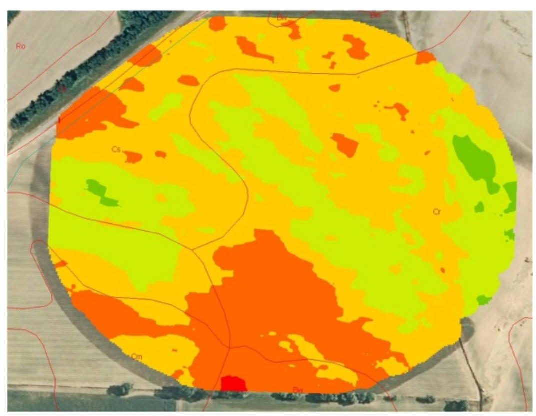


Figure 5, deep DualEM

The Dual EM data provided much better resolution than what was shown by the other available information. Using prescription software that was non geo-referenced allowed for manual design of a zone control package to proceed although it did not provide a way to evaluate the use of speed vs. zone control.

Additional, easy-to-use tools are obviously needed to quantify various field specific VRI packages. A computer program to provide spatial data analysis of geo-referenced data is needed to make a thorough analysis. One such option is using the VRI Optimization tool of CropMetrics™ (http://cropmetrics.com/). This appeared to be a tool that would help guide the decision to use speed or zone control based on specific data. The following example demonstrates how this tool can be used to evaluate a field. The VRI Optimization uses not only ECa data but also topographic information.

Figure 6 shows the deep Dual EM data for a specific field. From the Dual EM data the CropMetrics package calculated field variability as 26.7%. This indicates that with a uniform sprinkler package potentially only 73.3% of the field would receive the correct amount of irrigation and that 26.7% will either receive too much or too little irrigation. The roughly 27% that is under or over irrigated will probably not be able to reach its full yield potential, even with good irrigation scheduling.

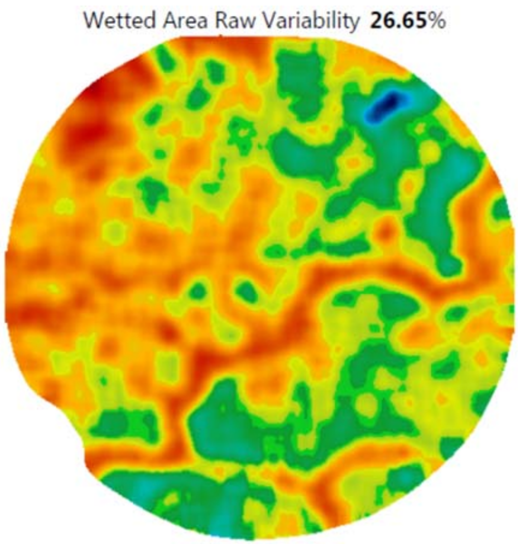


Figure 6

A VRI system would be able to compensate for these differences.
Every field is different as to what the potential yield improvement is possible for each crop being grown. Thus, another important component to consider is the recommendation to use a knowledgeable, local consultant or advisor to help analyze each particular situation.

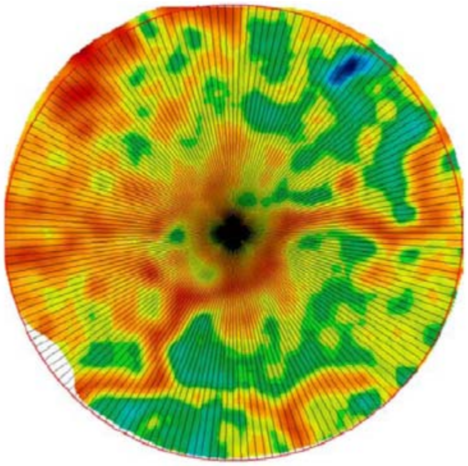


Figure 7

Next using a VRI optimization tool one can determine the potential improvement that may be possible using speed control as shown in figure 7. This shows the potential of how much the variability could be reduced by breaking the field into two degree sectors. The speed of the center pivot can be changed in each of the slices and by changing the speed change the application depth. In this case the variability in watering can be reduced to 21% with an improvement of 5% of the field being over or under watered.

Lastly how much improvement could be achieved if zone control is applied?

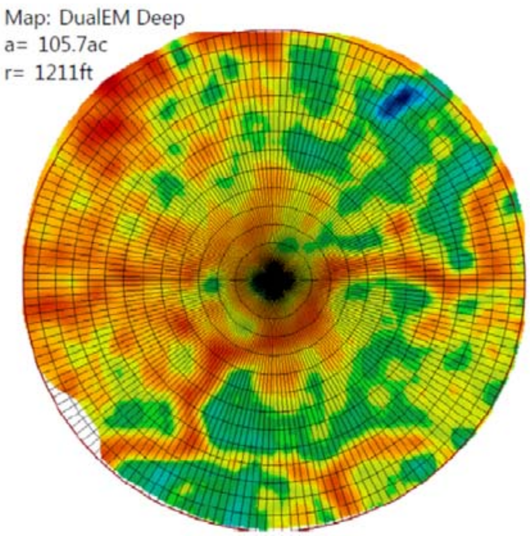


Figure 8

Again using the VRI Optimization tool shows the variability could potentially be reduced to 7.4% as shown in figure 8. This example uses fourteen zones and 180 sectors to reduce the variability to just over 7%. In this application there would be 2,520 different management zones that each could receive a different irrigation application depth.

Using speed control on this field one could achieve an improvement of 5% and with zone control could obtain another 14% improvement to the point 93% of the field is watered optimally.

CONCLUSIONS

When considering whether to switch to VRI the challenge is determining the value and the return on investment for changes. Each case is different due to the characteristics of the field and costs may vary significantly. Computer tools to evaluate a field using EC_a data from DualEM or Veris can simplify the decision process by providing comparison of VRI options. Often taking advantage of the capabilities of the features of a computerized control panel can help meet the need for a few management zones around the field. When one moves to true VRI, often speed control may be added to a center pivot as simply as updating the control panel software (depending on the manufacturer and the control panel). Another option would be to add a separate controller usually on the end of the center pivot independent of the control panel with costs in the range of $1,500 to $2,500. Zone control costs for a typical quarter mile center pivot may range from $12,000 to $28,000 or more depending on the specific design and field application. Since each field is different and has different yield potentials for each crop, it is not possible to make general statements on the potential value of switching to speed or zone control. In general and from data collected so far, a 5% or greater improvement seems to justify the change to speed control and 15% or more for zone control although exceptions exist. Specific numbers or potential improvement ranges for making decisions on whether to change to VRI are difficult to quantify. A combination of data analysis tools coupled with local agronomic expertise can provide guidance for a specific field. Other good reasons to consider VRI include the ability to reduce runoff and reduce or stop the watering of non crop areas. Work is needed to help better describe the potential value of changing to variable rate irrigation.

REFERENCES

American Society of Biological and Agricultural Engineers Standard SW-436

CropMetrics, 2011, North Bend Nebraska, http://cropmetrics.com

Evans, Robert; LaRue, Jacob; Stone, Kenneth; King, Bradley, 2011, Adoption of Site-Specific Variable Rate Sprinkler Irrigation Systems, Irrigation Association 2011 Expo

Moody, Jimmy. 2010. - personal communication, Dyersburg Tennessee

Valmont Irrigation. 2011. – engineering and application departments, Valley Nebraska

Vories, Earl, Kitchen, Newell, Sudduth, Ken, Sadler, John, Griffin, Terry and Stevens, Gene. 2008. Using Precision Agriculture Methods to Predict Soil Suitability for Rainfed Corn Production, 2008 ASABE Annual International Meeting, Rhode Island, American Society of Agricultural and Biological Engineers, paper 084437

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, KS, February 21-22, 2012
Available from CPIA, 760 N. Thompson, Colby, Kansas

INVESTIGATING STRATEGIES TO IMPROVE CROP GERMINATION WHEN USING SDI

James P. Bordovsky
Agricultural Engineer
Texas AgriLife Research, Texas A&M
Lubbock / Halfway, Texas
Voice: 806-889-3315 Fax: 806-889-3416
j-bordovsky@tamu.edu

Andy M. Cranmer
Farm Research Services Manager
Texas AgriLife Research, Texas A&M
Lubbock / Halfway, Texas
Voice: 806-889-3315 Fax: 806-889-3416
amcranmer@ag.tamu.edu

Paul D. Colaizzi
Agricultural Engineer
USDA Agricultural Research Service
Bushland, Texas
Voice: 806-356-5763 Fax: 806-356-5750
paul.colaizzi@ars.usda.gov

Freddie R. Lamm
Research Irrigation Engineer
Kansas State University
Colby, Kansas
Voice: 785-462-6281 Fax: 785-462-2315
flamm@ksu.edu

Steven R. Evett
Soil Scientist
USDA Agricultural Research Service
Bushland, Texas
Voice: 806-356-5775 Fax: 806-356-5750
steve.evett@ars.usda.gov

Terry A. Howell
Agricultural Engineer
USDA Agricultural Research Service
Bushland, Texas
Voice: 806-356-5746 Fax: 806-356-5750
terry.howell@ars.usda.gov

INTRODUCTION

As the nation's population increases and available irrigation water decreases, new technologies are being developed to maintain or increase production on fewer acres. One of these advancements has been the use of subsurface drip irrigation (SDI) on field crops. Research has shown that SDI is the most efficient in-season water application method available to producers, especially under deficit irrigation (Bordovsky and Porter, 2003; Colaizzi et al., 2009). For certain soils, one of the inherent problems with SDI is seed germination during periods without rainfall. This paper summarizes efforts to improve germination when irrigating with SDI at the agricultural research centers at Halfway, Texas; Bushland, Texas; and Colby, Kansas. These efforts were broadly categorized in terms of soil amendments, drip lateral installation depth and row geometry, and preplant irrigation timing and amounts.

SOIL AMENDMENTS

"Wick" water into the germination zone.

Soil amendments and/or soil conditioners have been used for years to improve soil physical properties in the hope of improving crop production or reducing erosion. Several materials were used in field experiments conducted at the Texas AgriLife Research and Extension Center at Halfway, Texas in 2006 and 2007 in an attempt to promote water movement upward from SDI laterals to the seed germination area in a Pullman clay-loam soil. In 2005, drip laterals were installed on 60-inch centers in an east-west direction using standard drip installation implement and tractor with RTK-GPS guidance. Drip lateral depth averaged 14 inches below the leveled soil surface. Thirty-inch wide rows were formed with each lateral serving two crop rows. SDI emitter spacing was 24 inches and emitter flow rate was 0.16 gph at 10 psi.

The study evaluated four soil amendment treatments compared to an undisturbed soil check and to an excavated soil with no soil amendments. The soil amendment treatments required the excavation of soil and placement of amendments from a depth adjacent to drip laterals up to the seed planting zone. The treatments included polyacrylamide or Pam at 20 lb/acre, (Earth Chem., Inc., Scottsbluff, Nebraska), Zeba™ at 20 lb/acre (Absorbent Technologies, Inc., Beaverton, Oregon), composted cow manure at 400 lb/acre (Back to Nature, Lubbock, Texas), a mixture of composted cow manure and gypsum at 400 lb/acre each, and a "no amendment" treatment where soil was excavated as if an amendment were applied, but no amendments were used. Zeba™ is a natural corn starch polymer. The five treatments were replicated four times, resulting in 20 amendment sites. Soil amendments were placed using hand tools in a two dimensional plane from the drip lateral to the crop germination zone. A detailed description of this process is reported by Cranmer et al., 2008. Time domain reflectometry (TDR) soil water measurement probes (Evett and Ruthardt, 2005) were installed at 2, 6, and 12 inch depths in arrays on each side of the SDI lateral (Figure 1). Treatment checks where no amendment or amendment excavation occurred were also established and soil probes installed. The soil probes were used to measure differences in soil volumetric water content (VWC) among the treatments as the soil was wetted with the SDI system. Values for VWC at each probe location and treatment site were acquired daily during the each test cycle.

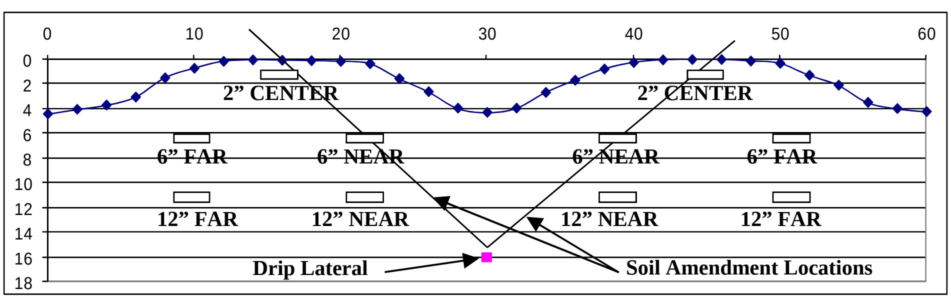


Figure 1. Locations of TDR probes and soil amendments relative to drip laterals and crop rows of treatment sites in the SDI cottonseed germination study at the Texas AgriLife Research Center, Halfway, TX, 2006 and 2007.

To prevent rainfall from masking the effects of irrigation, each site was covered with a small shelter and rain water routed away from treatment sites by modifying crop rows intersecting sheltered areas. In 2006, drip irrigation was started on 31 July and ended on 30 August. Daily irrigation run time was 7 hrs over two periods, 10:00 AM to 1:30 PM and 10:00 PM to 1:30 AM. Irrigation depth was

0.10 in per application or 0.20 in per day. Without reapplying amendments or reinstalling the TDR probes, the soil wetting cycle was repeated again in 2007. Total irrigation applied was 6.0 and 6.8 inches in 2006 and 2007, respectively.

In both years, VWC was recorded prior to irrigation initiation and continued for 30 days following irrigation termination with the treatment locations under rainout shelters the entire time. Irrigation water reaching probe locations was signified by a marked increase in soil VWC. Within each treatment and year, water reached the probe location closest to the drip lateral (12" Near) first and the top of the seedbed (2" Center), generally, last. The time for irrigation water to reach probes is given in Table 1. The average time for water to reach the 2" Center location, or the seed drill location, was 12.5 days in 2006 and 11.2 days in 2007. Of the soil amendments, the Pam treatment resulted in slightly quicker seed drill wetting at 11 and 10 days in 2006 and 2007, respectively, than the other treatments. The treatment that took the longest to wet was the Compost and Gypsum treatment in 2006 at 15 days and the Compost treatment at 12 days in 2007. As shown in Table 1, soil amendment treatments failed to substantially decrease the time required for wetting probe locations compared to the treatments where no amendments were applied or in the check areas where probes were installed in the undisturbed soil profile. Time required to wet probe locations was generally less at all locations and all amendment treatments in 2007 than 2006, indicating soil consolidation over this one year time period may have enhanced water movement from the drip lateral to the seed drill location.

Table 1. Number of days from irrigation initiation to evidence of increased volumetric soil water at given TDR probe locations in plots having different soil amendments at Texas AgriLife Research, Halfway, Texas, 2006-2007.

		Check Undisturbed Soil	Excavated, No Amendment	Zeba^{TM}	Pam	Compost	Compost and Gypsum	Avg.
2006	2" Center	10.0	13.0	13.0	11.0	13.0	15.0	12.5
	6" Far	8.0	13.0	13.0	12.0	10.0	11.0	11.2
	12" far	7.0	10.0	13.0	13.0	9.0	9.0	10.2
	6" Near	3.5	4.0	5.0	5.0	5.0	5.0	4.6
	12" Near	3.0	3.0	4.0	4.0	4.0	3.0	3.5
	Avg.	6.3	8.6	9.6	9.0	8.2	8.6	8.4
2007	2" Center	12.0	11.0	11.0	10.0	12.0	11.0	11.2
	6" Far	11.0	9.0	10.0	10.0	10.0	11.0	10.2
	12" far	9.0	8.0	9.0	9.0	9.0	11.0	9.2
	6" Near	4.0	3.0	4.0	3.0	3.0	4.0	3.5
	12" Near	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Avg.	7.6	6.6	7.2	6.8	7.2	7.8	7.2

Following initial probe wetting, irrigations were continued and soil water measurements were taken to document peak soil VWC at the seed drill position. Peak VWC and times to reach peak VWC of 2006 and 2007 treatments are contained in Figure 2. In both years, the highest water contents at the 2" Center location (i.e., intended seed zone location) were in the Check treatments where soil adjacent to drip laterals had not been disturbed resulting in peak soil VWC contents of 0.215 cm^3/cm^3. This was followed by the No Amendment and Compost and Gypsum treatments. The amount of time to reach peak VWC at the 2" Center locations of the No Amendment treatments were 28 days in 2006 and 18 days in 2007. All other treatments required 24 to 32 days to reach peak soil water content. Soil VWC at the 2" Center location in all treatments failed to reach the levels of the deeper locations, with soil locations at 12" depths generally wetter than those at 6" (data not shown).

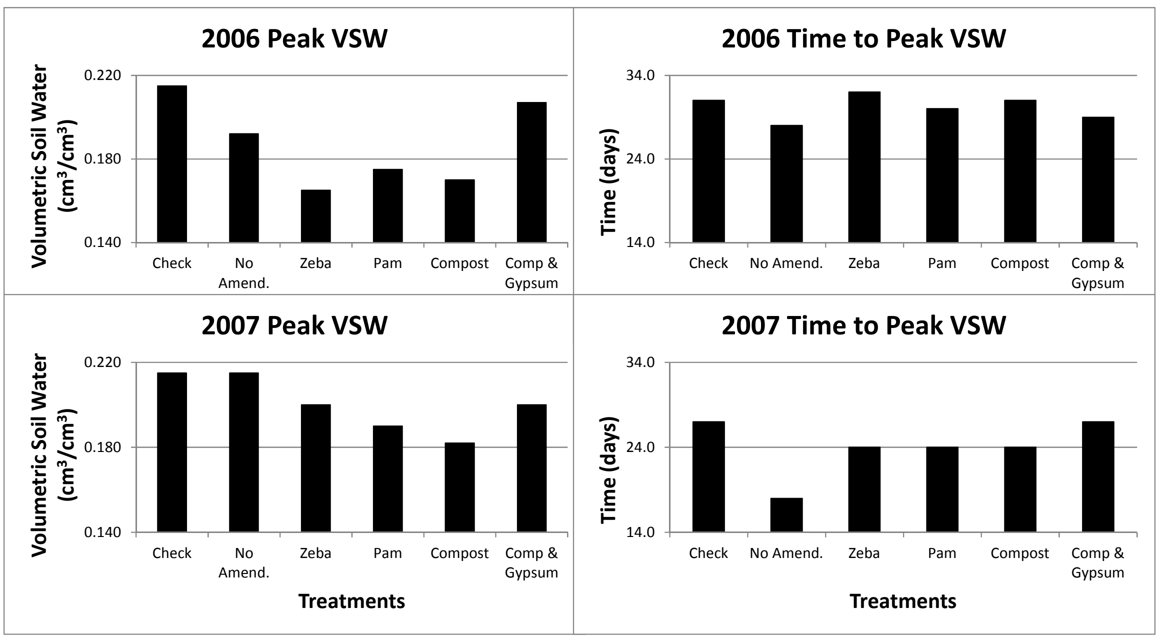


Figure 2. Peak VWC values and the time required to reach peak VWC at the 2" Center location of six soil amendment treatments in the SDI cottonseed germination study at Texas AgriLife Research Center, Halfway, TX, 2006 and 2007.

Although there seems to be little benefit in using these soil amendments to increase soil VWC in the seed germination zone by irrigation with SDI, the Zeba™ treatment appeared to slightly reduce the rate of soil drying following irrigation termination compared to other treatments. In the 2006 test year, rate of soil water loss following irrigation termination ranged from 0.0026 cm^3/cm^3-d for Zeba™ to 0.0043 cm^3/cm^3-d for the Compost treatment. In 2007, water losses ranging from 0.0076 cm^3/cm^3-d for Zeba™ to 0.0089 cm^3/cm^3-d in the Check treatment. These data suggest that the use of the Zeba™ soil amendment in the seed germination zone prior to planting might improve germination by retaining available soil water from rainfall or irrigation longer.

Incorporating polymers near the soil surface to reduce evaporation. The soil amendment Zeba™ was used in an experiment in 2008 in an attempt to improve cottonseed germination and yield. The field where the experiment was conducted was irrigated by SDI, lateral spacing of 60 inches, emitter spacing of 24 inches, emitter flow of 0.16 g/h at 10 psi, lateral depth of 15 inches below level soil surface, and crop row spacing of 30 inches. On 10 April, the polymer was placed two inches deep in rows where cottonseed would later be planted using an eight row planter with material being metered from insecticide boxes. Treatments included polymer rates of 3.2, 6.9, and 10.8 lbs/ac along with an untreated check, 0.0 lbs/ac. Plots were 2 rows wide by 200 ft long and were replicate eight times. Seasonal irrigation was daily with amounts determined by soil water balance and 100% ET_c replacement. Following planting on 10 May, TDR probes were installed in seedbeds perpendicular to the soil surface directly in the plant row at three locations per plot, and in three replicates of each treatment. The seedbeds were allowed to be wetted by precipitation events. Volumetric soil water content was measured from May through September.

The average volumetric soil water content for each treatment through the growing season is shown in Figure 3. All treatments followed the same pattern of change in soil water content and were not drastically affected by the quantity of polymer applied. In terms of cotton lint yield, the untreated check produced 1576 lbs/acre and was not significantly different than the yields of 1456, 1681, and 1701 lbs/acre from the 3.2, 6.9, and 10.8 lb/acre Zeba™ treatments, respectively (Figure 4).

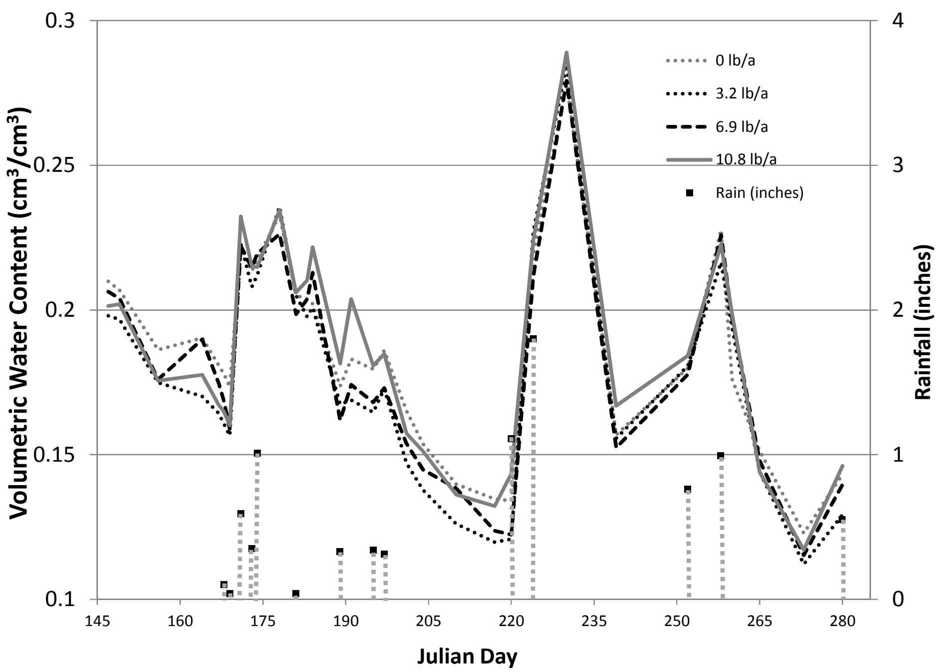


Figure 3. Volumetric soil water content resulting from three rates of Zeba™ polymer applied in the seed drill and determined by TDR probes placed in seedbeds near the soil surface at Texas AgriLife Research Center, Halfway, TX., 2008.

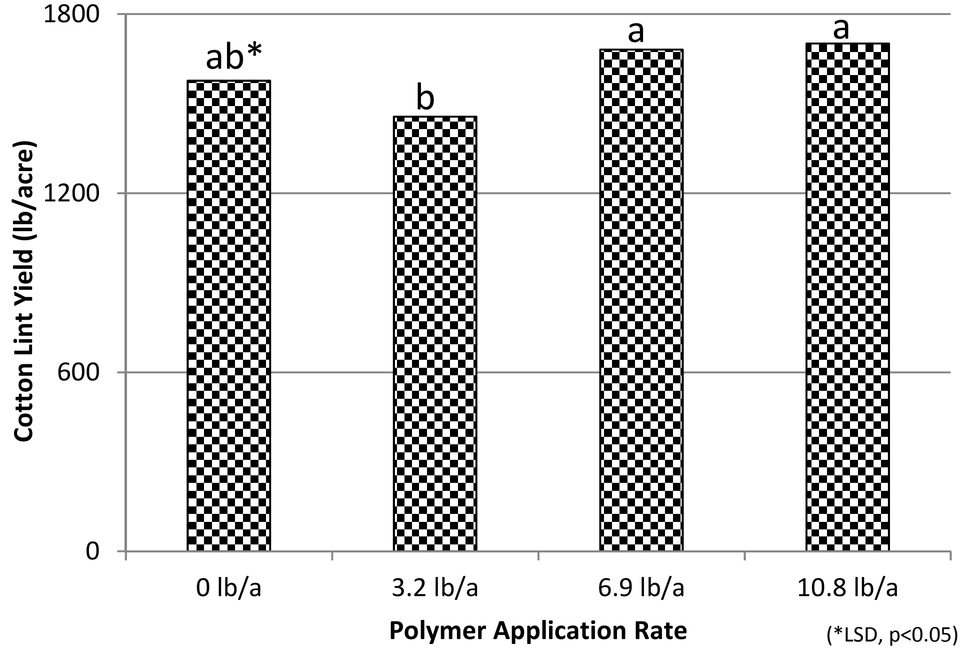


Figure 4. Effects of pre-plant Zeba™ application rates on cotton lint yield, at Texas AgriLife Research Center, Halfway, TX., 2008.

DRIP LATERAL INSTALLATION DEPTH AND ROW GEOMETRY

Bushland Studies

At the USDA Agricultural Research Service Conservation and Production Research Laboratory in Bushland, Texas, scientists evaluated emergence and grain yield with SDI laterals installed in wide beds containing two seed rows and compared this with laterals installed in alternate furrows and in every bed. Drip laterals are commonly installed in alternate furrows because installing laterals in every bed for low value crops is typically uneconomical (Enciso et al., 2005). The wide bed, or twin row design has been used successfully throughout the world for a wide variety of crops (Figure 5). This design has the same number of SDI laterals and plant rows per unit area as standard beds with laterals in alternate furrows, but the seed bed is much closer to the lateral, motivating the hypothesis that better crop establishment and yield would result.

Crop germination can also be influenced by lateral installation depth. Shallow laterals result in greater near-surface wetted soil areas compared with deeper laterals, which may result in more uniform seed germination. However, shallow laterals carry greater risk of mechanical (i.e., tillage operations) and animal (i.e., rodent) damage, engender greater soil water evaporation losses, and may reduce early season seed bed temperatures.

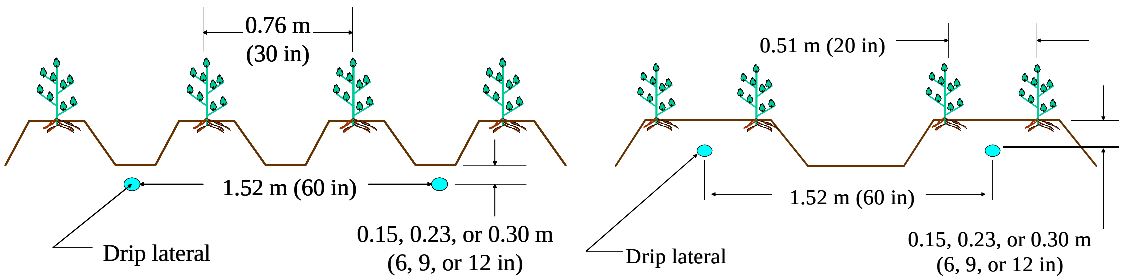


Figure 5. Standard bed design with SDI laterals in alternate furrows (left) and wide bed-twin row design with SDI laterals centered in each bed (right).

Crop yield and plant population were evaluated for each bed design and lateral depth at irrigation rates of 33, 66, and 100% of the full crop water requirement designated as I-33, I-66, and I-100, respectively. The crops were late-planted soybean in 2005 and corn (Pioneer 33B541) seeded at 32,000 plants/acre during the 2006, 2007, and 2008 seasons.

<u>Soybean</u>

Although the wide bed design generally resulted in greater plant emergence early in the season than that for standard beds (with SDI laterals installed in alternate furrows), bed designs and lateral installation depths usually did not result in significant differences in final grain yield (Figure 6). For the I33 and I100 treatments, grain yield was numerically greater for the wide beds, with the exception of the wide-bed I33 treatment with the 9-in lateral installation depth, for which grain yield was significantly less than that for the 12-in lateral depth. For the I66 treatment, grain yield was similar between the wide and standard bed designs, although early season plant emergence was often significantly less for the standard beds. Soybean is a crop that can compensate for sparse stands to some degree through larger plants and more pod set per plant, so the similarity in yields is not surprising. No consistent correlation between lateral installation depth and final yield was observed for the single season of data reported here.

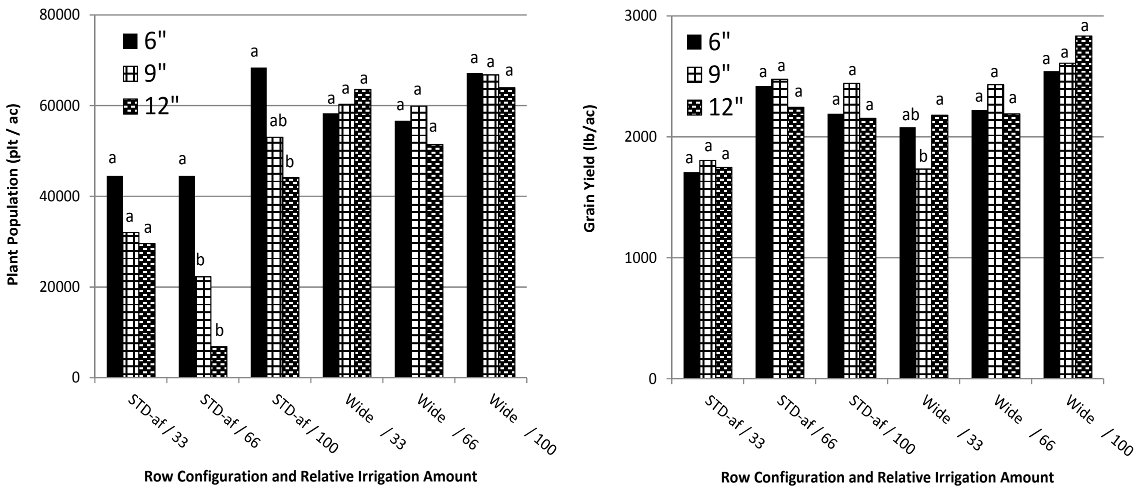


Figure 6. Plant population and soybean grain yield resulting from seed bed configurations, SDI lateral depths (6, 9 or 12 inches), and irrigation levels, Bushland, TX, 2005.

<u>Corn</u>

Early season precipitation and growing conditions were favorable from 2006 to 2008, making evaluation of crop germination response to alternative SDI designs difficult. Grain yield was most responsive to irrigation rate; nonetheless, some differences in grain yield and yield components were observed for bed design and lateral depths among irrigation rates (Table 2). Overall, the 9-inch lateral depth performed best for the standard bed design (except for the I-33 irrigation rate where grain yield for the 9- and 12-inch lateral depth were nearly equal), whereas the 12-inch lateral depth performed best for the wide bed design. The grain yield differences appeared mostly related to numerical differences in final plant population and kernel mass (I-66 and I-100 irrigation rates), or the number of kernels per ear (I-33 irrigation rate). The 12-inch lateral depth likely reduced evaporative losses of near-surface soil water, which was advantageous for the wide bed design. However, for the standard bed design, the 12-inch lateral depth resulted in reduced germination (and hence plant population) compared with shallower lateral depths.

The optimal lateral depth appeared to depend on the choice of bed design, where the 9- and 12-inch lateral depths performed best for the standard and wide bed designs, respectively. This was likely due to the relative influence of germination, soil water evaporation, and early season seed bed temperatures. In drier years, the deeper lateral depth for the wide bed design might reduce evaporative losses and improve yields, as seems to be the case here.

Table 2. Crop response to irrigation rate, bed geometry, and lateral depth, Bushland, Texas, 2006-2008.

Irrigation Rate	Bed Geometry	Irrigation Applied (inches)	Seasonal water use (inches)	Lateral Depth (inches)	Yield 15.5% wb (bu ac^{-1})	Plant Population (plants ac^{-1})	Kernel mass (g)	Kernels per ear
I-33	Standard	8.0	20.1	6	82.6 a	31,804 a	0.281 ab	247 b
				9	103.5 a	30,544 a	0.285 ab	305 ab
				12	103.7 a	30,004 a	0.275 ab	316 ab
	Wide	7.9	19.8	6	93.2 a	29,330 a	0.274 ab	300 ab
				9	91.9 a	29,734 a	0.266 b	321 ab
				12	111.6 a	29,510 a	0.303 a	335 a
I-66	Standard	14.4	26.2	6	237.0 ab	30,904 a	0.353 a	505 a
				9	246.2 a	31,309 a	0.354 a	513 a
				12	221.3 ab	30,724 a	0.350 a	482 a
	Wide	14.2	26.8	6	219.7 ab	29,240 a	0.342 a	514 a
				9	204.5 b	28,835 a	0.336 a	493 a
				12	233.6 ab	30,634 a	0.346 a	522 a
I-100	Standard	20.0	31.3	6	264.1 a	32,074 a	0.352 a	566 a
				9	266.2 a	32,883 a	0.355 a	541 a
				12	248.1 a	32,119 a	0.346 a	534 a
	Wide	20.3	33.6	6	245.8 a	29,510 a	0.358 a	564 a
				9	244.5 a	29,240 a	0.354 a	575 a
				12	253.3 a	30,859 a	0.358 a	549 a

Colby Study

A four-year yield study (1999-2002) was conducted to examine the effect of dripline depth on subsurface drip-irrigated field corn on the deep silt loam soils of western Kansas (Lamm and Trooien, 2005). Although crop germination and establishment were not examined in the study, soil water measurements taken within the study may provide some insight concerning the effect of dripline depth on movement of water towards the crop seed zone. The treatments were five dripline depths of 8, 12, 16, 20 or 24 inches replicated four times in a complete randomized block design. Low flow (0.22 gpm/100 ft) dripline with a 12 inch emitter spacing and 7/8 inch inside diameter was installed with a 5-ft dripline spacing with a shank type injector at the specified treatment depths.

During the study period, the Central Great Plains experienced a severe drought, beginning in the year 2000 and extending through the remaining duration of the study. Available soil water at the crop row (15 inches horizontally from the nearest dripline) was measured periodically during the growing season in 1-foot increments to a depth of 8 ft. During drier periods there was increased soil water availability in the top foot of the profile for the shallower dripline depths as shown in the seasonal progression of soil water from 2000 (Figure 7). The 8 and 12 inch depth showed considerably greater available soil water than the 16, 18, and 24 inch dripline depths for the majority of the season.

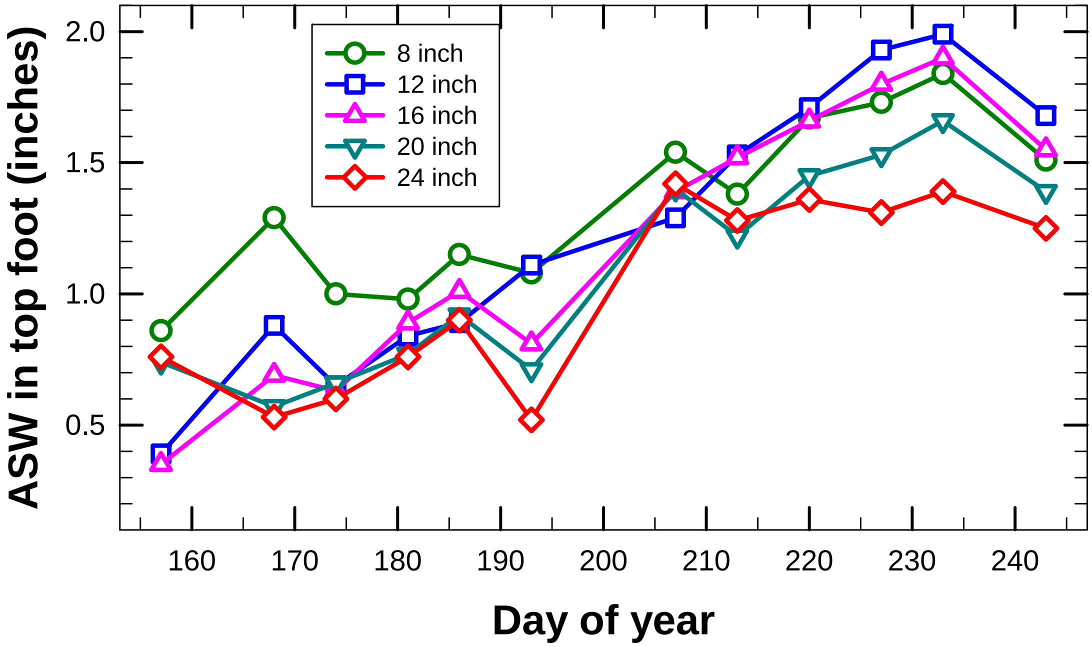


Figure 7. Seasonal progression of available soil water in the top foot of the profile at the crop row as affected by dripline depths ranging from 8 to 24 inches, Colby, KS, 2000.

PREPLANT IRRIGATION TIMING AND AMOUNTS

Pulsing water through SDI emitters verses continuous emitter flow, has been suggested as a possible solution to wetting the seed zone at planting. The theory is that the intermittent irrigation allows time for upward capillary movement of water in non-confined soil profiles and reduces the effects of saturated gravity flow in the downward direction. Although considerable research and theory to support this technique for improved wetting patterns are available for surface drip irrigation (Zur, 1976; Levin and van Rooyen, 1977; Levin et al., 1979), little research and few operational guidelines exist for SDI.

Halfway Study

A field experiment was conducted in 2011 at Halfway to evaluate preplant irrigation sequences in terms of cotton lint yield. The test area contained nine 1.2-acre zones irrigated by SDI laterals spaced at 60 inches. Crop rows were spaced 30 inches apart with two rows planted on single 60 inch beds. All tillage and seedbed shaping occurred immediately following the 2010 harvest, therefore, the seedbeds were undisturbed from December 2010 until cotton planting in May 2011. Rain occurring during this period totaled 1.44 inches.

Irrigation treatments were applied from 8 April to 2 May and totaled 5.0 inches in all plots. Three irrigation sequences replicated three times in a complete randomized block design were included in the experiment. The sequences included irrigating 0.2 in/d until significant rain or until total irrigation had reached 5.0 inches (T1); applying a large early irrigation, 2.5 in, delaying for any rainfall that might occur, then reinitiating irrigation at 0.2 in/d until reaching 5.0 inches (T2); and waiting to initiate irrigations until just prior to planting, then applying 5.0 inches (T3). Irrigation sequences and depths are shown in Figure 8. Additional treatments within each of the three sequences included removing dry soil from the planting bed surface with disks in front of planter units in an attempt to place seed into wetted soil (deep planting). Planting occurred on 11 May. Due to high temperatures, high wind speeds, and the lack of rainfall, irrigations continued in all treatments following preplant irrigation, from 3 May to 1 June, at 0.1 in/d in an attempt to germinate additional cottonseed.

Final plant establishment was extremely low and erratic in all treatments with final plant stands at less than 25% of initial seed drop. All treatments were identically irrigated through the growing season at approximately 40% ET_c. In-season rain was extremely low at 1.5 inches. The entire plot (~0.6 acres) of each treatment and replicate were harvested by traditional methods.

