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THE IMPACT OF IRRIGATED AGRICULTURE ON A STABLE FOOD SUPPLY

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Irrigated agriculture is one of the most critical human activities sustaining civilization. The current world population of 6.8 billion people is sustained in a large part by irrigated agriculture. USDA statistics show that 17% of cultivated crop land in the United States is irrigated. Yet this acreage produces nearly 50% of total US crop revenues. According to the FAO the approximate 1,260 million ha under rainfed agriculture, corresponding to 80% of the world's total cultivated land, supply 60% of the world's food; while the 277 million ha under irrigation, the remaining 20% of land under cultivation, contribute the other 40% of the food supplies. On average, irrigated crop yields are 2.3 times higher than those from rainfed ground. These numbers demonstrate that irrigated agriculture will continue to play an important role as a significant contributor to the worlds food supply.

Water is increasingly in the headlines and irrigated farmland is often to blame for shortages and quality issues. Government subsidized "cheap water" from century old dams and water projects are not viewed a foresight but as taxpayer subsidies to farmers dismissing the positive effect on food supply and prices. Farmers are blamed for maximizing yield at the expense of natural resources, as much a criticism of capitalistic philosophy as agriculture. The fact is that today's farmers are producing more food on less land than ever before. Given current trends in population growth and the loss of prime agricultural land to development this trend must continue if we are to maintain an adequate food supply for the world. The critical environmental vagary farmers have to deal with is precipitation. Other environmental factors such as temperature, sunlight even insects and disease are far more regular. Thus Irrigation is a powerful mitigator of main environmental risk associated with farming. To this end farmers in drought prone areas make large investments in irrigation. The risk mitigation provided by irrigation goes beyond simple economic advantage to the farmer. Irrigation allows for a more consistent food supply and higher productivity. Recent studies have shown increased CO_2 sequestration, reduced N_2O emissions and more efficient fertilizer use associated with irrigation. The evidence that irrigated farming has a positive effect on society and even the environment is compelling.

Drought and Famine

The causes of famine in the world are complex, often involving economic, political, and biological factors. Each of these factors paints the cause of famine with its own perspective.

Economically, famine is the failure of the poor to command sufficient resources to acquire essential food. The great famine in Ireland which began in 1845 occurred even as food was being shipped from Ireland to England because the English could afford to pay higher prices. The 1973 famine in Ethiopia also occurred as food was being shipped out of Wollo, the center of the famine, to Addis Abba because the capital city could afford to pay more.

Political causes of famine occur because of war, violence or poor public policy. The citizens of the social dictatorships of Ethiopia and Sudan in the 1970's and early 1980's suffered huge famines while the democracies of Zimbabwe and Botswana avoided them in spite of having worse drops in the national food production. This was done through the simple step of creating short term employment for the worst affected groups.

Biologically, famine is caused by the population outgrowing its regional carrying capacity to produce food resources. The failure of a harvest or the change in conditions such as drought can create a situation whereby large numbers of people live where the carrying capacity of the land has dropped radically. Interestingly, at a time when "industrial agriculture" is perceived as a villain, even portrayed as destroying the planet, famine due to crop failure is most often associated with subsistence agriculture, that is where most farming is aimed at simply supplying enough food energy to survive. This means that for farming to provide sufficient food it must be economically satisfying to the farmer not just in good years but year in and out.

Famine records indicate that farm programs that subsidize production may have a positive effect on famine reduction. Europe and the United States have not faced widespread famine due to crop failure in the past 200 years. Even during the dust bowl in the 1930's the United States did not face widespread famine and the famine that did occur was mostly economic, people not being able to afford food due to the great depression. Up until the middle of the 20th century Africa was not considered to be famine prone. Famine in Africa increased as the economics of agricultural pursuits has become less profitable. Africa does have an ample share of drought, soil problems, crop diseases and especially civil unrest and associated land issues. This has resulted in agrarian life to be uneconomic, and in some regions, fatal. It is the lack of this security that holds most of the blame for African food issues. Long term land and crop security could do much to relieve this.

Crop failures, whether due to natural or man made conditions, have been associated with famine since recordkeeping began. Manmade conditions most frequently include war, particularly attacks on land and farmers meant to starve the local populations. Natural crop failure occurs because of plant disease, such as occurred during the great potato famine, insects such as locusts and, most frequently, drought. Irrigated agriculture provides a buffer against crop failure due to drought.

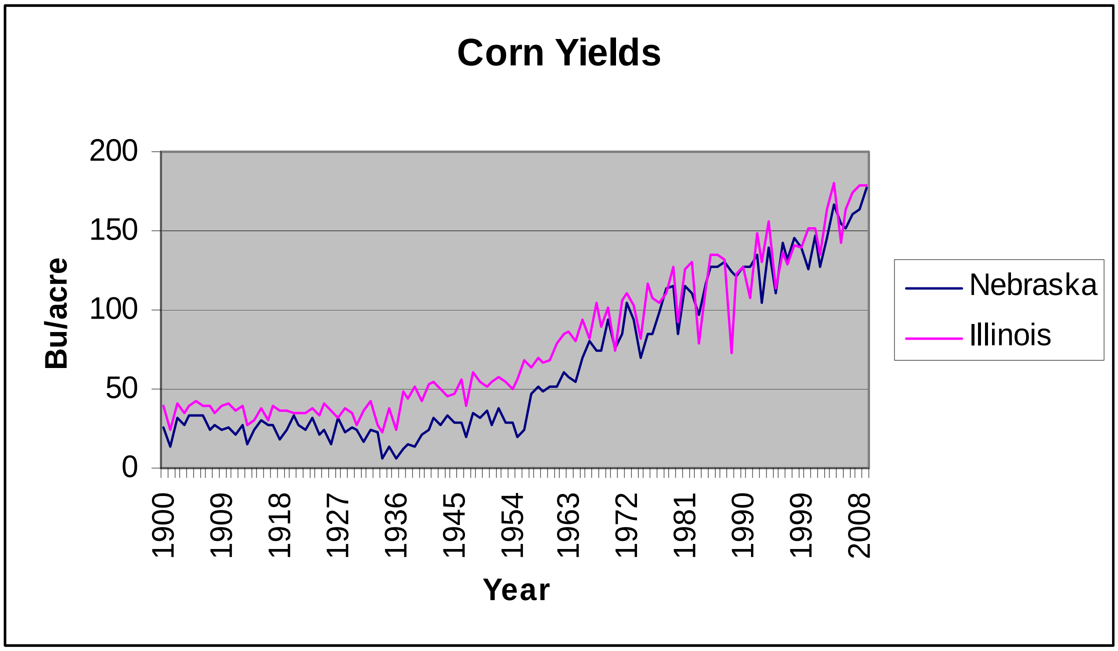

Figure 1. USDA corn yields data for Nebraska and Illinois. In the year 2007 Nebraska had over 80% irrigated corn acres while Illinois had less than 5% irrigated corn acres.

To investigate the effect of irrigation on agricultural productivity corn yields from 1900 to 2008 was compared for the rain irrigated state of Illinois averaging over 30 inches per year rainfall and the dryer state of Nebraska with less that 15 inches rainfall on average. To make up for the lack of rainfall, over the last 30 years irrigation has increases in Nebraska from 30% of planted corn in 1966 to over 80% of planted corn in 2008.

The yield data in Figure 1 can be roughly divided into three distinct segments. The relatively constant yields of 30 to 40 bushels/ acre that occurred from 1900 to 1933 covers the period when corn varieties were open pollinated. The rise in corn yields from the 1930's until the 1960's occurs concomitantly with the increased use of double cross hybrids during this time. The more rapid increase in yields from the 1960's until present day roughly corresponds to the introduction of single cross hybrids.