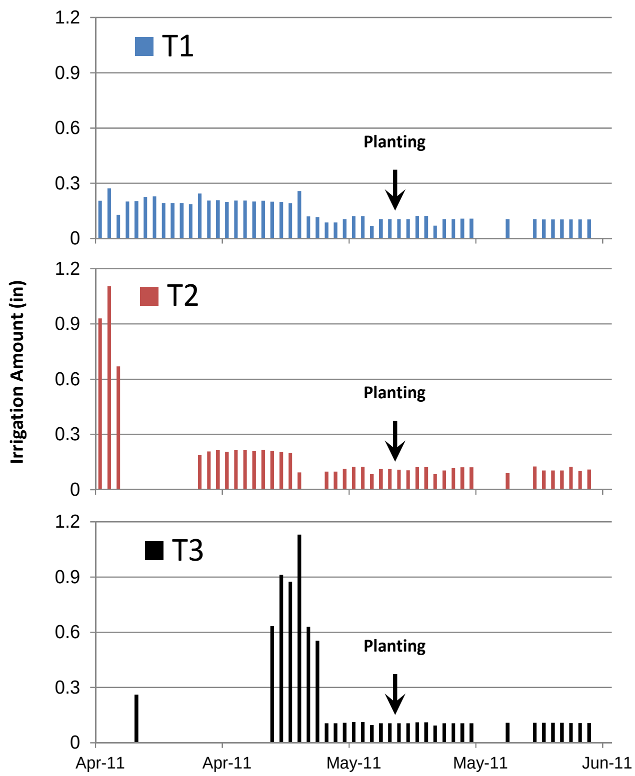


Figure 8. Pre-plant and early season irrigation sequences in a germination study at the Texas AgriLife Research Center, Halfway, TX, 2011.

Although plant stands were extremely poor, cotton lint yield of all treatments averaged 859 lb/ac (Figure 9). Removing dry soil in front of the planter failed to improve germination, failed to consistently improve yield, and would have caused additional germination problems if significant rain had occurred. When considering normal planting methods, applying a large preplant irrigation immediately prior to planting (T3) resulted in significantly less yield than applying a sequence of smaller irrigations (T1 and T2). The 2011 growing season was extremely hot, dry, and windy, particularly during the early stages. As such, these single year test results may not represent those of a more typical growing season.

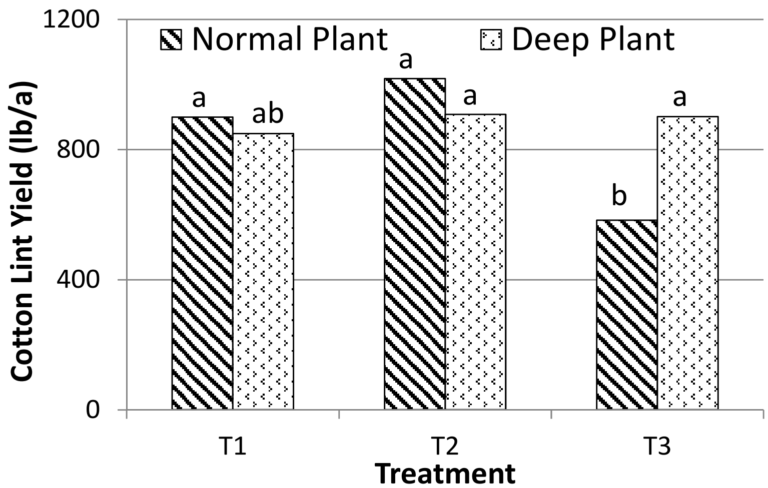


Figure 9. Cotton lint yield resulting from pre-plant irrigation sequences of 0.2 in/d for 25 days (T1), 2.5 inch plus 0.2 in/d for 12 days (T2), and 5.0 inch immediately prior to plant (T3). Cotton was planted with normal planter settings and also following the removal of some dry soil or "deep planting" at the Texas AgriLife Research Center, Halfway, TX, 2011.

Colby Study

A study was conducted on a deep silt loam soil at the KSU Northwest Research-Extension Center in the fall fallow periods of 1999, 2000 and 2001 to examine the effect of intermittent pulsing of irrigation events on soil water redistribution at the crop row. The studies were conducted in the fall because of reduced precipitation probabilities as compared to the spring and summer months. Soil water was measured gravimetrically (0 to 4, 4 to 8, 8 to 12, 12 to 18 and 18 to 24 inch increments) in the crop location which is at a horizontal distance of 15 inches perpendicular to the dripline (16-18 inch depth). Sampling was done prior and after the irrigation events. For brevity, only the results from 0 to 12 inch depth increments will be discussed in this report. The three irrigation treatments (4 replications in randomized complete block design) were a single 32-hour irrigation event, sixteen 2-hour events with 4-hour pauses in between, and eight 4-hour events with 8-hour pauses in between. The application intensity for these 5-ft spaced driplines with 12-inch emitter spacing was 0.048 inches/hour. Minor adjustments were made to the pressures in each plot so as to closely match application intensity. The overall irrigation amount was 1.54 inches. The irrigation events were staged so that the ending of all events were at the same time, thus soil water redistribution before the final soil water gravimetric sampling was for similar periods. In 1999, the study was conducted after the fall bedding tillage operation, so the surface soils were loosely consolidated, but in 2000 and 2001, fall tillage was delayed until after the final soil water sampling.

There was very little change in available soil water between the initial and final gravimetric samplings for the 0 to 4, 4 to 8 and 8 to12 inch soil depth increments in any of the three years (Figure 10). In many cases, at the crop location there was actually slight losses of soil water between the sampling events, although 1.5 inches of water had been applied by the 16-18 inch deep dripline. There were also no significant changes in soil water amounts attributable to the different irrigation strategies.

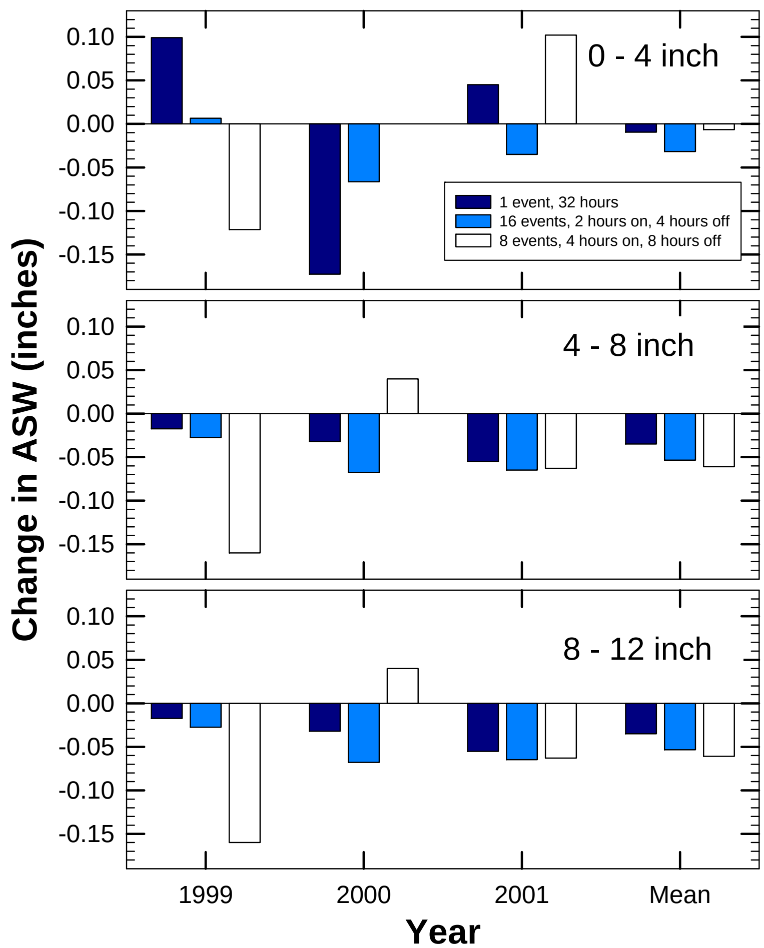


Figure 10. Change in available soil water for various depth increments at the crop row location as affected by timing strategy of irrigation events, Colby, KS, 1999-2001.

The results from the Colby study suggest that pulsing of SDI does not increase redistribution of soil water toward the crop seed zones. These results are similar to simulation and field study results reported by Skaggs et al. (2010) who found no differences in pulsed irrigation treatments. They concluded soil texture and antecedent soil water conditions play larger roles in soil water redistribution with SDI.

RESEARCH SUMMARY

The various experiments conducted at Halfway, Bushland and Colby did not result in procedures to ensure acceptable crop germination with alternate furrow SDI during dry periods. None of the soil amendment treatments improved soil wetting in the seed germination zone over the untreated checks under the conditions of these experiments. Alternate row geometries did not consistently provide significant differences in germination and yield in soybean and corn at Bushland. Shallow dripline depths, such as 8 to 9 inches, may improve soil water availability in the crop seed zone, but results will likely depend on the severity of the drought, soil texture and the amount of soil consolidation above the dripline. None of the three pre-plant irrigation sequences resulted in an acceptable stand of cotton in the hot, dry conditions encountered in 2011 at Halfway. Pulsing of irrigation events did not increase seed zone soil water on silt loam soils in northwest Kansas. Although there appears to be no "silver bullet" to ensure crop germination, the following section outlines general information used at the research centers to improve germination under challenging conditions.

STRATEGIES THAT SEEM TO HELP

Dry overwinter conditions which are prevalent in the semi-arid Great Plains region can result in inadequate near surface soil water for crop germination. Soil conditions such as excessively loose soil above the dripline can exacerbate the problem of water movement into the seedzone. When tillage is necessary or desired, it is best to complete the tillage operations as soon as practical following the previous year’s crop, so that any winter precipitation that does occur can help settle soil in the tillage zone allowing for better capillary movement of applied subsurface drip irrigation water. Minimizing the number of field operations that might disturb the seed zone near the time of planting can help reduce unnecessary drying of the soil. Whenever possible, fertilizers or pesticides that need incorporation into the soil should be done early or in a manner leaving an undisturbed seed zone (e.g. knife application of fertilizer parallel and to the side of the seed zone).

Similarly, excessively compacted soil above the dripline can cause crop establishment problems. Establishment of cotton was poor adjacent to driplines installed at a depth of 8 or 12 inches in wheel-tracked furrows as compared to cotton adjacent to non-tracked furrows (Enciso et al., 2005). They attributed the stand differences to possible flattening of the dripline (i.e., reducing the flow rate) or to reducing soil water redistribution into the seed zone (i.e., decreased soil hydraulic conductivity). Tillage above the wheel tracks following harvest and eliminating wheel tracks from the dripline furrow in a subsequent year eliminated the row-to row differences in establishment and cotton lint yield.

Seed beds that facilitate two crop rows (e.g., two 30-inch spaced rows on 60-inch crop bed centered on 60-inch dripline spacing) can be rebuilt in the fall after harvest and rolled to help with soil settling. Modifications of crop row spacing to reduce the perpendicular, horizontal distance that SDI applied water must travel can also help with crop establishment. For example, corn row spacing can be adjusted to 28 inches between corn rows centered on the dripline with a 32-inch spacing between adjacent crop row pairs. This planting arrangement can be harvested with a normal corn picker head spaced at 30 inches without any modification.

If the upper portions of the soil profile are very dry to a considerable depth, preseason irrigation during the early spring may reduce the amount of spring precipitation required to reconnect wet and dry zones within the profile. This preseason irrigation can also help fill the soil profile with water, and increase the soil hydraulic conductivity between the SDI lateral location and the seed zone area. Hot, windy and dry conditions can also dry adequately moist seed zones, so preseason irrigation can reduce the amount of precipitation required to rewet near surface soil layers. When applied subsurface drip irrigation does not move into the loosely consolidated soil surface layers in a bed cropping system, the dry soil can be removed to the traffic furrow, thus exposing wetter and firmer soils for crop establishment. This same technique could also be utilized through a listing operation on a flat-planted field, but would be more risky due to the possibility of severe crusting should heavy precipitation occur after planting.

Construction or reshaping of beds should be done in such a manner so that the number and size of soil voids and cracks within the bed are minimized. Soil voids can be reduced in the bedding operation itself such as with a roto-tilling operation or by rolling the beds with a cultipacking operation.

Maintenance of greater crop residue on the surface can enhance storage precipitation, through reduced runoff and soil water evaporative losses during fallow periods for both dryland and irrigated production systems, and increase crop water productivity (e.g., Unger and Cassel, 1991; Weise et al., 1998). Both permanent beds and reduced tillage would also reduce the risk of mechanical damage to shallow laterals. Unfortunately, the greater amounts of residue near the surface create a more favorable habitat for mice and other rodents that can damage SDI laterals during relatively dry winters.

ACKNOWLEDGEMENTS

This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University. This is a joint contribution from Texas A&M University, USDA Agricultural Research Service, and Kansas State University. Contribution no. 12-308-A from the Kansas Agricultural Experiment Station. Mention of tradenames is for informational purpose only and does not constitute endorsement.

REFERENCES

Bordovsky, J.P. and D.O. Porter, 2003. Comparison of Spray, LEPA, and Subsurface Drip Irrigated Cotton. Paper No. 032008. In *Proc. ASAE 2003 Annual Int. Meetings*, 1-11. St. Joseph, Mich.: ASAE.

Cranmer, A.M., J.P. Bordovsky, J.T. Mustian, and D.M Nesmith. 2009. Soil amendment and tillage evaluation to improve germination with subsurface drip irrigation. *2009 Proceedings of the Beltwide Cotton Conference*, San Antonio, Texas. Jan 5-8, 2009. Pp 411-421.

Colaizzi, P.D., S.R. Evett, T.A. Howell, and R.L. Baumhardt. 2009. Comparison of grain sorghum, soybean, and cotton production under spray, LEPA, and SDI. In *Proc. 21st Annual Central Plains Irrig. Conf.*, Colby Kansas, February 24-25, 2009. CPIA, 760 N.Thompson, Colby, KS. pp. 122-139.

Encisco, J. M., P. D. Colaizzi, and W. L. Multer. 2005. Economic analysis of subsurface drip irrigation lateral spacing and installation depth for cotton. *Trans. ASAE*. 48(1):197-204.

Evett, S.R. and B.B. Ruthardt. 2005. A Primer on TDR Probe Construction. http://www.cprl.ars.usda.gov/programs.

Lamm, F. R. and T. P. Trooien. 2005. Dripline depth effects on corn production when crop establishment is nonlimiting. *Appl. Engr. in Agric.* 21(5):835-840.

Levin, I. and F. C. van Rooyen. 1977. Soil water flow and distribution in horizontal and vertical directions as influenced by intermittent application rates. *Soil Sci.* 124(6):355-365.

Levin, I., P. C. van Rooyen, and F. C. van Rooyen. 1979. The effect of discharge rate and intermittent water application by point-source irrigation on the soil moisture distribution pattern. *Soil Sci. Soc. Am. J*. 43:8-16.

McMichael, B., Gitz, D.C., Lascano, R., Mahan, J.R., and D.F. Wanjura. 2006. The Growth and Development of Cotton under Sub-Surface Drip Irrigation. Agronomy Abstracts, ASA-CSSA-SSSA Annual Meeting, Indianapolis, Indiana. Paper No. 165-2.

Skaggs, T.H., T. J.Trout, and Y. Rothfuss. 2010. Drip irrigation water distribution patterns: Effects of emitter rate, pulsing, and antecedent water. *Soil Sci. Soc. Amer. J.* 74(6):1886- 1896.

Unger, P.W. and D. K. Cassel. 1991. Tillage implement disturbance effects on soil properties related to soil water conservation: a literature review. *Soil Tillage Research*. 19: 363–382.

Weise, A. F., T. H. Marek, and W. L. Harman. 1998. No tillage increases profit in a limited irrigation: dryland system. *Journal of Production Agriculture*. 11: 247–252.

Zur, B. 1976. The pulsed irrigation principle for controlled soil wetting. *Soil Sci.* 122(5):282-291.

SDI, THE BASICS OF SUCCESSFUL SYSTEMS

Freddie R. Lamm
Research Agricultural Engineer
Kansas State Research and Extension
Northwest Research-Extension Center
Colby, Kansas
Voice: 785-462-6281
Email: flamm@ksu.edu

Danny H. Rogers
Extension Agricultural Engineer
Kansas State Research and Extension
Biological and Agricultural Engineering
Manhattan, Kansas
Voice: 785-532-2933
Email: drogers@ksu.edu

INTRODUCTION

Overall, SDI systems have been successful in the Great Plains region despite minor technical difficulties during the adoption process. In a 2005 survey of SDI users, nearly 80% of Kansas producers indicated they were at least satisfied with the performance of their SDI system, and less than 4% indicated they were unsatisfied (Alam & Rogers, 2005). However, even satisfied users indicated a need for additional SDI management information. The most noted concern was rodent damage and subsequent repairs. A few systems had failed or been abandoned after limited use due to inadequate design, inadequate management, or a combination of both.

Design and management are closely linked in a successful SDI system. Research studies and on-farm producers consistently indicate that SDI systems result in high-yielding crops and water-conserving production practices only when the systems are properly designed, installed, operated and maintained. A system that is improperly designed and installed is difficult to operate and maintain and most likely will not achieve high irrigation water application uniformity and efficiency goals. Proper design and installation alone do not ensure high SDI efficiency and long system life, though. A successful SDI system also must be operated according to design specifications while utilizing appropriate irrigation water management techniques. SDI systems also are well-suited to automation and other advanced irrigation scheduling and management techniques. Additionally, proper maintenance is crucial for the continued life of an SDI system. This paper will review the basics of successful SDI systems.

WATER QUALITY ANALYSIS, THE STARTING POINT FOR ALL SUCCESSFUL SDI SYSTEMS

Because most SDI systems are planned for multiple-year use, water quality is an extremely important consideration. Clogging prevention is crucial to SDI system longevity and requires understanding of the potential hazards associated with a particular water source. Replacement of clogged driplines can be expensive, difficult, and time-consuming. Although nearly all water is potentially usable for SDI, the added cost of complex water filtration and chemical treatment of marginal-quality water might further reduce the feasibility of SDI use on lower-value crops. Therefore, no SDI system should be designed and installed without first assessing the quality of the proposed irrigation water supply. In some cases, poor water quality can also cause crop growth and/or long-term soil problems. However, with proper treatment and management, many waters high in minerals, nutrient enrichment, or salinity can be used successfully in SDI systems. A good water quality test (Table 1) provides information to growers and designers in the early stages of the planning process so that suitable water treatment, management, maintenance plans, and system components can be selected. Although a good water quality test may cost a few hundred dollars, the absence of it may result in an unwise investment in an SDI system that is difficult and expensive to manage and maintain. Tests 1 through 7 are usually provided in a standard irrigation water quality test package, whereas Tests 8 through 11 are generally offered as individual tests. The test for the presence of oil may be helpful in oil-producing areas or if a groundwater well with oil lubrication has experienced surging, allowing existing drip oil in the water column to mix with the pumped water.

Table 1. Recommended water quality tests to be completed before designing and installing an SDI system (after Rogers et al., 2003a).

1.	**Electrical Conductivity (EC),** a measure of total salinity or total dissolved solids, measured in dS/m or mmho/cm.
2.	**pH,** a measure of acidity, where a value of 1 is very acid, 14 is very alkali, and 7 is neutral.
3.	**Cations** include Calcium (Ca), Magnesium (Mg), and Sodium (Na), measured in measured in meq/L, (milliequivalent/liter).
4.	**Anions** include Chloride (Cl), Sulfate (SO4), Carbonate (CO3), and Bicarbonate (HCO3), measured in meq/L.
5.	**Sodium Absorption Ratio (SAR),** a measure of the potential for sodium in the water to develop sodium sodicity, deterioration in soil permeability and toxicity to crops. SAR is sometimes reported as Adjusted (Adj) SAR. The Adj. SAR value better accounts for the effect on the HCO3 concentration and salinity in the water and the subsequent potential damage to the soil because of sodium.
6.	**Nitrate nitrogen (NO3 - N),** measured in mg/L (milligram/liter).
7.	**Iron (Fe), Manganese (Mn), and Hydrogen Sulfide (H2S),** measured in mg/L.
8.	**Total suspended solids,** a measure of particles in suspension in mg/L.
9.	**Bacterial population,** a measure or count of bacterial presence in # / ml, (number per milliliter)
10.	**Boron*** measured in mg/L.
11.	**Presence of oil****

* *The boron test would be for crop toxicity concern.*

** *Oil in the water would present a concern of excessive filter clogging. It may not be a test option at some labs and could be considered an optional analysis.*

Additional information on assessing water quality and developing water treatment plans are available from a number of sources (Rogers et al., 2003a; Burt and Styles, 2007; Schwankl, et al., 2008).

FUNDAMENTAL SDI DESIGN CHARACTERISTICS

Fundamental SDI design characteristics need to be addressed early in the design process, namely dripline selection and dripline installation aspects. Interactions exist between these two and with other design aspects occur later in the design process. A complete discussion of these characteristics is beyond the scope of this paper, so the reader is referred to Lamm and Camp (2007) for further discussion. However, some brief discussion is necessary since the characteristics are so fundamental to SDI design.

Dripline Selection

The selection of a dripline involves consideration of dripline diameter and wall thickness, emitter type, discharge rate and emitter spacing.

Dripline inside diameter
Larger diameter driplines allow long lengths of run and large zone sizes without sacrificing water distribution uniformity. Although larger diameter driplines cost more per unit length, their selection may result in a less expensive SDI system because of reduction of trenching and system controls. Dripline diameters up to 1.375 inches are now available and often used in large fields to decrease the number of required zones and field obstructions posed by additional valve boxes. Each SDI system design is different, however, and the grower should not automatically choose the larger dripline diameter. Larger driplines require longer fill and drain times which can adversely affect water and chemical application uniformity and redistribution within the soil.

Dripline wall thickness
The wall thickness of SDI driplines is often greater than surface drip irrigation (DI) because of the additional risk of dripline damage during installation and because the SDI system is intended to have an extended, multiple-year life. Thin-walled, collapsible polyethylene (PE) driplines with wall thicknesses of 12 to15 mil are used primarily for SDI installations in the Great Plains. In situations where soil compaction or soil overburden may cause dripline deformation, thick-walled PE tubing (hard hose) can be selected, although it is considerably more expensive. Thicker-walled products allow higher maximum dripline pressures that can be used to open partly-collapsed driplines caused by soil compaction or overburden, or to increase flow of chemically treated water through partly-clogged emitters. In addition, anecdotal reports highlight less insect damage to hard hose driplines.

Emitter type
Subsurface drip irrigation emitters are fully contained within the dripline to avoid significant protrusions that may become damaged during the SDI system installation process. These internal emitters are typically formed using one of three different methods: 1) long, tortuous passageway is formed through an indention process within the seam of the dripline as it is formed; 2) integral short tortuous path emitter is fusion-welded to the internal wall of the PE tubing; and 3) continuous narrow strip containing the turbulent emitter passageway is fusion-

welded to the internal dripline wall. Integral short path emitters sometimes have a lower manufacturer's coefficient of variation (CV) than those of the other processes, but all processes provide acceptable CV values with the modern manufacturing processes currently available. All three of these emitter types are used in SDI systems within the Great Plains region.

Emitter types are also classified by their emitter exponent (i.e., typically referred to as X, the exponent on the pressure term in the emitter discharge equation). An exponent less than 0.5 allows an emitter to be classified as partially pressure compensating, whereas a value of zero represents full pressure compensation (PC). An emitter with an exponent greater than 0.5 is classified as non-pressure compensating. Many current SDI driplines have emitter exponents with values close to 0.5 and, traditionally, PC emitters were considered too expensive for SDI installations on lower-value crops. However, manufacturers continue to evolve product lines and processes, and some driplines with PC emitter characteristics are becoming more economically competitive.

Emitter discharge rate

Wide ranges of emitter discharge rates are available from the various dripline manufacturers. The evapotranspiration (ETc) needs of the crop have little influence on the choice of emitter discharge rate because most emitter discharge rates at typical emitter and dripline spacings provide SDI system application rates in excess of peak ETc. Some designers prefer emitters with greater discharge rates because they are less subject to clogging and allow more flexibility in scheduling irrigation. However, when emitters with greater discharge are chosen, the length of run may need to be reduced to maintain good uniformity and to allow for adequate flushing within the maximum allowable operating pressure. In addition, the zone size may need to be reduced to keep the total SDI system flowrate within the constraints of the water supply system. The choice of emitter discharge rate must also account for the soil hydraulic properties in order to avoid backpressure on the emitters and surfacing of water, although this problem is not common on SDI systems in the Great Plains.

Physical limitations exist to further reducing emitter discharge rate because smaller passageways are more easily clogged. The nominal dripline flowrate can be reduced by with smaller emitter discharge rates or by increasing the emitter spacing. Limitations also exist to increasing the emitter spacing that are related to adequately supplying the crop's water needs. Using a lower emitter discharge rate in combination with a greater emitter spacing is often economically attractive (reduced design and installation costs) on deeper, medium-textured soils for crops with extensive root systems.

Emitter spacing

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

Dripline installation aspects

Some dripline installation aspects require basic decisions about dripline spacing, dripline depth, and zone size (length and width). As noted earlier in the paper, these installation aspects may interact with the selection of the dripline.

Dripline spacing

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

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

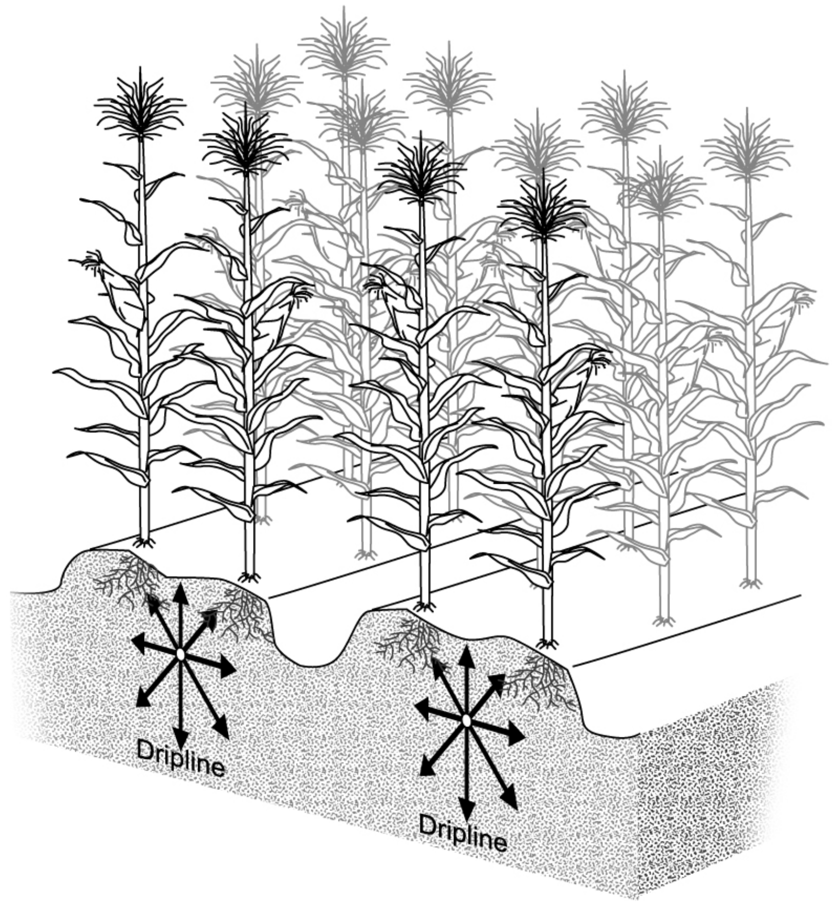


Figure 1. Alternate row/bed 5 ft SDI dripline spacing for corn rows spaced at 2.5 ft. Each plant row is approximately 1.25 ft m from the nearest dripline and has equal opportunity to the applied water.

<u>Dripline depth</u>

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

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

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

<u>Zone size (length and width) considerations</u>
The overall field size that can be subsurface drip irrigated is limited by the available water supply and SDI system flowrate. However, the ability to economically adjust the size of the irrigated field to the available water supply is a distinct advantage of SDI systems as compared to center pivot sprinklers. If sufficient water supply is available to adequately irrigate the crop for the overall field size, then system flowrate, field shape, and topography, along with the dripline hydraulic characteristics (i.e., emitter discharge characteristics and dripline diameter) are used to determine the number of zones and the zone dimensions. Minimizing the number of necessary zones and using longer driplines typically results in a more economical system to install and operate, which is of great importance to those growers using SDI on lower-valued crops.

SDI COMPONENTS FOR EFFICIENT WATER DISTRIBUTION AND SYSTEM LONGEVITY

SDI system design must consider individual management restraints and goals, as well as account for specific field and soil characteristics, water quality, well capabilities, desired crops, production systems, and producer goals. However, certain basic features should be universal throughout all SDI systems (Figure 2).

The long-term efficient operation and maintenance of the system is seriously undermined if any of the minimum components are omitted during the design process. Minimum SDI system components should not be sacrificed as design and installation cost-cutting measures. If minimum SDI components cannot be included as part of the system, an alternative type of irrigation system or a dryland production system should be considered.

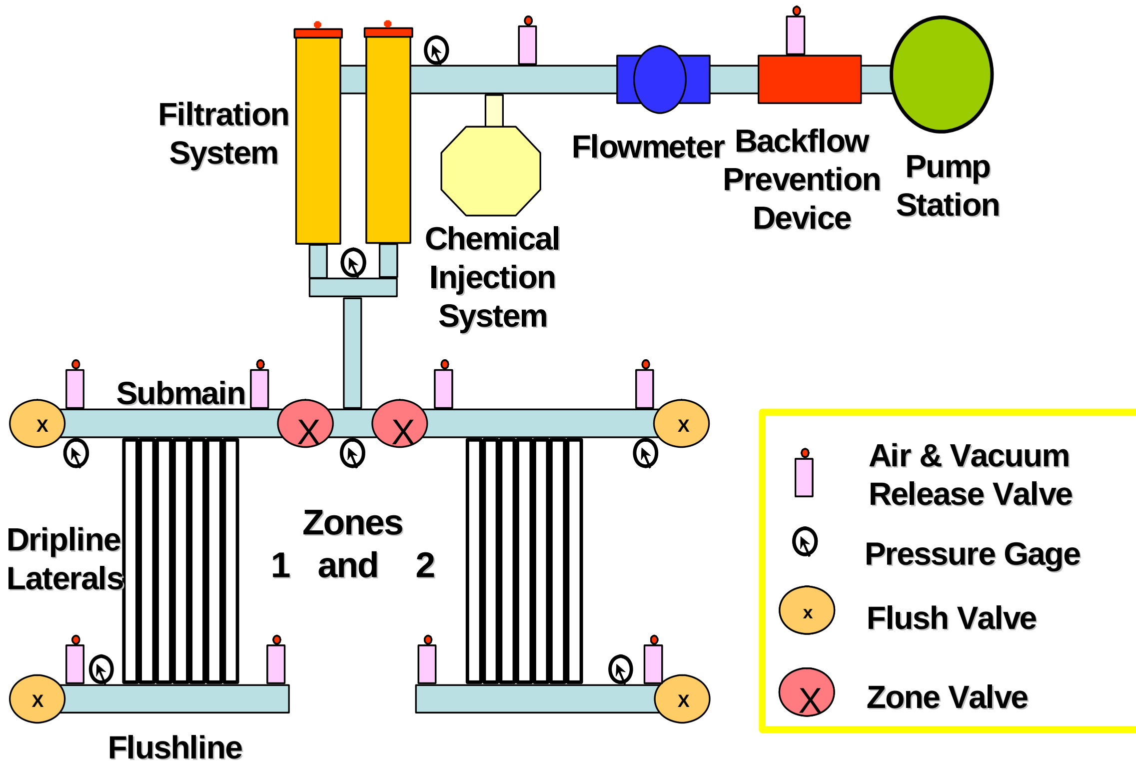


Figure 2. Minimum required components of an SDI system. Components are not to scale. After Rogers, 2003b.

Water distribution components of an SDI system include the pumping station, the main, submains and dripline laterals. Sizing requirements for the mains and submains are somewhat similar to underground service pipe to center pivot sprinklers or main pipelines for surface-irrigated gravity systems and are determined by the flowrate and acceptable friction loss within the pipe. In general, the flowrate and friction loss determine the dripline size (diameter) for a given dripline lateral length and land slope. An SDI system consisting of only the distribution components has no method to monitor system performance or conduct system maintenance, and the system would not have any protection from clogging. Clogging of dripline emitters is the primary reason for SDI system failure. In addition to basic water distribution components, other components allow the producers to monitor SDI system performance, allow flushing, and protect or maintain performance by injection of chemical treatments. The injection equipment can also be used to provide additional nutrients or chemicals for crop production. A backflow prevention device is required to protect the source water from accidental contamination if backflow should occur.

The actual characteristics and field layout of an SDI system vary from site to site, but irrigators often add additional capabilities to their systems. For example, the SDI system in Figure 3 shows additional valves that allow the irrigation zone to be split into two flushing zones. When the well or pump does not have the capacity to provide additional flow and pressure to meet the flushing requirements for the irrigation zone, splitting the zone into two parts may be an important design feature.

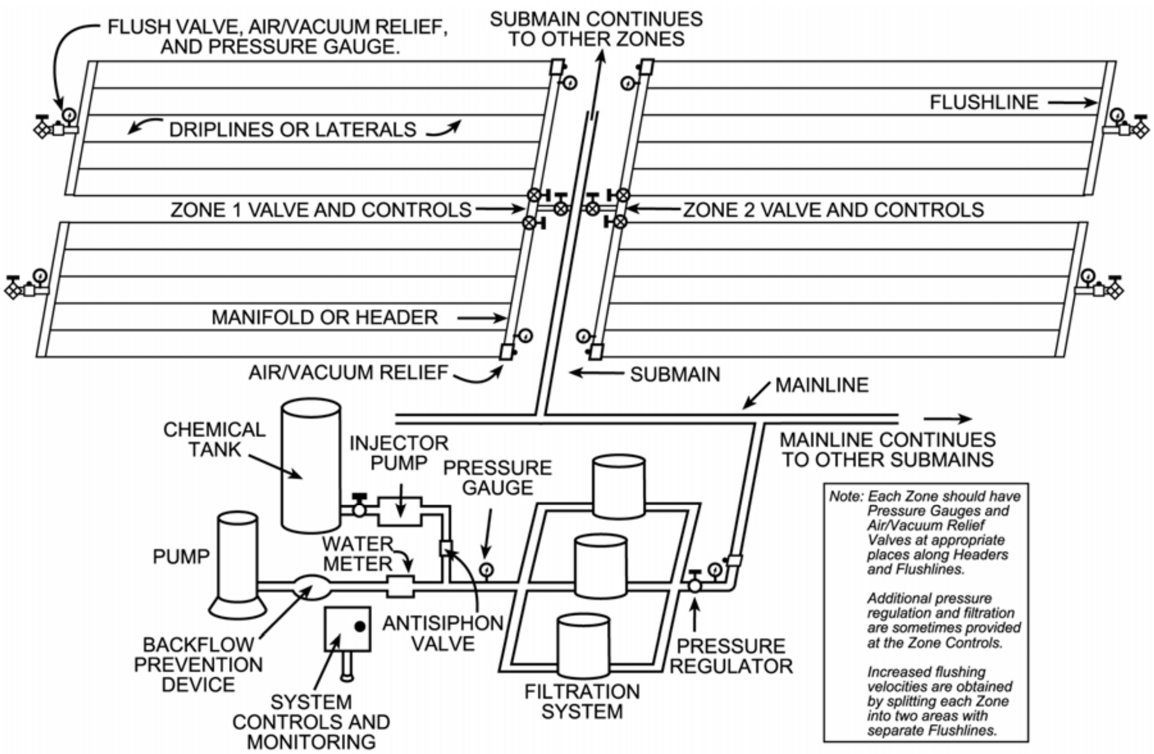


Figure 3. Schematic of a complete SDI system. After Lamm and Camp (2007).

Filtration system

The heart of the protection system for the dripline emitters is the filtration system. Many types of filtration systems (Figure 4) are commercially available and the selected type depends on the quality characteristics of the irrigation water and the clogging hazards.

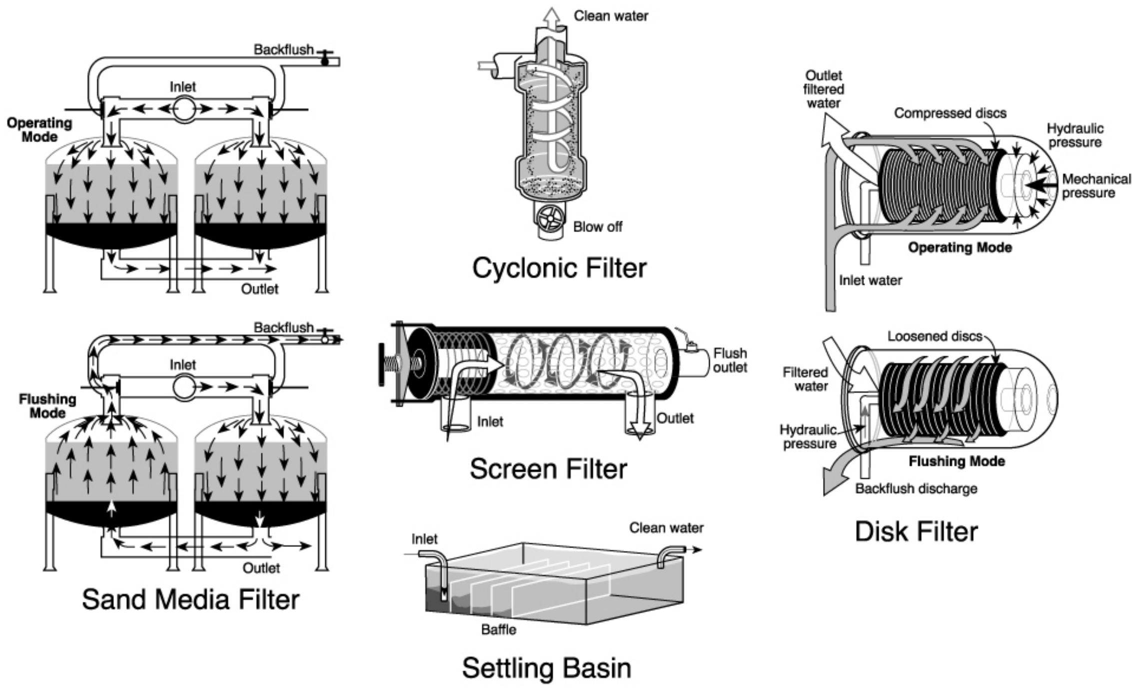


Figure 4. Schematic description of various filtration systems and components. (Courtesy of Kansas State University).

Screen filters are the simplest type of filtration and provide a single plane of filtration. They are most often used in situations where the water source is relatively clean. Sand media filtration systems, which consist of two or more large pressure tanks with specially graded filtration sand, provide three-dimensional filtration and are well-suited for surface water sources. Surface water supplies may require settling basins and/or several layers of bar screen barriers at the intake site to remove large debris and organic matter. Another common type of filtration system is the disc filter which also provides three-dimensional filtration. In some cases, the filtration system may be a combination of filtration components. For example, a well that produces a large amount of sand in the pumped water may require a cyclonic sand separator in advance of the main filter.

Clogging hazards are classified as physical, biological or chemical. Sand particles in the water represent a physical clogging hazard, whereas biological hazards are living organisms, or life by-products, that clog emitters. Water sources that have high iron content are also vulnerable to biological clogging hazards, such as an iron bacteria flare-up within the groundwater well. Control of bacterial growth generally requires water treatment in addition to filtration. Chemical clogging hazards relate to the chemical composition or quality of the irrigation water. As water flows from a well to the distribution system, chemical reactions occur due to changes in temperature, pressure, air exposure, or the introduction of other materials into the water stream. These chemical reactions may form precipitates that result in emitter clogging.

Flushlines

Filter systems are generally sized to remove particles that are approximately 1/10 the diameter of the smallest emitter passageway. However, small particles still pass through the filter and into the driplines, and over time, they may clump together. Also, biological or chemical processes produce materials that need to be removed in order to prevent emitter clogging or a build-up of material at the outlet or distal end of the system. A good design should allow flushing of all pipeline and system components. Opening the flushline valves allows water to rapidly pass through the driplines, carrying away any accumulated particles. The American Society of Agricultural and Biological Engineers (ASABE) recommends a minimum flushing velocity of 1 ft/s for microirrigation lateral maintenance (ASAE EP-405, 2008). This flushing velocity requirement needs to be carefully considered at the design stage and may dictate larger sizes for submains and flushlines to assure that maximum operating pressures for the driplines are not exceeded (Lamm and Camp, 2007).

The frequency of flushing is largely determined by the quality of the irrigation water and, to a degree, the level of filtration. Evaluation of the amount of debris caught in a mesh cloth during a flushing event is an indicator of the required frequency of flushing. When only a small amount of debris is found, the flushing interval may be increased. Heavy accumulations of debris, however, mean more frequent flushing is needed.