A closer look at each segment offers some insight into the factors affecting corn yields in these two different environments. The trends from 1900 to 1930 when farmers only had access to open pollinated corn varieties are illustrated in figure 2. During this period there was some flood irrigation in Nebraska but it accounted

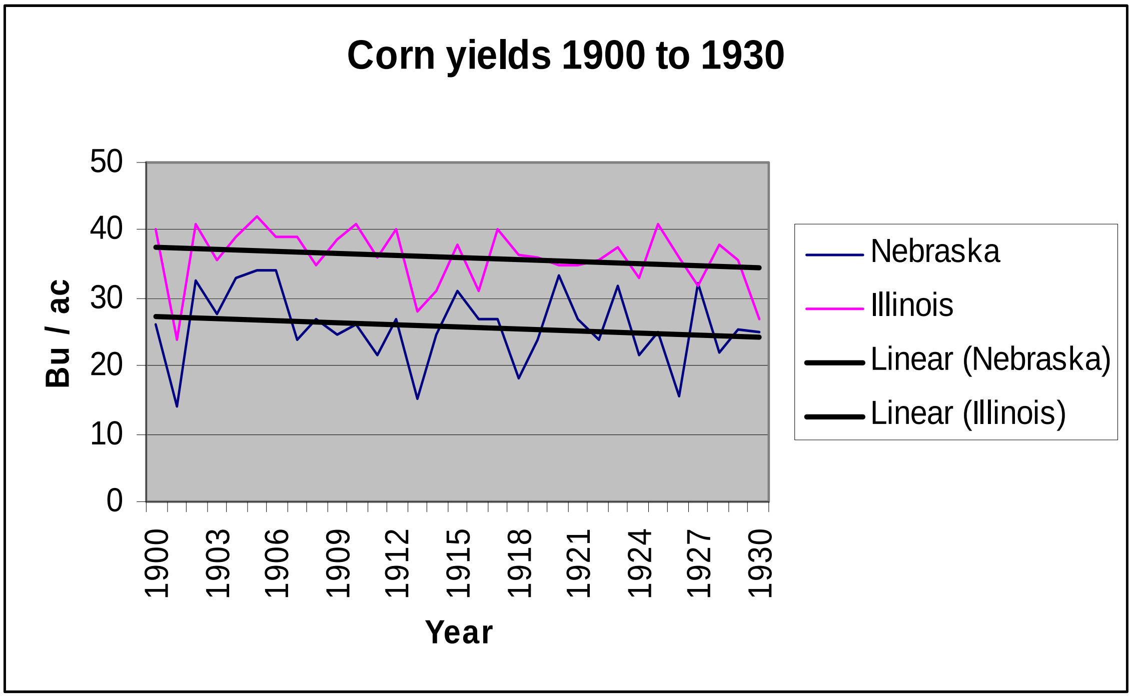

Figure 2. USDA statistics of corn yields in Illinois and Nebraska from 1900 to 1930.

for less than 10% of total corn acreage. During this period the total acreage planted to corn in these states was some 20% higher than that planted today, over 9 million acres in Nebraska and 13 million acres in Illinois. On average Illinois yielded about 10 bushels more per acre than Nebraska. It is clear from the data that the yields from Nebraska are more variable than the yields from Illinois. It is not possible to correlate yield to specific rainfall events because the timing of the rain is critical to corn yields but it can be said that greater variability in yields observed in Nebraska as opposed to Illinois can be related to the greater variability in rainfall found in this region. The general downward trend in yields during this time period is often associated with lack of sophisticated fertilization practices

The period from 1930 to 1935 corresponds to the drought that caused the dust bowl in the Great Plains. The collapse of corn yield in Nebraska is evident in Figure 1. The drought during this time did impinge upon yields in Illinois but was much less severe in this region. Following this period yields began to increase due to advanced genetics and better crop practices particularly fertilization practices developed by the land grant universities (Figure 3.).

Interestingly, the approximate 10 bushel higher yield observed for corn grown in Illinois compared to Nebraska was maintained during this period. Yield reductions due to a significant drought from 1952 to 1957 are obvious in this data. As was seen in the period 1930-1935, the effect was more pronounced in Nebraska relative to Illinois due to more variable precipitation in the more western state.

The period from 1965 to present is marked by a massive increase in irrigation in Nebraska. In 1966 there were 3 million irrigated acres while in 2002 there were 8 million acres. Over this time the area devoted to corn in the state of Nebraska was constant at a little over 9 million acres. This period also marked the largest increase in yields in both irrigated Nebraska and non-irrigated Illinois. This yield increase is often attributed to the "green revolution" of better fertilization methods along with improved varieties and crop protection chemicals. The reality is that the green revolution started as early as the turn of the century and started to take off in the 1930's. The large yield increases seen since the 1960's was the mainstreaming of the yield increasing technologies due to increased farm investment.

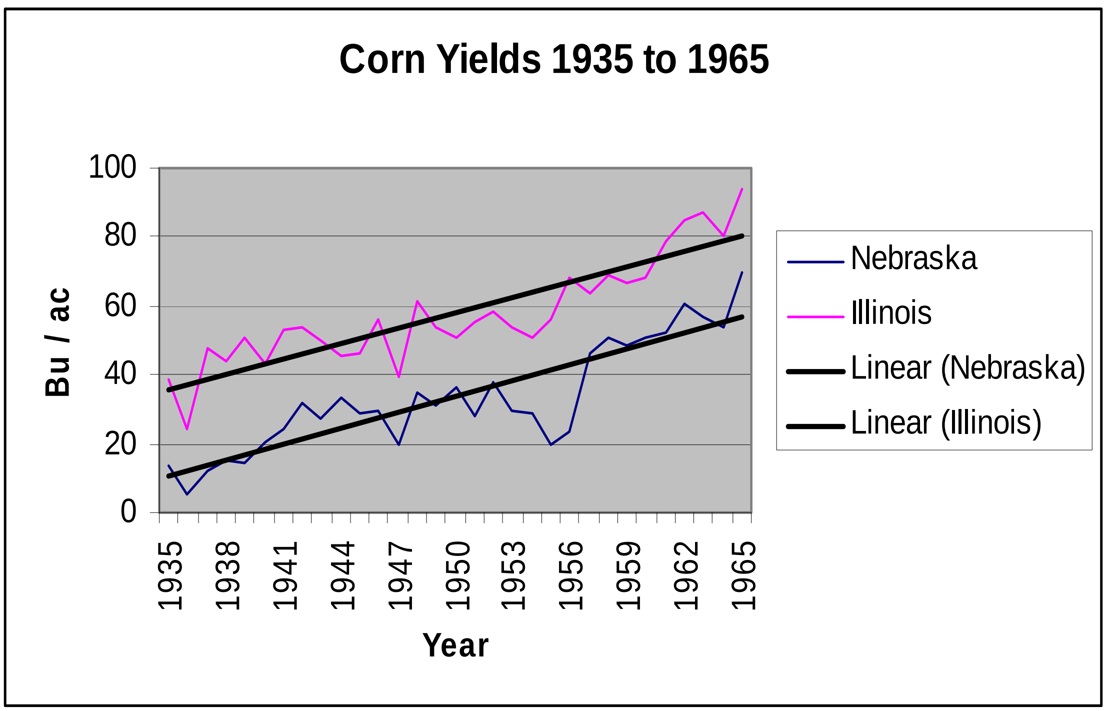

Figure 3. USDA statistics of corn yields in Illinois and Nebraska from 1935 to 1965.

The data in Figure 4 indicate that the average yield for the state of Nebraska is for the first time approaching the yield for Illinois. This suggests that irrigation, or the lack of it, was entirely responsible for the difference in yields between the two states. In addition over this time period the variability in yields is more pronounced in Illinois. A regression analysis confirms this giving an R squared for Nebraska of 0.85 while for Illinois a 0.68. This suggests that irrigation also reduces variability in yield.

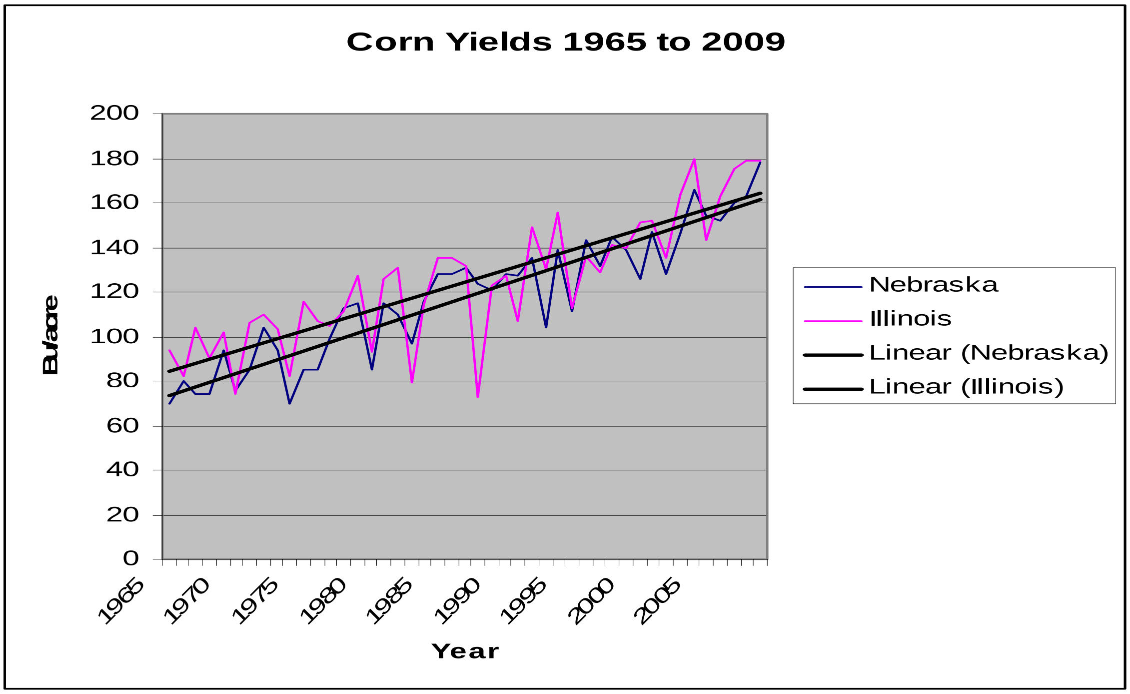

Figure 4. USDA statistics of corn yields in Illinois and Nebraska from 1965 to 2009.