Chemical injection system

In addition to SDI system protection, the chemical injection system may also be used to inject nutrients or chemicals into the water to enhance plant growth or yield. A variety of injectors can be used, but the choice of unit depends on the desired injection accuracy for the chemical, the rate of injection, and the chemical being injected. When a wide variety of chemicals are likely to be injected, then more than one type of injection system may be required. Also, state and federal laws govern the type of injectors, appropriate chemicals, application amounts, and required safety equipment that may be used in SDI systems, as illustrated by Figure 5.

Many different chemicals can be injected, including chlorine, acid, dripline cleaners, fertilizers, and some pesticides. Producers should avoid injecting any chemical into their SDI system without knowledge of the chemical compatibility with irrigation water. For example, various phosphorus fertilizers are incompatible with many water sources and may only be injected using additional precautions and management techniques. All applicable laws and labels should be followed when applying chemicals.

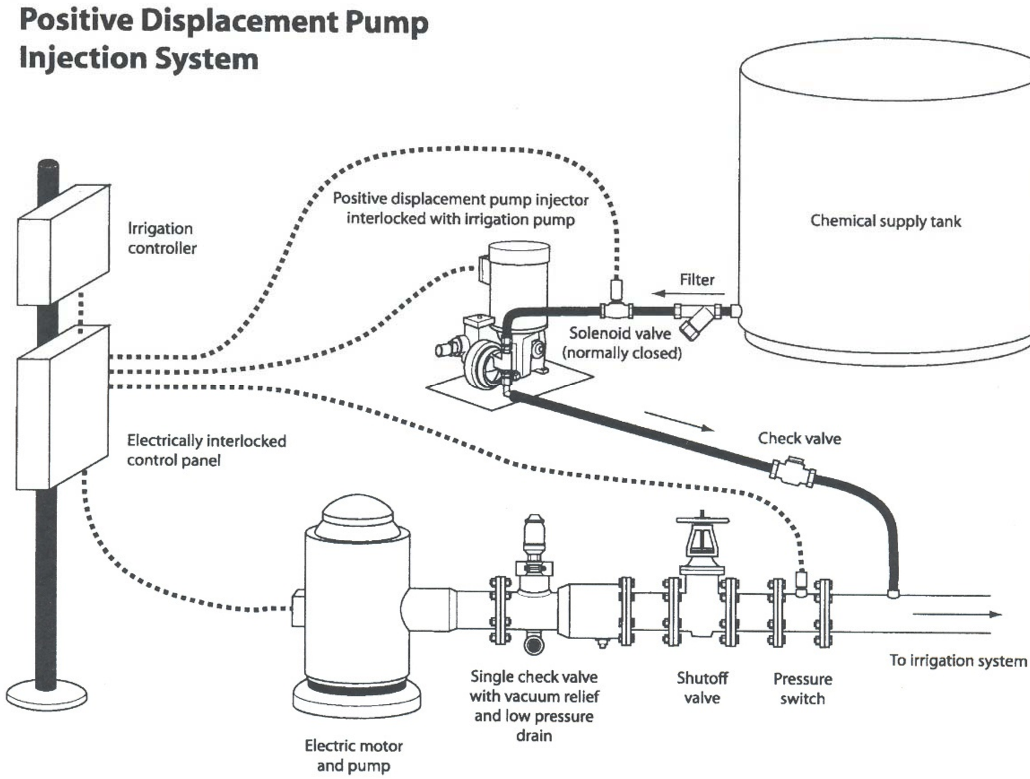


Figure 5. Layout of a chemical injection system with safety interlocks and backflow prevention devices (Courtesy of L.J. Schwankl, Univ. of California-Davis).

The injection systems in Figures 2 and 3 have a single injection point located upstream of the main filter, but some agrochemicals may require an injection point downstream from the filter to prevent filter damage. Care needs to be exercised in the location of the injection port to prevent system problems such as corrosion within the filters or chemical precipitation beyond the filter resulting in emitter clogging.

Chlorine is commonly used to disinfect the injection system and minimize the risk of clogging from biological organisms. Acid injection can also lower the pH chemical characteristic of the irrigation water. For example, water with a high pH clogs easily because minerals drop out of solution in the dripline after the water passes through the filter. A small amount of acid added to the water lowers the pH to minimize the potential for chemical precipitates.

MONITORING THE SDI SYSTEM

In SDI systems, all water application is underground. Because surface wetting seldom occurs in properly installed and operated systems, no visual cues of system operation are available to the manager. Therefore, the flow meter and pressure gauges must be used to provide operational feedback cues. The pressure gauges along the submain of each zone measure the inlet pressure to driplines. Decreasing flowrates and/or increasing pressure may indicate clogging, and increasing flowrates with decreasing pressure may indicate a major line leak. The inlet pressure gauges, along with those at the distal ends of the dripline laterals at the flushline valve, help establish the baseline performance characteristics of the system. Good quality pressure gauges should be used at each of these measurement locations and the gauges should be periodically replaced or inspected for accuracy. The flowrate and pressure measurements should be recorded and retained for the life of the system. A time series of flowrate and pressure measurements can be used as a diagnostic tool to discover operational problems and determine appropriate remediation techniques (Figure 6).

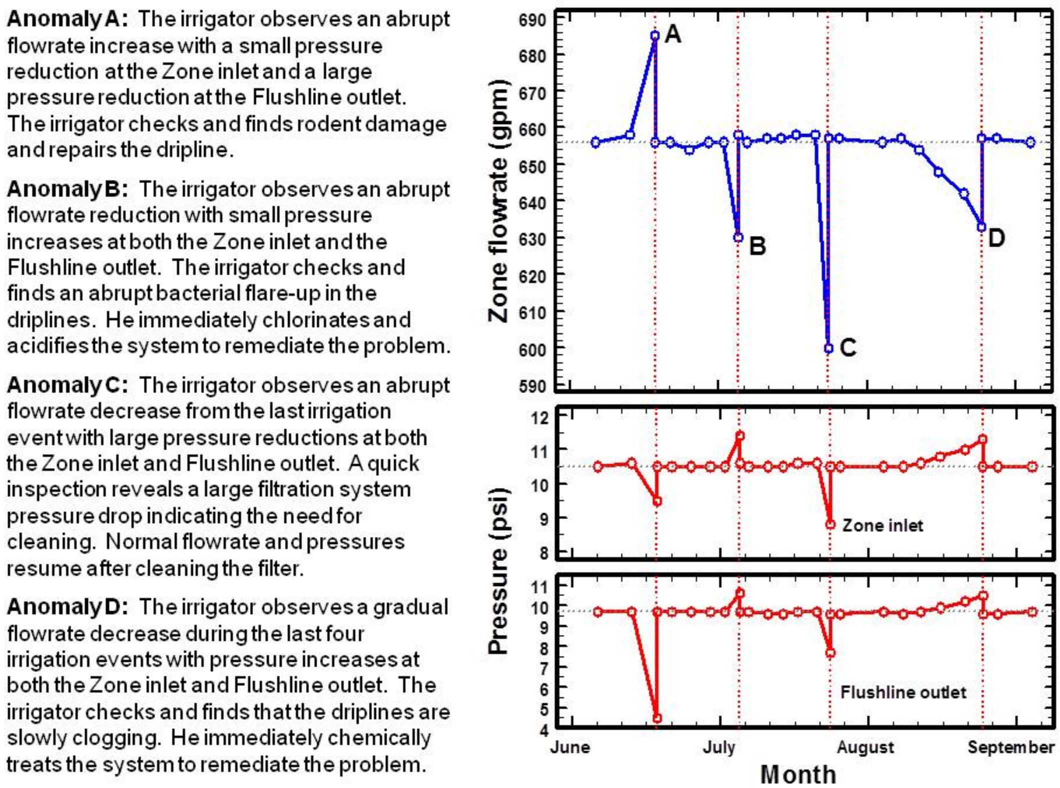


Figure 6. Hypothetical example of how pressure and flowrate measurement records could be used to discover and remediate operational problems. After Lamm and Camp (2007).

RODENT MANAGEMENT

Burrowing mammals, principally of the rodent family, can cause extensive leaks that reduce SDI system uniformity. Most rodents avoid digging into wet soil, so dripline leaks presumably are not caused by the animals looking for water. Rather, rodents must gnaw on hard materials, such as plastic, to wear down their continuously growing teeth. The difficulty in determining the actual location of a dripline leak is compounded by the fact that the leaking water may follow the rodent burrow path for a considerable distance before surfacing. Anecdotal reports from the Great Plains describe some of the typical habitat scenarios that tend to increase rodent problems. These scenarios include the close proximity of permanent pastures and alfalfa fields, railroad and highway easements, irrigation canals, sandy soils, crop and grain residues during an extended winter dormant period, or absence of tillage.

Cultural practices such as tillage and crop residue removal from around SDI control heads and above-ground system apparatus seem to decrease the occurrence of rodent problems. Some growers have used deep subsoiling and/or poison bait around the SDI system field perimeters as a means of reducing rodent subsurface entry into the field. Isolated patches of residue within a barren surrounding landscape provide an "oasis" effect conducive to rodent establishment. After the smaller rodents become established, other burrowing predators such as badgers can move into the field, further exacerbating the damage. Caustic, odoriferous, pungent, and unpalatable chemical materials have been applied through SDI systems in attempts to reduce rodent damage, but the success of these trials has been varied. Periodic wetting of the soil during the dormant period has been suggested as a possible means of reducing rodent damage. Deeper SDI depths (18 inches or greater) may avoid some rodent damage (Van der Gulik, 1999) since many of the burrowing mammals of concern in the United States have a typical depth range of activity that is less than 18 inches (Cline et al., 1982).

PRODUCER RESPONSIBILITIES

As with nearly all investments, the decision of whether an SDI investment is sound lies with the investor. Wise decisions generally require a thorough understanding of the fundamentals of the particular opportunity and/or the recommendations from a trusted and proven expert. While the microirrigation (drip) industry dates back nearly 50 years and SDI application in Kansas has been researched since 1989, the network of industry support is still evolving in portions of the Great Plains region. Individuals considering SDI should spend time to determine if SDI is a viable systems option for their situation. They might ask themselves:

What things should I consider before purchasing an SDI system?

1. Educate yourself before contacting a service provider or salesperson by
    a. Seeking out university and other educational resources. A good place to start is the K-State SDI website at www.ksre.ksu.edu/sdi
    Read the literature or websites of microirrigation companies as well.
    b. Review SDI minimum design components as recommended by K-State. http://www.ksre.ksu.edu/sdi/Reports/2003/mf2576.pdf
    c. Visit other producer sites that have installed and are using SDI. Most current producers are willing to show their SDI systems to others.

2. Interview at least two companies.
    a. Ask them for references, credentials (training and experience) and completed sites (including the names of contacts or references).
    b. Ask questions about design and operation details. Pay particular attention if the minimum SDI system components are not met. If not, ask why. System longevity is a critical factor for economical use of SDI.
    c. Ask companies to clearly define their role and responsibility in designing, installing, and servicing the system. Determine what guarantees are provided.
3. Obtain an independent review of the design by an individual that is not associated with the sale. This adds cost but is relatively minor in comparison to the total cost of a large SDI system.

CONCLUSION

SDI can be a viable irrigation system option, but many issues should be carefully considered by producers before any financial investment is made.

OTHER AVAILABLE INFORMATION

Additional SDI-related bulletins and irrigation-related websites are listed below:

MF-2361 *Filtration and Maintenance Considerations for Subsurface Drip Irrigation (SDI) Systems* *http://www.ksre.ksu.edu/sdi/Reports/2003/mf2361.pdf*

MF-2576 *Subsurface Drip Irrigation (SDI) Components: Minimum Requirements* *http://www.ksre.ksu.edu/sdi/Reports/2003/mf2576.pdf*

MF-2578 *Design Considerations for Subsurface Drip Irrigation* *http://www.ksre.ksu.edu/sdi/Reports/2003/mf2578.pdf*

MF-2590 *Management Consideration for Operating a Subsurface Drip Irrigation System* *http://www.ksre.ksu.edu/sdi/Reports/2003/MF2590.pdf*

MF-2575 *Water Quality Assessment Guidelines for Subsurface Drip Irrigation* *http://www.ksre.ksu.edu/sdi/Reports/2003/mf2575.pdf*

MF 2589 *Shock Chlorination Treatment for Irrigation Wells* *http://www.ksre.ksu.edu/sdi/Reports/2003/mf2589.pdf*

Subsurface Drip Irrigation website: www.ksre.ksu.edu/sdi

General Irrigation website: www.ksre.ksu.edu/irrigate

Mobile Irrigation Lab website: www.mobileirrigationlab.com

ACKNOWLEDGEMENTS

Contribution no. 12-312-A from the Kansas Agricultural Experiment Station.

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

Watch for this logo.

REFERENCES

Alam, M. and D.H. Rogers. 2005. Field Performance of Subsurface Drip Irrigation (SDI) in Kansas. In: Proc Irrigation Association International Irrigation Technical Conference, IA 05-1209. November 6-8, 2005. Phoenix, AZ. pp. 1-5. Also at http://www.ksre.ksu.edu/sdi/Reports/2005/IA05-1209.pdf

Arbat, G., F. R. Lamm, and A. A. Abou Kheira. 2010. Subsurface drip irrigation emitter spacing effects on soil water redistribution, corn yield and water productivity. Applied Engr. in Agric. 26(3):391-399. Also available at http://www.ksre.ksu.edu/sdi/Reports/2010/ESpace10.pdf

ASAE. 2008. Design and Installation of Microirrigation Systems. ASAE EP405.1 APR1988 (R2008). ASABE, St Joseph, MI. 5 pp.

Burt, C. and S. Styles. 2007. Ch. 11. Chemical injection for water treatment. pp 223-236 in Drip and micro irrigation design and management for trees, vines and field crops- Practice plus theory, C. Burt and S. Styles, 3rd Ed., ITRC, Cal Poly, San Luis Obispo, CA. 396 pp.

Camp, C. R. 1998. Subsurface drip irrigation: A review. Trans. ASAE 41(5):1353-1367.

Cline, J. F., F. G. Burton, D. A. Cataldo, W. E. Skiens, and K. A. Gano. 1982. Long-term biobarriers to plant and animal intrusions of uranium tailings. DOE/UMT-0209, PNL-4340, UC-70. U. S. Dept. of Energy Rep. under contract DE-AC06-76RLO 1830. Sep. 1982. Pacific Northwest Nat'l. Lab., Richland, Washington. 60 pp.

Gardner, W. H. 1979. How water moves in the soil. Crops & Soils 32(2):13-18.

Lamm, F.R. and C.R. Camp. 2007. Subsurface drip irrigation. Chapter 13 in Microirrigation for Crop Production - Design, Operation and Management. F.R. Lamm, J.E. Ayars, and F.S. Nakayama (Eds.), Elsevier Publications. pp. 473-551.

Lamm, F. R. and T. P. Trooien. 2005. Dripline depth effects on corn production when crop establishment is nonlimiting. Appl. Engr in Agric. 21(5):835-840. Also at http://www.ksre.ksu.edu/sdi/Reports/2005/DepthSDI.pdf

Lamm, F. R., A. A. Aboukheira, and T. P. Trooien. 2010. Sunflower, soybean, and grain sorghum crop production as affected by dripline depth. Applied Engr. in Agric. 26(5):873-882. Also at http://www.ksre.ksu.edu/sdi/Reports/2010/DDepth10.pdf

Rogers, D. H., F. R. Lamm, and M. Alam. 2003a. Subsurface drip irrigation systems (SDI) water quality assessment guidelines. K-State Research and Extension, MF-2575. July 2003. 8 pp. Also at http://www.ksre.ksu.edu/library/ageng2/mf2575.pdf

Rogers, D. H., F. R. Lamm, and M. Alam. 2003b. Subsurface drip irrigation (SDI) components: Minimum requirements. K-State Research and Extension, MF-2576. 4 pp. Also at http://www.ksre.ksu.edu/sdi/Reports/2003/mf2576.pdf

Seginer, I. 1979. Irrigation uniformity related to horizontal extent of root zone. Irrig. Sci. 1:89-96.

Schwankl, L., B. Hanson, and T. Prichard. 2008. Maintaining microirrigation systems. Univ. of California Agriculture and Natural Resources Pub. 21637. 53 pp.

Van der Gulik, T. W. 1999. B. C. Trickle Irrigation Manual. B. C. Ministry Agric. and Food Res. Manage. Branch and Irrig. Industry Assoc. of British Columbia, Abbotsford, B. C., Canada. 321 pp.

This paper was first presented at the Central Plains Irrigation Conference, February 21-22, 2012, Colby, Kansas. It can be cited as

Lamm, F.R. and D.H. Rogers. 2012. SDI, the basics of successful systems. In: Proc. 24th annual Central Plains Irrigation Conference, Feb. 21-22, 2012, Colby, Kansas. Available from CPIA, 760 N. Thompson, Colby, Kansas. pp. 133-149.

Harvesting 300 bu/acre field corn grown using SDI at KSU Northwest Research-Extension Center, Colby Kansas in 1998.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N. Thompson, Colby, Kansas

HYDRAULIC CONSIDERATIONS FOR SDI

Freddie R. Lamm
Research Irrigation Engineer
Kansas State University
Colby, Kansas
Voice: 785-462-6281
Fax: 785-462-2315
flamm@ksu.edu

Danny H. Rogers
Extension Irrigation Engineer
Kansas State University
Manhattan, KS
Voice: 785-532-2933
Fax: 785-532-5825
drogers@ksu.edu

INTRODUCTION

A guiding principle in microirrigation design is to obtain and maintain high water application uniformity along the length of the driplines. Dripline and emitter characteristics and hydraulic properties, system operating pressure, and land slope are the major governing factors controlling the hydraulic design. These factors determine the acceptable dripline lengths for the SDI system with respect to the field size and shape and grower preferences. Longer driplines may result in a less expensive system to install and operate, which is of great importance to those growers using SDI on lower-valued crops typically grown in the Great Plains. Additionally, longevity of SDI systems is affected by how well the system is maintained and periodic flushing with a sufficient flushing velocity is considered an important aspect of routine maintenance.

HYDRAULIC CONSIDERATIONS FOR DRIPLINE LENGTH

Many different design criteria and procedures are used to calculate the maximum dripline length. Two uniformity criteria often used in microirrigation design are emitter discharge variation, q_{var}, and design emission uniformity, *EU,* and are given by

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \qquad \text{(Eq. 1)}$$

and

$$EU = 100\left[1.0 - \frac{1.27\,CV}{\sqrt{n}}\right]\frac{q_{min}}{q_{avg}} \qquad \text{(Eq. 2)}$$

where q_{max}, q_{min}, and q_{avg}, are the maximum, minimum, and average emitter discharge rates (gal/hr), respectively, along the dripline, *EU* is the design emission uniformity, n is the number of drip emitters per plant or 1, whichever is greater, and *CV* is the manufacturer's coefficient of variation.

Emitter flow variation of 10% or less is generally desirable, between 10% and 20% is acceptable, and greater than 20% is unacceptable (Bralts et al., 1987). Design emission uniformities of 80 to 90 are recommended for line-source emitters on uniform slopes and 70 to 85 on steep or undulating slopes (ASAE EP405.1, 2010). It should be noted that the use of these recommended q_{var} and *EU* criteria produce different results. Both criteria are reasonable for design purposes, however, and interrelationships exist for many of the design criteria used in microirrigation. Other hydraulic design procedures are available (Burt and Styles, 2007) and many of the dripline manufacturers provide their own software programs for system design. Some of these software programs will be used in this discussion to demonstrate important factors related to dripline design.

Emitter flow variation increases and design emission uniformity decreases as the emitter discharge rate and dripline length increase (Figure 1). In this example, for a 0.785 inside diameter *(ID)* dripline and dripline lengths of 500, 750, or 1000 feet, only four options have q_{var} values less than 10%, the 500 ft length with any of the emitter discharge rates and the 750 ft length for the 0.20 g/h emitter discharge rate. The acceptable 20% q_{var} criterion allows more acceptable emitter discharge and length combinations. Figure 1 also illustrates some discrepancy in the acceptable ranges between the q_{var} and *EU* design criteria, with a larger number of emitter discharge rate and length combinations providing an acceptable *EU.* There has been discussion among irrigation engineers that the ASABE EP405.1 design emission uniformity criteria for line-source emitters may need to be increased to values similar to those for point-source emitters. Manufacturing processes for line-source emitters have improved over the years and lower *EU* values for these products may no longer be necessary. A portion of the rationale for allowing reduced *EU* for line-source products is related to the typical single-year use of these products for DI where the long-term effects (season to season) of reduced uniformity would not occur. Thus, greater *EU* values may have more importance for multiple-year SDI systems.

Longer driplines with higher uniformity can be designed by increasing the dripline diameter while holding the emitter discharge constant (Figure 2). This design technique is popular for larger SDI systems used on the lower-valued commodity crops (fiber, grains and oilseeds) because it helps to reduce installation costs through fewer pipelines, controls, and trenches. This design technique is not without its concerns, however, because larger dripline diameters increase the propagation time of applied chemicals (Figure 3), and flushing flowrates can become quite large. Chemigation travel times for the larger-diameter driplines can exceed the period of the planned irrigation event on coarse-textured soils and thus lead to leaching and/or improper chemical application. Figure 3 also illustrates that chemigation travel times are not greatly affected by dripline length (slight increases with increase length), are moderately affected by emitter discharge (moderate decrease with increased emitter discharge), and are strongly affected by dripline diameter (major increases with increased diameter).

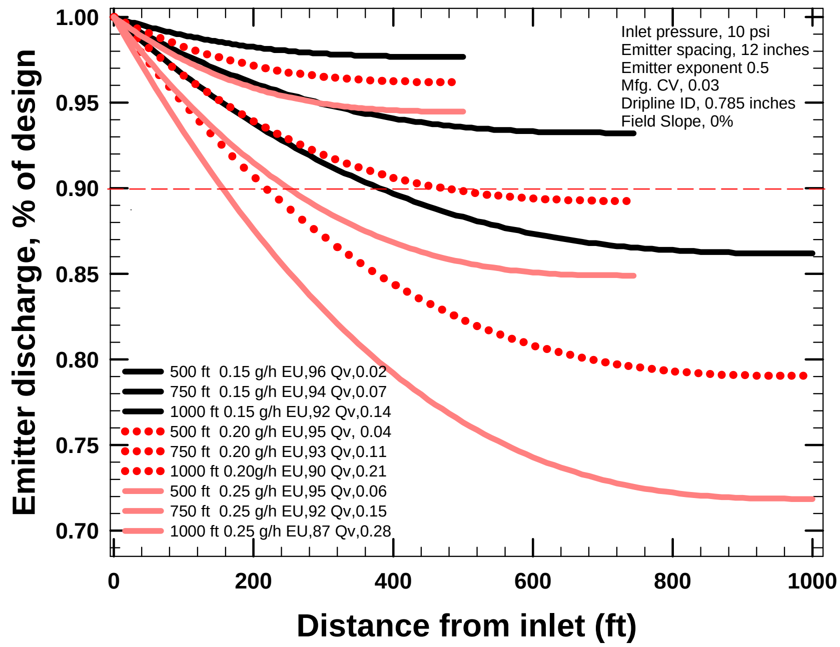


Figure 1. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by dripline length and nominal design emitter discharge. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

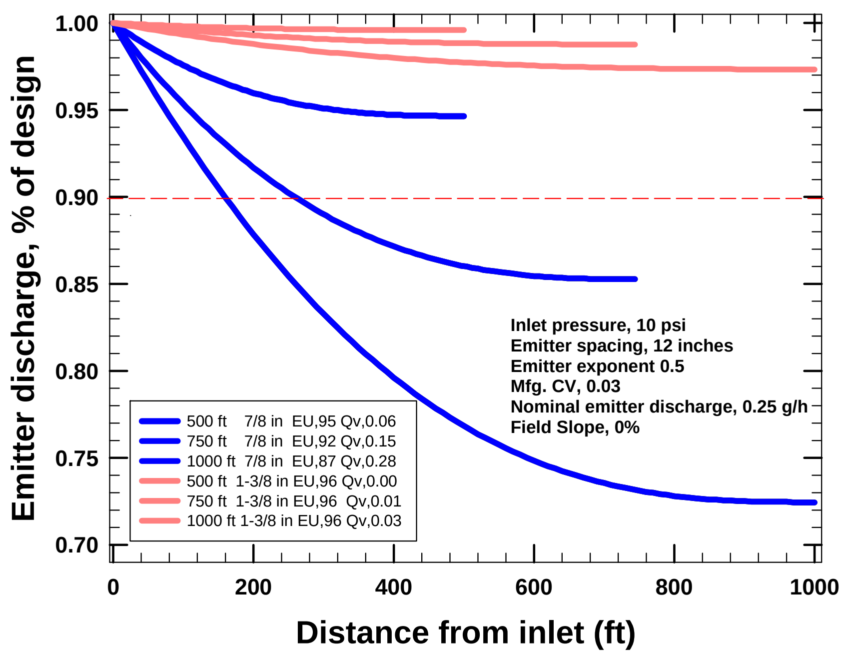


Figure 2. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by dripline length and inside diameter. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

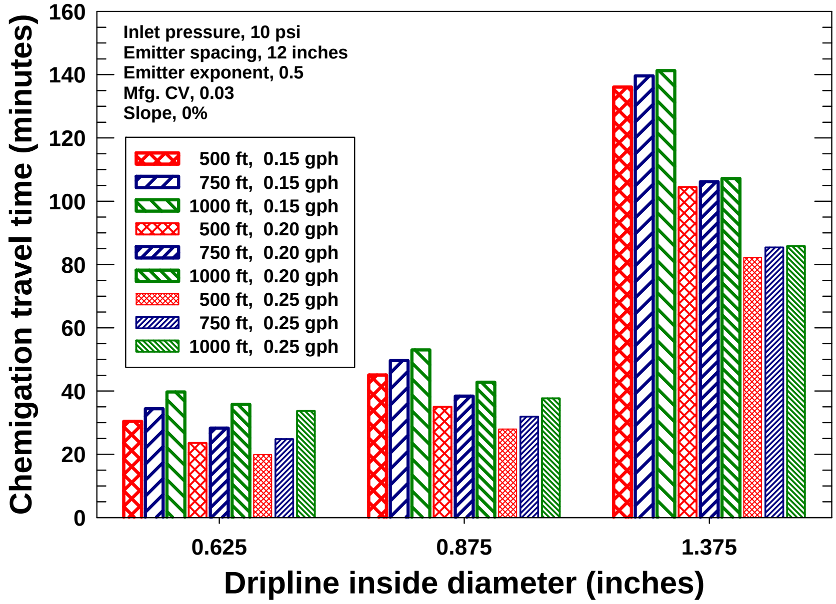


Figure 3. Approximate chemigation travel times as affected by dripline length and diameter, and emitter discharge rate. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

While maintaining system uniformity, dripline length can also be increased by increasing the emitter spacing while holding the emitter discharge rate constant (Figure 4). This is also a popular design technique for larger SDI systems used on lower-valued crops, but is limited because the emitter spacing must be consistent with uniform water uptake by the crop. Emitter spacing may become too great as random emitters begin to clog.

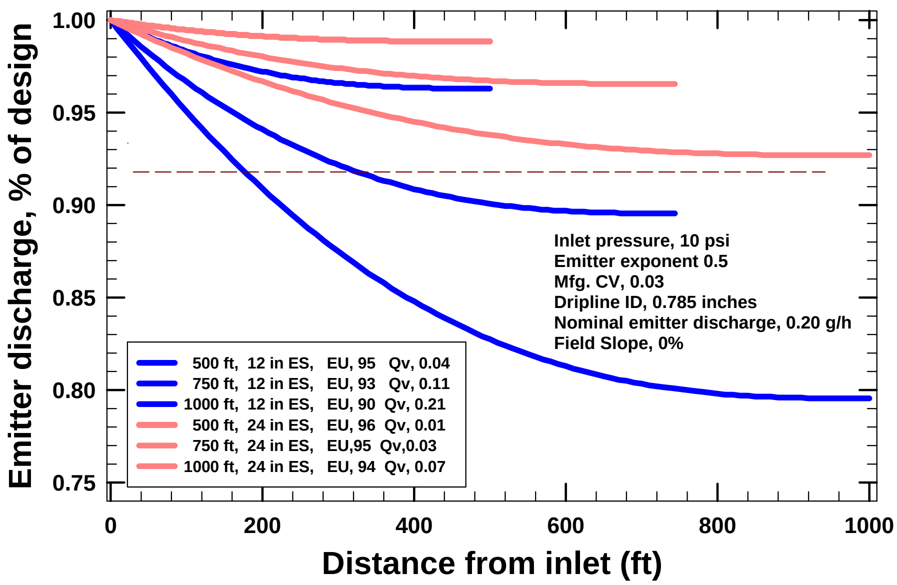


Figure 4. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by dripline length and emitter spacing *(ES)*. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

The land slope can have either a positive or negative effect on the emitter discharge rate along the dripline lateral (Figure 5). Driplines running uphill always result in increasing pressure losses along the dripline and thus lower system uniformity. When the downhill slope is too great, the emitter discharge rate at the end of the dripline becomes unacceptably high. In the example shown (Figure 5), the optimum slope is 1% downslope, but this will vary with dripline and emitter characteristics. Designers may even use these hydraulic factors to their advantage to balance elevation head gains with increased friction losses from smaller diameter driplines. When slopes are too great, designers may recommend that the driplines be installed across the slope or along the contour.

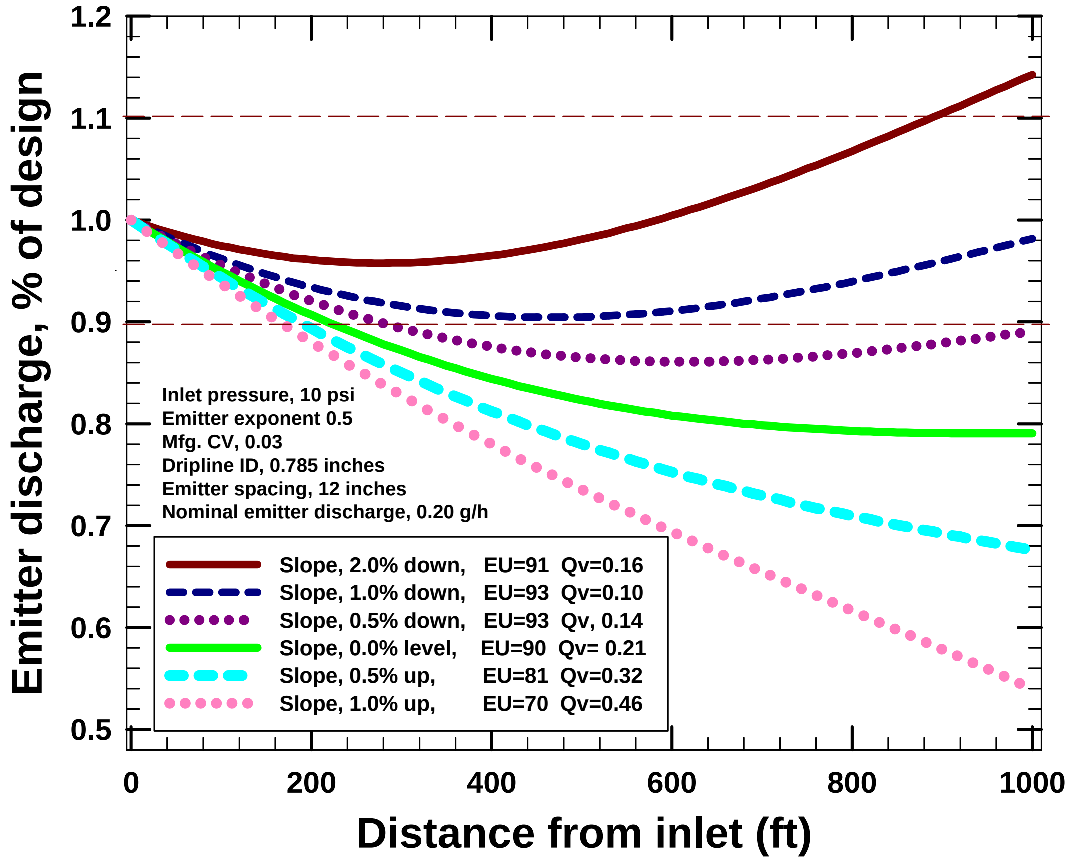


Figure 5. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by topography. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

The emitter discharge (q) can generally be characterized by a simple power equation

$$q = kH^x \qquad \text{(Eq. 3)}$$

where k is a constant depending upon the units of q and H, H is the pressure and x is the emitter exponent. The value of x is typically between 0 and 1, although values outside the range are possible. For an ideal product, x equals 0, meaning that the emitter discharge is independent of the pressure. This would allow for high uniformity on very long driplines, which would minimize cost (Figure 6). An emission product with an x of 0 is said to be fully pressure compensating (PC). An x value of 1 is noncompensating (NPC), meaning any percentage change in pressure results in an equal percentage change in emitter discharge rate. Many lay-flat dripline products have an emitter exponent of approximately 0.5. A 20% change in pressure along the dripline results in a 10% change in emitter discharge rate if the exponent is 0.5. Pressure-compensating emitters are widely used on steep land slopes, but are not always cost-competitive for lower-valued commodity crops.

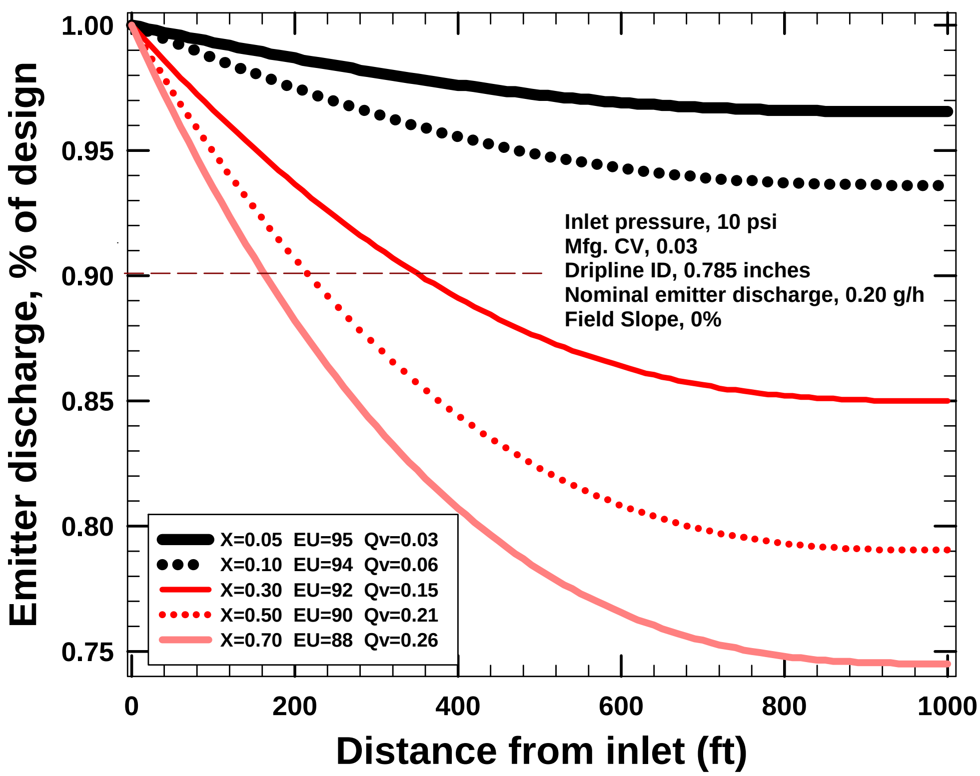


Figure 6. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by the emitter exponent (x). An emitter with an exponent of zero is said to be fully pressure compensating (PC). Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

HYDRAULIC CONSIDERATIONS FOR FLUSHING VELOCITY

A minimum flushing velocity of 1 ft/s is recommended for microirrigation systems by the American Society of Biological and Agricultural Engineers (ASAE EP405.1, 2003). However, disagreement exists about the recommended flushing velocity for SDI systems, with values ranging from 1 to 2 ft/s (Burt and Styles, 2007). The practical rationale for a higher flushing velocity for SDI is that perhaps it could provide better overall flushing of materials. Many of these systems are used for multiple years and system longevity is very important in determining SDI economic feasibility, especially for lower-valued crops. The required flushing velocity and flushline hydraulics greatly affect the SDI system design. Higher velocities require large supply lines and flushlines and shorter lengths of run to keep the flushing pressures below the maximum allowable dripline operating pressure. The general guideline is that the required flushing velocity be maintained in all segments of the SDI system, but there are locations where this guideline cannot be followed. The water velocity in the flushline at the farthest point from the flush valve is very low because only a single dripline is contributing flow. Decreasing the flushline diameter at this point in the system could help maintain a higher velocity but also increases the downstream pressure on the dripline. It is more important to maintain adequate flushing velocity in the driplines because the emitters are subject to clogging.

Some pressure usually exists on the end of driplines during flushing for SDI systems that use a flushline common to a group of driplines. This downstream pressure represents the sum of elevation changes between the dripline and the point where the water exits the flush valve, friction losses in the flushline, friction losses in the flush valve, and the friction losses associated with the dripline/flushline connection. It is difficult to design for a dripline downstream pressure during flushing of less than 1 psi and values of 3 psi are reasonable under some circumstances. Downstream pressures that are greater than 3 psi during flushing will often require driplines with higher maximum allowable operating pressure or that the designer must reduce dripline length and/or emitter discharge rates. The inlet pressure during flushing often has more restriction on design dripline length and emitter discharge rate than system uniformity (Figure 7). Adjustable pressure regulators or other design characteristics may be required to accommodate the higher inlet pressure requirements during flushing.

The required flowrate during flushing can be considerably higher than the nominal dripline flowrate (Figure 8). This may require larger pipe size (mains, submains and headers), adjustments to the pumping plant to provide the larger flow, and/or splitting the normal irrigation zone into more than one flushing zone.

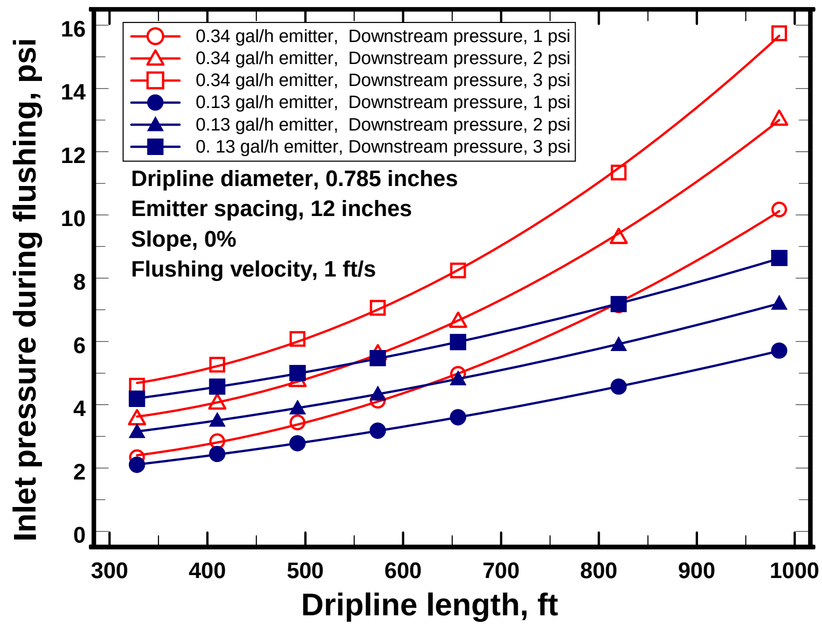


Figure 7. Required inlet pressure to maintain a 1 ft/s dripline flushing velocity, as affected by the nominal emitter discharge rate, dripline length, and downstream pressure. Results for hypothetical dripline calculated with software from Toro Ag Irrigation (2002).

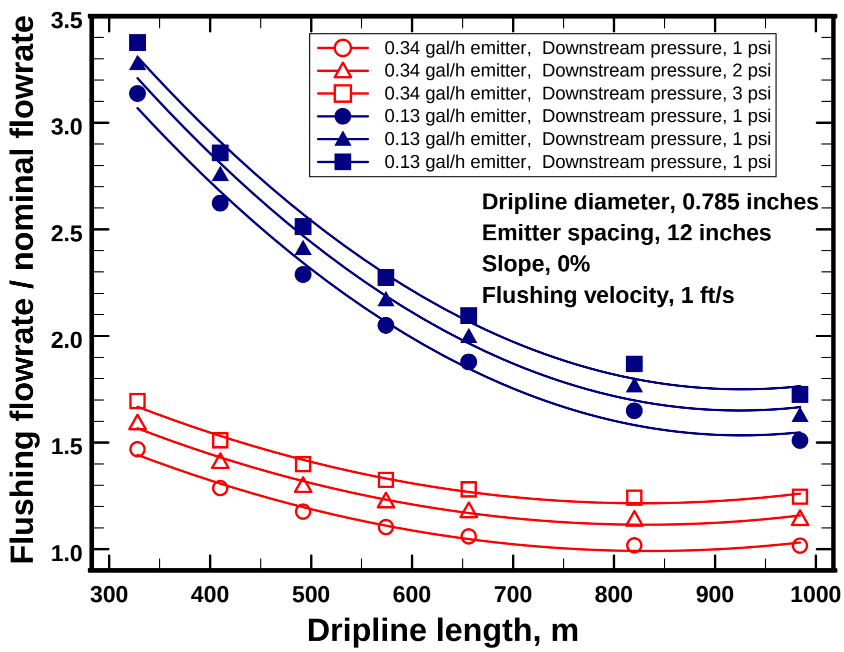


Figure 8: Ratio of required flushing flowrate to nominal design flowrate to maintain a 1 ft/s dripline flushing velocity as affected by nominal emitter discharge rate, dripline length, and downstream pressure. Results for hypothetical dripline calculated using software from Toro Ag Irrigation (2002).

CONCLUSIONS

Careful consideration must be given to the hydraulic design of SDI systems because of the complex manner in which the different factors interact. An improperly designed SDI system is less forgiving than an improperly designed center pivot sprinkler system. Water distribution problems may be difficult or impossible to correct for an improperly designed SDI system. The SDI system must also be properly designed to ensure system longevity. Minimizing investment costs through cheaper designs can be a double-edged sword, as a cheaper system may increase operating costs and/or possibly increase the chance of system failure.

ACKNOWLEDGEMENTS

Much of this material presented here is adapted from Lamm and Camp (2007).

Contribution no. 12-310-A from the Kansas Agricultural Experiment Station.

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

Watch for this logo.

REFERENCES

ASAE EP405.1. 2010 ASAE Engineering Practice EP405.1, APR1988, Design and Installation of Microirrigation Systems. ASAE, St. Joseph, Michigan. pp. 1140-1144.

Bralts, V. F., D. M. Edwards, and I. P. Wu. 1987. Drip irrigation design and evaluation based on the statistical uniformity concept. Adv. Irrig. 4:67-117.

Burt, C. and S. Styles. 2007. Drip and micro irrigation design and management for trees, vines and field crops- Practice plus theory, C. Burt and S. Styles, 3rd Ed., ITRC, Cal Poly, San Luis Obispo, CA. 396 pp.

Lamm, F.R. and C.R. Camp. 2007. Subsurface drip irrigation. Chapter 13 in Microirrigation for Crop Production - Design, Operation and Management. F.R. Lamm, J.E. Ayars, and F.S. Nakayama (Eds.), Elsevier Publications. pp. 473-551.

Roberts Irrigation Products. 2003. RO-DRIP designer for Windows. Software on compact disc from Roberts Irrigation Products, San Marcos, California. Version. 2.1. *(Roberts Irrigation is now part of John Deere Water).*

Toro Ag Irrigation. 2002. AquaFlow. Software on compact disc from Toro Ag Irrigation, El Cajon, California. Version. 1.0.5.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

USING THE K-STATE CENTER PIVOT SPRINKLER AND SDI ECONOMIC COMPARISON SPREADSHEET - 2012

Freddie R. Lamm
Research Irrigation Engineer
Northwest Research-Extension Center
Colby, Kansas
Voice: 785-462-6281 Fax 785-462-2315
Email: flamm@ksu.edu

Daniel M. O'Brien
Northwest Area Director
Northwest Research-Extension Center
Colby, Kansas
Voice: 785-462-6281 Fax 785-462-2315
Email: dobrien@ksu.edu

Danny H. Rogers
Extension Irrigation Engineer
Biological and Agricultural Engineering
Manhattan, Kansas
Voice: 785-532-5813 Fax 785-532-6944
Email: drogers@ksu.edu

Troy J. Dumler
Extension Agricultural Economist
Southwest Research-Extension Center
Garden City, Kansas
Voice: 620-275-9164 Fax 620-276-6028
Email: tdumler@ksu.edu

Kansas State University

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 12.2, modified by F.R. Lamm, D. M. O'Brien, D. H. Rogers, T. J. Dumler, 2-19-12

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 $			$71,815	← $71,815	$202,617	← $202,617
Irrigation system investment cost, $/irrigated acre			$574.52		$1,307.21	
Irrigation system life, years			25	← 25	22	← 22
Interest rate for system investment, %	6.5%	← 6.5%				
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)			$614.46	← $614.46	$597.53	← $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	$5.50	← $5.50				
Net return to cropped dryland area of field ($/acre)	$64.00	← $36.00				
Advantage of SDI over Center Pivot Sprinkler *				$/total field each year		**$7,915**
*** Advantage in net returns to land and management**				$/acres each year		**$49**

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 O’Brien et al. (2011), 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.

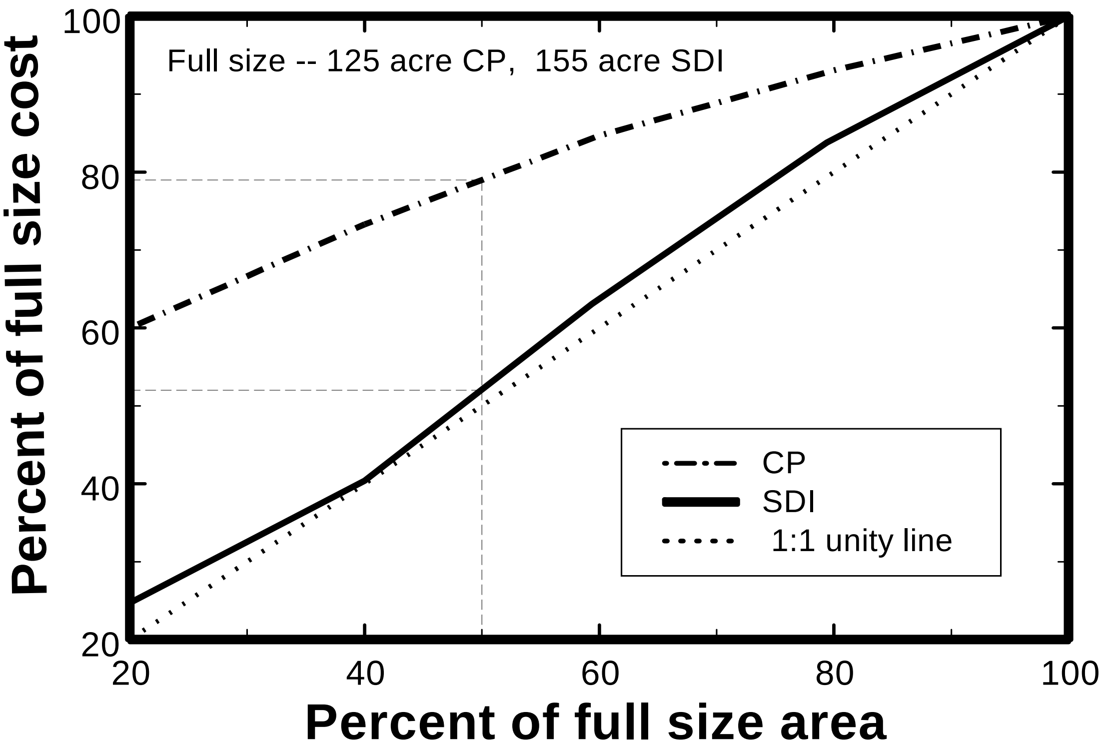


Figure 2. CP and SDI system costs as related to field size. (after O'Brien et al., 1998)

The annual interest rate can be entered as a variable, but is currently assumed to be 6.5%. 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., 2011). 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	$2.89	← $2.89	$98.26		$98.26	
Herbicide, $/acre			$26.20	← $26.20	$26.20	← $26.20
Insecticide, $/acre			$36.48	← $36.48	$36.48	← $36.48
Nitrogen fertilizer, lb/acre	$/lb	**Suggested**	242	← 242	242	← 242
Nitrogen fertilizer, $/acre	$0.44	← $0.44	$106.48		$106.48	
Phosphorus fertilizer, lb/acre	$/lb	**Suggested**	50	← 50	50	← 50
Phosphorus fertilizer, $/acre	$0.80	← $0.80	$40.00		$40.00	
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			$175.00	← $175.00	$175.00	← $175.00
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	6.5%	← 6.5%	$19.34		$18.81	
Total Variable Costs			**$614.46**		**$597.53**	

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 $5.50/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 $64.00/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	$574.52	$670.12	$808.81	$1,053.78	$1,723.90	**$1,122.11**	
CP Dry	30	24	18	12	6	**14**	
SDI Size	155	124	93	62	31	78	
SDI Cost	$1,307.21	$1,336.29	$1,367.77	$1,415.05	$1,525.51	$1,387.51	
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	**$146.24**	**$147.50**	**$145.55**	**$138.02**	**$117.21**	**$133.68**	
10	**$19.60**	**$17.03**	**$11.65**	**$0.94**	**-$30.58**	**-$1.61**	
15	**-$22.61**	**-$26.46**	**-$32.98**	**-$44.76**	**-$79.84**	**-$46.70**	
20	**-$43.71**	**-$48.21**	**-$55.30**	**-$67.61**	**-$104.47**	**-$69.25**	
25	**-$56.38**	**-$61.25**	**-$68.69**	**-$81.31**	**-$119.25**	**-$82.77**	

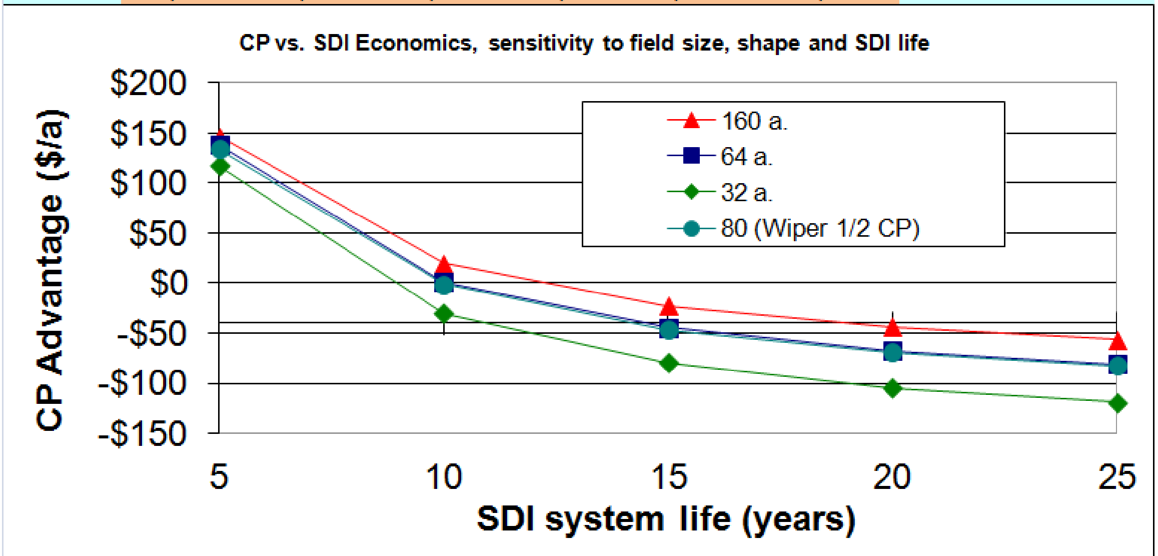


Figure 4. The Field size & SDI life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

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 $/acre	SDI system life, years 5	10	15	20	25	30
1000	$75.26	-$21.62	-$53.91	-$70.05	-$79.74	-$86.20
1100	$98.36	-$8.20	-$43.72	-$61.48	-$72.14	-$79.24
1200	$121.47	$5.22	-$33.53	-$52.91	-$64.53	-$72.28
1300	$144.57	$18.64	-$23.34	-$44.33	-$56.93	-$65.32
1400	$167.68	$32.05	-$13.16	-$35.76	-$49.32	-$58.36
1500	$190.78	$45.47	-$2.97	-$27.19	-$41.72	-$51.40
1600	$213.89	$58.89	$7.22	-$18.61	-$34.11	-$44.45

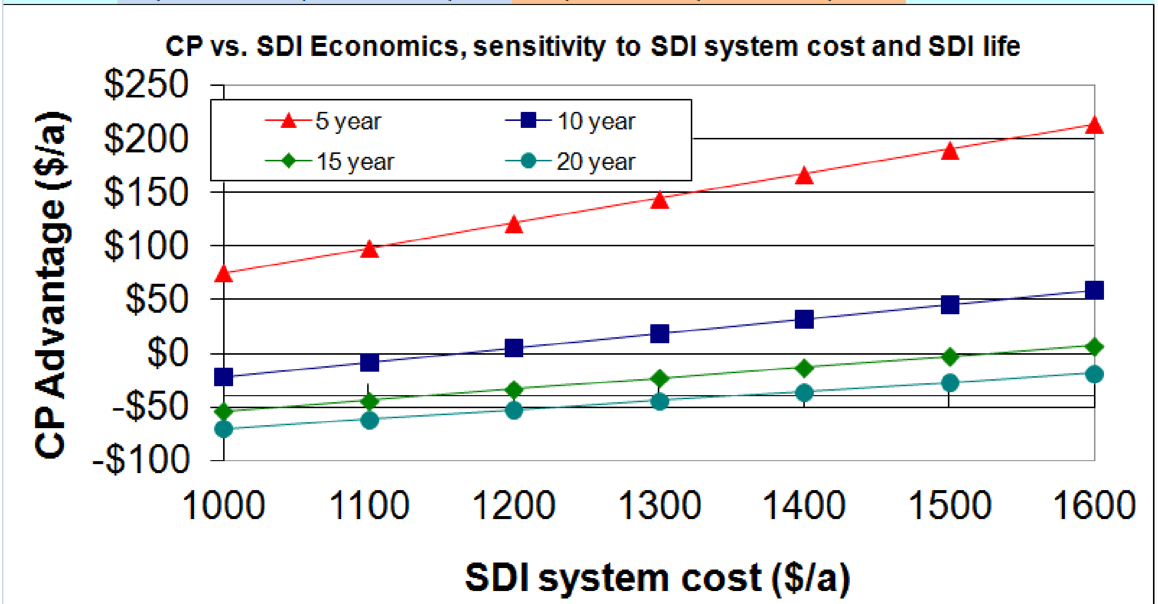


Figure 5. The SDI cost and life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

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	**$4.30**	**$4.70**	**$5.10**	**$5.50**	**$5.90**	**$6.30**	**$6.70**
160	$48.40	$36.40	$24.40	$12.40	$0.40	-$11.60	-$23.60
170	$40.34	$27.59	$14.84	$2.09	-$10.66	-$23.41	-$36.16
180	$32.28	$18.78	$5.28	-$8.22	-$21.72	-$35.22	-$48.72
190	$24.22	$9.97	-$4.28	-$18.53	-$32.78	-$47.03	-$61.28
200	$16.15	$1.15	-$13.85	-$28.85	-$43.85	-$58.85	-$73.85
210	$8.09	-$7.66	-$23.41	-$39.16	-$54.91	-$70.66	-$86.41
220	$0.03	-$16.47	-$32.97	-$49.47	-$65.97	-$82.47	-$98.97
230	-$8.03	-$25.28	-$42.53	-$59.78	-$77.03	-$94.28	-$111.53
240	-$16.10	-$34.10	-$52.10	-$70.10	-$88.10	-$106.10	-$124.10
250	-$24.16	-$42.91	-$61.66	-$80.41	-$99.16	-$117.91	-$136.66
260	-$32.22	-$51.72	-$71.22	-$90.72	-$110.22	-$129.72	-$149.22
270	-$40.28	-$60.53	-$80.78	-$101.03	-$121.28	-$141.53	-$161.78

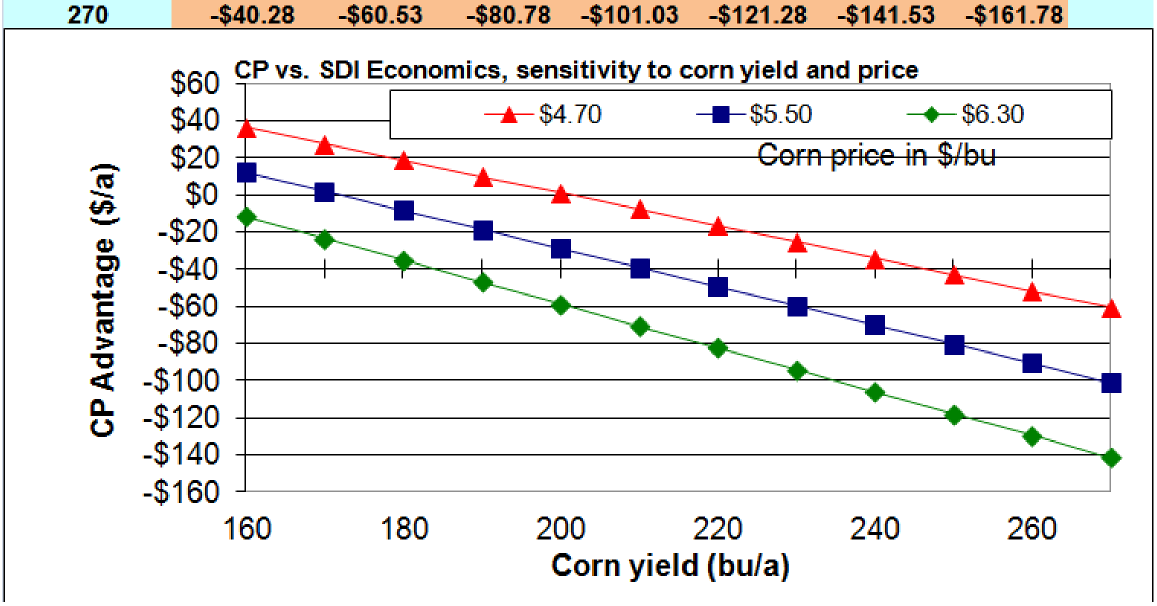


Figure 6. The Yield and Price worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

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 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.

REFERENCES

Dumler, T. J., D. M. O'Brien, and K. L. Martin. 2011. Center-pivot-irrigated corn cost-return budget in Western Kansas. KSU Farm Management Guide, MF-585. Manhattan, Kansas. 4 pp. Also available at http://www.ksre.ksu.edu/library/agec2/mf585.pdf

O'Brien, D. M., T. J. Dumler, and D. H. Rogers. 2011. Irrigation capital requirements and energy costs. KSU Farm Management Guide, MF-836. Manhattan, Kansas. 4 pp. Also available at http://www.ksre.ksu.edu/library/agec2/mf836.pdf

Lamm, F. R. and C. R. Camp. 2007. Subsurface drip irrigation. Chapter 13 in Microirrigation for Crop Production - Design, Operation and Management. F.R. Lamm, J.E. Ayars, and F.S. Nakayama (Eds.), Elsevier Publications. pp. 473-551.

Lamm, F. R., H. L. Manges, L. R. Stone, A. H. Khan, and D. H. Rogers. 1995. Water requirement of subsurface drip-irrigated corn in northwest Kansas. Trans. ASAE, 38(2):441-448. Also available at http://www.ksre.ksu.edu/sdi/Reports/1995/WaterReq.pdf

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1998. An economic comparison of subsurface drip and center pivot sprinkler irrigation systems. App. Engr. in Agr. 14(4):391-398. Also available at http://www.ksre.ksu.edu/sdi/Reports/1998/EconSDICP.pdf

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

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

INTEGRATING MULTIPLE IRRIGATION TECHNOLOGIES FOR OVERALL IMPROVEMENT IN IRRIGATION MANAGEMENT [1]

T.A. Howell*, S.A. O'Shaughnessy, and S.R. Evett
Lab. Director, Research Agric. Engr., and Research Soil Sci.
USDA-ARS
Bushland, Texas
*Contact Author — Voice: 806-356-5746 Fax: 806-356-5750
Email: terry.howell@ars.usda.gov

INTRODUCTION

There are many tools, techniques, and/or schemes to assist producers in irrigation water management and specifically in irrigation scheduling. This paper will highlight several of those but emphasize that several methods should be used simultaneously as an improved or advanced procedure to avoid biases and to improve reliability.

Water management decisions are basically strategic and tactical ones. Strategic decisions are decisions made after reviewing a season's data (e.g. reviewing field yield maps, accounting reviews of field/farm productivity and costs to determine profits or losses) or pre-season ones like changing or modifying irrigation system methods or technology; irrigation well additions, treatment, or power selection; selecting field crop hybrids/varieties; selecting field water management techniques; and field agronomic decisions on tillage, fertility, planting, etc. Tactical decisions for water management include the day to day ones on field to farm irrigation scheduling as well as scheduling irrigation system maintenance or emergency repairs (e.g. pipeline leaks or ruptures, irrigation well failures, power outages, etc.). Not every decision option may be necessary for either strategic or tactical options for specific operations. Figure 1 illustrates a diagrammatic flow chart for these decisions. An area of engineering or statistics is known as Decision Theory (DT). DT has several interesting concepts on the application to probabilistic or stochastic processes such as agriculture and

[1] The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

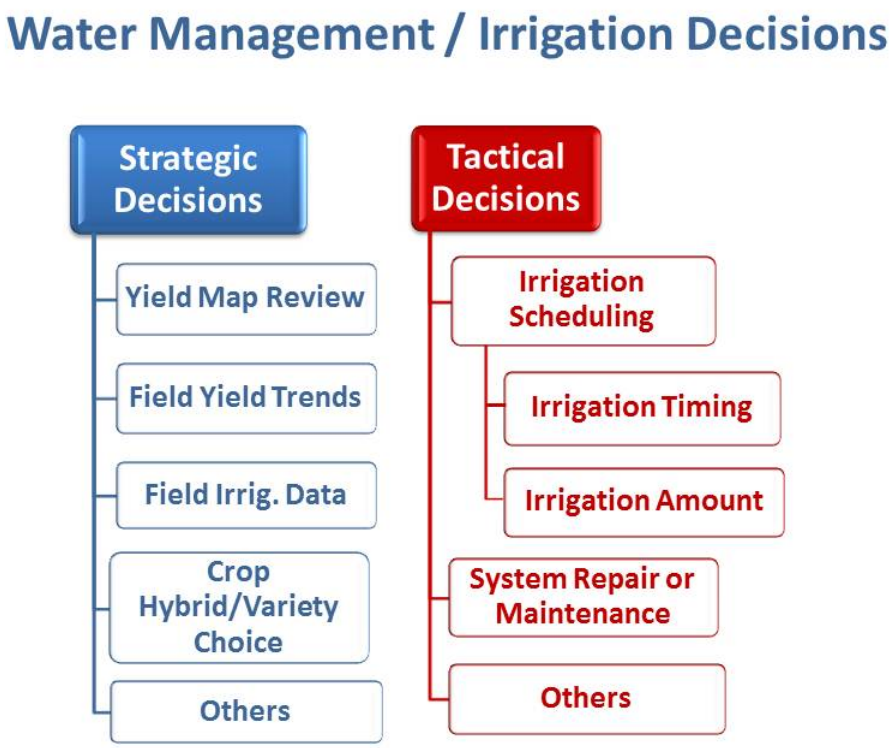


Figure 1. Water management / Irrigation decision diagram for illustration.

irrigation engineering. In some cases, not to be made light of, DT is a form of Game Theory (GT). GT is common in gambling not unlike agriculture where the card turn or dice roll (analogous to next day's events in agriculture) could dramatically impact profit or losses as well as affecting subsequent decisions. These decisions are all based on subjectivity based judgments, advice information or data, previous experiences, etc.

This paper will present a brief overview of these water management decisions both strategically and tactically and how multiple systems of measurements might impact the decisions. Our goal is not to suggest any information source or irrigation scheduling tool as superior but to illustrate each add valuable information to aid the decision maker. The decision maker must weigh the cost for the information, its reliability, and its suitability for his/her production system. Although other production decisions besides water management are important too, this brief paper will confine to water management.

IRRIGATION *STRATEGERY*

Strategery is a good Texan term that we'll export to the US Central Plains region for making strategic decisions. In the current context, strategery will be defined as a planning process to prepare for the best possible success given the producer's circumstances (land, capital, labor, etc.) and importantly, Risk Aversion (RA). Some producers opt for one of the most Risk Adverse options to simply not farm, lease/rent the farm, or even to regain the capital investment or gain by selling the farm. This type of decision may be based on any number of rational and defensible factors. Essentially, this removes the producer from the game (if a game concept is applied to crop production in this case). Other producers have varying levels of RA that vary from highly conservative (adverse to much risk; seek rather 'safer' strategies) to risk loving or risk seeking (willing to accept greater risks of larger losses with the small possibility of a large profit). Typically, this is a continuum of situations as opposed to just one position. Producers, in general, are by nature somewhat risk seeking, although irrigated producers have the irrigation protection (i.e., their ace-in-the-hole, to speak) afforded from droughts that rainfed or dryland producers will not have. Some state or water district regulations may control on-farm irrigation area, irrigation volume (in a set time period), or even irrigation season depth volume per season per unit of irrigated land and, therefore, affect even an irrigated producers' RA. To illustrate two examples of this RA, we'll define an irrigated producer that is more conservative as a "water concentrator" to use a greater irrigation capacity (available flow rate per unit irrigated area). We'll define an irrigated producer willing to accept greater risk as a "water spreader" irrigating more area per unit available capacity expecting seasonal precipitation to match or exceed normal (median or probability equal to 50%) hoping (or gambling on) a greater opportunity for the return per unit irrigation water. The water concentrator may produce more consistent long-term mean profits while the water spreader may capture the greater opportunity for returns in years with greater than normal seasonal rainfall.

<u>Options for Water Spreading</u>

The most common form of water spreading is 'stretching' or using a small irrigation capacity to irrigate more area. This can be effective if based on accurate knowledge (soil water profile status, degree of tolerance of the hybrid/variety selected for soil water defects or more commonly named crop water stress, reliable long-range seasonal weather forecast, etc.). Most of this knowledge is provided from secondary sources or advisors (consultants, seed dealers, variety trials, various weather forecast sources). When the information provided is accurate then the chances of making a reliable (high probability of being correct) choice to 'stretch' the irrigation capacity and utilize the favorable opportunity could improve the overall profitability of the producer. This is often referred to as opportunity cropping to take advantage of better situations.

Most commonly water 'stretching' involves some form of deficit irrigation where the producer knowingly produces more area than can be profitably irrigated in normal or below normal rainfall seasons. Crop sequencing can provide some aid in this case (e.g. irrigating a previously fallowed area where precipitation has been captured and stored in the soil). Other strategic decisions might include conservation tillage (e.g. no till or ridge till or even furrow diking). The strategic decision to switch to conservation tillage will require a capital investment in different equipment and trial and effort to study and learn the equipment operation. These systems might retain previous crop residues to enhance winter/spring precipitation capture through better infiltration and reduced surface evaporation or precipitation detention and runoff reduction in the case of furrow diking.

Essentially, effective deficit irrigation involves a planned soil water depletion scheme. Usually, these require precise knowledge of planting soil profile water status, crop development stages when the crop hybrid/variety is least damaged by soil water deficits, and the exact gross and effective irrigation system capacity as well as solid information for the field on crop extractable soil water. Most of this information is gained from secondary sources (crop consultants, extension specialists, etc.) or built first-hand through experience.

Irrigation Technology

Certainly, irrigation application efficiency and reliability are important strategic irrigation decisions. Most of the irrigation in the Central Plains of the US began as some form of surface irrigation (border, furrow, etc.), but has migrated to predominately center pivot sprinkler irrigation since the late 1960s or 1970s. Center pivots now irrigate over 90% or more of the irrigated area in the Central Plains. Subsurface drip irrigation (SDI) has gained popularity, but remains a much lower percentage. These systems offer many advantages over surface irrigation:

Greater application efficiency and uniformity
Less labor
Ease of automation or control
Reduced dependence on soil to be the hydraulic distribution network
Ability to utilize smaller application depths

The strategic decision to modify irrigation technology involves an economic investment as well as time and effort to learn the newer technology. These might be individual step-wise developments over a multi-year time frame to reduce the capital investment per year. The availability of less expensive capital (lower interest rates, cost sharing programs, etc.) has made these attractive means to maintain irrigated area as irrigation capacity declines or to enhance profits through greater yields from the better irrigation uniformity and multiple system utility (chemigation, fertigation, etc.).

Agronomics

One of the best strategic tools is simply good farm or field economic records. These should be a routine year end strategic decision opportunity to observe trends as well as possible trial practices that may or may not have performed as planned. One of the more valuable tools from Precision Agriculture is yield maps generated at harvest (for most crops) easily from combine equipment or accessories. These can show possible abiotic (water or soil issues) or biotic stresses (crop disease, insect damages, etc.). The former might be a lower yielding streak around a center pivot where incorrect nozzles were installed, nozzles were plugged or broken or distinct sections of a field that may have a soil textural difference that was inadequately fertilized or where nutrients leached from the root zone. The latter biotic damages are more likely to be sections or parts of a field. These are clues that need investigating and don't always easily lead to direct corrective strategic decisions without other corroborating measurements or observations.

Field crop yield records may also indicate a field that performed differently than anticipated for that crop hybrid/variety selection based on either seed company variety or university variety trials. The private or public sector variety trials may have been conducted under differing soils, fertility, irrigation, or climatic regimes than experienced in the year of record or without confounding biotic influences. Using these combined information sources, the producer can decide whether the crop hybrid/variety should be used in the future on a field or farm.

Water Management and Irrigation Scheduling

The post-season or post-year review should include of all available water management data on a field by field basis. These data might include any of the following (although seldom will all example items listed below be appropriate or feasible for a specific operation or field):

Preplant soil nutrient tests and fertilizer application records
Field rainfall and irrigation application records
Irrigation system performance records (any pressure gauge observation or water flow/volume records)
Soil water measurement records
Visual observation notes by calendar date
Crop advisor reports (whether insects, fertilizer, or irrigation)
Aerial photographs or satellite images

These records and data are invaluable in constructing a post-harvest review on a field or farm basis of the water management. The data allows determination of what changes in water management procedures or agronomic practices might maximize future profits or economic returns to land, labor and capital for the water investment. A useful index of the field water productivity is the crop yield per unit of water given as

$$WP_i = \frac{CY_i}{\left(R_i + I_i + SWD_i\right)} \qquad (1)$$

where WP is water productivity (lb/ac per inch or bu/ac per inch or kg/ha per mm or as kg/m^3) for field *i*, CY is crop yield (lb/ac or bu/ac or kg/ha), R is rainfall (effective growing season rainfall if possibly estimated in inches or mm), I is ‘net’ irrigation application (in inches or mm) [Net irrigation = Gross irrigation x Irrigation application efficiency], and SWD is soil water deficit or seasonal water use from the crop root zone (in inches or mm). The field WP index calculated in this manner is much less precise than might be measured in controlled experiments, but can still provide producers with useful information.
However, this index provides an invaluable tool for inter-field or farm comparisons for specific crops. County extension, NRCS conservationists, or crop consultants should have available local information on WP values for major crops in specific regions.

TACTICAL WATER MANAGEMENT

Day to day tactical irrigation decisions depend on the irrigation supply system and/or the irrigation capacity (IC; flow rate per unit irrigated area). In the Central Plains of the US, almost all irrigation is supplied by wells and considered as an ‘on demand’ basis supply system regulated by state laws and/or water districts rules or regulations. So in these cases, the producer is essentially in control of decisions subject to only the constraints imposed by regulations or the IC. If the well power source is electrical, then the electrical supply company may have peak load controls that might override producer decisions.

Irrigation Scheduling

Irrigation scheduling generally determines the next time for irrigation and the amount of water to apply. For center pivots this might be the decisions of when to start the irrigation event and the selection of a center pivot rotation speed (sets the irrigation amount for a given IC). For SDI systems this might be the date to begin a SDI set and the length of time to run the irrigation set. Irrigation scheduling for these systems in common use in the Central Plains is different from surface irrigation methods because the application amount per irrigation is smaller and the applications are typically applied more frequently. Martin et al. (1990), Heermann et al. (1990), and Hill (1991) provide a thorough discussion of irrigation scheduling principles.

Irrigation scheduling integrates elements of the system hydraulic design and maintenance together with aspects of the soil and the crop characteristics with the atmospheric evaporative demand. It involves providing managers with the irrigation needs of the crop that must be organized together with the cultural aspects of growing and harvesting the crop. Irrigation scheduling for center pivots or SDI systems can be integrated into the system controls through automation.

Irrigation scheduling is typically accomplished by 1) measuring or estimating crop water needs, 2) measuring a soil water status property, or 3) measuring a plant water status property. The latter two are more often used to determine the need for irrigation and are easily integrated into an automated control system (Phene et al., 1990). The second can also be used to determine how much water to apply. The former, traditionally, has been used through an evapotranspiration-water balance model soil water balance model and is adaptable to both indicating the need as well as the amount of water that should be applied (Jensen et al., 1990; and Allen et al., 1998). Other factors influencing scheduling of irrigation systems may include soil salinity, impact of water deficits on crop quality, or the impact of rain on salt leaching into the root zone. These last factors are not typically an issue for crops in the Central Plains and are beyond the scope of this paper.

Irrigation System Capacity

Irrigation system capacity, IC, is a critical design and operational parameter. System capacity is typically defined as the ratio of the system flow rate (Q in gpm or m^3/s) to the land area (A in ac or ha). Common units for IC are gpm/ac or m/s). It is typically more convenient to express the IC ratio in units of inches/d or mm/d. Table 1 gives some common conversions for IC units.

Table 1. Irrigation system capacity conversions.

Base	English Units		Metric Units	
gpm/ac	1.0 gpm/ac	0.053 in./d	$1.558x10^{-4}$ m^3 s^{-1} ha^{-1}	1.34 mm/d

The IC and the irrigation application depth determine the least amount of time necessary to complete irrigation or the irrigation frequency. IC is one of the main tactical irrigation scheduling constraint variables. IC importantly can estimate the irrigation system excess (rare) or deficiency in meeting the crop irrigation demand for a defined interval. As an example, if we assume a 500 gpm well irrigates a ¼ section center pivot (~125 ac or 51 ha), then for a mean ET of 0.35 in./d (8.9 mm/d), the ‘net’ irrigation plus ‘effective’ rainfall would need to exceed 1.38 in. or 35 mm to avoid depleting profile soil water reserves Additionally, for this IC center pivot to apply 1.25 in. (32 mm) of irrigation, it would take approximately 6 days for a complete revolution.

The soil water balance is commonly used in irrigation water management decisions and expressed as

$$SW_j = SW_{j-1} + R_j + I_j - ET_j - DP_j \qquad (2)$$

where SW is profile soil water in the crop root zone for day '*j*,' R and I are defined previously, and ET is evapotranspiration and DP is percolation from the root zone with all terms in depth units (inches or mm). DP can be estimated several ways (Wilcox, 1959; Gardner, 1960; Stone et al., 2011). I and R each include application water losses and runoff, respectively. The soil water balance is widely used to estimate crop evapotranspiration (ET) as

$$ET_{(j-1)\text{ to }j} = \frac{\Delta SW_{(j-1)\text{ to j}} + P_j + I_j - DP_j}{j - (j-1)} \qquad (3)$$

where ET_j is the crop water use (in./d or mm/d). If $ET_j > IC$, then the system is deficit irrigating and the soil water (SW) profile is declining; however, if $ET_j < IC$ then the system can match or maintain or increase the soil water in the profile. The degree of management flexibility in water management is largely dependent upon the difference between IC and the 'peak' crop ET rate called ET_{max}. For new systems being installed the design can correctly consider IC and the risk. For older system, the IC is a constraint that must be considered with the producer's risk.

Irrigation Flow/Volume Measurements

For any irrigation water management technique to be useful, accurate measurements of irrigation water applications are required. Since most Central Plains producers are using individual irrigation wells or well networks, flow metering should be considered essential. Many State and water districts now require annual reporting of water use data making metering both required and essential. Water application amount can be estimated without a water meter (although a water meter is preferred) based on indirect energy use (natural gas amount, electrical meter observations, or diesel fuel use); however, these indirect measurement methods require calibration to account for inefficiencies in energy conversion to water from engine or motor efficiency, drive efficiency, and pump efficiency. Flow metering, especially volume, is essential to estimate reliably the I value in the soil water balance (Eqn. 3) besides providing feedback verification on well flow rates and volumes. Flow metering now being required by State and water district regulations are being widely accepted despite earlier concerns about them being used for that purpose. In most Texas High Plains water districts, well metering and annual reporting is a requirement now (some have a 2013 report date for 2012 water usage). Water metering and system performance (pressure gauge observations) are required in water management decisions to both comply with regulations and to verify irrigation applications.

Visual Irrigation Management Observations

Visual crop and/or soil observations have long been used to guide irrigation targeting or timing based upon vegetation characteristics (leaf color changes, leaf rolling, leaf wilting, upper petiole flexibility, etc.). These are expanded aerially by photography whether black & white (B&W), color, or false color infrared (IR) imagery.

Similarly to crop observations, physical soil sampling and visual and 'feel' techniques are widely employed for their simplicity, ease, and minimum time requirement. However, all visual crop observations as well as soil water sampling require extensive training and experience for best results to indicate irrigation need. The single difficulty with crop visual indicators is that observations are likely to occur after yield impacting soil deficits have occurred. They can provide useful feedback information for water management decisions, particularly soil water measurements by the 'feel and appearance' method, if the observer is experienced and familiar with a specific field, farm, or region. A problem with the soil 'feel and appearance' method is the inability to quantify SW aswell as the need to sample many areas in a field to obtain reliable information. However, the SW 'feel' method can provide some feedback information to aid irrigation scheduling on both the profile soil water status to target or trigger irrigation as well as the root zone SWD to estimate approximate irrigation amounts to refill the soil profile. The "feel and appearance" method remains widely used by crop consultants and can be reliable with experience and knowledge of the field, farm, or region.

Soil Water Balance or Crop Growth Models

Soil water balance methods have long been advocated in various systems from simple checkbook methods to advanced computer models. All are based on some form of Eqn. [3] or [4]. The simpler ET methods rely on crop coefficients as

$$ET_j = \left(K_c K_s\right)_j \left(ET_{os}\right)_j \tag{4}$$

or

$$ET_j = \left(K_s K_{cb} + K_e\right)_j \left(ET_{os}\right)_j \tag{5}$$

where K_c is the crop coefficient for day j, K_s is a soil water deficit coefficient (0 to 1), ET_{os} is the reference ET for a short, smooth crop coefficient (i.e., mowed, irrigated grass) for a well irrigated crop but with a 'dry' soil surface, and K_e is a soil water evaporation coefficient to adjust the ET for a 'wet' soil from rain or irrigation (Allen et al., 1998). Eqn. [4] is known as the single coefficient approach, and Eqn. [6] is known as the dual coefficient approach. Eqn. [4] is used in the KanSched irrigation scheduling model (Clark et al., 2004) as well as in the Texas High Plains ET Network (Howell et al., 1998). Some form of Eqns. [4] or [5] is incorporated in most crop growth simulation models, too. In most crop growth models, the crop coefficient values are not directly used but similar relationships based on crop development or leaf area index simulated by the model are used.

Soil Water Measurements

Many methods exist to measure soil water (Evett, 2007) but few are designed for automated or continuous soil profile measurements desirable for irrigation scheduling. Many methods can make point or multiple vertical measurements, but only a few extend deep enough to measure the entire crop root zone depth (5-6 ft; 1.5-1.8 m). Although no instrument is perfect (Evett, 2008), several can be used reliably for irrigation management. Only a few offer a complete crop root zone measurement, but even a few point measurements, if accurate, can aid irrigation scheduling.

These measurements can verify irrigation or rain penetration into the crop root zone as well as excess soil water (leading to DP and nutrient leaching from the root zone and/or root oxygen deprivation or depleting soil water leading to crop water deficits impacting yield).

Soil water measurements can be categorized as either direct (sampling) or indirect (some soil property being measured) (Evett, 2007). Direct measurements include either gravimetric (mass based) or volumetric based or measurements. Seldom is volumetric soil sampling used commercially for irrigation scheduling.

Measurement of the soil water potential (energy) is useful because it represents the energy gradient against which crop roots must work to extract soil water and soluble nutrients. The volumetric water content and the soil water potential are interrelated through the soil hydraulic properties, and the function is called a soil characteristic curve or function. Figure 2 shows example soil characteristic curves for several soil textures from Evett (2007). Curves illustrated in Figure 2 typically exhibit hysteresis characteristics where the curves are really a ‘family’ of curves, called scanning curves, depending on if the soil is wetting or drying. More commonly, the soil characteristic curve is plotted with the soil water potential as the independent variable (X-axis).