Productivity of Irrigated land

According to the FAO, average crop yields for irrigated acres are 2.3 times those from rainfed areas. The actual yield increases vary according to the region and the crop. In Nebraska the yield boost attributed to irrigation between 1992 and 2007 ranged from 10% for sorghum in 1998 to 268% for corn grown in 2002 (Table 1.) Corn wheat and alfalfa exhibited the greatest response to irrigation while sorghum and soybeans had a lower positive response. The high productivity of irrigated agriculture allows fewer acres to feed a larger proportion of the global population. Increasing productivity per acre is critical as farmland acreage continues to be converted to residential property.

The need for increasing yields on increasingly poor quality land is becoming more pressing as land development for housing increases. The United States looses two acres of prime farmland every two minutes. From 1992 to 1997, six million acres of agricultural land was converted to developed uses (Table 2). This represents an area the size of Maryland. Much of this land is prime land.

Yield per Acre of Major Crops in Nebraska

	Corn for Grain (Bu.)		Sorghum Grain (Bu.)		Wheat (Bu)		Soybeans (Bu.)		Alfalfa Hay (Tons)	
	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated
1992	144	117	101	93	49	29	45	41	4.5	3.4
1993	111	90	70	58	56	28	41	34	4.1	3.2
1994	153	113	109	97	55	34	53	45	4.5	3.2
1995	130	73	74	57	62	40	42	29	4.4	3.2
1996	156	115	106	94	53	35	50	43	4.8	3.3
1997	151	99	101	80	48	36	51	37	4.5	2.8
1998	161	119	104	94	68	45	51	41	4.8	3.4
1999	159	111	102	91	66	47	51	38	4.6	3.4
2000	154	84	98	69	63	34	50	30	4.5	2.6
2001	173	110	106	83	59	35	53	39	4.7	3
2002	166	62	83	48	63	30	51	29	4.4	2.3
2003	186	82	117	56	67	44	54	31	4.8	2.9
2004	186	134	110	78	66	33	54	40	4.7	2.9
2005	185	108	113	84	60	37	59	43	na	2.4
2006	185	101	109	77	67	32	59	42	na	2.1
2007	181	125	117	96	58	40	55	47	na	2.4

Table 1. Yield of irrigated and non-irrigated crops in Nebraska 1992 to 2007

The rate of conversion of prime land was 30% faster than for non prime land. This results in more marginal land being put into production. In addition, most of the development is occurring in areas that receive significant natural rainfall. Of the top 12 states losing prime farm land only one, Texas, significantly relies on irrigation. This development forces more production into irrigated lands increasing the pressure on water supplies.

Development is also pushing agriculture to more marginal lands. Flat, well drained land is considered prime land for farming. It is also the least expensive to develop into housing and commercial properties. The San Joaquin Valley in California averages 10 to 15 inches of rainfall a year while the coastal valley including Watsonville and Salinas averages twice that amount. Yet housing is pushing vegetable production out of the relatively wet coastal valley to the dryer central valley where more irrigation is required. In another example, most of the best farmland in New Jersey is now covered by houses. This is occurring at a time when “buy local” is being promoted as the most sustainable food option. Loss of arable land is increasing as the world population gets wealthier. The general fact is that agricultural land and water use cannot compete economically with industrialized or residential uses. As discussed earlier farming must result in economic benefit for the farmers or crop production will not keep up with demand

and food shortages will result. Water use policy must also include land use policy as part of the conversation.

Irrigated Agriculture and Environmental Quality

Researchers are beginning to consider the effect of irrigated agriculture on greenhouse gasses and air quality. Researchers in Idaho looked at the organic carbon stored in soils having long-term cropping histories of various crops. They found that irrigated pasture and irrigated reduced till cropping sequestered more carbon in the soil than native rainfed vegetation. Full tillage irrigated crops sequestered the least carbon. The authors concluded that if worldwide irrigated acreage were expanded 10% and the same amount of rainfed land were converted to native grassland that 5.9% of the total carbon emitted in the next 30 years could be sequestered. Studies of the effects of irrigation on the environment are new but show promise.

Prime Acres Lost

State	87-92	92 -97
TX	234,300	332,800
OH	146,400	212,200
GA	110,900	184,000
NC	167,100	168,300
IL	67,900	160,900
PA	109,700	134,900
IN	75,100	124,200
TN	87,200	124,000
MI	72,700	121,400
AL	50,200	113,800
VA	59,800	105,000
WI	54,200	91,900
NY	36,900	89,100
SC	52,600	86,200
CA	73,800	85,200

Table 2 Farm acres lost by state

Another study compared drip and furrow irrigation relative to CO_2 and N_2O emissions. The CO_2 emissions were lower in drip irrigated compared to flood irrigated treatments but the differences were small (4%). More significantly, of the 100 pounds of N/acre added as fertilizer 18% was lost as N_2O in the furrow irrigated treatments compared to only 4% in the drip irrigated treatments. Although both gases are significant contributors to global warming N_2O is 300 times more potent than CO_2. Other studies indicate a positive relationship between irrigation and fertilization efficiency, supporting the conclusion that efficient irrigation reduces N_2O emissions.

Rainfall leaches nutrients from the soil. This is why, even in areas of high rainfall such as Florida, many growers practice plasticulture, the practice of using plastic mulch and drip irrigation to better manage the soil environment. Strawberries and tomatoes are often grown in beds that are covered with plastic mulch. In addition to creating a clean surface for the fruit, this mulch prevents the natural heavy rains from saturating the soil and leaching out the applied nutrients. Irrigation is then used to supply the necessary water.

Studies conducted in West Texas from 2000 to 2007 revealed that recovery efficiency of added N fertilizer ranged from a minimum of 12% in furrow irrigated fields to a maximum of 75% in fertigated fields. The relationship of total N uptake (pounds/acre) relative to yield in bales for all irrigation systems indicates that a bale of yield requires 40 pounds N per acre regardless of the treatment. Thus a furrow system that is only 12% efficient must apply 300 lbs N/bale/acre compared to 53 lbs N/bale/acre for a drip system that is 75% efficient. This saves money, potential runoff and N_2O emissions.

Irrigated Agriculture and Business planning

The risk associated with Agricultural production can be divided into three components

1) Systemic Risk – this is the risk associated with lost production most often associated with the weather, particularly rainfall but also insects and disease
2) Market risk – that associated with crop prices
3) Credit risk – usually associate with the low value of farm land relative to the cost of production.

The systemic risk is mitigated through the implementation of a crop insurance program, crop protection program, nutrient management program and irrigation program. The first three are usually treated as variable expenses while the irrigation system is a capital expense. The United States offers an excellent laboratory for considering the systemic risk associated with irrigated agriculture. In the Western arid states most crops cannot be grown without irrigation so irrigation is a necessary component of production. As you move east to the high plains, most crops can be successfully grown using natural rainfall but irrigation is necessary to obtain maximum yields (see Table 1). In this case there are measurable benefits and risks to choosing or not choosing to irrigate. The actual choice is many times dictated by incentives and subsidies but the result is more consistent high yields. Table1 indicates the risk for dryland farming of corn in Nebraska ranges from a minimum of 21 bushels to a maximum of 102 bushels per acre. The average difference is 58 Bu. This yield increase significantly reduces the risk associated with production in this region which is why over 80% of Nebraska farmland is irrigated.

Moving east of the Mississippi, rainfall is usually adequate for crop product except for exceptionally dry years. The decision then is whether to invest in irrigation as an insurance against 2 or 3 out of 10 dry years. This type of irrigation insurance is strongly dependent on the price of the irrigation system.

Market risks are mitigated through various selling contracts, futures, cash sales and hedge contracts. These instruments, while complicated, add significant upside potential to the farmer. The credit risk of farming is usually associated with lenders but can affect farmers looking for funds to make significant investment in equipment such as irrigation systems.

In addition to risk mitigation, irrigation also allows for a more consistent yield year after year. This was shown to be true in irrigated Nebraska compared to Illinois (Figure 4). More consistent yields allow for more consistent application of market risk management tools such as futures and hedges. Also, the regular income associated with more consistent yields also improves the credit risk position of farmers seeking credit. This results in lower rates and better profitability. Finally consistent yields and revenues contribute to better business planning on a longer time scale, resulting in increased resource efficiencies.

Conclusion

Irrigated agriculture is critical to maintaining and growing the world's food supply as population grows. Analysis of yield data from Nebraska and Illinois indicates that irrigation mitigates the effects of drought, the number one environmental factor reducing yields. In addition irrigation results in more consistent yields which allow for better business planning particularly with regard to market dynamics. Prime agricultural land is being lost to development at an astonishing rate. Irrigation improves agricultural productivity particularly on marginal ground. This is necessary to meet future food needs in the face of reduced growing area. Irrigation may also help sequester carbon dioxide, reduce N_2O emissions from the soil and reduce fertilizer needs. This is not to say that water supplies, both ground and surface, need not be managed. Water must be available for people, industry, nature and food. Food is critical because it is the abundance of food that sustains people and industry and allows us the freedom to consider and preserve nature.