The examples illustrated in Figure 2 show that the Loamy Sand soil has much less ‘available’ soil water (θ_{fc} - θ_{pw}) than the Silt Loam or Clay soil. Of these three example soil textures, the Silt Loam soil has much greater ‘available’ soil water based on the 1/3 bar definition for 'field capacity' and 15 bar definition for 'permanent wilting point.'

Soil water instrumentation is described in more detail in Evett (2007, 2008), Chávez et al. (2011), and Chávez and Evett (2012). Chávez and Evett (2012) compared four commercial soil water sensor instruments in field experiments in Colorado and Texas and recommended on site calibrations for each, which are typically beyond the capabilities of most producers or even consultants. However, as long as the sensor measurements are consistent, 'absolute' calibrations may not be required for most irrigation water management decisions.

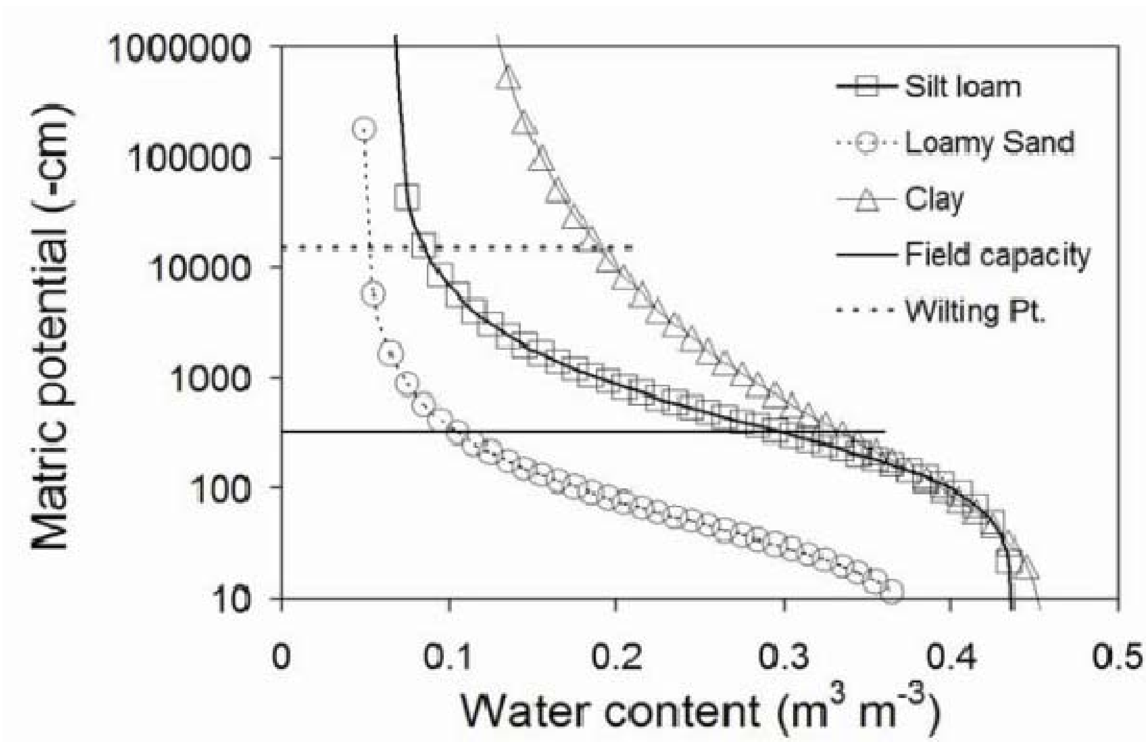


Figure 2. The soil water content vs. soil water matric potential relationship for three soil textures as predicted by the Rosetta pedotransfer model (Schaap et al., 2001). Horizontal lines are plotted for the field capacity, taken as −333 cm (~−33 kPa), and for the wilting point, taken as −15 000 cm. http://www.ars.usda.gov/Services/docs.htm?docid=8953. Source Fig. 2-2 from Evett (2007) p 30. Note: that the -333 cm equals 1/3rd bar (θ_{fc}; field capacity) and -15,000 cm equals 15 bar (θ_{pw}; permanent wilting point), and the Y-axis is plotted as a log scale.

Plant Water Measurements

Plant water status measurements used for irrigation scheduling or control usually are leaf water potential (energy), canopy or leaf temperature, or direct measurements of plant transpiration (e.g., stomatal conductance or sap flow) (Jones , 2004). Although the latter is highly desirable and possible, its field application and equipment costs are generally not practical for producers or consultants.

Leaf water potential (LWP) is one part of the driving force for water movement through a plant (Jarvis, 1976). In a non-stressed, well-transpiring plant, there is a difference in potential energy between water in the leaves and water in the root system. This difference is what causes water to move through the plant. The difference in potential can be assessed from leaf stem water potential measurements made using a pressure chamber instrument (e.g., PMS Instrument Company, Albany, Ore.). LWP measurements are commonly used in viticulture (Moller et al., 2007) to schedule irrigations and for characterizing water stress in cotton crops (Alchanatis et al., 2009). Although LWP measurements are an accepted method to characterize water stress, the method is tedious, inconvenient and not amenable to automation.

Another plant-based method for determining crop water status involves crop canopy (leaves) temperature measurements. A decrease in water uptake reduces transpiration and increases leaf temperature (Blonquist et al., 2009). Stressed plants typically exhibit greater differences in canopy to air temperature. These measurements are usually accomplished using non-contact infrared thermometers. Hand-held infrared thermometers have been used to time irrigations (Nielsen, 1990; Garrot et al., 1994; Gontia and Tiwari, 2008), however these measurements represent spot assessments of a limited number of plants, usually taken at one time per day (Hattendorf et al., 1988; Nielsen, 1990; Farahani et al., 1993) near solar noon and may provide inadequate information for decision making. However, continuous crop canopy temperature measurements

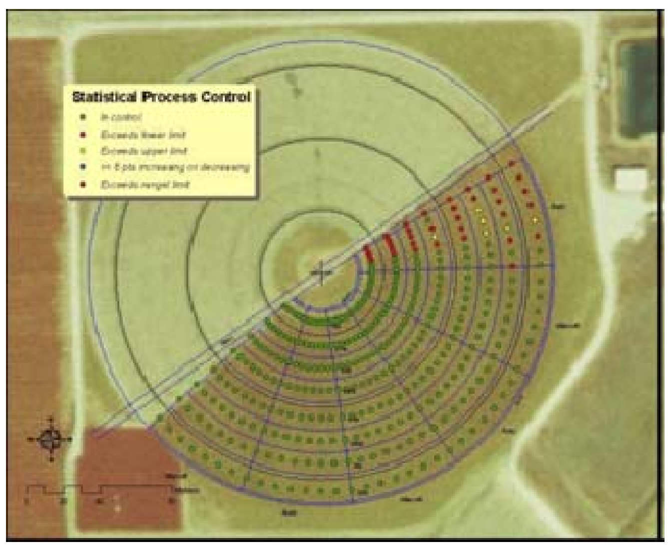


Figure 3. Field map for DOY 258, 2005 showing out-of-control points in a soybean field. Although the effects were not visible to the naked eye, the out-of-control points highlight the region where excess herbicide was sprayed (Peters and Evett, 2007).

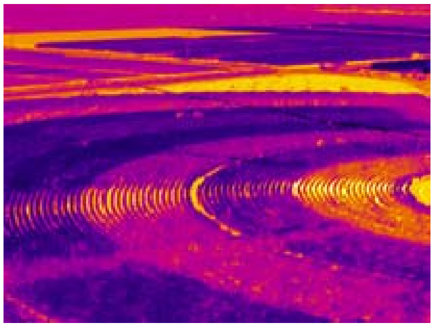


Figure 4. Whole-field image of a cotton field under a 3-span center pivot irrigation system showing the inner four concentric treatment plots (I100%, I33%, I67%, and I0%) and the corresponding values of CWSIe (0.51, 0.78, 0.64, and 1.08, respectively). Thermal image taken at Bushland, TX, on DOY 213 (Jul 31) in 2008 (O'Shaughnessy and Evett, 2009).

made during daylight hours using wired or wireless infrared thermometers mounted on moving mechanical irrigation systems, or on masts in subsurface drip irrigated fields are capable of assessing a larger field area on a frequent basis, automatically.

Irrigation scheduling that makes use of canopy temperature measurements typically involves a stress index and a predefined threshold value that is crop and region specific. If the threshold value is exceeded, irrigation is scheduled. Examples of such stress indices include the Time Temperature Threshold (Evett et al., 1996; Peters and Evett, 2008; O'Shaughnessy and Evett, 2010) and the integrated CWSI (O'Shaughnessy et al., 2012). Both of these plant-monitoring irrigation control systems have been successful in producing crop yields and crop water use efficiency responses that are similar to or better than those achieved with irrigations based on direct soil water measurements with the neutron probe. Continuous crop canopy measurements not only provide a measure for calculating an integrated stress index, they can also provide a spatial picture of performance or crop water status feedback to a farmer throughout the growing season when the data are mapped, either as raw temperature data or as out-of-control points (Fig. 3), a stress index (e.g., the CWSI as shown in Figures 4 and 5), relative leaf water potential or potential yield (Peters and Evett, 2007; O'Shaughnessy and Evett, 2009; O'Shaughnessy et al., 2011).

INTEGRATION OF WATER MANAGEMENT TECHNOLOGIES

Although there are numerous techniques and instruments that can aid irrigation water management decisions or even automate irrigation control, none are perfect and without error or bias. Irrigation scheduling can tolerate considerable error if it is random. However, bias errors that are common with many soil, crop, or water metering systems can lead to erroneous or non-optimum irrigation decisions. Relying on one measurement technology may miss diagnose either abiotic (water or soil effects) or biotic effects (crop, insect, or disease) on irrigation decisions.

It is rather simple to use one or more water management techniques as a check to avoid these problems. The checkbook or ET model approach is for near ideal crop conditions, but various forms of abiotic or biotic crop stress could be detected by crop thermal methods or even imagery, and/or soil water measurements. Soil sampling can be used to correct or reset an ET model or a crop growth development model that may be either missing the crop development or the crop water use. These biased measurements or models may offer inaccurate information for irrigation water management decisions. Biased information is particularly harmful in deficit irrigation water management where the IC constrains irrigation making it difficult to catch up the SWD and where the tolerance for acceptable crop yield or profit is small. The risk adverse producer would likely invest more capital in water management systems that are more reliable and accurate to obtain more nearly ‘perfect’ information to guide and assist in the water management decision. Improved dividends or profits should accrue for this water management capital investment, whether monetary capital or intellectual capital, over the longer operational horizon.

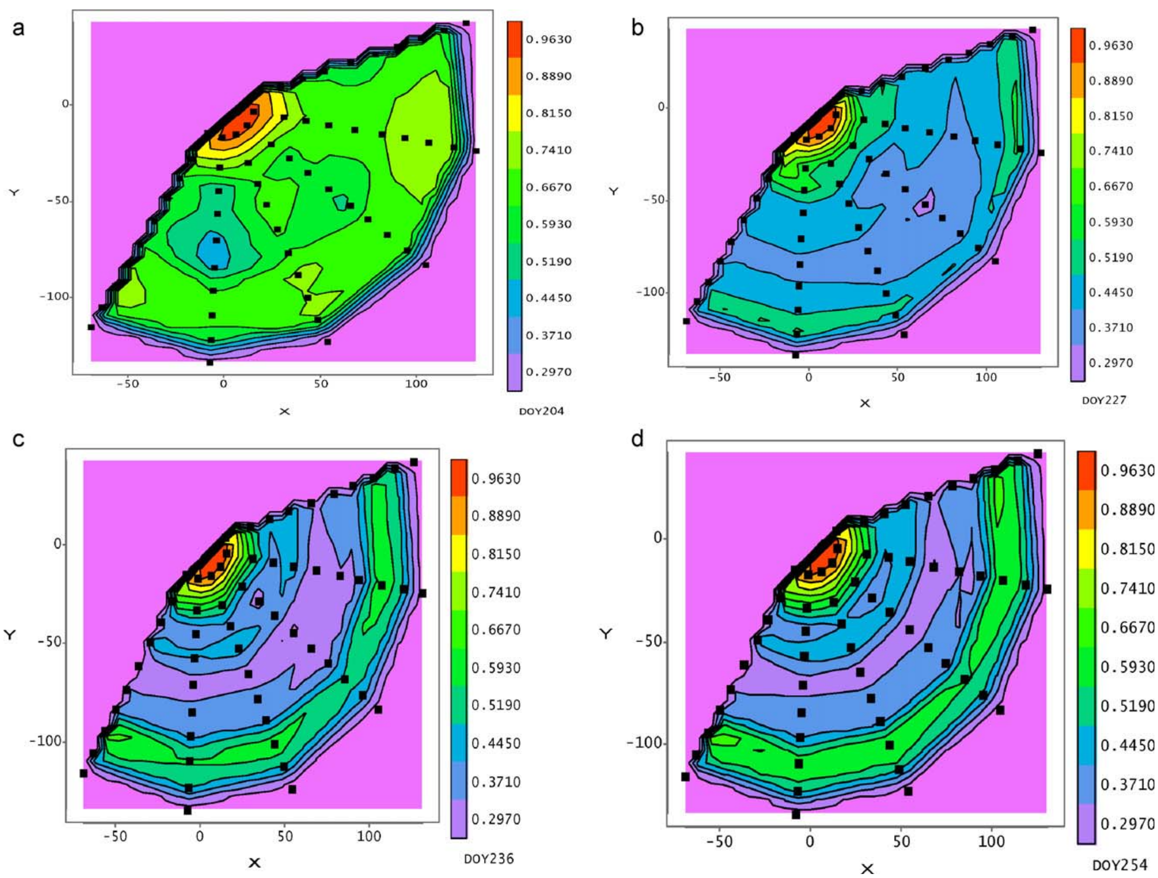


Figure 5. Spatial map of average empirical CWSIe for cotton over growing season 2007, averaged values from DOY 198 through listed date: (a) DOY 204, 6 days after start of irrigation treatments; (b) DOY 227, 29 days after start of irrigation treatments; (c) DOY 236, 38 days after start of irrigation treatments; and (d) DOY 254, 2 weeks after halting irrigation treatments (O’Shaughnessy et al., 2011).

For a producer to have knowledge and awareness of the potential effects of irrigation decisions with inaccurate or even erroneous data is reduced by having good data or information about the crop water requirements and the stochastic effects of the probabilistic variations in weather (whether temperature, rainfall, or reference ET). These 'good' or accurate data should permit better irrigation decisions. These better decisions are important in water conservation as well as producer profit. Soil or crop based measurements together with water metering offer insurance for making better water management decisions.

The irrigation decisions should always consider the 1) no later than date of irrigation and 2) the no sooner than date for a specific irrigation amount. Then the irrigation amount decision may avoid over filling the profile SWD with its non-uniformity and possible nutrient leaching and avoid critical SWD where the soil water deficits that may reduce crop yields and profits.

Although many of these water management measurement tools can be expensive, the cost needs to be weighed against the opportunity to make better water management decisions as well as the lost opportunity costs when incorrect water management decisions are made.

ACKNOWLEDGEMENTS

This paper is the result of cooperative efforts of the authors through the Ogallala Aquifer Program, a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, D., and M. Smith. 1998. Crop evapotranspiration, guidelines for computing crop water requirements. FAO Irrig. and Drain. Paper 56. Rome, Italy: Food and Agric. Orgn. of the United Nations. 300 pp.

Alchanati, V., Y. Cohen, S. Cohen, M. Moeller, M. Sprinstin, M. Meron, J. Tsipris, Y. Saranaga, and E. Sela. 2009. Evaluation of different approaches for estimating and mapping crop water status in cotton with thermal imaging. Precision Agric. DOI 10.1007/s11119-009-911-7.

Blonquist, J.M., J.M. Norman, and B. Bugbee. 2009. Automated measurement of canopy stomatal conductance based on infrared temperature. Agric. For. Met. 149:1931-1945.

Chávez, J.L., J.L. Varble, and A.A. Andales. 2011. Performance evaluation of selected soil moisture sensors. In Proceedings of the Central Plains Irrigation Confere3nce, Burlington, CO, Feb. 22-23. pp. 29-38.

Clark, G.A., D.H. Rogers, S. Briggeman. 2004. KanSched An ET-based irrigation scheduling tool for Kansas summer annual crops. In Proceedings Central Plains Irrigation Conference, Kearny, NE, Feb. 17-18. pp. 120-129.

Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 1996. Canopy temperature based automatic irrigation control. In C.R. Camp et al. (ed.), Proc. Int. Conf. Evapotranspiration and Irrigation Scheduling, San Antonio, Tex. 3-6 Nov. 1996. ASAE, St. Joseph, MI. pp. 207-213.

Evett, S.R. 2007. Soil water and monitoring technology. In R.J. Lascano and R.E. Sojka (ed.) Irrigation of agricultural crops. Agron. Monogr. 30, 2nd ed. ASA, CSSA, and SSSA, Madison, WI . pp. 25-84.

Evett, S.R., L.K. Heng, P. Moutonnet and M.L. Nguyen (eds.). 2008. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna , Austria. ISSN 1018–5518.

Farahani, H.R., D.C. Slack, D.M. Kopec, and A.D. Matthias. 1993. Crop water stress index models for Bermuda grass turf: a comparison. Agron. J. 85:1210-1217.

Gardner, W.R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89(2): 63-73.

Garrot, D.J., M.J. Ottman, D. Fangmeier, and S.H. Husman. 1994. Quantifying wheat water stress with the crop water stress index to schedule irrigations. Agron. J. 86: 195-199.

Gontia, N.K., and K.N. Tiwari. 2008. Development of crop water stress index of wheat crop for scheduling irrigation using infrared thermometry. Agric. Water Manage. 95(10): 1144-1152.

Hattendorf, M.J., R.E. Carlson, R.A. Halim, and D.R. Buston. 1988. Crop water stress index and yield of water-deficit-stressed alfalfa. Agron. J. 80:871-875.

Heermann, D.L., D.L. Martin, R.D. Jackson, and E.C. Stegman. 1990. Irrigation scheduling controls and techniques. In Irrigation of Agricultural Crops, Agron. Mono. No. 30, eds. B.A. Stewart and D.R. Nielsen, pp. 509-535. Madison, WI: Am. Soc. of Agron., Crop Sci. Soc. of Am., and Soil Sci. Soc. of Am.

Howell, T. A., T. H. Marek, L. New, and D. Dusek. 1998. Weather network defends Texas water tables. Irrig. Bus. & Tech. I: 16-20.

Hill, R.W. 1991. Irrigation scheduling. In Modeling Plant and Soil Systems, Agron. Mono. No. 31, eds. J. Hanks and J.T. Ritchie, 491-509. Madison, WI: Am. Soc. of Agron., Crop Sci. Soc. of Am., and Soil Sci. Soc. of Am.

Jarvis, P.G. 1976. The interpretation of variations in leaf water potential and stomatal conductance found in canopies in the field. Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences 273(927):593-610.

Jensen, M.E., R.D. Burman, and R,G. Allen, eds. 1990. Evaporation and irrigation water requirements. ASCE Manuals and Reports on Eng. Practices No. 70. New York, NY: Am. Soc. of Civil Eng. 360 pp.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. J. Experimental Botany 55(407):2427-2436.

Klocke, N. L., L. R. Stone, G. A. Clark, T. J. Dumler, and S. Briggeman. 2006. Water allocation model for limited irrigation. Appl. Eng. Agric. 22(3): 381-389.

Nielsen, D.C. 1990. Scheduling irrigations for soybeans with the Crop Water Stress Index. Field Crop Research 23(2): 103-116.

NRCS. 1997. Irrigation water management, Chapter 9. In Irrigation Guide, National Engineering Handbook, Part 652, E.A. Ross and L.A. Hardy (ed.), pp. 9-1– 9-223. Washington, D.C.:USDA-NRCS.

Martin, D. L., E. C. Stegman, and E. Fereres. 1990. Irrigation scheduling principles. In: Management of Farm Irrigation Systems, ASAE Mono., G. J. Hoffman, T. A. Howell, and K.H. Solomon, (Eds.), ASAE, St. Joseph, Michigan. pp. 155-203.

Moeller, M, V. Alchanatis, Y. Cohenm M. Meron, J. Tsipris, A. Naor, V. Ostrovsky, M. Sprintsin, and S. Cohen. 2007. Use of thermal and visible imagery for estimatinig crop water status in irrigate grapevine. J. Exp. Botany 58(4): 827-838.

O'Shaughnessy, S.A., and S.R. Evett. 2009. Using Radiation Thermometry to Assess Spatial Variation of Water Stressed Cotton, Paper IA09-1012, Proc. Irrigation Association Technical Conference, 2-4 December 2009.

O'Shaughnessy, S.A., and S.R. Evett. 2010. Canopy temperature based system effectively schedules and controls center pivot irrigation for cotton. Agric. Water Mgmt. 97: 1310-1316.

O'Shaughnessy, S.A., S.R. Evett, P.D. Colaizzi, and T.A. Howell. 2011.Using radiation thermography and thermometery to evaluate crop water stress in soybean and cotton. Agric. Water Manage 98:1523-1535.

Peters, R.T. and S.R. Evett. 2007. Spatial and temporal analysis of crop conditions using multiple canopy temperature maps created with center-pivot-mounted infrared thermometers. Trans. ASABE 50(3): 919-927.

Peters, R.T. and S.R. Evett. 2008. Automation of a center pivot using the temperature-time-threshold method of irrigation scheduling. J. Irrig. Drainage Engr. 134 (3): 286-290.

Phene, C.J., R.L. Reginato, B. Itier, B., and B.R. Tanner. 1990. Sensing irrigation needs. In Management of Farm Irrigation Systems, ASAE Mono., eds. G.J. Hoffman, T.A. Howell, and K.H. Solomon, pp. 208-261. St. Joseph, MI: Am. Soc. of Agric. Eng.

Schaap, M.G., F.J. Leij, and T. van Genuchten. 2001. ROSETTA: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251(3/4): 163-176.

Stone, L. R. Stone, N. L. Klocke, A. J. Schlegel, F. R. Lamm, D. J. Tomsicek. 2011. Equations for drainage component of the field water balance. Appl. Engr. Agric. 27(3): 345-350.

Wilcox, J. C. 1959. Rate of soil drainage following an irrigation: I. Nature of soil drainage curves. Can. J. Soil Sci. 39(2): 107-119.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, KS., February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

USING SOIL WATER SENSORS TO IMPROVE IRRIGATION MANAGEMENT

José L. Chávez
Assistant Professor
Civil & Environ. Engineering Dept.
Colorado State University
Fort Collins, Colorado
Voice: 970-491-6095
Fax: 970-491-7727
Jose.Chavez@colostate.edu

Steven R. Evett
Research Soil Scientist
Soil & Water Management Research
USDA-ARS[1]
Bushland, Texas
Voice: 806-356-5775
Fax: 803-356-5750
Steve.Evett@ars.usda.gov

ABSTRACT

Irrigation water management has to do with the appropriate application of water to soils, in terms of amounts, rates, and timing to satisfy crop water demands while protecting the soil and water resources from degradation. In this regard, sensors can be used to monitor the soil water status; and some can be used to calculate irrigation amounts and to decide when to optimally irrigate. This article consists of two parts: 1) presentation of different soil water sensor technologies, and 2) accuracy assessment of selected sensors. The selected sensors included the Acclima[2] (ACC) time domain transmissometer (Acclima, Inc., Meridian, ID), the CS616 and CS655 water content reflectometers (Campbell Scientific, Inc., Logan, UT), the Hydra Probe (Stevens Water Monitoring Systems, Inc., Portland, OR), and the 5TE (Decagon Devices, Inc., Pullman, WA). Sensed soil water content values, in a sandy clay loam soil and a silty clay loam soil, were compared with corresponding values derived from gravimetric samples and TDR readings. Factory based calibrations performed well for the ACC and CS655, but not for the other sensors. The ACC and CS655 sensors were promising for irrigation management, although proper installation is important. Evaluations indicated that a linear calibration for the ACC and the CS616 sensors could improve the water content readings.

---

[1] The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

[2] The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

INTRODUCTION

Nowadays we live in a scenario of climate change and population growth that challenges farmers to be more efficient with their water resources; i.e. to obtain a larger yield with the same or with less water. Improvements in water use efficiency can be achieved utilizing soil water sensors to track the daily soil water content status.

Many methods of determining soil water content have been developed, from simple manual gravimetric sampling to sophisticated neutron probe (NP) and time domain reflectometry (TDR) sensors. One common technique is to measure the soil dielectric permittivity, that is, the capacitive and conductive parts of a soil's electrical response. If the dielectric permittivity is determined at a sensor effective frequency in the range where permittivity is not frequency dependent and if it is determined using a time domain measurement, then the permittivity measurement can be directly related to soil volumetric water content through the use of an appropriate calibration curve (Topp et al. 1980; Evett et al., 2012). However, there are several different types of sensors commercially available that operate at different effective frequencies and that use either time domain or frequency domain measurement methods. These present different levels of soil water content/potential reading 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."* Therefore, the accuracy of sensors needs to be assessed for a proper utilization of the sensors' measurements in irrigation water management.

Evett et al. (2010) reported field studies of soil water sensors that could be buried or inserted into the soil or that could be used from within plastic access tubes inserted into the soil. Since then, new sensors have been put on the market. In this article, the following is presented: a) a description of an array of selected soil water content sensor technologies, and b) an assessment of the accuracy of selected soil water content sensors, including those not reported on earlier.

MATERIALS AND METHODS

Part 1. Description of important soil water content sensor types

Neutron Probe (NP)

Neutron probes use a radioactive, non-directional, neutron emitting source along with a detector of slow neutrons. The hydrogen in water molecules slows down (thermalizes) the fast (high energy) neutrons, and the slow neutrons randomly return to the detector where they are counted (Evett, 2008). Because it can be used with a cable of practically any length, measurements with the NP can be made at depths ranging from 4 in (10 cm) to >10 ft (>3 m) below the soil surface. The typical soil volume radius sampled by the probe ranges from 6 to 20 in (15 to 50 cm) depending on the soil water content (larger radius for drier soil conditions).

The NP is somewhat expensive and, by regulation, must be operated by a trained and licensed person since using the NP involves manipulating a radiation source. Therefore the NP is mainly used in research and to evaluate other sensors. The NP sensor can be very accurate when field calibrated and provides quick readings. However, the NP needs to be calibrated for the soil and access tube. The calibration is a linear relationship between neutron count ratio (neutron count in soil divided by standard neutron count in shield) readings and soil volumetric water content (ft/ft or m^3/m^3) obtained with the gravimetric/volumetric sampling method. By regulation, the NP cannot be used unattended, so automatic, unattended datalogging is not possible.

Porous Blocks (Resistance)

These sensors consist of blocks made of gypsum, nylon, granular matrix, or fiberglass. Embedded in the blocks are electrodes that measure the resistance (Ohms) between these electrodes. The resistance changes as a function of soil water tension (matric potential), which is related to the soil water content. Watermark sensors (e.g., 200SS, Irrometer Company, Inc., Riverside, CA) are of the resistance block type sensors. These sensors have their electrodes covered by a synthetic porous membrane housed in a perforated plastic casing. The Watermark is a low cost sensor that works in most soils. It contains a gypsum tablet that helps in buffering soil salinity. As a resistance sensor its readings are in “Ohms.” A calibration equation (e.g., Shock et al., 1998) is used to convert the “Ohms” or rather “kOhms” to soil matric potential or suction (kPa, mb, or cb). The sensor operating range is said to be 0-200 kPa. In contrast, blocks made of gypsum such as the GB-1 (Delmhorst Instrument CO., Towaco, NJ) allegedly read the resistance in the soil over a wider range (10-1,500 kPa or 0.1-15 b). With a resistance based sensor one obtains the tension at which the water is being held in the soil. To convert soil matric potential to soil volumetric water content (VWC or θ_v) one uses a soil characteristic curve (or soil water release/retention curve), which is specific for each soil and each soil layer, and which changes with soil bulk density (compaction).

Measurements Related to Soil Dielectric Permittivity

There are several sensor types that respond to changes in the soil dielectric permittivity (also known as the dielectric constant, although it is not a constant in soils). The permittivity increases with soil water content, but depending on the measurement method and effective frequency, the permittivity may also be strongly dependent on bulk electrical conductivity (which is affected by clay content and type and by soil salinity and temperature), bound water (water held tightly to clay surfaces, the permittivity of which is temperature dependent), and even by the effective frequency of the electronic signal used. The major classes of methods are those that work 1) in the time domain, measuring the time it takes an electronic pulse to travel through an electrode buried in the soil, and 2) in the frequency domain, measuring the resonant frequency of an oscillating electronic circuit, part of which is coupled with the soil through electrodes buried in the soil or contained in a plastic access tube inserted into the soil.

Time Domain Methods

A basic conventional time domain reflectometry (TDR) instrument consists of a fast oscilloscope and a pulse generator. The instrument is used in a TDR system, which typically consists of, at minimum, the instrument, a computer or datalogger to control the instrument and interpret data, and a TDR probe consisting of rigid electrodes that are inserted into the soil (length varies, but 4 to 8 inches are common). A fast rise time electromagnetic pulse is sent through the electrodes (two or three). The pulse is reflected from the ends of the electrodes and returned to the instrument, which captures a waveform showing the pulse relative voltage as it passes through the electrodes. The speed of the pulse is inversely proportional to the soil VWC.

The TDR system interprets the waveform to find the travel time of the pulse. The system can be calibrated using a linear equation relating VWC to travel time. Or, the system can calculate the soil dielectric permittivity (which is inversely and non-linearly related to the velocity of the electromagnetic pulse). Then, an equation like Topp's equation (Topp et al., 1980) can be used to convert the permittivity readings to VWC. Conventional TDR systems are very accurate, expensive, used mainly in research, and provide an integrated/average soil water content along the depth/length of the probe. Soil-specific calibrations are needed in some soils or if high accuracy is needed; but a single calibration can be used in many soils because TDR readings are relatively independent of soil texture, bound water, salinity, density, or temperature. Highly accurate calibration methods used for science applications may use ancillary measurements of soil temperature and bulk electrical conductivity. Most conventional TDR systems can accurately measure the bulk EC, which not only is useful for enhanced calibration equations but is useful for irrigation management, including leaching, to deal with saline soils.

Several sensors employ time domain transmissometry, which is similar to TDR but measures transmission time in a loop circuit and does not rely on a reflection. These include the Acclima ACC, the ESI Gro-Point, and the Aquaflex SE200. These time domain transmission (TDT) sensors vary in the way in which they determine the pulse travel time. Of the three mentioned, only the Acclima ACC captures and interprets a waveform to determine travel time as accurately as a conventional TDR system. The TDT sensors all have the electronics embedded in a plastic sensor head, so that the expensive TDR instrument is avoided. We studied the ACC (Acclima, Inc., Meridian, ID) sensor, which has a waveguide consisting of two looping rods 8 in (20.3 cm) long. Besides providing readings of VWC (by Topp's equation), the sensor also provides soil temperature and soil bulk electric conductivity (EC_b, dS/m). This sensor communicates with a datalogger using the SDI-12 interface which is "Serial Data Interface at 1200 Baud". SDI-12 is an asynchronous, ASCII, serial communications protocol.

Other time domain methods attempt to measure travel time of a reflected pulse using electronics embedded in sensor heads, but do not capture a waveform. Although these may be called TDR sensors, the ways in which they determine pulse travel time may have limited accuracy due to strong effects of soil bulk electrical conductivity and temperature. We studied the CS616 and CS655 "water content reflectometers" (Campbell Scientific, Inc., Logan, UT), which employ two electrode rods (lengths of 4 to 12 in). An electronic pulse is sent from the probe head and reflected from the ends of the rods. Once the probe head detects the return of the pulse, another pulse is sent. The probe then records the frequency of these pulses and reports the inverse of the frequency (also called a period, with units of micro seconds or µs). The soil's dielectric permittivity influences the velocity of the electromagnetic pulse, which in turn influences the period. The probe then relays the data sensed to a datalogger. A calibration equation (provided by the manufacturer), that can be coded in the datalogger program, then relates the probe's output period to volumetric soil water content (Campbell, 2011; Ruelle and Laurent, 2008).

Frequency Domain Methods (Capacitance Sensors)

The capacitance sensors (e.g., Diviner 2000 and EnviroScan, Sentek Sensor Technologies, Stepney SA, Australia) are based on the varying frequency of oscillation of an electromagnetic field in the soil. An oscillating current is induced in a circuit, part of which is a capacitor that is arranged so that the soil becomes part of the dielectric medium affected by the electromagnetic field between the capacitor's electrodes. Varying soil VWC influences the dielectric permittivity of the soil, which in turn affects the capacitance, causing the frequency of oscillation to shift. These sensors are referred to as Frequency Domain sensors. The manufacturer provides a calibration equation (embedded in the sensor electronics or applied separately) relating readings from the sensor to VWC. According to Evett et al. (2008), in general the manufacturer calibration may not perform well in field conditions due to temporal variation of soil bulk electrical conductivity and due to the small scale spatial variability of soil water content and bulk EC.

We studied the 5TE capacitance sensor (Decagon Devices, Inc., Pullman, WA). This sensor measures the relative permittivity of the soil by supplying "a 70 MHz oscillating wave to the sensor prongs … [and the resulting] stored electric charge [in the prongs] is proportional to [the] soil dielectric properties." In SDI-12 communication mode, the 5TE reports the relative permittivity to the datalogger. The relative permittivity values in turn can be converted to VWC automatically within the datalogger. The standard calibration equation recommended by the manufacturer is the previously-mentioned Topp's equation.

We also studied the Hydra Probe, which reports values of the real (ε_r) and imaginary (ε_i) components of permittivity, the temperature (*T*) and bulk electric conductivity (σ_a).

Part 2. Selected soil water content sensors accuracy assessment

Two different sensor evaluation studies were carried out. One in Greeley, Colorado evaluated CS616 and ACC sensors while the other study in Bushland, Texas evaluated CS616, CS655, ACC, Hydra Probe, and 5TE sensors.

Colorado Study

This study took place during the 2011 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 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 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

The ACC 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 (VWC), soil temperature (°C), and bulk electrical conductivity (σ_a, dS/m). According to Acclima (2010), the volumetric water content accuracy of the sensor is ±1% (full scale) under temperature conditions of 0.5 to 50°C and σ_a of 0 to 3 dS/m.

During August of 2011, ACC and CS616 sensors were installed at the study site. Three sensors of each type were installed, at different locations 45 m apart, one ACC and one CS616 were installed at each site under the corn bed, roughly 0.3 m (1 ft) away from each other, at a depth of approximately 1-5 inches (2-12 cm) (slanted) below the average level of the corn beds. Sensor readings were recorded every fifteen minutes using an automatic datalogger (CR1000, Campbell Scientific, Inc., Logan, UT). Sensor evaluation was performed using the data collected in 2011.

The VWC from the sensors were compared with VWC measurements obtained with a portable TDR sensor (MiniTrase kit, Soil Moisture Equipment Corp., Santa Barbara, CA), in the 0-6 in (0-15 cm) surface layer. Ten VWC readings were taken with the TDR sensor during the month of August in 2011 at a location approximately 1 m from the location of the ACC and CS616 sensors. The TDR system used incorporated a calibration defined by the manufacturer.

Texas Study

The study was done at the USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas in the plow layer (Ap horizon) of the Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll). A 40 in by 80 in (1-m by 2-m) field area was prepared by installing straight, parallel rails leveled end to end and side to side. The soil was scraped away between the rails to a depth of 2 in (5.4) cm using a purpose-built tool, leaving a firm surface. Sensors were installed horizontally on this surface, after which soil was manually packed over the sensors, and brought to the top surface of the rails so that all sensors were buried at the same depth. Sensors were placed so that the six sensors of each type were intermixed in position with the six sensors of the other types. All measurements were made every 0.5 h for two years. The plot area was surrounded by a low berm and flooded by irrigation after sensor installation, then flooded by irrigation or wetted by precipitation periodically during the testing period. Minor soil settling occurred after the 1st flooding, indicating that the pre-flooding bulk density (ρ_b, Mg m^{-3}) was <1.54, the target ρ_b to achieve a porosity of 0.42 m^3 m^{-3}; so soil was added to the plot and leveled between the rails to achieve the target depth of 5.4 cm and bulk density of 1.54. The bulk density was confirmed by volumetric sampling. This meant that the water content could not exceed the soil porosity of 0.42 m^3 m^{-3}, which allowed over estimation of water content by any sensor to be easily confirmed. The plot was kept bare of vegetation. In contrast with the Colorado study, the Texas study was designed so that all sensors would be subjected to the same conditions of soil texture, air-filled porosity, water content, temperature and bulk electrical conductivity so that comparisons could be made between each sensor type and the TDR system and between sensors of the same type (to assess inter-sensor variation).

Sensors included six CS616 sensors (Campbell Scientific Inc., Logan, UT, USA); six ACC sensors (model ACC-SEN-TDT, Acclima, Inc., Meridian, ID, USA); six Hydra Probes (Stevens Water Monitoring Systems, Inc., Portland, OR, USA); and six type-T thermocouples (hand made). Later in the study, the CS616 sensors were exchanged for CS655 sensors, also from Campbell Scientific, Inc., and six 5TE sensors (Decagon, Inc., Pullman, WA) were included.

Comparisons were made with data from six conventional TDR probes (20-cm, planar trifilar), built as described by Evett (2000a) except that RG6 cable was used to reduce attenuation. The TDR probes were connected to a TDR instrument (model 1502C, Tektronix, Inc., Redmond, OR, USA) through a coaxial multiplexer (Evett, 1998); and θ_v and σ_a were determined automatically using the TACQ software and methods described by Evett (2000b) and Evett *et al.* (2005), including the soil-specific calibration and the σ_a and effective frequency based temperature correction of Evett *et al.* (2005). Because it employed a soil-specfiic calibration and could determine dielectric permittivity, bulk electrical conductivity and water content with high accuracy (Evett et al., 2005), the TDR system served as the control in this study. Dataloggers were used to measure sensor and thermocouple outputs (model CR3000, CSI, Logan, UT, USA in the case of Hydra Probe, CS616 and thermocouple sensors; and model ACC-AGR-007, Acclima, Inc., Meridian, ID, USA for the ACC sensors). Factory recommended calibrations were used for sensors other than TDR. This included the “general” calibration of Seyfried *et al.* (2005), which the manufacturer recommended for the Hydra Probe. Thermocouple measurements of temperature were used as the control or standard against which temperatures from the other sensors were compared.

Statistical Analysis

Statistical measures were computed to compare and evaluate each model-predicted (*P*) VWC with the observed (*O*) VWC values ($m^3\ m^{-3}$) taken from the field. These include the mean bias error (*MBE*; Equation 1), and the root mean square error (RMSE; Equation 2), as defined by Willmott (1982).

$$\mathrm{MBE} = \mathrm{n}^{-1}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{P_i} - \mathrm{O_i}) \qquad 1$$

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

where *n* is the sample size. The units for MBE and RMSE are absolute volumetric water content errors ($m^3\ m^{-3}$).

RESULTS AND DISCUSSION

Colorado Study

The factory calibration was evaluated with the 2011 VWC measured data collected with the TDR sensor. The absolute errors were -0.049±0.059 $m^3 m^{-3}$, and 0.314±0.062 $m^3 m^{-3}$, for the ACC and CS616 sensors, respectively. This result shows that the CS616 sensor is not reliable and indeed needs site specific (soil/sensor) calibration; while the ACC sensor showed much less error. One issue with the ACC sensor might be the difficulty of installing it properly in drier soils due to the nature of the looping probes that may prevent full contact of the soil with the probe (air voids). Figure 1 show the graphical representation of the comparison of the sensors' VWC data.

Texas study

All the TDR probes exhibited similar θ_v values, reaching a peak of 0.48 $m^3 m^{-3}$ during the 1st flooding, which indicated an initial ρ_b of 1.39 Mg m^{-3} (Fig. 2). After settling, the peak θ_v was 0.42 $m^3 m^{-3}$, which is a typical porosity for the Pullman clay loam Ap horizon after consolidation. Temperature interference was < 0.01 $m^3 m^{-3}$ diurnally. Importantly, values of θ_v were quite similar over the small plot area. Values of σ_a ranged from 0.2 to 1.3 dS m^{-1} over the course of the study. The ACC sensor performed similarly to the TDR system, exhibiting similar small temperature interference and slightly more difference in θ_v among the sensors (Fig. 2). Since the relationship between ε_a from the ACC to ε_a from the TDR system was highly linear (Table 2) and temperature interference was minimal in both systems, a soil-specific calibration can be easily achieved for the Acclima by applying a linear correction to ε_a.

The Hydra Probe overestimated ε_a more than did the ACC (Table 2), but its θ_v estimates were similar in magnitude to those of the ACC (Figures 2-3). However, it was more temperature sensitive, with diurnal variations up to 0.02 $m^3 m^{-3}$, and it exhibited larger inter-sensor variation, up to 0.08 $m^3 m^{-3}$. The temperature sensitivity may have been why the relationship between Hydra Probe ε_a and that from the TDR system was not as linear as for the ACC. The CS616 does not directly report *T*, ε_a or σ_a. The 5TE underestimated ε_a and exhibited the largest error and smallest r^2 value, the latter of which indicates a lack of linearity in response. This was due to soil temperature effects that caused hysteresis in the response. Such temperature effects are common with capacitance based sensors. The CS655 overestimated ε_a by about 30%, but with the second smallest error (after the ACC) and high linearity, indicated that a simple linear correction would be effective in correcting its output in the Pullman soil.

Table 2. Linear regressions comparing Acclima ACC, 5TE and CS655 apparent permittivity, ε_a, and Hydra Probe real permittivity, ε_r, to that from the TDR system.

Sensor	Intercept (-)	slope	RMSE (-)	r^2
ACC	2.00	1.088	0.40	0.988
Hydra Probe	0.88	1.328	0.85	0.965
5TE	4.76	0.815	1.004	0.877
CS655	0.03	1.334	0.541	0.985

Knowing the soil bulk electrical conductivity is important since high conductivities can affect plant growth and indicate the need for leaching. The Acclima greatly overestimated σ_a (Table 3), but had a more linear relationship with σ_a determined by TDR than did the Hydra Probe and so could be easily corrected with a linear calibration. However, the great overestimation of σ_a by the ACC indicates a problem with the algorithm by which σ_a is computed in that sensor. The Hydra Probe exhibited a less linear relationship with σ_a values from TDR, particularly for the “temperature corrected” values from the Hydra Probe, which exhibited hysteresis in the relationship with σ_a from TDR due to incorrect compensation for temperature interference in the Hydra Probe sensor. The 5TE underestimated σ_a by about 35% and exhibited by far the largest error. Its response was also not linear (r^2=0.58), indicating that a correction is not practical. The CS655 estimated σ_a very well with nearly perfect 1:1 correlation.

Table 3. Linear regression relationships comparing Acclima ACC and Hydra Probe bulk electrical conductivity, σ_a, to that from the TDR system.

Sensor	Intercept (S/m)	slope	RMSE (S/m)	r^2
ACC	-0.014	2.347	0.009	0.950
Hydra Probe	0.000	0.850	0.004	0.924
Hydra Probe (temperature corrected)	0.013	0.706	0.010	0.584
5TE	0.005	0.650	0.009	0.588
CS655	-0.008	1.007	0.001	0.993

Knowing soil temperature is important early in the season to guide planting and also in order to apply temperature corrections to water content data. Temperature was determined with sufficient accuracy by all the sensors as shown by nearly 1:1 responses that were highly linear with errors <1°C (Table 4). An earlier report of overestimation of temperature by the Hydra Probe (Evett et al., 2010) was found to be related to continuous reading of the sensor, which apparently caused self heating. Turning off the sensor between half-hourly readings resolved this problem.

Table 4. Linear regression relationships comparing Acclima ACC and Hydra Probe temperatures, *T*, to that from the six thermocouples.

Sensor	Intercept (°C)	slope	RMSE (°C)	r^2
ACC	0.10	1.008	0.62	0.997
Hydra Probe	0.48	0.989	0.80	0.995
5TE	0.11	0.992	0.85	0.994
CS655	-0.19	1.000	0.95	0.992

Most producers and irrigators will not take the time to do soil-specific calibration of sensors, so it is important to know how well each sensor estimates water content using the best factory or otherwise known calibration. Given the range of σ_a measured by TDR, a CS616 calibration from the manufacturer for ρ_b of 1.6 Mg m^{-3} and σ_a = 0.75 dS m^{-1} at saturation was used. Even so, the CS616 overestimated θ_v more than the ACC or Hydra Probe and was more temperature dependent (Figs. 2-3, not shown in Table 5), with diurnal variations due to temperature of up to 0.05 m^3 m^{-3}. Unlike the ACC and Hydra Probe, the CS616 does not report *T* or σ_a, so temperature correction would require additional measurements. Differences in θ_v between sensors were also larger for the CS616, up to 0.12 m^3 m^{-3}. In contrast, the newer CS655 performed much better; it was well correlated with water content, with a slope of close to unity and root mean square error (RMSE) of 0.01 m^3 m^{-3}. The ACC exhibited the smallest root mean square error and was the most well correlated with water content, probably due to the fact that it captures and interprets a waveform for pulse travel time, as does a conventional TDR system. The Hydra Probe was less well correlated with water content than the ACC or CS655 and exhibited a larger root mean squared error of 0.015 m^3 m^{-3}; both problems are related to it sensitivity to σ_a interference, which is influenced by temperature changes. The 5TE was the worst performing sensor using the factory calibration. It was the least well correlated with water content (smallest r^2), and had the largest error, largest intercept and slope furthest from unity.

Table 5. Linear regression relationships comparing estimated water contents from the Acclima ACC, Hydra Probe, 5TE, CS616 and CS655 to data from the TDR system.

Sensor	Intercept (m^3 m^{-3})	slope	RMSE (m^3 m^{-3})	r^2
ACC	0.05	0.932	0.004	0.994
Hydra Probe	0.02	1.027	0.015	0.938
5TE	0.10	0.687	0.018	0.820
CS655	0.04	1.037	0.010	0.973

CONCLUSIONS

This article presents several soil water content sensor technologies along with an assessment of the performance of selected soil water content sensors. The ACC, Hydra Probe, 5TE, CS655 and CS616 sensors were evaluated in the field. The sensor measurements of soil water content were compared with corresponding values derived from gravimetric samples and with values from a TDR system. Linear calibration equations could be developed easily for the ACC and CS655 sensors based on volumetric soil water content data obtained in the field by gravimetric/volumetric sampling or with a calibrated TDR system. According to evaluations, the ACC and CS655 sensors seem to be more robust and accurate sensors overall. The Acclima algorithm for finding the travel time makes it an accurate time domain method (Anderson 2003) and thus suitably accurate for irrigation scheduling. However, the nature of its looping probes may hinder the correct installation of the sensor and therefore the appropriate use of the resulting data. The CS655 was easily installed since it could be pushed into the soil. Regarding the CS616 sensor, it showed a very large error if used with the factory calibration and was overly temperature sensitive. However the sensor needs a better calibration, perhaps incorporating the effect of soil temperature and salinity in order to lower its error to around 0.03 m^3 m^{-3}. Unfortunately, it measures neither. The authors can recommend the ACC and CS655 sensors for irrigation scheduling. The results found in this study are encouraging in that some of the studied soil water content sensors have the potential to be used in irrigation water management schemes.

ACKNOWLEDGMENT

We want to express our gratitude to the following individuals who in one way or another contributed to this study: Dr. Thomas Trout, Dr. William Sanford, Jonathan King, Jordan Varble, Evan Rambikur, and Brice Ruthardt.

REFERENCES

Acclima, 2010. TDT Soil Moisture Sensor. Cutsheet, Acclima, Inc., Meridian, ID. Also available at http://acclima.com/wd/acclimadocs/MoistureSensor/TDT%20Moisture%20Sensor%20Cut%20Sheet.pdf

Anderson. S.K. 2003. Absolute-reading soil moisture and conductivity sensor. Patent No.: US 6,657,443 B2.

Campbell Scientific. 2011. Instruction Manual: Models 253-L and 257-L (Watermark 200) Soil Matric Potential Sensors. Revision 3/09. Also available at http://www.campbellsci.com/documents/manuals/253-257.pdf

Evett, S.R. 2000a. The TACQ Program for Automatic Time Domain Reflectometry Measurements: I. Design and Operating Characteristics. Trans. Am. Soc. Agric. Engr. 43:1939-1946.

Evett, S.R. 2000b. The TACQ Program for Automatic Time Domain Reflectometry Measurements: II. Waveform Interpretation Methods. Trans. Am. Soc. Agric. Engr. 43:1947-1956.

Evett, S.R. 2008. Neutron Moisture Meters. Chapter 3 (pp. 39-54) In S.R. Evett, L.K. Heng, P. Moutonnet and M.L. Nguyen (eds.) Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. Available at http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801

Evett, S.R., R.C. Schwartz, R.J. Lascano, and M.G. Pelletier. 2010. In-soil and down-hole soil water sensors: Characteristics for irrigation management. Proc. 5th Decennial National Irrigation Conf., 5-8 December 2010, Phoenix, Arizona. Paper No. IRR10-8346. ASABE, St. Joseph, Mich. (CD-ROM).

Evett, S.R., R.C. Schwartz, J.J. Casanova, and Lee K. Heng. 2012. Soil water sensing for water balance, ET and WUE. Agric. Water Manage. 104:1-9.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2005. TDR laboratory calibration in travel time, bulk electrical conductivity, and effective frequency. Vadose Zone J. 4:1020-1029.

Gavlak, R.G., D.A. Horneck, and R.O. Miller, 2003. Plant, Soil and Water Reference Methods for the Western Region, 2nd ed. WREP 125.

Hignett, C., and S. Evett, 2008. Direct and Surrogate Measures of Soil Water Content. In: Evett, S.R., L.K. Heng, P. Moutonnet, and M.L. Nguyen, editors. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018-5518. p. 107-109.

Ruelle, P., and J.P. Laurent. 2008. CS616 (CS615) Water Content Reflectometers. In: Evett, S.R., L.K. Heng, P. Moutonnet, and M.L. Nguyen, editors. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018-5518.

Seyfried M.S., L.E. Grant, E. Du, and K. Humes. 2005. Dielectric loss and calibration of the Hydra Probe soil water sensor. Vadose Zone J. 4:1070-1079.

Shock, C.C., J.M. Barnum, and M. Seddigh. 1998. Calibration of Watermark soil moisture sensors for irrigation management, pp.139-146, Proceedings of the International Irrigation Show, San Diego, CA. Irrigation Association.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurement in coaxial transmission lines. Water Resources Research 16(3):574-582.

Willmott, C.J. 1982. Some Comments on the Evaluation of Model Performance. Bull. of Am. Meteorol. Soc., 63, 1309-1313.

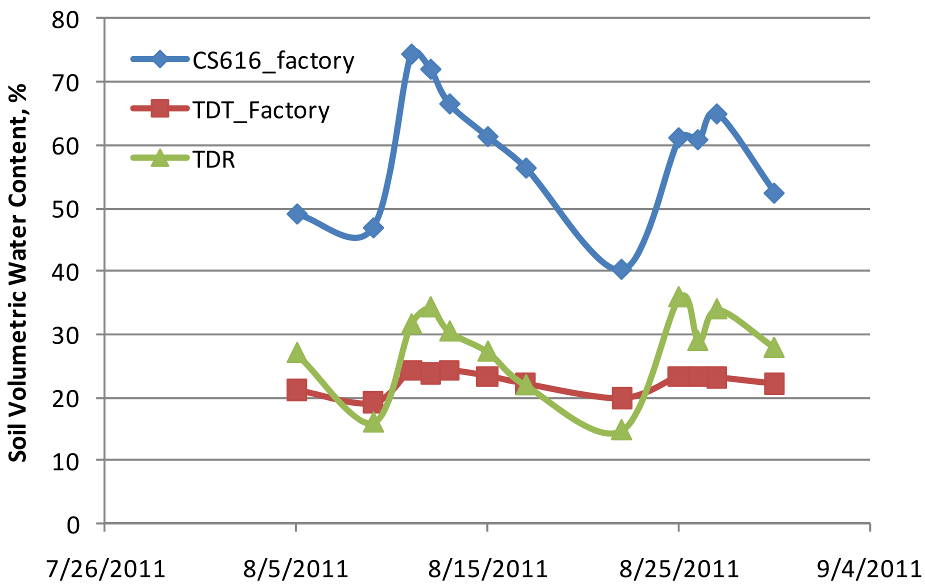


Figure 1. Comparison of the VWC of the CS616 and ACC (TDT) factory calibration readings with TDR VWC values in Colorado.

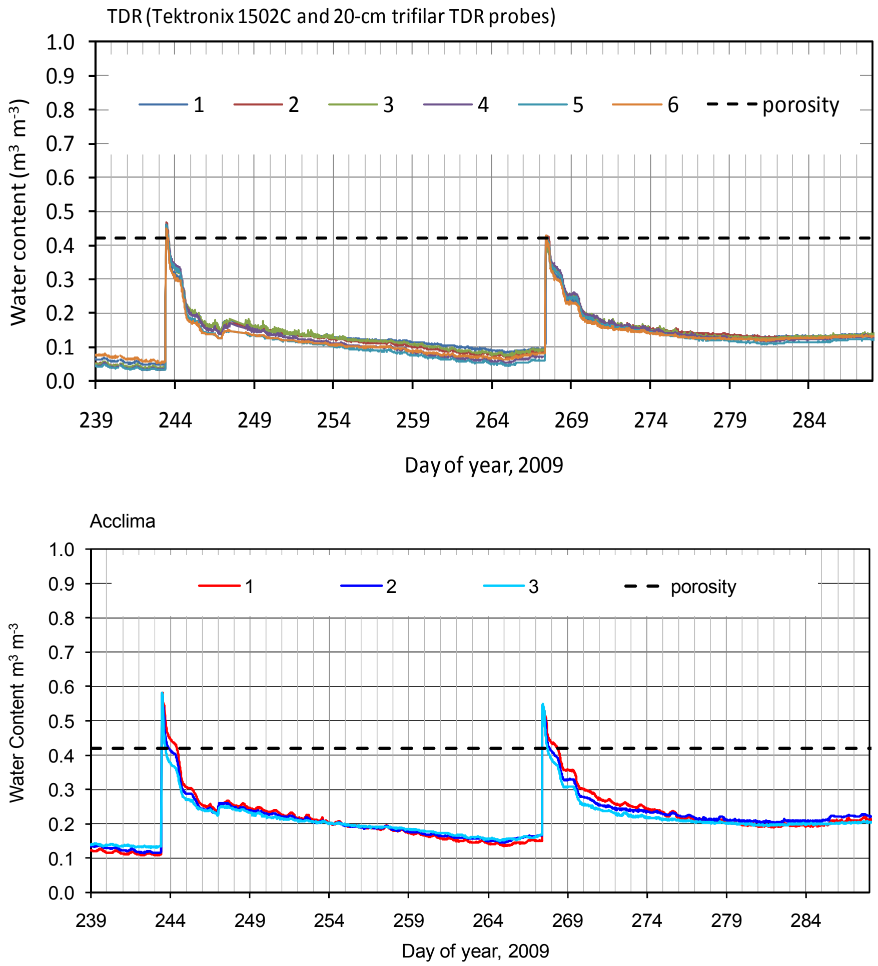
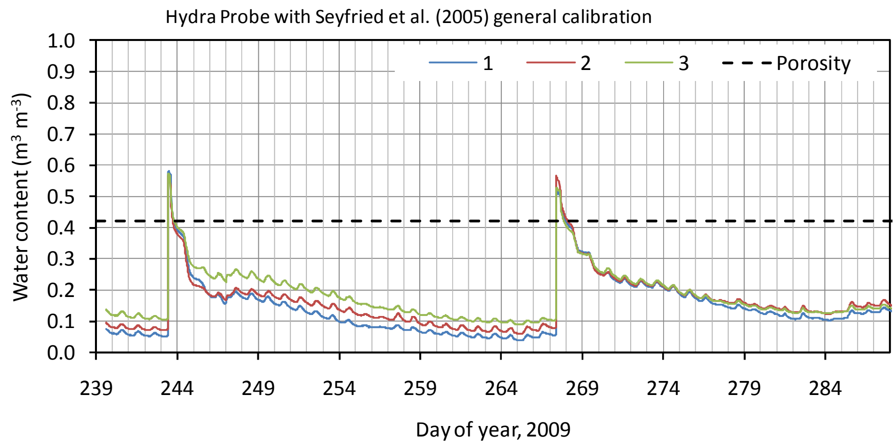


Figure 2. Conventional time domain reflectometry (TDR) water contents using soil-specific calibration (top) and Acclima sensor water contents (bottom) during the first two plot flooding and dry down periods, in Texas.



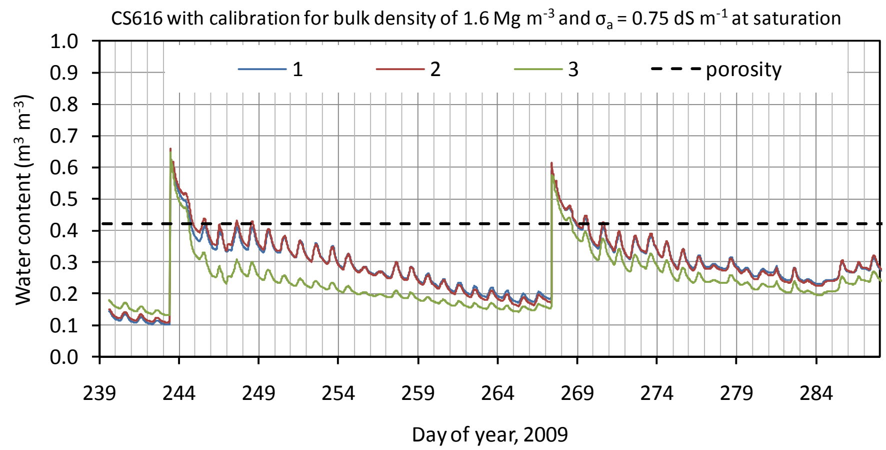


Figure 3. Hydra Probe water contents using Seyfried et al. (2005) general calibration (top); and CS616 water contents from calibration for sandy clay loam, ρ_b of 1.6 Mg m^{-3} and σ_a = 0.75 dS m^{-1} at saturation (bottom) for the first two flooding and dry down periods, in Texas.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, Kansas, February 21-22, 2012
Available from CPIA, 760 N. Thompson, Colby, Kansas

USING PLANT CANOPY TEMPERATURE TO IMPROVE IRRIGATED CROP MANAGEMENT

Paul D. Colaizzi
Research Agricultural Engineer
USDA Agricultural Research Service
Bushland, Texas
Voice: 806-356-5763 Fax: 806-356-5750
paul.colaizzi@ars.usda.gov

Susan A. O'Shaughnessy
Research Agricultural Engineer
USDA Agricultural Research Service
Bushland, Texas
Voice: 806-356-5770 Fax: 806-356-5750
susan.o'shaughnessy@ars.usda.gov

Steven R. Evett
Research Soil Scientist
USDA Agricultural Research Service
Bushland, Texas
Voice: 806-356-5775 Fax: 806-356-5750
steve.evett@ars.usda.gov

Terry A. Howell
Laboratory Director
USDA Agricultural Research Service
Bushland, Texas
Voice: 806-356-5746 Fax: 806-356-5750
terry.howell@ars.usda.gov

ABSTRACT

Remotely sensed plant canopy temperature has long been recognized as having potential as a tool for irrigation management. However, a number of barriers have prevented its routine use in practice, such as the spatial and temporal resolution of remote sensing platforms, limitations in computing capacity and algorithm accuracy, and the cost and ruggedness of sensors and related components that can transmit and receive data wirelessly. Recent advances in all of these areas have made remote sensing more feasible in providing real-time feedback of field conditions. This can potentially reduce management time, maintain crop yield and crop water productivity, and detect unusual conditions such as equipment malfunctions or biotic stress sooner. Center pivots equipped with wireless infrared thermometers (IRTs) have been found to be suitable as a remote sensing platform. Canopy temperature-based algorithms have successfully automated drip and center pivot irrigation schedules where crop yield, water use efficiency, seasonal water use, and irrigation amounts applied were comparable to irrigations scheduled manually with a field-calibrated neutron probe. Even without automation, these algorithms can provide timely and valuable information on plant and soil water status, which can improve the management of irrigated crops.

INTRODUCTION

Plant canopy temperature is useful as an irrigation management tool because it is related to the water status of the plant and soil, and it can be measured noninvasively by remote sensing. As plants transpire, the evaporation of water from liquid to vapor state consumes heat energy, which lowers the leaf temperature; this and the movement of water vapor away from the canopy removes heat and results in a cooling effect. When the plant evapotranspiration (ET) rate is reduced, such as by soil water depletion, the rate of heat removal is reduced and the canopy temperature increases. This process links canopy temperature with crop water stress and ET. Detection of crop water stress and ET enable rational irrigation timing and application amounts, which can increase crop water productivity, reduce leaching of water and nutrients below the root zone, and reduce the time required for irrigation management. Measurement of canopy temperature is possible using radiometers that are filtered to the thermal infrared (8 to 14 μm) wavelengths, making them non-contact infrared thermometers (IRTs). Because all surfaces emit thermal radiation, temperature can measure an area from a few cm^2 to several km^2. These characteristics can carry advantages over sensors that require physical contact with the plant or soil, which often sample an area or volume of insufficient size to be representative of the soil – plant – atmosphere energy and water balance.

The concept of using remote sensing for farm management, including irrigation management, dates to the 1960s. Monteith and Szeicz (1962) and Tanner (1963) were the first to report plant canopy measurements using portable radiometers, from which evolved the basic design of modern hand-held and miniature IRTs. Wiegand et al. (1968) and Bartholic et al. (1972) were among the first to use airborne thermal scanners to differentiate crop and soil water status. The launch of the Landsat series of satellites beginning in 1972 led to agricultural monitoring applications such as commodity market forecasting, but mainly on a seasonal basis and at regional scales, because the spatial resolution and repeat frequency of satellites were inadequate for real-time and farm field-scale management (Moran, 1994). Phene et al. (1985) described one of the earliest applications of IRTs aboard a moving irrigation system. These developments prompted further research in agricultural remote sensing, which have been reviewed by Jackson (1982; 1984), Moran et al. (1997), and Gowda et al. (2008). Several technical barriers have impeded the widespread adoption of remote sensing for real-time irrigation management. These are related to remote sensing platform requirements, the need for wireless data transmission, sensor cost and ruggedness, computing capacity, and crop water stress and ET models, among other factors. However, many of these barriers have been mitigated in recent years, which may finally make remote sensing a feasible and cost-effective option for producers.

This paper provides a brief review of the use of remotely sensed plant canopy temperature for irrigation management. The review includes an overview of canopy temperature algorithms, remote sensing platforms, and some recent experimental results in irrigation automation at the USDA Agricultural Research Service Conservation and Production Research Laboratory at Bushland, Texas.

OVERVIEW OF CANOPY TEMPERATURE-BASED ALGORITHMS

Canopy temperature is a component of the soil-plant-atmosphere energy and water balance; it is the result of complex interactions with the soil and plant water status, crop phenology, and the crop micrometeorological climate. Because of this, a single measurement of canopy temperature by itself usually does not reveal much about plant water status. Hence algorithms have been developed that in various ways integrate canopy temperature with the physical environment. Three general types of algorithms shown to be useful in irrigation management are (i) water stress indices, (ii) the time – temperature threshold, and (iii) the ET-based soil water balance. Each can provide guidance on the timing of irrigation, and the ET-based soil water balance can also provide guidance on the appropriate amount of irrigation.

Water Stress Indices

The word stress, in the context of plants, is a broad term used to describe some type of adversity that, if prolonged, can result in economic yield loss (Jackson, 1982). Water stress then describes a condition where the supply of water in plant leaves inhibits photosynthesis and respiration. The shortage of water could be caused by abiotic stresses (i.e., resulting from soil water depletion) or biotic stresses (i.e., resulting from pests or disease that inhibit water flow to leaves). Under water stress conditions, transpiration is reduced, resulting in a greater amount of available energy at the canopy surface being converted to sensible heat compared with what would have occurred for non-water-stressed conditions. The result is that the temperature of the plant canopy (i.e., the ensemble of plant leaves) increases over the temperature that would have resulted for no shortages in water.

Crop water stress index

The Crop Water Stress Index (CWSI; Jackson et al., 1981; Idso et al., 1981) has received the most attention of any water stress index. It is derived from the energy balance where, for a given set of meteorological conditions, a range of canopy - air temperature differences exist that are bound by a lower limit (no water stress) and an upper limit (complete water stress where no ET is occurring). The measured canopy - air temperature difference should fall within these lower and upper limits, and is normalized as an index where a value of zero indicates no water stress and a value of unity indicates complete water stress:

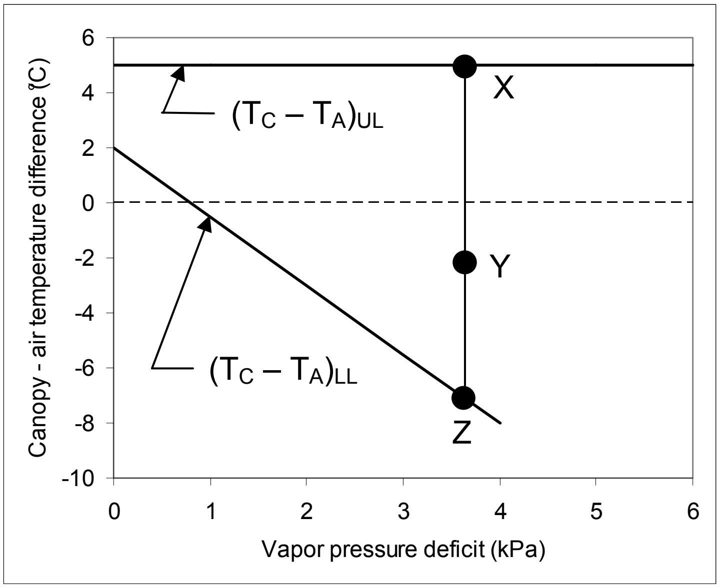
$$\mathrm{CWSI} = \frac{\left(T_C - T_A\right)_M - \left(T_C - T_A\right)_{LL}}{\left(T_C - T_A\right)_{UL} - \left(T_C - T_A\right)_{LL}} = \frac{YZ}{XZ} \tag{1}$$

where T_C and T_A are the canopy and air temperatures, respectively (°C), the subscripts M, LL, and UL denote measured, lower limit (no stress), and upper limit (complete stress), respectively, and YZ / XZ is the graphical calculation in Figure 1, where measured canopy temperature (T_C) is at point Y. The $(T_C – T_A)_{LL}$ and $(T_C – T_A)_{UL}$ can be calculated using equations based on the surface energy balance (Jackson et al., 1981), which require concurrent measurement of micrometeorological variables (solar irradiance, air temperature, relative humidity, and wind speed) and some information on the crop (height, width, row spacing, row orientation). It is also possible to measure $(T_C – T_A)_{LL}$ and $(T_C – T_A)_{UL}$ directly over well-watered and dry crop surfaces, respectively. Although direct measurement can reduce potential biases compared with calculations (calculation biases can be caused by faulty meteorological data, assumptions within the model, or both), maintaining well-watered and dry surfaces is not really practical in day-to-day farm operations. Several simplifying approaches have been used to calculate $(T_C – T_A)_{LL}$ and $(T_C – T_A)_{UL}$ with some success, such as substituting T_C in the lower limit with the wet bulb temperature, which is close to $T_{C,UL}$, and taking $T_{C,UL}$ as the maximum daily air temperature plus 5°C (O'Shaughnessy et al., 2011a).

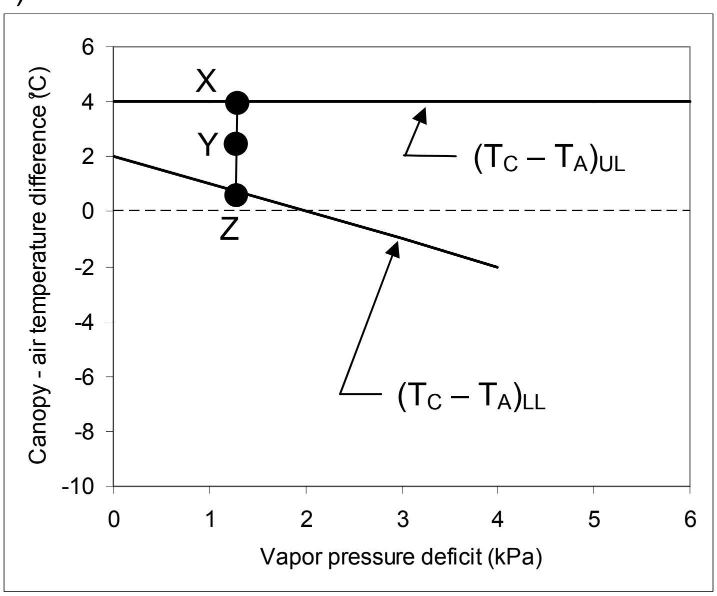
The $(T_C – T_A)_{LL}$ has been shown to have a strong inverse linear correlation with vapor pressure deficit (VPD) (Figure 1). Here, VPD is related to relative humidity, where increases in VPD correspond to decreases in relative humidity. As VPD increases (i.e., air becomes drier), T_C of well-watered plants decreases relative to T_A because drier air induces a greater evaporation rate of water. Since a completely stressed canopy has no water available, VPD has no influence on $(T_C – T_A)_{UL}$, resulting in the upper limit line being flat in Figure 1. Both $(T_C – T_A)_{LL}$ and $(T_C – T_A)_{UL}$ also depend on crop species, solar irradiance, and wind speed, any of which will impact the location of the lines and points in Figure 1. A non-water stressed canopy may be cooler or warmer than air depending on meteorological variables (mainly VPD); however, a completely water stressed canopy is generally warmer than the air during the daytime.

The accuracy of the CWSI is impaired when VPD is small. As VPD decreases, the range between the $(T_C – T_A)$ upper and lower temperature limits becomes smaller, and the distances between points X, Y, and Z in Figure 1 decrease. The result is that small errors in $(T_C – T_A)_M$, $(T_C – T_A)_{LL}$, and $(T_C – T_A)_{UL}$ will lead to increasingly larger errors in CWSI, increasing the probability of out-of-bounds CWSI values; i.e., less than zero and greater than one (Jones, 2004). Somewhat related is the influence of solar irradiance, where overcast skies also reduce the range of temperature limits. Both conditions are more prevalent in humid climates, but in arid and semiarid climates, low VPD is common in the morning (especially over irrigated fields) and, in the U.S. Great Plains, greater cloud cover occurs frequently in the afternoon during summer months. Consequently, the

CWSI is less responsive to plant and soil water conditions in humid locations, and has been found to be most responsive during clear skies and within a few hours of solar noon.



a)



b)

Figure 1. Crop Water Stress Index (CWSI), defined as CWSI = YZ / XZ, where lower and upper temperature limits are $(T_C – T_A)_{LL}$ and $(T_C – T_A)_{UL}$, respectively, for a) arid and b) humid conditions (Jackson, 1982).

Incomplete canopy cover, which exists during some (and perhaps all) of the irrigation season, can also a serious limitation of the CWSI and other canopy temperature based algorithms. The temperature of dry, sunlit soil can be 30 °C greater than green, transpiring vegetation (Kustas and Norman, 1999).

Therefore, T_C measurements can be greatly overestimated, resulting in overestimates of CWSI if soil appears in the radiometer view. The temperature of shaded soil is also usually different from vegetation, which may also introduce errors in CWSI calculations. The view of vegetation can be maximized and soil minimized by aiming a radiometer at an angle below the horizon and perpendicular to crop rows (e.g., Colaizzi et al., 2003a), and the radiometer can be designed to have a more narrow field of view (e.g., O'Shaughnessy et al., 2011b). However, the radiometer view still may not be completely free of soil, especially early in the season.

<u>Water deficit index</u>

The Water Deficit Index (WDI, Moran et al., 1994) is an extension of the CWSI that accounts for varying canopy cover and the influence of soil temperature, but is defined in a similar way. The WDI is represented graphically as a trapezoid, and WDI = YZ / XZ, analogous to the CWSI (Figure 2). The four corners represent (1) non water stressed canopy; (2) completely water stressed canopy; (3) wet bare soil; and (4) dry bare soil. Hence the top and bottom horizontal lines of the trapezoid represent full vegetation cover and bare soil, respectively. Similar to the CWSI, the surface – air difference ($T_S – T_A$) for each trapezoid corner can be calculated using surface energy balance equations, or can be measured directly if suitable surfaces are available. Note that ($T_C – T_A$) has been replaced with ($T_S – T_A$), which refers to a composite surface that may include both canopy and soil temperatures. The fraction of canopy cover that appears in the radiometer view (f_{CR}) can be estimated by empirically relating f_{CR} to a reflectance-based vegetation index. Concurrent to the temperature measurements, a vegetation index, such as the normalized difference vegetation index (NDVI), is calculated from measurements of reflectance, usually the red and near-infrared bands. The $(T_S – T_A)_{LL}$ and $(T_S – T_A)_{UL}$ (i.e., points Z and X in Figure 2, respectively) are then calculated by linear interpolation as

$$\left(T_S - T_A\right)_{LL} = f_{CR}\left(T_S - T_A\right)_1 + \left(1 - f_{CR}\right)\left(T_S - T_A\right)_3 \tag{2a}$$

$$\left(T_S - T_A\right)_{UL} = f_{CR}\left(T_S - T_A\right)_2 + \left(1 - f_{CR}\right)\left(T_S - T_A\right)_4 \tag{2b}$$

where all terms as as defined previously. WDI is calculated using equation (1) where ($T_C – T_A$) is replaced with ($T_S – T_A$) in each term. Colaizzi et al. (2003b) showed that the WDI was well-correlated to soil water depletion for a wide range of canopy cover and soil water profiles for cotton in Arizona. However, the WDI has not received as much attention as the CWSI, perhaps because it also requires reflectance measurements (or other suitable method) to estimate f_{CR}, and may also share the limitations of the CWSI under humid or overcast conditions.

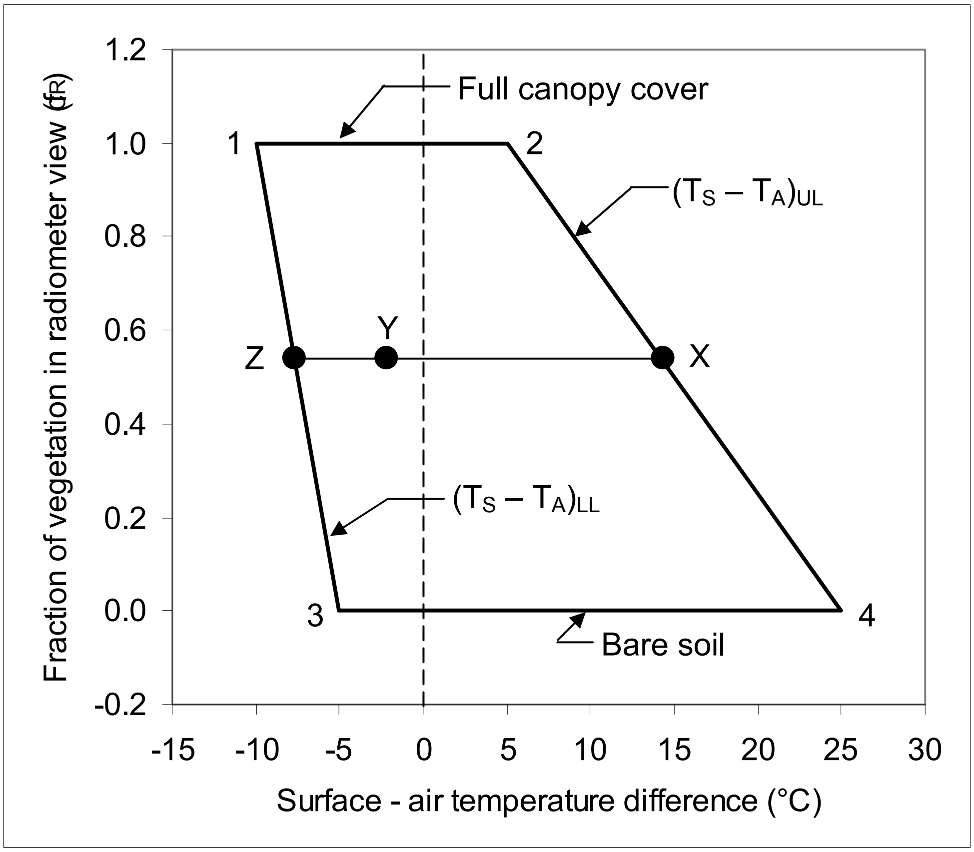


Figure 2. Water Deficit Index (WDI), defined as WDI = YZ / XZ. Point 1 is non water stressed full canopy, 2 is completely water stressed canopy, 3 is wet bare soil, and 4 is dry bare soil, and the lower and upper temperature limits are $(T_S – T_A)_{LL}$ and $(T_S – T_A)_{UL}$, respectively (Moran et al., 1994).

Time – Temperature Threshold

The time – temperature threshold (TTT) method was developed from the observation that plant enzymes are most productive under a relatively narrow range of temperatures, termed the thermal kinetic window (Burke, 1993; Burke and Oliver, 1993). Although the plant canopy temperature varies with meteorological conditions, and may not always be within its thermal kinetic window, the concept of a threshold canopy temperature has proven to be useful in irrigation management (Wanjura et al., 1992; 1993; 1995). A system using this approach, termed the Biologically – Identified Optimal Temperature Interactive Console (BIOTIC), was issued US Patent No. 5,539,637 (Upchurch et al., 1996).

In the TTT method, the accumulated time that the canopy temperature exceeds a threshold temperature is used as the criterion for an irrigation event (Figure 3). Here, the threshold temperature for corn was 28 °C, the threshold time is 240 min, and the canopy temperature was measured over corn. On day of year 234, the canopy temperature exceeded the threshold temperature for longer than 240 min. Therefore, an irrigation occurred that evening. The following day, the canopy temperature also exceeded the threshold temperature, but for a duration of less than 240 min. Therefore, no irrigation occurred on day of year 235. The TTT method is advantageous over the CWSI and the WDI for its simplicity, in that it does not require calculation or measurement of lower and upper temperature limits. Furthermore, it is a time-integrating approach and appears to be more responsive to a wider range of meteorological conditions, such as low VPD and overcast skies, compared with one-time-of day water stress indices (O'Shaughnessy and Evett, 2010a).

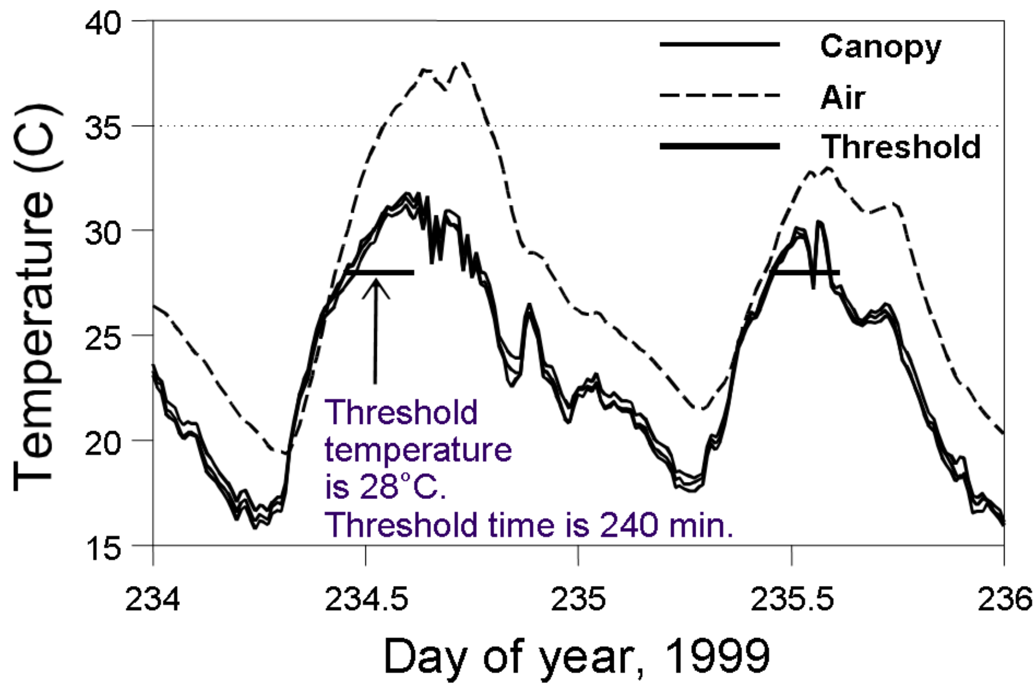


Figure 3. Canopy, air, and threshold temperature for corn at Bushland, TX. The canopy temperature exceeded the threshold temperature (28° C) for a duration greater than the threshold time (240 min) on day 234 but not on day 235. Therefore, irrigation was applied automatically on the evening of day 234 but not on day 235 (Evett et al., 2000; Peters and Evett, 2008).