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VALUE OF CROP RESIDUE FOR WATER CONSERVATION

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Practicing less tillage and retaining more crop residue on the soil surface reduce the rate of evaporation of water from the soil. These practices also increase the amount of soil water by increasing the amount of water that infiltrates into the soil and by decreasing the amount of water that runs off across the soil surface. Less tillage and more residue coverage can significantly reduce the amount of irrigation water needed to grow a crop.

EVAPORATION

When the soil surface is wet, evaporation from a bare soil will occur at a rate controlled by atmospheric demand. The evaporation rate decreases as the soil surface dries over time (Figure 1). Water that is deeper in the soil cannot be transported to the surface quickly enough to maintain wet-soil evaporation. The drying surface soil starts to act as a barrier to water transport.

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 a bare soil. Surface moisture under the residue will continue to evaporate slowly. A number of days after the wetting event, the evaporation rate from the covered surface can exceed that of the bare surface (Figure 1).

Eventually, after many days without rain or irrigation, the total evaporation from the bare and residue-covered soil would be the same. In the conceptual diagram of 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 will be greater from a bare soil.

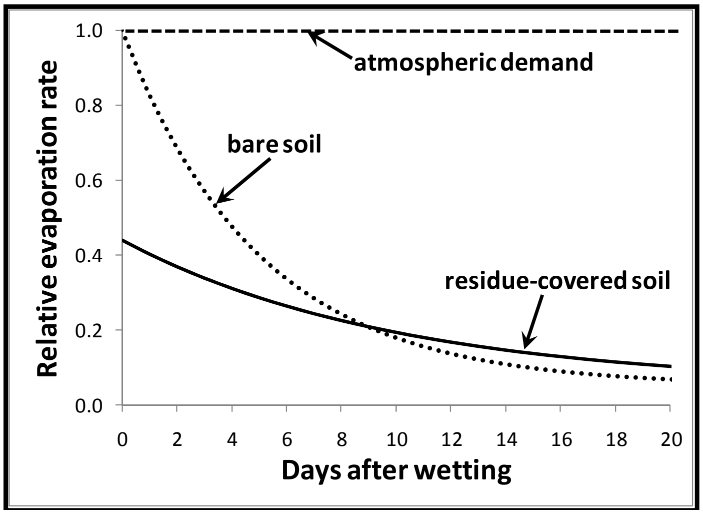

Figure 1. Evaporation rates, relative to atmospheric demand, from bare and residue-covered soil after a single wetting event (irrigation or rainfall) – conceptual diagram.

Residue reduces, but does not eliminate evaporation, which still takes place from the crop canopy, the residue itself, and the soil every time they are wet. This loss has been estimated to be 0.08 to 0.1 inch for each wetting event. 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 inch each time. One tenth of an inch of evaporation out of 0.5 inch is a 20 percent loss. When adopting continuous no-till, the 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. Each tillage operation can cause 0.5 to 0.75 inch of soil water evaporation. 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.

INFILTRATION AND RUNOFF

Long term no-till management leads to better soil structure, less soil crusting, higher infiltration rates, and less surface 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. Subsequent soil surface drying can cause further crusting. This sealing and crusting process 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 slows the velocity of runoff water across the soil surface, allowing more time for infiltration.

Researchers of the University of Nebraska-Lincoln (UNL) 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, more than 3.75 inches of water was applied in 90 minutes to no-till soils before runoff started compared with 1.0 inch of water applied in 20 minutes on plowed soil before runoff started.

Standing residue can also 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 because the stubble slows runoff thus storing more water, which can be used for crop production later in the growing season.

CROP YIELD, RESIDUE MASS AND COVER

The amount of residue produced at harvest by a crop can be estimated from crop yield. For wheat, yield (bu/ac) is multiplied by 100 to get residue mass in lb/ac. For example, a 60 bu/ac wheat crop is expected to produce approximately 6000 lb/ac of residue. For corn, yield is multiplied by 50 and for soybean by 60. Thus, a 180 bu/ac corn crop is expected to produce approximately 9000 lb/ac of residue.

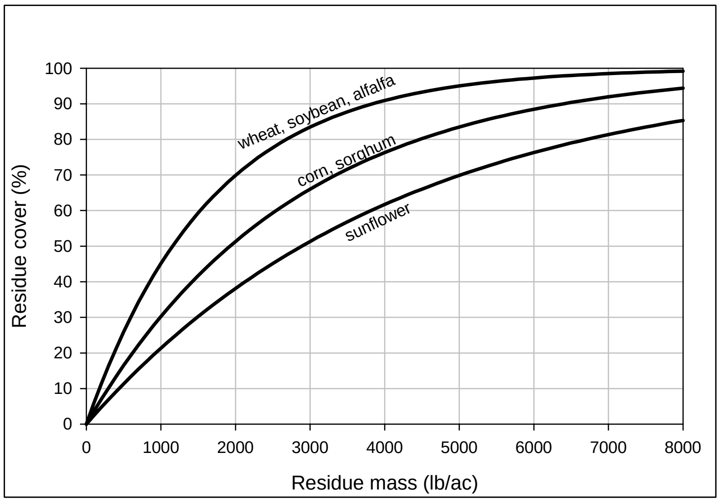

Figure 2. Relationship of residue mass to percent residue cover for various crops (USDA-NRCS, 2002).

The amount of residue cover is also important to gage the soil and water conservation benefits of the residue. The relationship of residue mass and residue surface cover is shown in Figure 2. For example, for wheat, 6000 lb/ac corresponds to a residue cover of almost 100% and 1000 lb/ac of corn residue corresponds to a cover of 30%. The thickness of residue also affects conservation benefits and is related to residue mass and residue cover.

EFFECT OF CROP RESIDUE ON EVAPORATION – SEVERAL EXPERIMENTS

Research conducted near North Platte, Nebraska and Garden City, Kansas (Klocke et al., 2009; Klocke et al., 2008; Todd et al., 1991), showed that soil water evaporation from bare fine sand and silt loam soils can be as much as 30% of evapotranspiration (ET) during the irrigation season of corn and soybean. The studies suggested that evaporation is 15% of total ET when wheat straw or no-till corn stover completely cover the soil surface from early June to the end of the growing season. This translates into a 2.5- to 3-inch water savings. Dryland research indicates that wheat stubble can save an additional 2 inches of water during the non-growing season if the soil profile can retain the water (Nielsen, 2006). The water savings in the growing and non-growing seasons would combine to a total of 5 inches per year. Not all of this can be effective for later crop growth and yield. Assuming that 50% of the 5-inch water savings can contribute to crop yield, yield increases may be as much as 10 bu/ac for soybeans and 30 bu/ac for corn.

EFFECT OF CROP RESIDUE ON SOIL WATER CONTENT AND CROP YIELD - NORTH PLATTE EXPERIMENTS

In 2007, a study was initiated on the effect of crop residue on soil water content and crop yield at the UNL West Central Research and Extension Center in North Platte, Nebraska. 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, bare-soil plots were created by using a dethatcher and subsequent hand-raking, removing most of the residue (Table 1). 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.

Residue cover was measured with the line-transect method (USDA-NRCS, 2002) using a 50-ft measuring tape. Residue hits or misses were evaluated at each of the 50 footmarks. The tape was laid out over the two diagonals of each plot. This way, 100 points per plot were evaluated. The percent residue cover equals the total number of residue hits out of 100 point evaluations. Residue mass was measured by collecting three (residue-covered plots) or two (bare-soil plots) samples from each plot. The area of each sample was 30 inch (equal to the row spacing) by 20 inch. Maximum and average residue thickness was measured inside each sample area using a ruler. The average thickness was area-weighted and was an estimate rather than a measurement.

The residue mass, mostly from previous no-till soybean crops, on the residue-covered plots was slightly greater than 3000 lb/ac in 2007 (Table 1). In October 2007, the bare-soil plots were no longer bare, because many newly-senesced corn leaves covered the soil surface, explaining the average residue cover of 81% (Table 1). 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). An additional <u>2.5 to 3.5 inches</u> of irrigation water on the bare-soil plots would be required to produce the same yield as obtained in the residue-covered plots.

Table 1. Residue cover, mass, and thickness for bare-soil and residue-covered plots. Residue cover data is the result of evaluating 100 points for the presence or absence of residue (2 times 50 points on a 50-ft measuring tape). Mass and thickness data is the mean of three (residue-covered plots) or two (bare plots) samples per plot.