The TTT method requires canopy temperature data throughout the daytime. In its initial development and application, continuous canopy temperature measurements were provided by stationary IRTs that viewed drip irrigated plots (Wanjura et al., 1995; Evett et al., 2000; Mahan et al., 2010). Thus at first it would appear that the TTT method would not be amenable to an array of moving IRTs, such as those aboard a moving center pivot. In this case, only a single canopy temperature measurement every few days would be possible at a remote location. However, Peters and Evett (2004) showed that the diurnal canopy temperature for remote locations can be calculated using a scaling procedure based on a one-time-of-day measurement ($T_{RMT,t}$) taken at a field (remote) location and a diurnal reference temperature (T_{REF}) taken at a stationary location:

$$T_{RMT} = T_E + \frac{(T_{RMT,t} - T_E)(T_{REF} - T_E)}{(T_{REF,t} - T_E)} \qquad (3)$$

where T_{RMT} is the calculated remote canopy temperature at any time of day, T_E is the predawn canopy temperature (assumed to be the same throughout the entire field), $T_{RMT,t}$ is the measured remote canopy temperature at the single time of day t (i.e., when the center pivot carries the IRT over the remote location), T_{REF} is the measured reference temperature at any time of day, and $T_{REF,t}$ is the reference temperature at the single time (t) of day. A stationary IRT at some location in the field provides the reference temperatures T_{REF} (throughout the day), $T_{REF,t}$ (at the time of day t when $T_{RMT,t}$ is measured), and T_E. During the day, T_{RMT} and T_{REF} will probably differ due spatial variability in the field, but follow a similar overall trend (Figure 4).

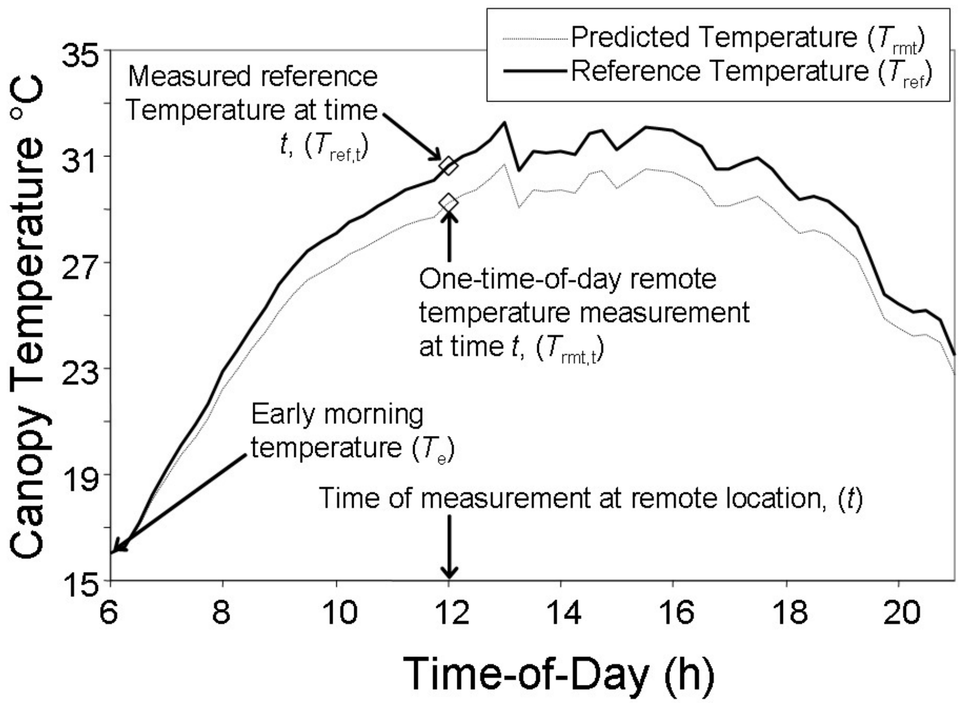


Figure 4. Scaling diurnal canopy temperature from one-time-of-day canopy temperature measurement (Peters and Evett, 2004).

The scaling method permits use of one-time-of-day canopy temperature measurements over a wide duration of the day. Peters and Evett (2004) reported that the mean absolute error between calculated (using equation 3) and measured T_{RMT} was less than 0.5 °C if $T_{RMT,t}$ was measured within the period approximately 2 h after sunrise and 2 h before sunset, but increased to over 6° C within 2 h of sunrise or sunset. For example, if the day length is 14 h, up to a 10 h window would be available to obtain remote measurements. As discussed later, the scaling method has expanded application of the TTT method to the automation of center pivots. The scaling method can also be applied to calculate water stress indices over a longer portion of the day. This was recently developed and shown to be effective in automatically scheduling center pivot irrigations for grain sorghum using a time-integrated water stress index (O'Shaughnessy et al., 2012).

ET-Based Soil Water Balance

Water stress indices such as the TTT method can improve irrigation management by providing guidance, including automation, on the *timing* of irrigations. With the TTT method, the amount of irrigation is preset, usually at some multiple of the crop's peak daily water use. The premise is that if the crop is water stressed, then the root zone soil will be depleted enough to accept that much water. Being a feedback system, the TTT algorithm will repeat such irrigations each day that a water stress is sensed. However, the exact *amount* of irrigation that the soil will accept depends partly on soil water depletion in the root zone (infiltration is also limiting). Soil water depletion is determined most directly by in-situ measurement of the soil water profile. Gravimetric/volumetric sampling and the neutron probe are the most accurate measurement methods, but these are cost and labor intensive, which imposes limitations in the number of locations and the repeat frequency of measurements. Furthermore, the neutron probe is a radioactive device that is subject to regulation, and cannot be operated unattended. Recently, wireless electromagnetic profile probes (capacitance type) have become available that can be operated remotely and continuously, but the depth of sampling is usually less than the depth of the fully developed root zone for most crops, and capacitance type electromagnetic devices can be impacted by soil temperature, soil salinity, and small-scale variations in soil water content and bulk electrical conductivity that affect the volume of soil being measured, among other factors. All of these have been shown to limit their accuracy, and the unit cost of a device may still preclude obtaining an adequate number of measurement locations in fields (Evett et al., 2012).

With measurement frequency being one fundamental constraint (at least until recently), soil water depletion has usually been calculated between measurement times using a soil water balance, where ET is the primary sink. ET is most readily calculated by the reference ET – crop coefficient method, which does not require canopy temperature and hence avoids many of the barriers that have previously been associated with remote sensing. The reference ET – crop coefficient method has been used for irrigation management for several decades, and can be effective even when minimal soil water profile measurements are available (Howell et al., 1998; Colaizzi et al., 2009). Nonetheless, real-time feedback on a spatial basis of plant and soil water status, including ET, is desirable in order to prioritize irrigation schedules, detect unexpected field conditions (e.g., biotic stress, malfunctioning or broken sprinkler heads, misapplication of fertilizer or chemicals, salinity, hail or wind damage) or conditions otherwise not readily captured by modeling alone (e.g., soil texture variability) (Peters and Evett, 2007; O'Shaughnessy et al., 2011a).

ET can also be calculated by using canopy temperature directly in an energy balance model. In this approach, canopy temperature measurements provide the real-time feedback aspect. Since water stress indices are also derived from energy balance considerations, they are related to ET in the following general form:

$$ET = ET_P(1 - WSI) \quad (4)$$

where WSI is a water stress index (e.g., CWSI or WDI), and ET_P is the potential ET where water is non-limiting (i.e., when WSI = 0). This shows that if the required ancillary information is available to calculate a WSI (i.e., incoming solar irradiance, air temperature, humidity, wind speed, canopy temperature, and crop phenology), then ET can also be calculated and applied to a soil water balance model (Colaizzi et al., 2003a). Recent refinements to a two-source energy balance model (where the energy balance of the soil and canopy sources are calculated separately) improved the accuracy of the calculated soil evaporation (E) and plant transpiration (T_P) components, as well as total ET, for row crops with partial cover (Colaizzi et al., 2012a; 2012b). From this development, the two-source energy balance model will be tested in scheduling irrigations for a center pivot equipped with wireless IRTs, as a continuation of the work described in O'Shaughnessy et al. (2012). In addition, separate calculation of E and T_P can be a powerful tool in assessing management strategies aimed at reducing E losses and increasing water use efficiency (Evett and Tolk, 2009).

REMOTE SENSING PLATFORMS

Measurement of canopy temperature or other remotely sensed variable requires some type of platform. Remote sensing platforms generally consist of three types, including ground-based, aircraft, or satellite. Ground-based platforms may be either stationary or moving; in the case of the latter, the remote sensors may be hand-held or otherwise portable, or aboard moving machinery such as a center pivot or spray rig. Spatial scales range from a few cm^2 using ground-based or aircraft platforms, to several km using satellite platforms. In general, moving platforms enable the greater spatial coverage using fewer sensors compared with stationary ones. However, there is usually a trade-off between coverage and measurement frequency, where moving platforms typically obtain measurements at a single time-of-day but at many locations in a field, whereas a stationary device can obtain measurements continuously but at only one field location. As noted previously and explained below, combining these can routinely provide continuous coverage over at least some part of a field.

In order for plant canopy temperature to be useful as an irrigation management tool, measurements must meet several criteria in terms of spatial scale, repeat frequency, and data processing time. Jackson (1984) reviewed measurement requirements for day-to-day farm management in the context of remote sensing platforms, and described these as having ~5 m or less spatial scale, a repeat frequency of no more than 7 days, with continuous (minute to hourly) monitoring ideal, and data processing time (i.e., the time from measurement to meaningful information product) of a few minutes. In addition, measurements should contain adequate coverage of the area to be managed, which is usually met by aircraft and satellite platforms, but may not be met by ground-based platforms.

Historically, each type of platform has in some way fallen short of these requirements. Some commercially-available satellites (e.g., QuickBird) now nearly meet these requirements, but measure only in the visible and near-infrared wavelengths. Most algorithms that have been shown to be useful for irrigation management require measurements in the longer thermal infrared wavelengths. A satellite platform equipped with a thermal sensor system that also meets all measurement criteria for real-time irrigation management is technically feasible, but such a platform is not expected to become commercially available in the foreseeable future. As an alternative, Norman et al. (2003) and Anderson et al. (2004) described a thermal sharpening procedure where frequent, coarse resolution thermal satellite data (i.e., daily and 1-km pixels) were combined with less frequent, fine resolution reflectance satellite data. However, Agam et al. (2007) found that this procedure had limited accuracy for wet soil with less than full canopy cover in the Texas High Plains. Some crop consulting services offer aircraft imagery with sufficient spatial resolution and coverage, but these also usually lack the thermal band, and flights more frequent than 7 days can be cost prohibitive. Both satellite and aircraft platforms also carry substantial image processing requirements (e.g., atmospheric and geometric correction), which increases their cost and usually prevents the timeliness requirement of a few minutes from being met (Moran, 1994).

Ground-based sensors (e.g., IRTs) largely circumvent the disadvantages of satellite and aircraft platforms, but measure a relatively small area of a few m^2 or less. Therefore, adequate field coverage would require a relatively large number of sensors. The appropriate number of sensors to be deployed depends on many factors that are beyond the scope of this paper, but a few examples include field slope and soil variability, the profit margin of the crop, and the sensor cost. The number of sensors could be reduced if a platform that passes over the field at sufficient intervals was available, such as a center pivot irrigation system, which is the dominant irrigation method in the US Great Plains (USDA, 2008; Colaizzi et al., 2009). Therefore, recent efforts have focused on designing ground-based remote sensing systems specifically for center pivots, including algorithms (Peters and Evett, 2004; Colaizzi et al., 2010); wireless sensor networks (O'Shaughnessy and Evett, 2010b), and low-cost wireless IRTs (O'Shaughnessy et al., 2011b). Nonetheless, subsurface drip irrigation continues to grow substantially in the Texas High Plains (Bordovsky et al., 2012), which can be managed using stationary IRT networks (Wanjura et al., 1995; Evett et al., 2000).

The Smartcrop© Automated Crop Stress Monitoring System (Smartfield, Inc., Lubbock, Texas) is a wireless IRT system that is now commercially available, and has been used as a stationary system to manage drip irrigation schedules (Mahan et al., 2010), but could also be used to manage gravity or sprinkler systems.

IRRIGATION AUTOMATION AT BUSHLAND, TX

Canopy temperature – based algorithms have been used successfully to automate irrigation scheduling and provide field maps of crop water status, where the latter can reduce irrigation management time even if automation is not employed. Several canopy temperature – based automation schemes have been investigated and compared with manual scheduling, where the latter entails measurement of the soil water profile with a field-calibrated neutron probe. To be viable, automatic scheduling should achieve similar or better crop yield and crop water productivity compared with manual scheduling. The following briefly reviews some automatic vs. manual results at the USDA Conservation and Production Research Laboratory, Bushland, Texas.

The TTT method has been used to automate both drip and center pivot systems for various crops, including corn, cotton, and soybean. Evett et al. (2000) used wired, stationary IRTs that measured canopy temperatures in a drip irrigated, four year corn and soybean rotation. For each crop, four TTT combinations were used, and these were compared to manually – irrigated plots where three irrigation rates (33%, 67% and 100% of meeting full crop ET) were used. Corn threshold temperatures were 28 °C and 30 °C, and threshold times were 240 and 160 min. Soybean threshold temperatures were 27 °C and 29 °C, and threshold times were 256 and 171 min. The automatic irrigation decision interval was 1 d, and each automatic irrigation event was 10 mm (i.e., equivalent to expected peak daily crop ET). Manual treatments were irrigated at weekly intervals. The automatic treatments generally resulted in similar or greater yield, similar seasonal irrigation amounts applied, and similar seasonal ET compared with the 100% manual irrigation treatment.

Peters and Evett (2008) used the TTT method to schedule irrigations for two seasons (2004 and 2005) of soybeans irrigated with a center pivot equipped with low energy precision applicator (LEPA) drag socks. The IRTs used to schedule irrigations were wired and aboard the center pivot, and viewed the canopy ahead of the direction of travel to avoid viewing the area being irrigated. Diurnal canopy temperature data required for the TTT method were calculated with the scaling method (equation 3; Peters and Evett, 2004), where IRTs aboard the center pivot provided one-time-of-day measurements ($T_{RMT,t}$ in equation 3), and stationary IRTs provided the other required variables (T_{REF}, $T_{REF,t}$, and T_E in equation 3). The threshold temperatures were 30 °C and 27 °C in 2004 and 2005, respectively, and the threshold time was 256 min in both years. Automatic and manual treatments included 33%, 67%, and 100% of the full irrigation rate. The automatic and manual irrigation decision intervals were 2 d, and each 100% automatic irrigation event was 20 mm, and deficit irrigation events were 33% and 67% of 20 mm. In 2004, yield, irrigations applied, seasonal ET, and water use efficiency (WUE = Yield/ET) were mostly greater for the manual compared with the automatic treatments, because a defect in the IRTs resulted in too large of a threshold temperature (30 °C instead of the desired 27 °C), resulting in the automatic plots being under-irrigated. In 2005, the desired 27 °C threshold temperature was achieved, and yield, seasonal ET, and WUE were greater (sometimes significantly so) in the automatic compared with the manual treatments.

In that same experiment, Peters and Evett (2007) showed that soybean yield, above ground biomass, and seasonal ET were well-correlated to canopy temperatures. They also used a novel approach where the statistical process control method was applied to canopy temperatures to detect significant spatial and temporal variability (Figure 5). Statistical process control is commonly used in manufacturing to detect product defects. The variability shown was caused by an intentional over-application of herbicide and was not apparent by visual observation.

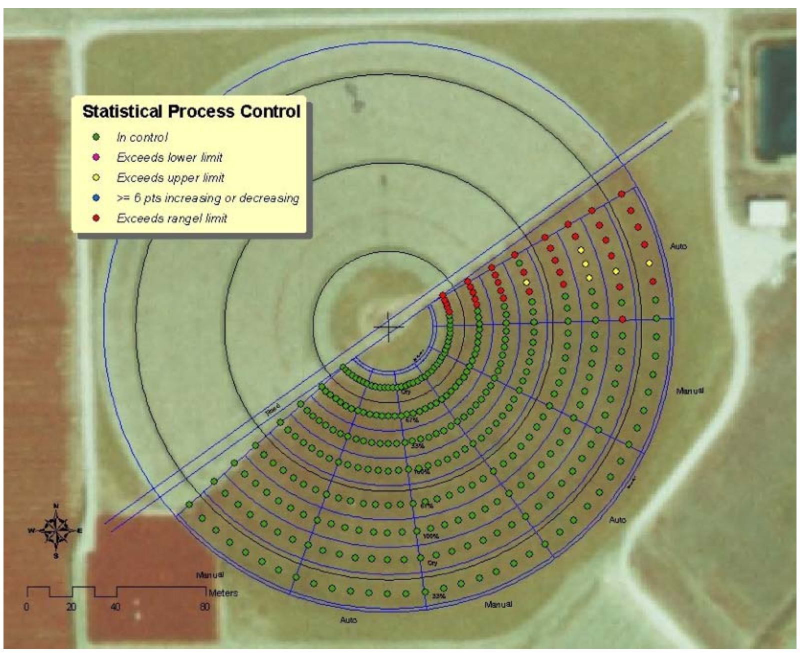


Figure 5. Canopy temperature measurement locations in soybean irrigated by center pivot, day of year 258, 2005, Bushland, TX. Canopy temperature measurements were evaluated by statistical process control to detect unusual spatial and temporal variability. Green indicates “in control” locations, and yellow and red locations indicate “out of control” locations where the field was sprayed by herbicide in order to test the sensitivity of the statistical process control algorithm. The algorithm detected the damage even though it was not apparent by visual observation (Peters and Evett, 2007).

O'Shaughnessy and Evett (2010a) used the TTT method to automatically schedule center pivot irrigations (equipped with LEPA drag socks) for the 2007 and 2008 cotton seasons. The experiment was similar to that of Peters and Evett (2008), where automatic and manual irrigation treatments were 33%, 67%, and 100% of full irrigation. IRTs were wired in 2007 and wireless in 2008. For cotton, the temperature and time thresholds were 28 °C and 452 min, the irrigation frequency was not more than 2 d, but the irrigation decision interval was 1 d, where canopy temperature measurements from the previous 1 d (not 2 d) determined whether an irrigation event was to occur. Each 100% automatic irrigation event was 20 mm, and the deficit irrigation events were 33% and 67% of 20 mm. In both years, total irrigation applied and seasonal ET were less for automatic compared with manual scheduling within an irrigation rate treatment. In 2007, lint yield and WUE were generally not significantly different for automatic vs. manual treatments among irrigation rates, but in 2008, lint yield and WUE were greater (often significantly so) for the automatic compared with the manual control methods among all irrigation rate treatments.

Data from the O'Shaughnessy and Evett (2010a) experiment and the soybean data from Evett and Peters (2007; 2008) were used in calculating a slightly different version of the CWSI (O'Shaughnessy et al., 2011a). They set the upper temperature limit ($T_{C,UL}$) as the maximum daily air temperature plus 5 °C, and used for the lower temperature limit ($T_{C,LL}$) the wet bulb temperature calculated at $T_{C,UL}$. They used canopy temperatures (T_C) found by the scaling method for a 2-hour window near solar noon. They found that the CWSI calculated in this way and averaged over the season had generally good correlation with midday leaf water potential, seasonal ET, and grain and lint yields. A few exceptions where correlation was poor were related to unfavorable growing conditions in 2008. This demonstrates the application of multiple canopy temperature algorithms, where the TTT was used to automate irrigations, and the CWSI was used to estimate midday leaf water potential, and final yield and ET. It should be noted that although leaf water potential was measured around midday, this was not necessarily the case for canopy temperature, as the temperature scaling method permitted measurements over a much wider span of the day to be used to estimate T_C near solar noon. Their study also demonstrated the utility of a CWSI map, where differences in irrigation rates were clearly visible as the season progressed, and could be used to prioritize manual irrigation scheduling (Figure 6).

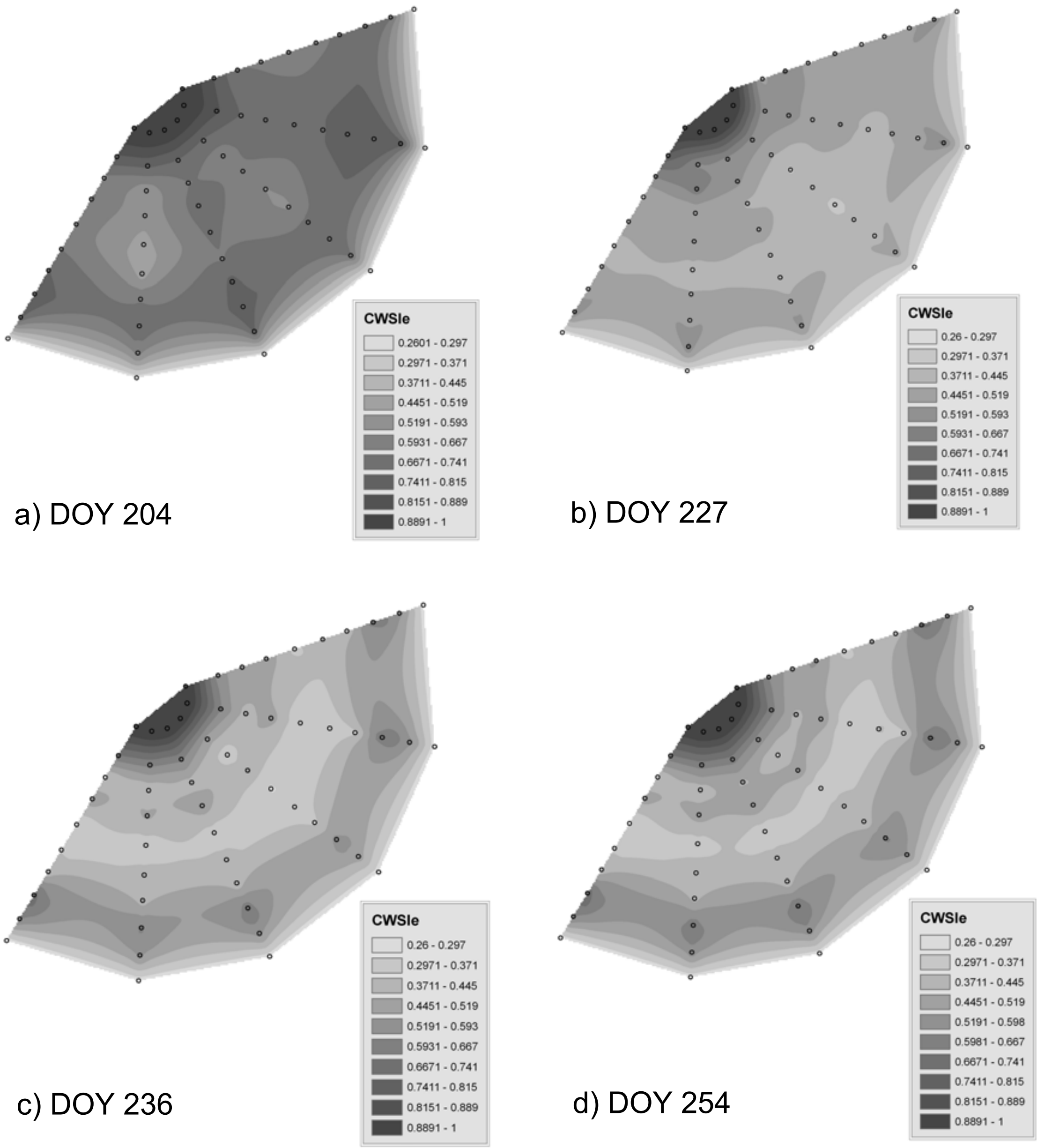


Figure 6. Maps of CWSI for cotton at Bushland, TX, average CWSI from DOY 198 to (a) DOY 204; (b) DOY 227; (c) DOY 236; (d) DOY 254 (O'Shaughnessy and Evett, 2011a). Darker shading means less water stress.

Algorithms based on time integration, such as the TTT method, attempt to account for conditions over most of the day. This likely has certain advantages over algorithms that relate only to instantaneous conditions, such as the conventional CWSI. Time integration can average short-term fluctuations in meteorological conditions, which would reduce the algorithm's sensitivity to the time of day that measurements are obtained. O'Shaughnessy et al. (2012) hypothesized that a time-threshold form of the CWSI (termed CWSI-TT) could automate irrigation scheduling and exploit the time-integrating and energy balance strengths of the TTT and CWSI methods, respectively. They tested this approach over two seasons (2009 and 2010) for grain sorghum that was irrigated by a center pivot equipped with LEPA drag socks and wireless IRTs. As with previous experiments, automatic and manual treatments were compared, but irrigation rates were 30%, 55%, and 80% of full crop ET. The CWSI was calculated at 5-minute intervals during the daytime, and the lower and upper temperature limits were calculated following Jackson et al. (1981). The threshold CWSI value was taken as 0.45, and the threshold time was 420 min. For each 5-min interval, if CWSI > 0.45, then 5-min was added to the accumulated time. If accumulated time exceeded 420 min by midnight over the previous 24 h, then irrigation was initiated the following morning. The threshold time was determined by analyzing well-watered sorghum canopy temperature data acquired in previous years on the large weighing lysimeters at Bushland. In both years, grain yield and WUE were not significantly different between automatic and manually scheduled plots for most irrigation rates. Two exceptions were in 2009 in the 30% and 55% irrigation rates, where grain yields were significantly less in the automatic compared with the manual treatment. This was related to greater variability in soil water at the beginning of the season, which somewhat favored the manually irrigated treatment plots. Total irrigation amounts applied to the automatic compared with the manual treatments were less in 2009 but nearly the same in 2010.

The ARS irrigation research team at Bushland is currently involved in a Cooperative Research and Development Agreement with a center pivot irrigation system manufacturer to transfer the technology in the successful ARS irrigation automation system to commercial production.

SUMMARY AND CONCLUSIONS

This paper reviewed the use of remotely sensed plant canopy temperature for irrigation management. This included an overview of canopy temperature – based algorithms, remote sensing platforms, some recent results in irrigation automation research at the USDA Agricultural Research Service Conservation and Production Laboratory at Bushland, Texas.

Canopy temperature algorithms were categorized as water stress indices, the time temperature threshold method, and the ET – based soil water balance. Each type of algorithm can provide guidance on the timing of irrigation, and ET – based approaches also indicate the varying needed irrigation application amounts as demand varies over time.

In order to be useful for day-to-day, site-specific irrigation management, canopy temperature data generally must have a spatial resolution of a few meters, a repeat frequency of no more than 7 d, and a turnaround time (i.e., the time from measurement to useful information product) of a few minutes. In addition, field coverage must be adequate in terms of the number and spatial distribution of samples. Historically, neither, ground-based, aircraft, or satellite platforms have been able to meet these requirements. However, recent advances in wireless technology, computing capacity, canopy temperature data processing algorithms, and reductions in infrared thermometer (IRT) and related component costs, appear to have made feasible a ground-based system where a center pivot is used as the platform to transport IRTs over the field.

A center pivot platform equipped with IRTs was used by the USDA at Bushland, TX, to automate irrigation schedules, and automatic treatments were compared with manual treatments where a field-calibrated neutron probe was used to schedule irrigations. The time temperature threshold method was evaluated for soybean and cotton, and a crop water stress index threshold time method was evaluated for grain sorghum. Previous research also evaluated the time temperature threshold method using stationary IRTs on drip irrigated corn and soybean. In most cases, the automatic treatments compared favorably with manual treatments in terms of crop yield, seasonal water use, water use efficiency, and irrigation amounts applied. This indicates that canopy temperature-based algorithms are a viable tool in automating irrigation scheduling, which can reduce management time required but achieve the same crop water productivity that is possible with manual scheduling.

Even if automation is not chosen, canopy temperature-based algorithms were shown to be strongly correlated to crop yield, water use efficiency, seasonal ET, midday leaf water potential, irrigation rates, and herbicide damage not visible by eye. This can provide timely information not previously available that can also reduce management time, prioritize irrigation schedules, and improve crop water productivity. Additional research will investigate how well ET-based algorithms can prescribe appropriate irrigation application amounts, where ET is calculated using a canopy temperature driven energy balance model.

ACKNOWLEDGEMENTS

Partial funding for this project was from the Ogallala Aquifer Program, a consortium between USDA Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

REFERENCES

Agam, N., W. P. Kustas, M. C. Anderson, F. Li, and P. D. Colaizzi. 2007. Utility of thermal image sharpening for monitoring field-scale evapotranspiration over rainfed and irrigated agricultural regions. *Geophys. Res. Lett.* 35: L02402. DOI:10.1029/2007GL032195.

Anderson, M. C., J. M. Norman, J. R. Mecikalski, R. D. Torn, W. P. Kustas, and J. B. Basara. 2004. A multi-scale remote sensing model for disaggregating regional fluxes to micrometeorological scales. *J. Hydrometeorol*. 5: 343–363.

Bartholic, J. F., L. N. Namken, and C. L. Weigand. 1972. Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water stress. *Agron. J.* 64: 603-608.

Bordovsky, J. P., A. M. Cranmer, P. D. Colaizzi, F. R. Lamm, S. R. Evett, and T. A. Howell. 2012. Investigating strategies to improve crop germination when using SDI. In: *Proc. 24th Annual Central Plains Irrigation Conf.*, February 21-22, 2012, Colby, KS.

Burke, J. J. 1993. Thermal kinetic windows of plant enzymes. In: *Biotechnology for Arid Plants.*, 73-82.

Burke, J. J., and M. J. Oliver. 1993. Optimal thermal environments for plant metabolic processes (Cucumis sativus L.): Light-harvesting chlorophyll a/b pigment-protein complex of photosystem II and seedling establishment in cucumber. *Plant Phys.* 102: 295-302.

Colaizzi, P. D., E. M Barnes, T. R Clarke, C. Y Choi, and P. M. Waller, 2003a. Estimating soil moisture under low–frequency surface irrigation using crop water stress index. *J. Irrig. Drain. Engr.* 129: 27-35.

Colaizzi, P. D., E. M. Barnes, T. R.Clarke, C. Y Choi, P. M. Waller, J. Haberland, and M. Kostrzewski. 2003b. Water stress detection under high frequency sprinkler irrigation with water deficit index. *J. Irrig. Drain. Engr.* 129: 36-43.

Colaizzi, P. D., P. H. Gowda, T. H. Marek, and D. O. Porter, 2009. Irrigation in the Texas High Plains: A brief history and potential reductions in demand. *Irrig. and Drain*. 58: 257-274. DOI: 10.1002/ird.418.

Colaizzi, P. D., S. A. O'Shaughnessy, P. H. Gowda, S. R. Evett, T. A. Howell, W. P. Kustas, and M. C. Anderson. 2010. Radiometer footprint model to estimate sunlit and shaded components for row crops. *Agron. J.* 102: 942-955. DOI: 10.2134/agronj2009.0393.

Colaizzi, P. D., S. R. Evett, T. A. Howell, P. H. Gowda, S. A. O'Shaughnessy, J. A. Tolk, W. P. Kustas, M. C. Anderson. 2012a. Two source energy balance model-refinements and lysimeter tests in the Southern High Plains. *Trans ASABE*, in review.

Colaizzi, P. D., W. P. Kustas, M. C. Anderson, N. Agam, J. A. Tolk, S. R. Evett, T. A. Howell, P. H. Gowda, S. A. O'Shaughnessy. 2012b. Two-source energy balance model estimates of evapotranspiration using component and composite surface temperatures. *Adv. Water Res*., in review.

Evett, S. R. and J. A. Tolk. 2009. Introduction: Can water use efficiency be modeled well enough to impact crop management? *Agron. J.* 101: 423–425.

Evett, S. R., T. A. Howell, A. D. Schneider, D. R. Upchurch, and D. F. Wanjura. 2000. Automatic drip irrigation of corn and soybean. In: *Proc. 4th Dec. Nat. Irrig. Symp.* (R. G. Evans, B. L. Benham, and T. P. Trooien, eds.), Nov. 14-16, 2000, Phoenix, AZ., 401-408.

Evett, S. R., R. C. Schwartz, J. J. Casanova, and L. K. Heng. 2012. Soil water sensing for water balance, ET and WUE. *Agric. Water Manage.* 104: 1-9.

Gowda, P. H, J. L. Chavez, P. D. Colaizzi, S. R. Evett, T. A. Howell, and J. A. Tolk. 2008. ET mapping for agricultural water management: Present status and challenges. *Irrig. Sci.* 26: 223-237. DOI:10.1007/s00271-007-0088-6.

Howell, T. A., T. H. Marek, L. New, and D. Dusek. 1998. Weather network defends Texas water tables. *Irrig. Bus. & Tech*. I: 16-20.

Idso, S. B., R. D. Jackson, P. J. Pinter, Jr., R. J. Reginato, and J. L. Hatfield. 1981. Normalizing the stress-degree parameter for environmental variability. *Agric. Meterol.*, 24: 45–55.

Jackson, R. D. 1982. Canopy temperature and crop water stress. In: *Advances in Irrigation* (D. Hillel, ed)., Academic Press, New York, NY. 1: 43-85.

Jackson, R. D. 1984. Remote sensing of vegetation characteristics for farm management. *SPIE.* 475: 81–96.

Jackson, R. D., S. B. Idso, R. J. Reginato, and P. J. Pinter, Jr. 1981. Canopy temperatures as a crop water stress indicator. *Water Resour. Res*. 17: 1133–1138.

Jones, H. G. 2004. Irrigation scheduling: Advantages and pitfalls of plant-based methods. *J. Exp. Bot*. 55: 2427-2436. DOI:10.1093/jxb/erh213.

Kustas, W. P., and J. M. Norman. 1999. Evaluation of soil and vegetation heat flux predictions using a simple two source model with radiometric temperatures for partial canopy cover. *Agric. For. Meteorol*. 94: 13-29.

Mahan, J. R., W. Conaty, J. Neilsen, P. Payton, and S. B. Cox. 2010. Field performance in agricultural settings of a wireless temperature monitoring system based on a low-cost infrared sensor. *Comp. Elec. Agric*. 71: 176-181.

Monteith, J. L., and G. Szeicz. 1962. Radiative temperature in the heat balance of natural surfaces. *Q. J. R. Meteorol*. Soc. 88: 496-507.

Moran, M. S. 1994. Irrigation management in Arizona using satellites and airplanes. *Irrig. Sci*. 15: 35–44.

Moran, M. S., T. R. Clarke, Y. Inoue, and A. Vidal. 1994. Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. *Remote Sens. Environ*. 49: 246–263.

Moran, M. S., Y. Inoue, and E. M. Barnes. 1997. Opportunities and limitations for image-based remote sensing in precision crop management. *Remote Sens. Environ.* 61: 319–346.

Norman, J. M., M. C. Anderson, W. P. Kustas, A. N. French, J. Mecikalski, R. Torn, G. R. Diak, T. J. Schmugge, and B. C. W. Tanner. 2003. Remote sensing of surface energy fluxes at 101-m pixel resolutions. *Water Resour. Res*. 39: 1221, DOI:10.1029/2002WR001775.

O'Shaughnessy, S. A., and S. R. Evett. 2010a. Canopy temperature based system effectively schedules and controls center pivot irrigation of cotton. *Agric. Water Manage*. 97:1310-1316.

O'Shaughnessy, S.A., and S.R. Evett. 2010b. Developing wireless sensor networks for monitoring crop canopy temperature using a moving sprinkler system as a platform. App. Eng. Agric. 26(2):331-341.

O'Shaughnessy, S. A., S. R. Evett, P. D. Colaizzi, and T. A. Howell. 2011a. Using radiation thermography and thermometry to evaluate crop water stress in soybean and cotton. *Agric. Water Manage*. 98:1523-1535.

O'Shaughnessy, S. A., M. A. Hebel, S. R. Evett, and P. D. Colaizzi, 2011b. Evaluation of a wireless infrared thermometer with a narrow field of view. *Comp. Elec. Agric*. 76: 59-68.

O'Shaughnessy, S. A., S. R. Evett, P. D. Colaizzi, and T. A. Howell. 2012. A crop water stress index and time threshold for automatic irrigation scheduling of grain sorghum. *Agric. Water. Manage*., accepted.

Peters, R. T., and S. R. Evett. 2004. Modeling diurnal canopy temperature dynamics using one-time-of-day measurements and a reference temperature curve. *Agron. J*. 96: 1553-1561.

Peters, R. T. and S. R. 2007. Evett Spatial and temporal analysis of crop stress using multiple canopy temperature maps created with an array of center-pivot-mounted infrared thermometers. *Trans. ASABE*. 50: 919-927.

Peters, R. T., and S. R. Evett. 2008. Automation of a center pivot using the temperature-time-threshold method of irrigation scheduling. *J. Irrig. Drain. Engr*. 134: 286-291.

Phene, C. J., T. A. Howell, and M. D. Sikorski. 1985. A traveling trickle irrigation system. In: *Advances in Irrigation* (D. Hillel, ed.), Academic Press, Orlando, FL. 3: 1-49.

Tanner, C. B. 1963. Plant temperatures. *Agron. J.* 55: 201-211.

Upchurch, D. R., D. F. Wanjura, J. J. Burke, and J. R. Mahan. 1996. Biologically- Identified optimal temperature interactive console (BIOTIC) for managing irrigation. United States Patent 5,539,637, July 23, 1996.

USDA-NASS. 2008. Farm and Ranch Irrigation Survey, Vol. 3, Special Studies, Part 1. National Agricultural Statistics Service. Washington, D. C. Available at: http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.asp. Accessed 2 Feb 2012.

Wanjura, D. F., D. R. Upchurch, and J. R. Mahan. 1992. Automated irrigation based on threshold canopy temperature. *Trans. ASAE*. 35: 153-159.

Wanjura, D. F., D. R. Upchurch, and J. R. Mahan. 1993. Canopy temperature controlled irrigation scheduling. *Acta Horticulturae* 335: 477-490.

Wanjura, D. F., D. R. Upchurch, and J. R. Mahan. 1995. Control of irrigation scheduling using temperature-time thresholds. *Trans. ASAE*. 38: 403-409.

Wiegand, C. L., M. D. Heilman, and A. H. Gerbermann. 1968. Detailed plant and soil thermal regime in agronomy. *Proc. 5th Int. Symp. Remote Sens. Environ.*, 325-342.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, KS, February 21-22, 2012
Available from CPIA, 760 N. Thompson, Colby, Kansas

CROP SELECTIONS AND WATER ALLOCATIONS FOR LIMITED IRRIGATION

Norman L. Klocke,
Water Resources Engineer
Kansas State University
Garden City, Kansas
Voice: 620-276-8286
Fax: 620-276-6028
nklocke@ksu.edu

Troy J. Dumler
Extension Agricultural Economist,
Kansas State University
Garden City, Kansas
Voice:620-276-8286
Fax: 620-276-6028
tdumler@ksu.edu

Loyd R. Stone
Soil Physicist
Kansas State University
Manhattan, Kansas
Voice: 785-532-5732
Fax: 785-532-6094
stoner@ksu.edu

Steven Briggeman
Software Developer,
Sprout Software
Manhattan, Kansas

INTRODUCTION

Irrigators are facing challenges with declining well yields or reduced allocations from water districts. To make reductions in water use, irrigators are considering shifts in cropping patterns that earn better net economic returns. A decision planning tool, the Crop Water Allocator (CWA), available at **www.mobileirrigationlab.com**, has been developed to find optimum net returns from combinations of crops, irrigation amounts, and land allocations (crop rotations) that program users choose to examine. The model uses yield-irrigation relationships for 11-21 in. of rainfall in western Kansas as a basis to estimate yields for particular rainfall zones. The user can customize the program with crop localized crop production costs or rely on default values from typical western Kansas farming operations. Irrigators are able to plan for the optimum economic use of their limited water supply by testing options with CWA.

Irrigators choose crops on the basis of production capabilities, economic returns, and crop adaptability to the area, government programs, crop water use, and their preferences. When full crop evapotranspiration demand cannot be met, yield-irrigation relationships and production costs become even more important inputs for management decisions. Under full irrigation, crop selection often is driven by the prevailing economics and production patterns of the region. Crops that respond well to water, return profitably in the marketplace and/or receive favorable government subsidies are usually selected. These crops still can perform in limited irrigation systems, but management decisions arise as water is limited: should fully watered cops continue to be used; should other crops be considered; what proportions of land should be devoted to each crop; and finally, how much water should be apportioned to each crop? The outcome of these questions is finding optimal economic return for the available inputs.

Determining the relative importance of the factors that influence the outcome of limited-irrigation management decisions can become complex. Commodity prices and government programs can fluctuate and change advantages for one crop relative to another. Water availability, determined by governmental policy or by irrigation system capacity, may also change with time. Precipitation probabilities influence the level of risk the producer is willing to assume. Production costs give competitive advantage or disadvantage to the crops under consideration.

The objective of this project has been to create a decision tool with user interaction to examine crop mixes and limited water allocations within land allocation constraints to find optimum net economic returns from these combinations. This decision aid is for intended producers with limited water supplies to allocate their seasonal water resource among a mix of crops. But, it may be used by others interested in crop rotations and water allocation choices.

BACKGROUND

CWA (Klocke et al., 2006) calculates net economic return for all combinations of crops selected for a rotation and water allocated to each crop. Subsequent model executions of land-split (crop rotation) scenarios can lead to more comparisons. Individual fields or groups of fields can be divided into in the following ways: 100%; 50%-50%; 25%-75%; 33%-33%-33%; 25%-25%-%50; 25%-25%-25%-25%. The number of crops eligible for consideration in the crop rotation could be more than the number of land splits under consideration. Optimum outcomes may recommend fewer crops than selected land splits. Fallowing part of the field is a valid option. Irrigation system parameters, production costs, commodity prices, yield maximums, annual rainfall, and water supplied to the field were held constant for each model execution, but can be changed by the user in subsequent executions.

The model examines each possible combination of crops selected for every possible combination of water allocation by 10% increments of the water supply. The model has an option for larger water iteration increments to save computing time. For all iterations, net return to land, management, and irrigation equipment is calculated:

Net return = (commodity price X yield) – (irrigation cost + production cost)

where:

commodity prices were determined from user inputs; crop yields were calculated from yield-irrigation relationships derived from a simulation model based on field research; irrigation costs were calculated from lift, water flow, water pressure, fuel cost, pumping hours, repair, maintenance, and labor for irrigation; and production costs were calculated from user inputs or default values derived from Kansas State University projected crop budgets (**www.agmanager.info/crops/**). All of the resulting calculations of net return are sorted from maximum to minimum and several of the top scenarios are summarized and presented to the user.

Field research results have been used to find relationships between crop yields and amounts of irrigation (figure 1). Yields from given irrigation amounts multiplied by commodity prices are used to calculate gross income. Grain yields for corn, grain sorghum, sunflower, and winter wheat were estimated by using the “Kansas Water Budget” software. Software development and use are described in Stone et al. (1995). Yield for each crop was estimated from irrigation amount for annual rainfall and silt loam soils.

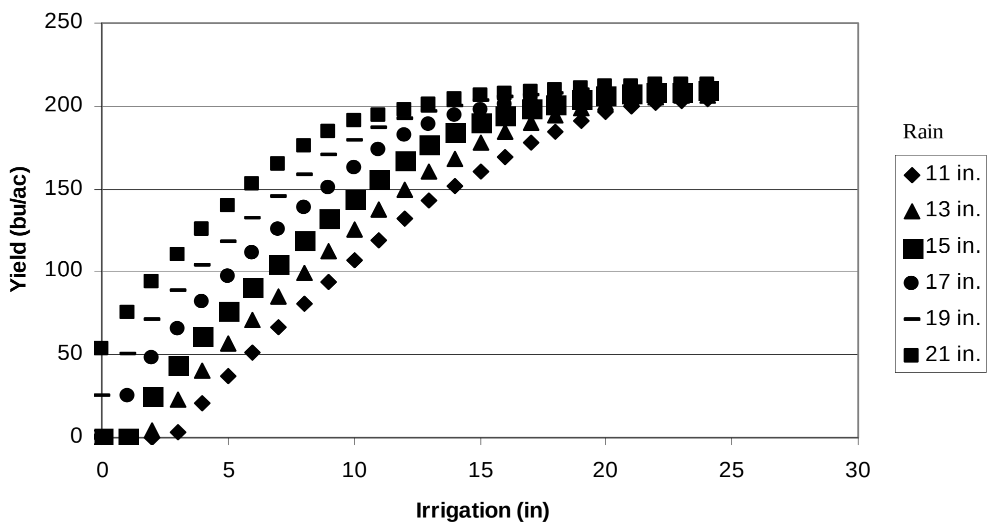


Figure 1. Yield-irrigation relationship for corn with annual rainfall from 11-21 in.

The resulting yield-irrigation relationship for corn (fig. 1) shows a convergence to a maximum yield of 220 bu/ac from the various combinations of rainfall and irrigation. A diminishing-return relationship of yield with irrigation applied was typical for all crops. Each broken line represents normal annual rainfall for an area.

The crop production budgets are the foundation for default production costs used in CWA. Program users can input their own costs or bring up default costs to make comparisons. For western Kansas, cost-return budgets for center-pivot irrigation of crops (**www.agmanager.info/crops/**) provided the basis for default production-cost values for CWA. Results can be sensitive to production costs, which require realistic production inputs.

CROP SELECTION WITH RESTRICTED IRRIGTION

In 2012 irrigators need to tailor their water management to have the expectation of producing at least their irrigated proven yield to qualify for crop insurance as an irrigated practice. If they do not have enough water to produce their proven yield on the whole field, they may need to reduce irrigated acreage to fully irrigate the planted area. They need to know how much water it will take to produce their proven yield.

Predicted corn and sorghum yields for 2012 (tables 1-4) were based on a crop simulation model developed by Kansas State University (Crop Yield Predictor available at www.mobileirrigationlab.com. The stored soil water available for plant use at the beginning of the growing season is one of the sources of water to produce the crop. The other sources are growing season precipitation and irrigation.

Each row in the yield table is for the available soil water on October 1, 2011 and April 1, 2012. The change in soil water from October 1 through April 1 is based on the average annual precipitation expected during the dormant season. Water accumulates if there is room enough to store it, depending on how much evaporation occurs at the soil surface, and how much water drains below the expected root zone. KSU researches (Lamm and Rogers) measured available soil water (ASW) after the 2011 harvest in producer irrigated fields in southwest Kansas. They found a minimum of 17% ASW and a maximum of 95% ASW among the sampled fields. This demonstrates that producers need to determine ASW in their own fields. Within each row in the table, there are columns for the amount of irrigation it will take to produce the predicted yield. An irrigator can find his/her proven yield on the table for each value of ASW (rows) and applied irrigation (columns). The volume of irrigation, available for that field in 2012, needs to be determined in units of acre-inches, This volume divided by the inches of irrigation required to produce the proven yield (from the table) is the acreage that can be planted (see example.

These tables are provided by Kansas State University for producers as information for determining possible strategies for 2012. They were not derived by the Risk Management Agency. Crop insurance underwriters should be contacted for additional information.

Table 1. Predicted corn yields for annual precipitation of 17 inches.

Available Soil Water 1-Oct	Available Soil Water 1-Apr	Applied Irrigation							
		5"	8"	11"	14"	17"	20"	23"	26"
		Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield
%	%	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac
10	20	92	124	149	**168**	184	198	210	220
30	35	120	148	169	186	200	213	220	220
50	50	148	171	189	203	215	220	220	220
70	60	164	184	200	213	220	220	220	220

Example:
Corn from table1; annual precipitation = 17 inches; available water on April 1= 20%;
proven yield = 168 bu/ac; irrigation needed = 14 inches;
irrigation volume available = 1200 ac-inches (12 inches for 100 acres);
Irrigated acres to produce proven yield = (1200 ac-inches)/14 inches) = 88 acres

Table 2. Predicted corn yields for annual precipitation of 21 inches.

Available Soil Water 1-Oct	Available Soil Water 1-Apr	Applied Irrigation							
		5"	8"	11"	14"	17"	20"	23"	26"
		Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield
%	%	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac
10	25	135	165	183	193	205	217	220	220
30	45	156	182	197	206	216	220	220	220
50	60	172	194	207	214	220	220	220	220
70	70	178	197	210	217	220	220	220	220

Table 3. Predicted sorghum yields for annual precipitation of 17 inches.

Available Soil Water 1-Oct	Available Soil Water 1-Apr	Applied Irrigation							
		5"	8"	11"	14"	17"	20"	23"	26"
		Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield
%	%	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac
10	20	108	125	139	149	158	160	160	160
30	35	123	137	149	158	160	160	160	160
50	50	136	148	158	160	160	160	160	160
70	60	144	154	160	160	160	160	160	160

Table 4. Predicted sorghum yields for annual precipitation of 21 inches.

Available Soil Water	Available Soil Water	-------------------------Applied Irrigation---------------------------------							
		5"	8"	11"	14"	17"	20"	23"	26"
1-Oct	1-Apr	Yield	Yield	Yield	Yield	Yield	Yield	Yield	Yield
%	%	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac	bu/ac
10	25	123	139	147	155	160	160	160	160
30	45	139	148	155	160	160	160	160	160
50	60	146	154	160	160	160	160	160	160
70	70	148	156	160	160	160	160	160	160

ACKNOWLEDGEMENTS

This work was partly supported by the US Department of Interior, Kansas Water Resources Institute, and the USDA-ARS Ogallala Aquifer Program.

REFERENCES

Kansas State University. 2011. Crop Water Allocator (CWA): KSU Mobile Irrigation Lab. Available at: www.mobileirrigationlab.com.

Klocke, N.L., L. R. Stone, G. A. Clark, T. J. Dumler, S. Briggeman. 2006. Water allocation model for limited irrigation. Appl. Engr. In Agric. 22:3:381-389.

Stone, L.R., O.H. Buller, A.J. Schlegel, M.C. Knapp, J.-I. Perng, A.H. Khan, H.L. Manges, and D.H. Rogers. 1995. Description and use of KS Water Budget v. T1 software. Resource Manual, Department of Agronomy., Kansas State Univ., Manhattan, KS.

INTRODUCING THE WEB-BASED VERSION OF KANSCHED: AN ET-BASED IRRIGATION SCHEDULING TOOL

Danny H. Rogers,
Professor and Extension Engineer, Irrigation
Biological and Agricultural Engineering
K-State Research and Extension
Manhattan, KS 66506
Telephone: 785-532-5813 Email: drogers@ksu.edu

INTRODUCTION

Irrigation scheduling is a process of determining when and how much water to apply to a crop to meet specific management goals – generally to prevent yield limiting crop water stress. Evapotranspiration (ET) or crop water use information can be used for irrigation scheduling and is often described as being similar to a checkbook accounting procedure except in this case, root zone soil water content, rather than money, is the account balance. Deposits to the account would be effective rainfall and irrigation and withdrawal is the crop water use One notable difference is that the water balance can become too large and the additional deposits would be lost to surface water runoff or deep percolation as well as being too low or deficient for optimal crop growth.

The upper limit of root zone soil water is determined by the soil water holding capacity which for irrigation water management purposes is known as field capacity and the managed crop root zone. The desired lower limit for optimal crop growth can be a more variable value depending on the crop, the stage of growth, and management goal. Often it is referred to as the managed allowable deficit or MAD. A common MAD is 50 percent of the total available soil water holding capacity. The normal goal of the irrigation scheduling procedure is to help the irrigation manager keep track of the amount of water in reserve above a minimum soil water balance level to prevent water stress to the growing crop

The irrigation manager also considers the irrigation system capacity, the application amount that can be efficiently applied, the soil intake rate, and other factors when making the final irrigation scheduling decision, so irrigation scheduling tools that can be customized to a field's characteristics can greatly facilitate the irrigation scheduling decision process.

Irrigation scheduling procedures can help eliminate unnecessary irrigation water applications, although even the most rigorously followed schedule cannot prevent all losses since large rainfall events can exceed soil water storage capacity by themselves. The benefits of irrigation scheduling generally translate into increased net returns through several possible avenues, such as reducing irrigation labor and equipment operation pumping cost, and may also result in improved yields due to less water stress or less loss of fertilizer due to leaching.

One of the early obstacles to adoption of on-farm irrigation scheduling had been the time management problem of gathering, processing, and implementing scheduling on a daily irrigation cycle period. Computer technology presents the opportunity for information gathering, transferring, and processing to be done much more easily, efficiently, and sometimes automatically. Scheduling software, communication, and control technology exists that can provide management recommendations which could then be remotely implemented.

In the early 1990's, an excel spreadsheet program was introduced by Kansas State University Research and Extension to help facilitate ET based irrigation scheduling. This eventually evolved into KanSched. KanSched features have been described in previous CPIC programs and shown to be useful to a variety of climatic conditions and irrigation capacities.

KANSCHED – THE WEB BASED VERSION

This text introduces the next version of KanSched which will be a web-based. For the sake of clarity in this paper it will be referred to as KanSched3. As a web based program, users will have to set up their own user accounts and identities. However, once the user accesses the account, KanSched3 will appear very similar to the KanSched2 stand-alone version (Rogers and Alam, 2007). Figure 1 shows the initial field set up page, the user can not advance in the field until the field characteristics are entered (Figure 2).

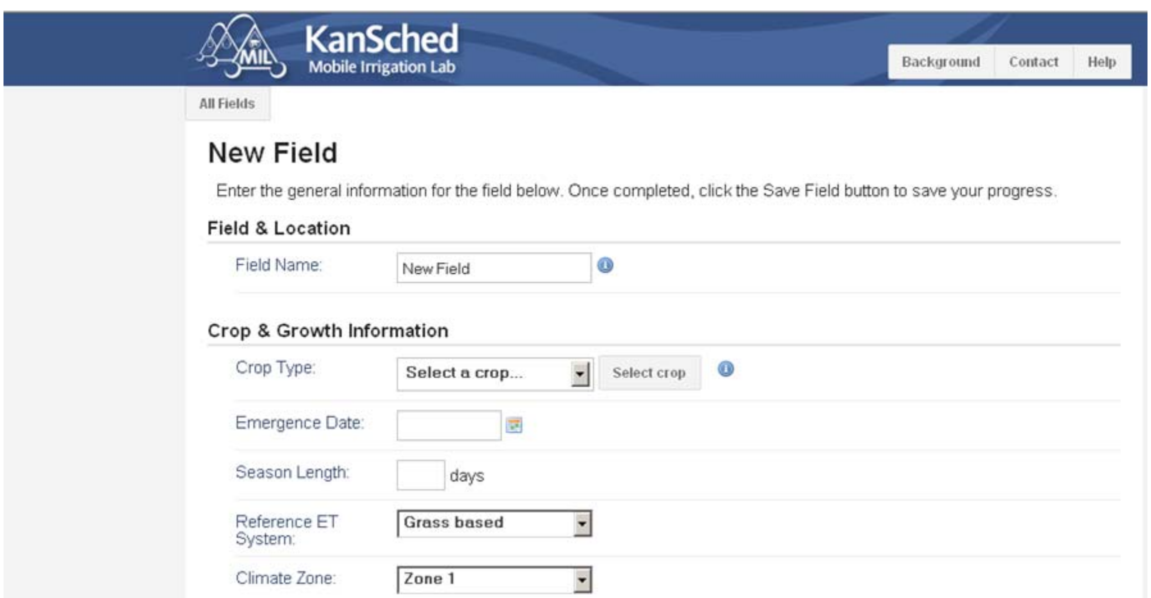


Figure 1. Initial field set up page for KanSched3

The field set up information is the same entires as in KanSched2, crop and crop growth information, reference ET source and crop coefficients (Kco), soil and system efficiency. In KanSched3, a new feature will allow the user to select a climatic zone that will further custimize the crop coefficients to their location, although custimized Kcos can still be entered as in KanSched2.

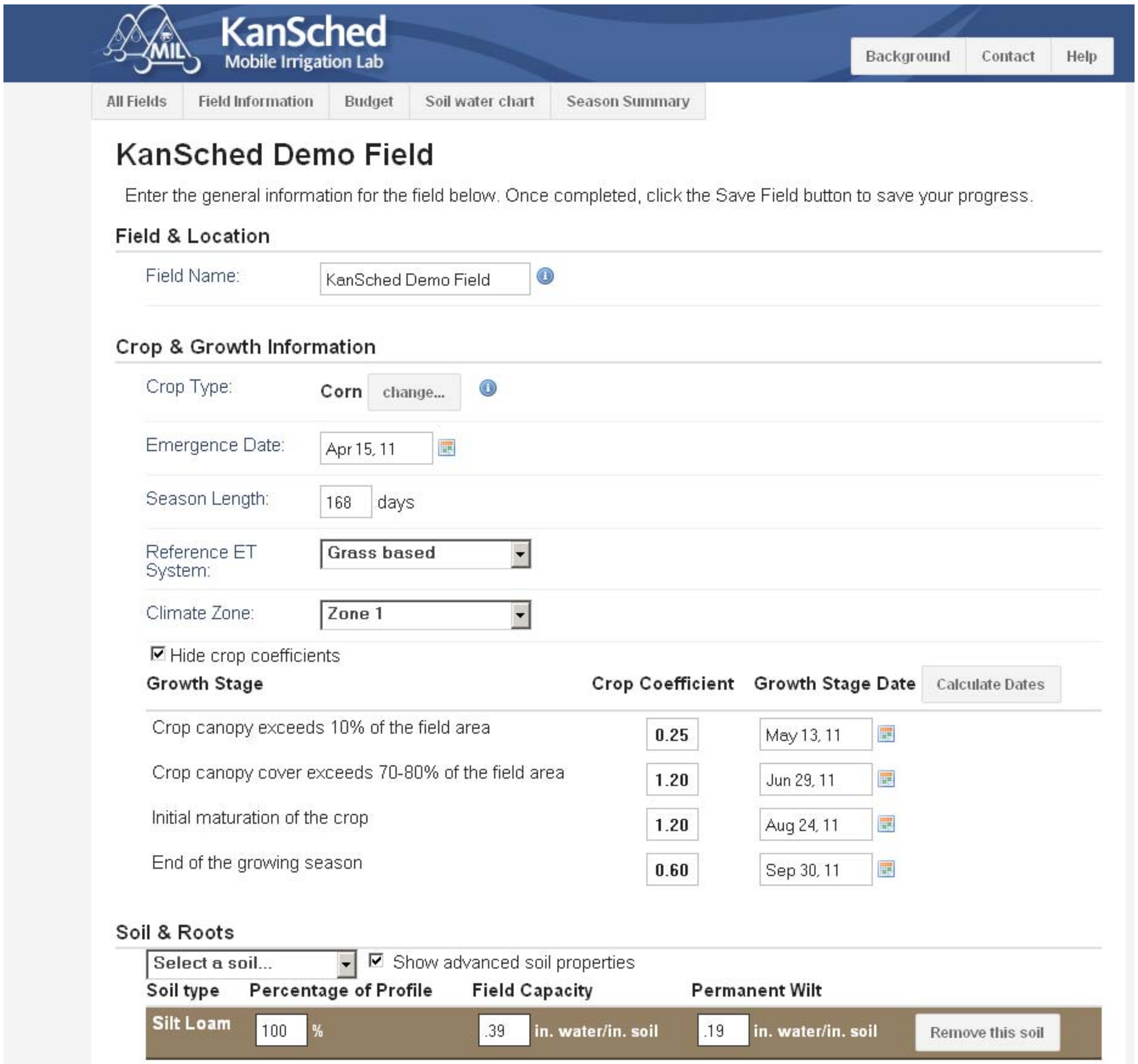


Figure 2: Initial field set up page for KanSched3 with entries. Note the additional control options are now available.

In KanSched3, soil information related to water holding capacity is can also be selected from the list of soils (Figure 2) but will allow layers of soil to be selected as shown in Figure 3. Multiple soils can be selected, only two are shown in Figure 3. The thickness of the layer is adjusted by changing the percentage of the layer (Figure 4).

Figure 5 shows the advanced section of KanSched3 with the features of Managed Allowable Deficit (MAD), system efficiency, rainfall discount and a new feature, the SDI adjustment factor. The SDI adjustment factor could allow the user to enter a percentage value to discount the ET for an SDI irrigated field.

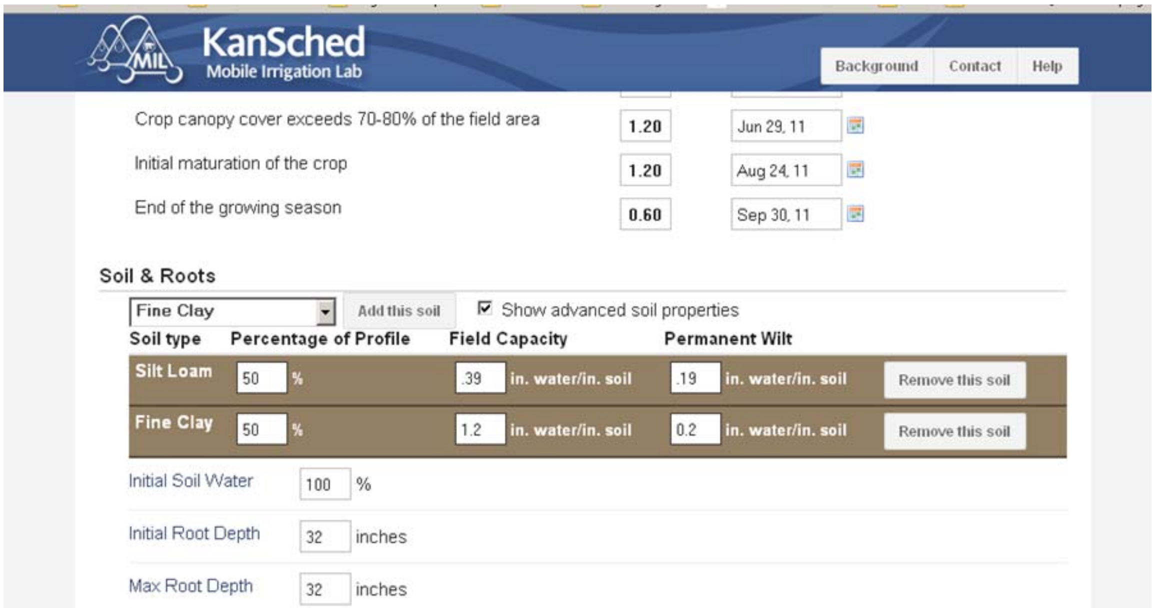


Figure 3. KanSched3 set page showing the multi-layered soil entry.

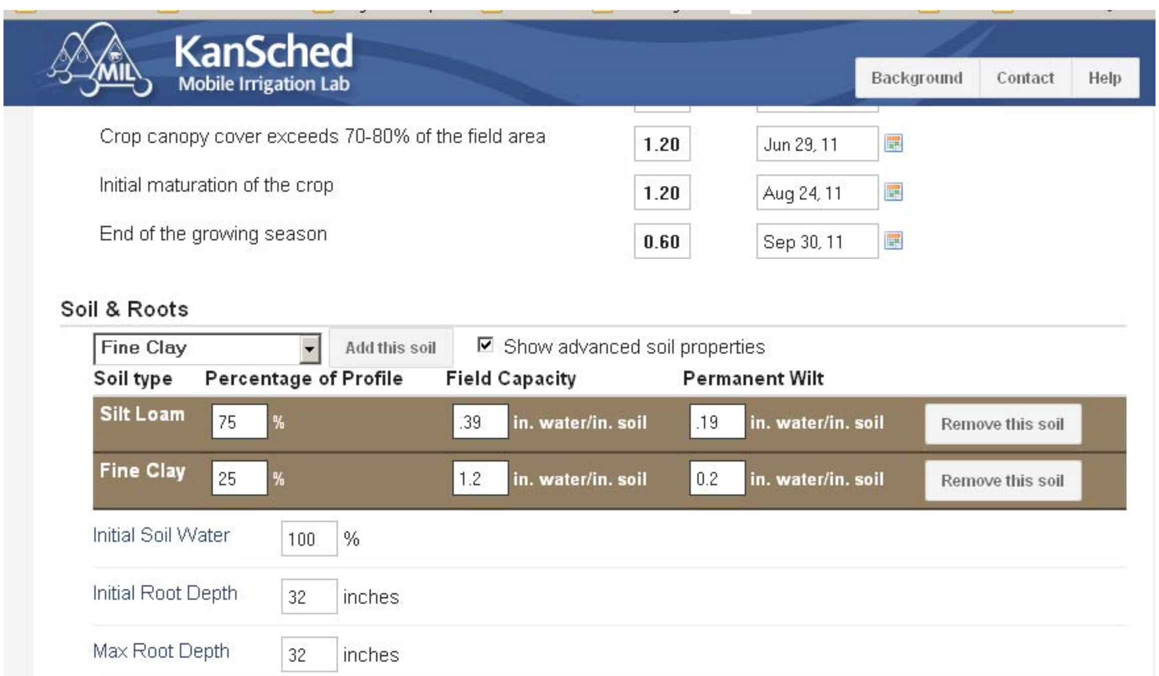


Figure 4. KanSched3 set page showing the multi-layered soil entry adjusted by altering the percentage depth of each layer.

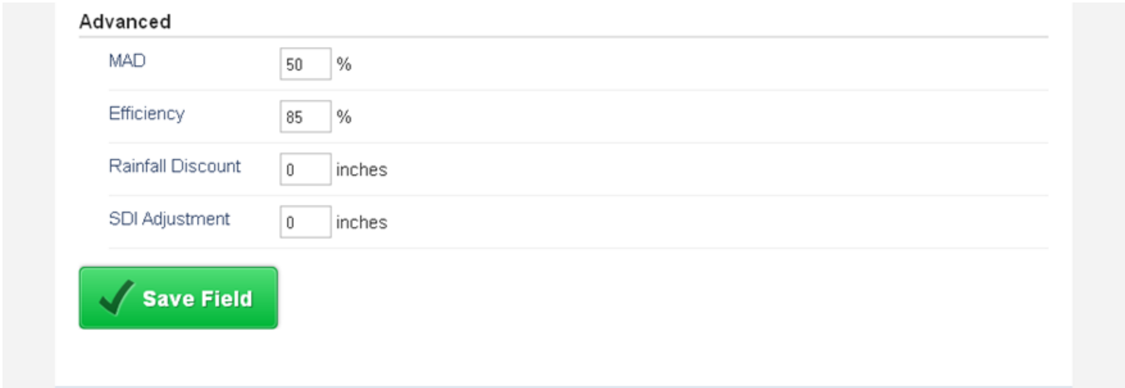
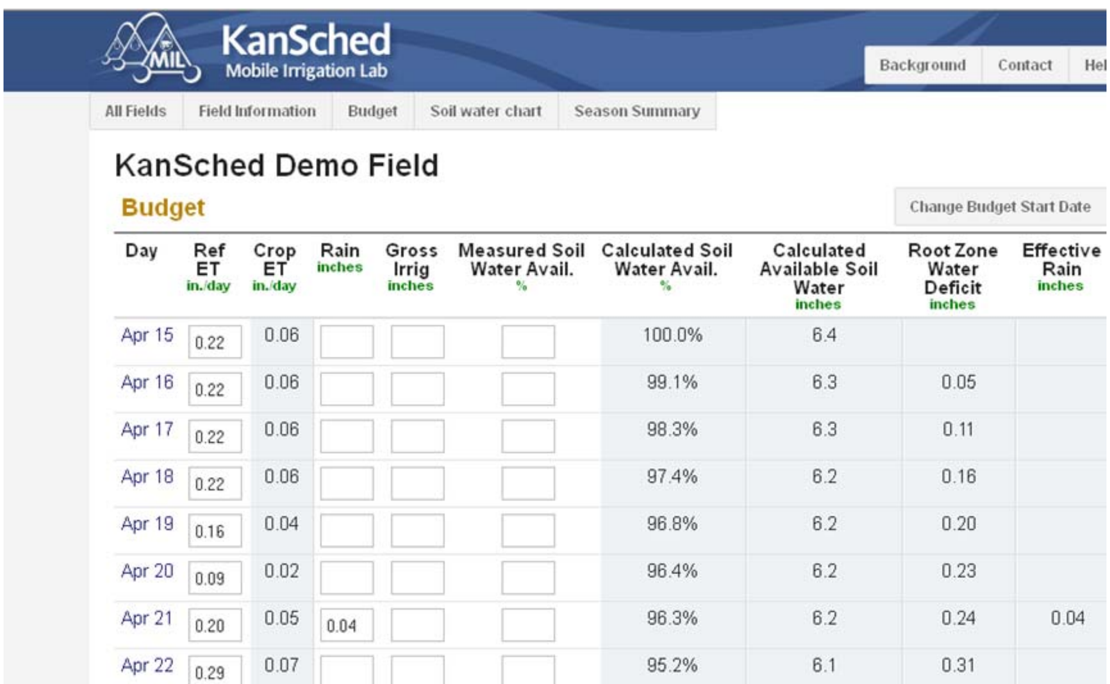


Figure 5. Advanced KanSched3 field set up page.

After the field set up page is completed the budget page (Figure 6), soil water chart (Figure 7), and season summary (Figure 8) are activated. Note that in the soil water chart, the cursor can be placed in the chart area to get a date and soil water content value reading.



Day	Ref ET in./day	Crop ET in./day	Rain inches	Gross Irrig inches	Measured Soil Water Avail. %	Calculated Soil Water Avail. %	Calculated Available Soil Water inches	Root Zone Water Deficit inches	Effective Rain inches
Apr 15	0.22	0.06				100.0%	6.4		
Apr 16	0.22	0.06				99.1%	6.3	0.05	
Apr 17	0.22	0.06				98.3%	6.3	0.11	
Apr 18	0.22	0.06				97.4%	6.2	0.16	
Apr 19	0.16	0.04				96.8%	6.2	0.20	
Apr 20	0.09	0.02				96.4%	6.2	0.23	
Apr 21	0.20	0.05	0.04			96.3%	6.2	0.24	0.04
Apr 22	0.29	0.07				95.2%	6.1	0.31	

Figure 6. KanSched3 Budget page

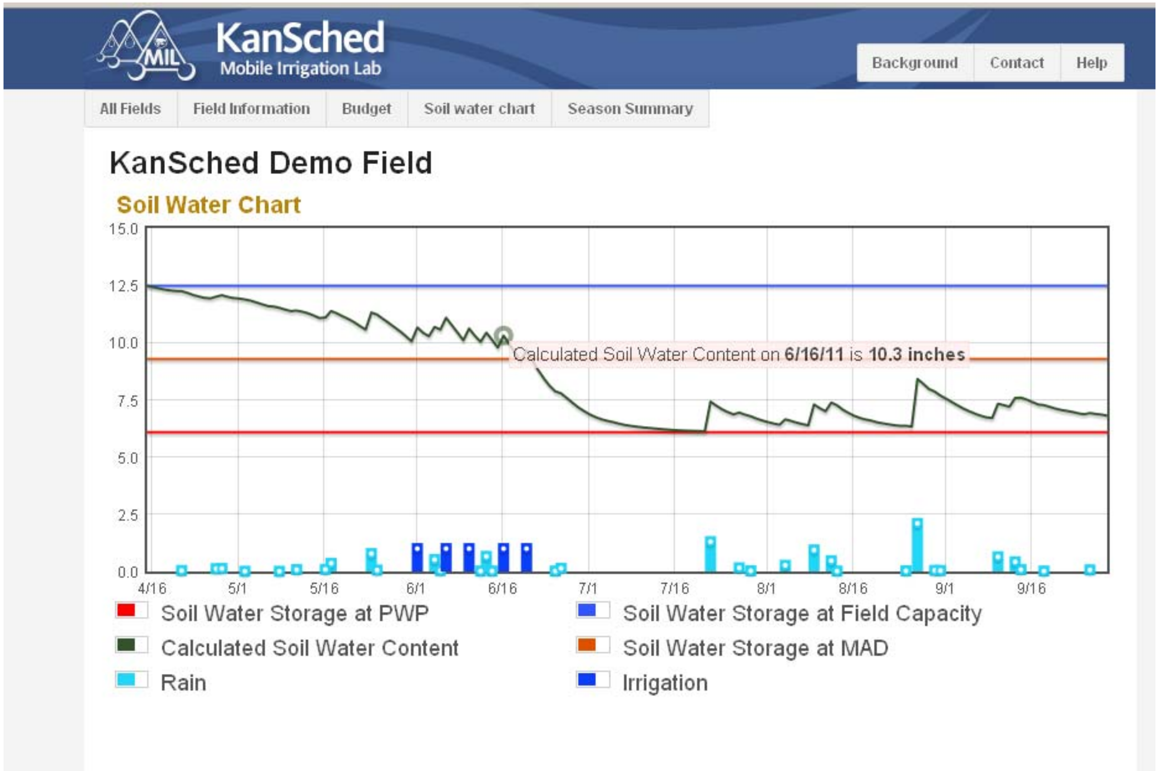


Figure 7. KanSched3 soil water chart.

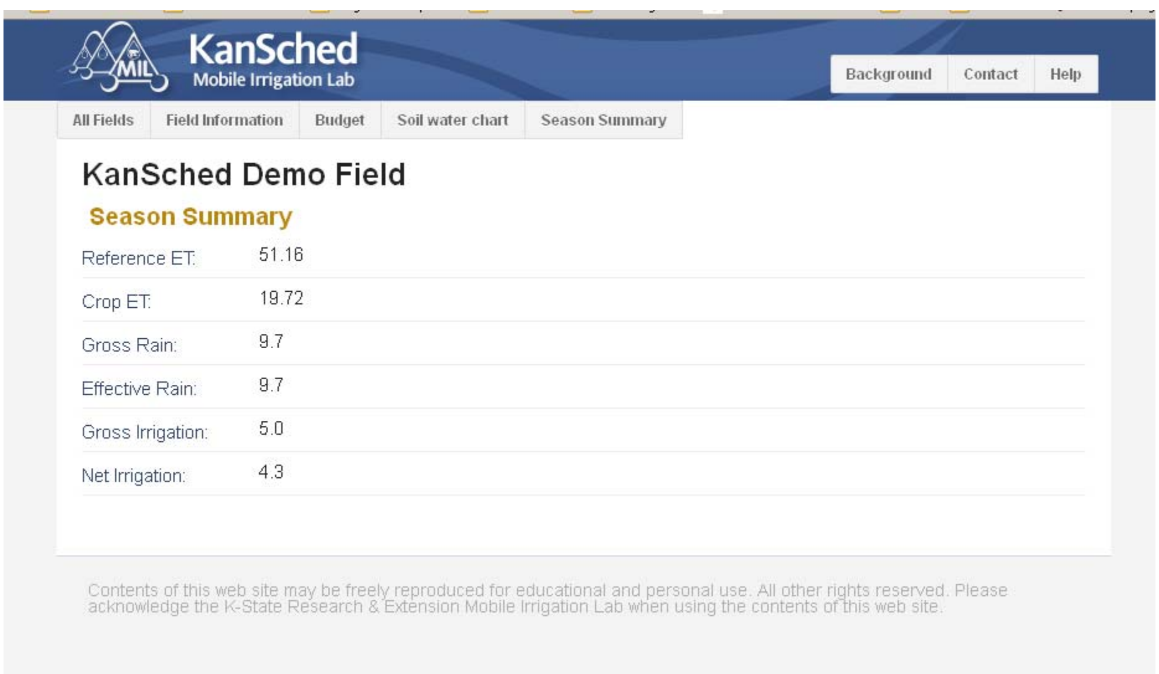


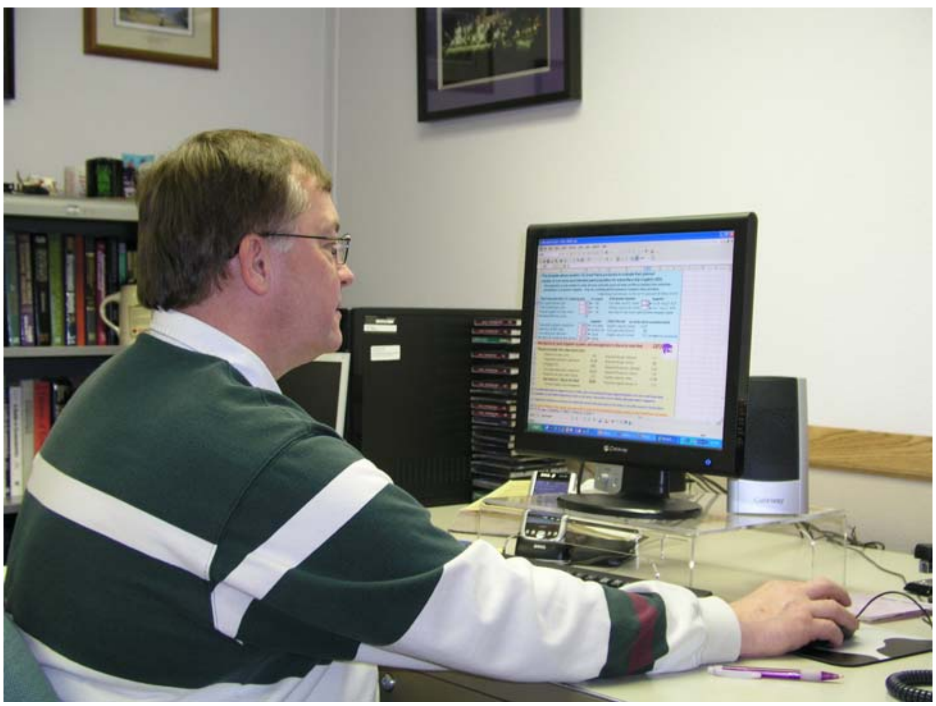
Figure 8. KanSched3 season summary page.

SUMMARY

As a web-based version, new features and revisions will be automatically available to the user. At the time of the writing of this proceeding paper, several features had not yet been installed, such as the printing options. KanSched3 is an advancement to allow producers easier access to ET based irrigation scheduling as a next generation of improved irrigation management tool. KanSched3 will be distributed via the web site: mobileirrigationlab.com.

REFERENCES

Rogers, D. H. and M. Alam. 2007. KanSched2 – An ET-based irrigation scheduling tool users guide. Kansas State University Research and Extension. Electronic Publication Only. EP- 129. 12 pp. Available at http://www.ksre.ksu.edu/library/ageng2/EP129.pdf



Using computers to manage irrigation decisions is a part of modern farming.

Proceedings of the 24th Annual Central Plains Irrigation Conference, Colby, KS., February 21-22, 2012
Available from CPIA, 760 N.Thompson, Colby, Kansas

PROPOSED PROCEDURES FOR LIMITED IRRIGATION FOR CROP INSURANCE

Jay Waechter
Senior Risk Management Specialist
Topeka Regional Office Risk Management Agency
Topeka, Kansas
Voice: 785-228-5512 Fax: 785-228-1456
Email:jay.waechter@rma.usda.gov

LIMITED IRRIGATION AND CROP INSURANCE

Currently RMA only recognizes two basic practices for most crops: irrigated and non-irrigated. If a producer intends to implement limited irrigation on a unit that had APH built on full irrigation, that unit could not be insured as irrigated; it would have to be insured as non-irrigated. Current procedure provides:

- Insured producers that become aware of decreased irrigation water before coverage begins may reduce the number of irrigated acres planted to the crop.
- Producers may plant and report as irrigated only those acres for which they can show they have adequate water and facilities to produce the yield on which the guarantee is based. The remainder of the acres can be planted and reported as non-irrigated.

RMA currently has a cooperative agreement with the University of Nebraska – Lincoln to assist producers facing reduced irrigation water supplies.

- As part of this agreement, yield adjustment tables have been developed for most counties in Nebraska, the Western 2/3 of Kansas, and Eastern Colorado.
- The tables provide an estimated yield reduction associated with decreased irrigation water.

The Topeka RO has been working closely with researchers at UNL, KSU, and CSU regarding the review of methodology used for generating these tables and the potential for incorporating them into the crop insurance program.

As early as the 2013 crop year, we believe we can incorporate the research and provide coverage for producers who carry out a less than fully irrigated practice. To implement such a change:

- A Special Provision statement would be added that would allow insurance to attach to a less than fully irrigated crop if a yield reduction is made to the irrigated APH yield. Yield adjustment tables developed by UNL would be published on the Special Provisions for making such adjustments. Yield adjustments would continue to be made until the APH yield was representative of the limited irrigation yield.

- The reduced yield would become the yield upon which the insurance guarantee is based. Amendments would be made to RMA procedures and Handbooks.

- A documentation tool/certification form for recording historical and current year water application would be needed.

Carrying out a limited irrigation practice would be strictly voluntary for the producers, they could still cut back on acres insured as irrigated when water supplies are reduced, or claim prevented planting, if eligible.