JUNE 2007									
Bare-soil plots					**Residue-covered plots**				
			Thickness					**Thickness**	
plot #	**Cover %**	**Mass lb/ac**	**Avg. inch**	**Max. inch**	**plot #**	**Cover %**	**Mass lb/ac**	**Avg. inch**	**Max. inch**
62	2	113	<0.04	0.31	61	63	2950	0.47	1.30
72	1	216	<0.04	0.59	71	60	3263	0.59	1.50
81	1	91	<0.04	0.79	82	66	2925	0.47	1.10
83	3	102	<0.04	0.51	73	63	3873	0.51	1.57
Mean	**2**	**130**	**<0.04**	**0.55**	**Mean**	**63**	**3253**	**0.51**	**1.38**
St. dev.	**1**	**50**	**0.00**	**0.16**	**St. dev.**	**2**	**382**	**0.04**	**0.20**
OCTOBER 2007									
Bare-soil plots					**Residue-covered plots**				
			Thickness					**Thickness**	
plot #	**Cover %**	**Mass lb/ac**	**Avg. inch**	**Max. inch**	**plot #**	**Cover %**	**Mass lb/ac**	**Avg. inch**	**Max. inch**
62	82	1203	0.08	0.20	61	91	2671	0.39	0.98
72	77	1533	0.08	0.28	71	95	2868	0.47	1.10
81	79	1153	<0.04	0.39	82	95	3218	0.39	1.38
83	87	828	<0.04	0.20	73	94	3438	0.35	1.26
Mean	**81**	**1179**	**0.04**	**0.28**	**Mean**	**94**	**3049**	**0.39**	**1.18**
St. dev.	**4**	**250**	**0.04**	**0.08**	**St. dev.**	**2**	**298**	**0.04**	**0.16**
JULY 2008									
Bare-soil plots					**Residue-covered plots**				
			Thickness					**Thickness**	
plot #	**Cover %**	**Mass lb/ac**	**Avg. inch**	**Max. inch**	**plot #**	**Cover %**	**Mass lb/ac**	**Avg. inch**	**Max. inch**
62	2	150	<0.04	0.51	61	88	5281	0.51	1.46
72	1	249	<0.04	0.51	71	89	6854	0.67	2.36
81	3	503	<0.04	1.18	82	90	4656	0.51	1.77
83	2	502	<0.04	0.51	73	97	7132	0.71	2.09
Mean	**2**	**352**	**<0.04**	**0.67**	**Mean**	**91**	**5981**	**0.59**	**1.93**
St. dev.	**1**	**155**	**0.00**	**0.28**	**St. dev.**	**4**	**1040**	**0.08**	**0.35**

This assumes that the yield difference was entirely due to the corn in the bare plots experiencing more water stress. There are good reasons for this assumption. Visually, there were signs that the corn in the bare-soil plots was water-stressed more than the corn in the residue-covered plots: in September the corn on the bare-soil plots turned brown earlier than the corn in the residue-covered plots. It is unlikely the yield difference was caused by a lack of nutrients in the bare-soil plots, because the corn was fertilized adequately in all plots. Also, it is unlikely differences in compaction caused the difference in yield because all plots had the same history up to the residue removal in April 2007. Compaction differences may be expected in long-term no-till plots compared to long-term tilled plots, but not over this short time frame.

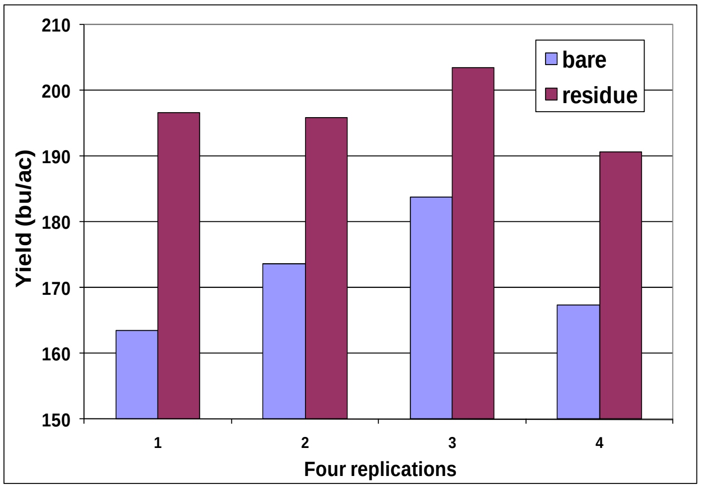

Figure 3. Corn yield on bare soil (avg. 172 bu/ac) and residue-covered soil (avg. 197 bu/ac) in 2007 at North Platte on small field plots.

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. It would take an additional 1.5 to 2.5 inches of irrigation water on the 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 (Figure 4). The soil dried out quickly at the shallower depths (Figure 4a, b) during late June and July, especially in the bare-soil plots. This may have been because of greater evaporation in the bare-soil plots, but most likely also because the corn plants were bigger in the bare-soil plots at this time, therefore using more water than the plants in the residue-covered plots. This difference in plant development was visually observed in all four replications and likely caused by soil temperatures being cooler in the residue-covered soil in May and June. A difference in plant size was not observed in 2007 when the weather during the early growing season was warmer than in 2008, thus making cooler temperatures under residue less of an issue for the growth of corn plants.

Two irrigations during late July 2008 caused the soil water content to increase at the shallower depths (Figure 4a, b). By the first half of August, the bare-soil plots were much drier than the residue-covered plots in the top 4 ft of soil (Figure 4a, b, c, d) but not yet at the greater depths (Figure 4e, f). During late August and September, the soil dried out faster in the bare-soil plots than in the residue-covered plots at the two deepest depths (Figure 4e, f). At the shallower depths (Figure 4b, c, d), the bare-soil plots no longer dried out, whereas the residue-covered plots still did. Apparently, in the bare-soil plots, the corn plants could no longer easily find water at the shallower depths, but they could find it at the deeper depths.

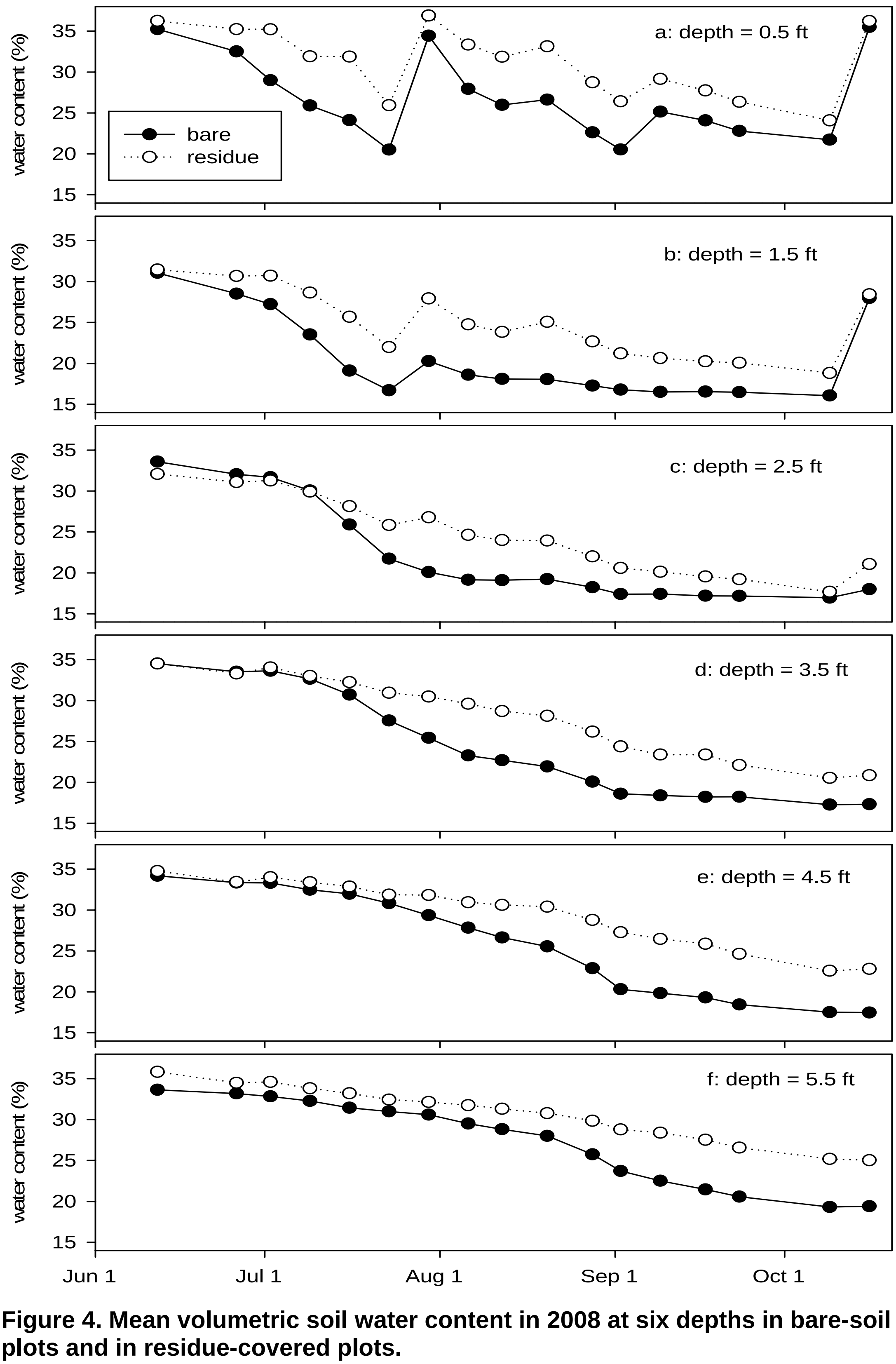

Figure 4. Mean volumetric soil water content in 2008 at six depths in bare-soil plots and in residue-covered plots.

At the end of the 2008 growing season, there was 1.5 inches more water in the residue-covered plots than in the bare-soil plots in the top 4 ft. Thus, the combined effect (actual water plus water needed to produce the extra yield of 17 bu/ac) in 2008 is estimated to be a total of 3 to 4 inches of water savings on the residue-covered plots.

In April 2009, residue was again removed from the same four plots as in the two previous years. As before, all plots were irrigated at the same time with the same amount of water, but the crop (soybean this time) 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. As in 2008, the residue-covered plots held 1.5 inches more water towards the end of the 2009 growing season in the top 4 ft.

ECONOMIC BENEFITS

The economic benefits of the water savings discussed here can be calculated. Less irrigation water needs to be pumped when water is saved with more residue/less tillage. This translates into a savings in pumping cost. An example follows:

- Water savings anticipated from more residue/less tillage: 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.
- Pumping cost savings is shown in Table 2.

Table 2. Pumping cost savings ($) resulting from the above conditions for a dynamic pumping lift ranging between 0 and 400 ft and a cost of diesel fuel ranging between $2.00 and $4.00 per gallon.

Lift (ft)	$2.00	$2.50	$3.00	$3.50	$4.00
0	$1025	1281	1538	1794	2050
50	1469	1836	2203	2570	2937
100	1912	2390	2868	3346	3824
150	2356	2945	3534	4123	4712
200	2799	3499	4199	4899	5599
250	3243	4054	4865	5675	6486
300	3687	4608	5530	6452	7373
350	4130	5163	6195	7228	8260
400	4574	5717	6861	8004	9148

For example, for a dynamic pumping lift of 150 ft and diesel at $2.50 per gallon, the pumping cost savings is $2945. A calculator was developed to make the above calculations using your own input data. It is available at *http://water.unl.edu/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 the 2007 experiment at North Platte, described above. For corn at $3/bu, this would be $75/acre and almost $10,000 for a 130-acre field. For a soybean yield that is 10 bu/ac higher (2009 case at North Platte), with soybean at $10/bu, this would be $100/acre and $13,000 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. Light, frequent rains or irrigations are less effective than heavy, infrequent ones, because, with every wetting event, evaporation takes place from the crop canopy, the residue, and the soil.

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.

Research at Garden City, Kansas showed that a 5-inch water savings is possible with a cover of wheat straw or no-till corn stover. Earlier UNL research results at North Platte, Nebraska largely agree with the findings from Kansas. Another study was initiated in 2007 at North Platte, on 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 2007, the average corn yield was 25 bu/ac more in the residue-covered plots compared to the bare-soil plots. It would take approximately 3 more inches of irrigation water on the bare-soil plots to reach the same yield as obtained in the residue-covered plots. Results were similar in 2008 and 2009.

Water conservation of the magnitudes discussed here will help reduce pumping cost significantly, which can amount to a savings of a few thousand dollars on a typical 130-acre field. But not only irrigators would benefit, because more water would be available for competing needs including those of wildlife, endangered species, municipalities, hydroelectricity plants, and compacts with other states.

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Crop Residue and Soil Physical Properties

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INTRODUCTION

Soil physical properties such as bulk density, porosity, water sorptivity, and aggregation dictate the water infiltration characteristics of the soil. Most important are the physical properties of the surface soil as this layer is the initial soil-water interface. Crop residue and tillage management may affect surface soil physical properties important to water capture and infiltration. Management practices that minimally disturb the soil and produce, return, and leave more residue biomass on the soil surface (such as no-till) have the potential to decrease soil bulk density, increase porosity, and increase sorptivity in the soil over time. Also, systems that produce, return, and leave the largest amounts of crop residue in the soil have the highest potential for increased root activity, soil aggregation, and channels that can increase water infiltration.

A study was conducted to determine the effect of crop residue on soil physical properties after 12 years of dryland no-till cropping management in eastern Colorado. Although the study was conducted under dryland conditions the principles behind crop residue and its effect on soil physical properties hold under irrigated condition as well. The objectives of the study were: (1) determine how differing amounts of crop residue affect bulk density, soil porosity, and soil aggregation in the surface 1 inch of soil after 12 years. And, (2) determine how these soil physical properties affect water sorptivity.

MATERIALS AND METHODS

Crop Residue:

Annual post-harvest above ground crop residue samples were collected across 3 cropping systems of increasing production intensity (wheat-fallow, wheat-corn-fallow, and continuous cropping) using a 39.4 inch quadrant for 12 years. Samples were sifted to remove any soil, dried, and weighed. The cropping systems created a gradient of crop residue returned to the system, from relatively low, to relatively high. The overall amount of residue returned to each system over a 12 year period was then tabulated.

Soil Bulk Density and Porosity:

Bulk density was determined using a modified core method. Exact procedures for determining bulk density are listed in Shaver et al. (2002).Samples were collected across 3 cropping systems of increasing production intensity (wheat-fallow, wheat-corn-fallow, and continuous cropping). Soil total porosity was then calculated using bulk density and particle density figures.

Sorptivity:

Sorptivity is defined as the cumulative infiltration proportionality constant and is essentially a measure of the amount time it takes a given head of water to infiltrate. Sorptivity measurements were collected across all positions using rings pushed into the soil surface by hand. Any debris or plant material that could be removed without disturbing the surface was removed. Water was poured into the ring to a depth of 1 cm (.4 inches). A stopwatch was used to measure the time it took for the water to infiltrate. Sorptivity was calculated using the following equation (Smith 1999):

Sorptivity (s) = 1 / $\sqrt{t}$ Where: 1 = head of water (cm) t = time (seconds)

Aggregation and Organic Carbon:

Soil samples from each position were collected and then analyzed in the lab to determine aggregate stability. Organic carbon content was also determined from these samples. A detailed synopsis of the procedures are listed in Shaver et al. (2002).

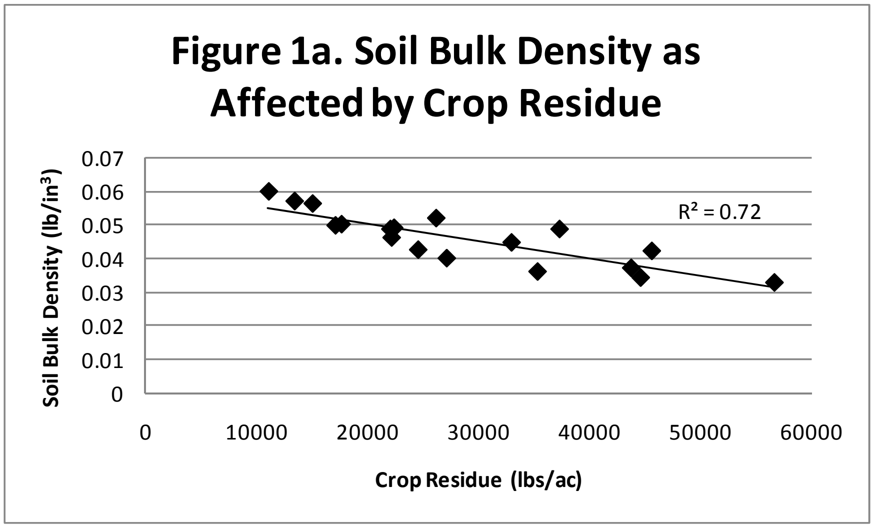
Analysis:

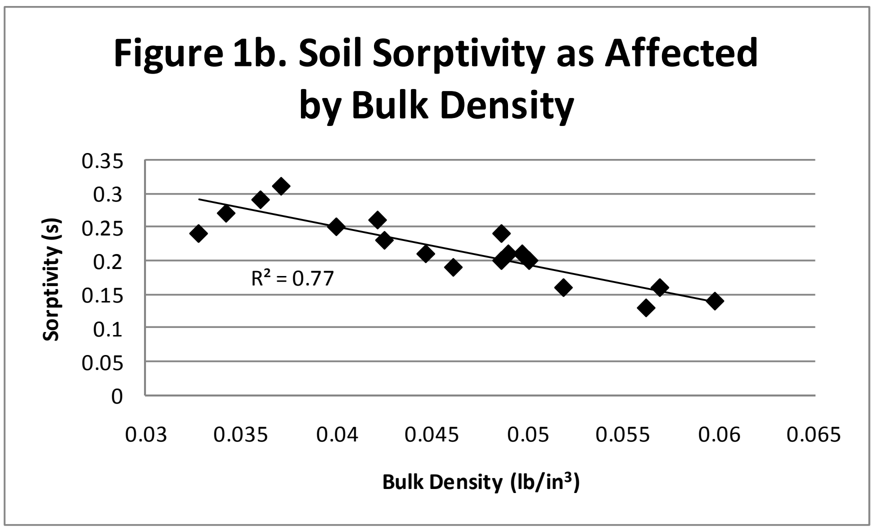
Regression analysis was performed to determine the linear relationship between crop residue and soil bulk density, soil porosity, soil aggregation, and aggregate organic carbon. Similar analysis was performed to determine the linear association between sorptivity and the aforementioned soil physical properties.

RESULTS

Bulk Density:

Bulk density is an important soil property because it affects soil porosity, which in turn affects water infiltration. Systems that produce and return more crop residue to the soil surface should reduce its bulk density because under no-till conditions the residue accumulates in the surface soil. This accumulation should do three things: 1) Residue is lighter than mineral matter, and therefore bulk density should decrease by dilution; 2) Residue decomposition products should promote more aggregation and thus reduce bulk density; and 3) The root activity in the surface should increase because of the improved water conditions and the root activity in turn favors aggregation.

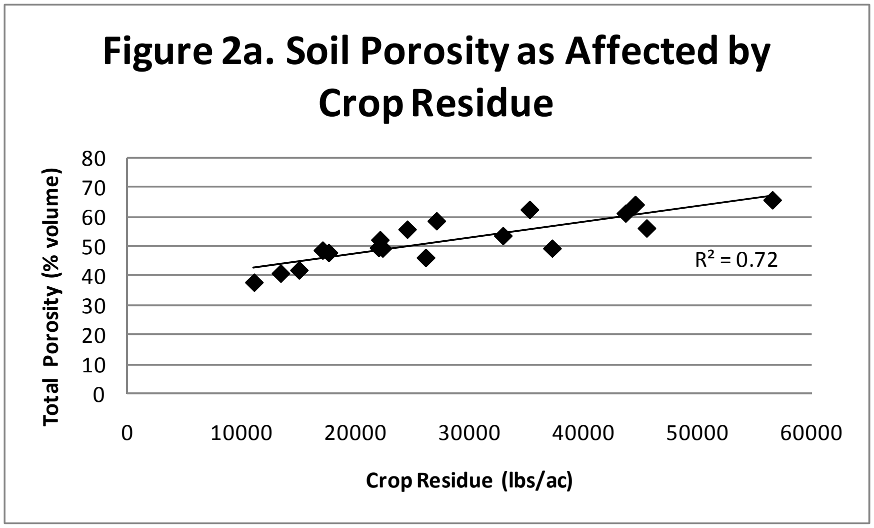


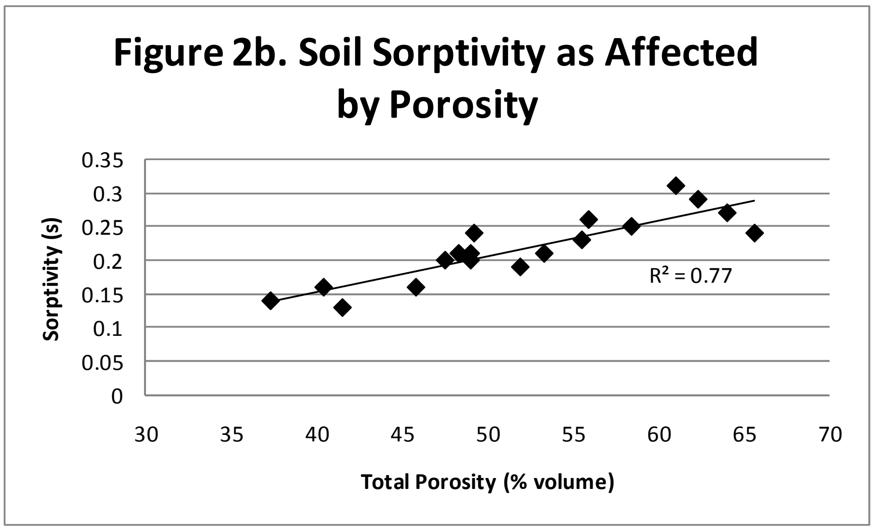


Our results indicate that increased quantities of crop residue decrease soil bulk density over time and that 72% of the variability observed in bulk density was explained by the amount of crop residue returned to the system over the 12 year period (Figure 1a). As soil bulk density decreases with crop residue addition, water sorptivity increases linearly with bulk density (Figure 1b) meaning water enters the soil more quickly as bulk density decreases. Results also show that 77% of the variability observed in sorptivity can be explained by bulk density. These results suggest that increased amounts of crop residue coupled with no-till management can lead to beneficial soil properties that can increase levels of water sorptivity and infiltration.

Porosity:

Porosity is directly related to bulk density because as bulk density decreases, porosity increases. As aggregates form and increase in size, inter-aggregate and intra-aggregate cavities form and increase. These cavities connect with other cavities creating conduits for fluid transport.

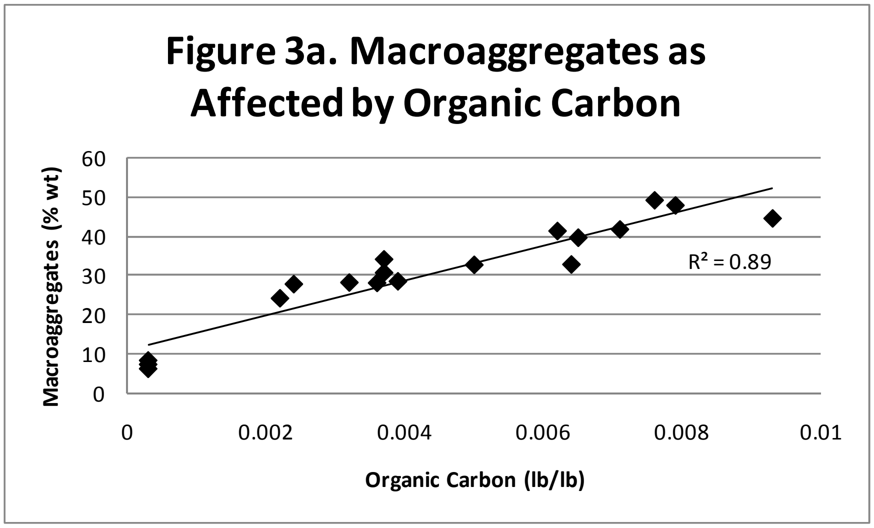


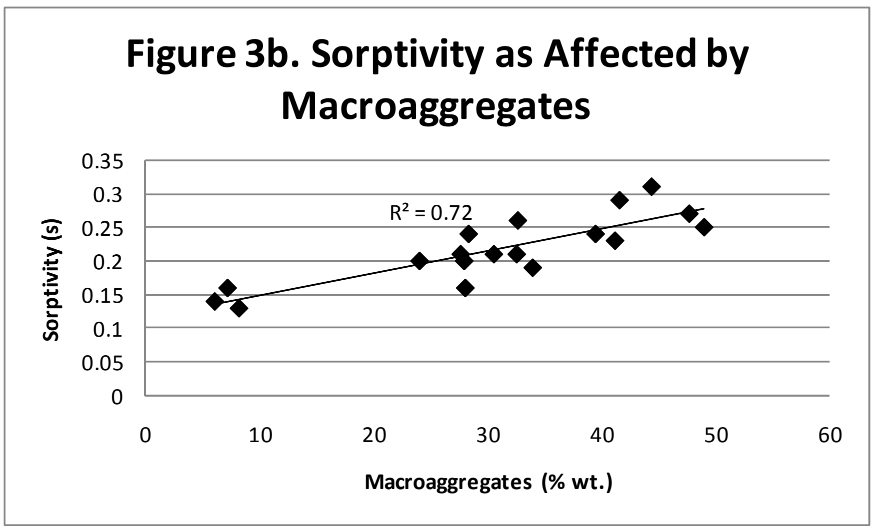


By utilizing management practices that increase the porosity we should be able to increase water capture as well. Our results show that porosity was related to crop residue production (Figure 2). As crop residue increased, so did soil porosity and nearly 72% of the variability in porosity was explained by biomass production. Our results also show that sorptivity is highly related with soil porosity (Figure 2b). This is to be expected as the pores are how the water moves into and through the soil. These results again suggest that increased crop residue can lead to the development of soil physical properties that increase the potential for water getting into the soil.

Aggregation:

Aggregation is an important soil physical property because it affects water infiltration, wind and water erosion, and crop yield. Aggregation is affected by many factors, but most importantly by organic matter (from crop residue and roots) and soil texture. Aggregation is also a dynamic factor that is affected (reduced) by tillage. Increasing aggregation is important because of its affects on bulk density, porosity, and subsequently, infiltration and water use efficiency of the system. It is also important in decreasing soil erosion. All of these factors are important to crop production and sustainability.





Aggregates are generally placed in one of two categories, macroaggregates, and microaggregates. Microaggregates form first, and then combine to form larger and larger aggregate structures eventually building into macroaggregates (Elliott, 1986; Tisdall and Oades, 1982). Microaggregate stability itself is not affected by management practices or soil organic matter content (Elliott, 1986; Tisdall and Oades, 1980). Aromatic humic materials associated with amorphous Fe and Al compounds and polyvalent metal cations are thought to be responsible for microaggregate stability (Elliott, 1986; Tisall and Oades 1982). Macroaggregate stability has been correlated to sterols, lipids, organic carbon and many other organic matter structures (Monreal et al. 1995) that bind and stabilize macroaggregates. Thus, macroaggregates should increase as these binding agents increase with increased residue production and decomposition. Our study confirms past findings showing that as organic carbon increases so too did macroaggregation (Figure 3a), and organic carbon is directly related to crop residue quantities. Macroaggregation is important for water infiltration. As macroaggregates form larger channels and pores in the soil also form allowing for greater water capture. This is shown in Figure 3b. As macroaggregation increased sorptivity increased as well.

CONCLUSIONS

Overall, the results of systems that create and return higher levels of crop residue to the soil are positive. Soil physical properties are directly related to crop residue and by decreasing the bulk density and increasing porosity there is increased potential for rapid capture of water (both irrigated and rainfall), greater infiltration, and increased water use efficiency for the system. The decreased bulk density and increased porosity and macro-aggregation also decrease the potential for runoff, erosion, and evaporation by increasing the potential for faster water capture leaving more water available for plant use. This ultimately leads to a more efficient, sustainable, and economically viable system.

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LIMITED IRRIGATION OF CONVENTIONAL AND BIOFUEL CROPS

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BACKGROUND

Declining ground water is not a new dilemma in Nebraska or throughout the Great Plains. The drought across the High Plains and inter-mountain west from 1999 to 2008 magnified the seriousness of the problem, however. The passage of Nebraska legislation to conjunctively manage groundwater and surface water has changed ground and surface water management. In many areas it simply means less water for producers. The economic reality is that irrigation provides more stability and income than dryland farming. UNL research suggests that applying limited water to an optimum number of acres provides more profit potential and has less impact on the local economy than converting some land to dryland (Schneekloth et al., 2001).

Under limited irrigation, less water is applied than is required to meet full ET demand and the crop will be stressed. The goal is to manage cultural practices and irrigation timing such that the resulting water stress has less of a negative impact on grain yield. Previous NE research on the concepts of moisture conservation from dryland no-till ecofallow (Burnside et al., 1980) and the timing of limited irrigation (Garrity et al., 1982; Klocke, et al., 1989; Maurer et al., 1979) were combined in a project at North Platte, NE in the 1980's (Hergert et al, 1993; Schneekloth et al., 1991). Yields with 6 inches of irrigation for winter wheat (*Triticum asetivum* L.), corn (*Zea mays* L.) and soybean (*Glycine max* L.) were 99%, 86% and 88% of the fully irrigated yields (Hergert et al, 1993).

The western portion of the Central Great Plains is defined as the High Plains region. It presents challenges when converting to limited irrigation compared to eastern portions of the Great Plains because of lower rainfall, sandier soils and higher elevation. Alternative crops that use less water than corn and are adapted to this region include winter wheat, chickpea, canola, camelina, crambe, dry beans, sunflower, dry or forage pea, and millets and forage sorghums. Grain sorghums often do not perform because of lack of cold tolerance or inability to mature before killing frost. These crops use 16 to 18 inches of ET versus 23 to 25 inches for corn in the NE panhandle.

METHODS AND MATERIALS

Based on earlier research with limited irrigation at North Platte, NE experiments were initiated at Scottsbluff, NE in 2005. The soil is a Tripp very fine sandy loam (Coarse-silty, mixed, superactive, mesic Aridic Haplustolls) with a pH of 7.8 and an organic matter content of 1.2**%.** Slope ranges from 0.8 to 1.5%. Plant available water holding capacity of this soil is 1.5 in/ft for the 0 to 4 foot normal rooting depth. The 30-yr average precipitation at Scottsbluff (elevation 3900 ft) is 15.5 in with a mean annual temperature of 48^0 F. The frost-free period (50% probability) is 125 days. The primary objectives of this experiment were (1) to determine yields from limited-irrigated corn, winter wheat, dry beans and canola grown in a no-till cropping system versus full irrigation and (2) to determine the agronomic feasibility and problems encountered in using no-till on crops that have primarily been grown under conventional full tillage in this area.

The cropping system initially included winter wheat, corn, and dry beans (*Phaseolus vulgaris*) grown under no-tillage. In 2006, spring canola (*Brassica napus*) was added following wheat. This provided a cropping system with two grass crops and two broadleaf crops. Inclusion of canola also allowed for more timely planting of winter wheat. Canola is harvested in August. Planting winter wheat after dry beans is a challenge some years due to late maturity of the beans which delays wheat planting beyond optimum time (mid-September) and affects wheat stand and ultimate yield potential, especially under full irrigation.

Each phase of the rotation is present each year under a linear move sprinkler irrigation system. A randomized complete block design with four replications was used. The irrigation levels for the crops were 4, 8 and 12 inches per crop per growing season. In 2007, the irrigation levels for the corn were changed to 5, 10 and 15 inches. The highest irrigation level was designed to be near the long-term average non-ET limiting irrigation. Individual plots are 40 ft by 70 ft. All crops were surface planted with no-till equipment. A Monosem® planter fitted with finger-spoke disk furrow openers and a single-disk starter fertilizer attachment 2 in to the side of the row were used for corn and dry beans. A no-till drill was used to plant winter wheat and canola (7.5 in row spacing). Plant populations for dry beans (96,000/ac), canola (7 lb/ac) and winter wheat (110 lb/ac) were the same for all water levels, but were modified for corn based on prior research. Corn plant populations for the low, medium and high irrigation levels were 16,000/ac, 24,000/ac and 32,000/ac.

The lowest level limited irrigated corn was usually not irrigated until tassel emergence based on conclusions from Maurer et al. (1979) but in extremely dry years (2007 and 2008) some water was applied earlier. Irrigations of 1 to 2 in per week approximating farmer practice were applied from late vegetative stage until water was used. For the medium irrigation level, irrigation was started earlier in the vegetative period. Similar strategies were used for winter wheat. For canola at the lowest water level, irrigation was applied during flowering and early pod-fill as noted periods of stress sensitivity (Nielsen, 1997). For higher levels irrigation began earlier and was extended through pod-fill.

For dry bean, the lowest irrigation level presented a management challenge as there was not published information on irrigation timing for limited water. After our first two years, we learned that we could not withhold water until the reproductive period because it slowed development and delayed maturity which significantly reduced yield. After 2007, we applied limited amounts of irrigation (usually ½ in per week) beginning about 50% cover to keep the crop growing and developing with limited stress. Irrigation was usually completed just as pod-fill began. Irrigation scheduling was modified depending on rainfall, but during this experiment with drought in 2006 through 2008, that was not a consideration during the high water use periods except during 2005 and 2009. Rainfall for the five years was: 2005: 19.6 in; 2006: 13.3 in; 2007: 8 in; 2008: 11" and 2009: 19.76 in.

Herbicides were selected to provide optimum weed control in the current crop without carryover that would injure the next crop. Roundup®-ready corn and canola were used. Plots were routinely scouted during the summer for insect problems. Helix seed treatment was required for canola to protect against flea beetle but no other insects were a problem. Because of the crop rotation there were not major insect problems in the other crops and plant diseases were not a problem. There was some spider mite infestation on corn, but it did not reach economic thresholds that required treatment.

RESULTS AND DISCUSSION

Wheat Yields

Winter wheat yields are shown in Table 1. For the initial year (2005) spring wheat was planted as the plot area was in corn during the fall of 2004 so winter wheat could not be planted. Spring wheat was planted early, stands were excellent but the low yields compared to what we can grow using winter wheat show why irrigated spring wheat is not an economically viable option for the panhandle.

Table 1. Wheat yields at Scottsbluff.

	2005*	2006	2007	2008	2009**
Irrig	------Bushels per acre------				
0 in	40	45	20	25	50
4 in	53	83	45	55	58
8 in	58	91	75	78	72
12 in	57	100	100	99	72

*Spring wheat yields, winter wheat 2006 and later.
**Sooty mold and black point reduced yields due to wet conditions

The 0 inch irrigation data is provided only as a comparison and in most cases is a county-average from NE Agricultural Statistic or represents data from companion studies in the plot area that are true dryland. The 0 inch irrigation yields also show that continuous dryland yields in this environment are very low many years, ranging from 0 to only 25% of fully irrigated yields. The average relative yields for the four years of winter wheat were 67% for the 4 in treatment and 88% for the 8 in treatment. Because both 2006 and 2007 were so dry, maximum yields were not attained unless full irrigation was applied. In an 'average' year or wetter year such as 2005 or 2009, the 8 inch irrigation or less would produce near maximum yields.

Relative yield levels were calculated each year and are presented in Figure 1. Over the course of the experiment we have established an upper and lower boundary that hopefully encompasses the range of wet to dry conditions we might see. This information can be used to check against current optimization programs as verification and provide information for economic analysis.

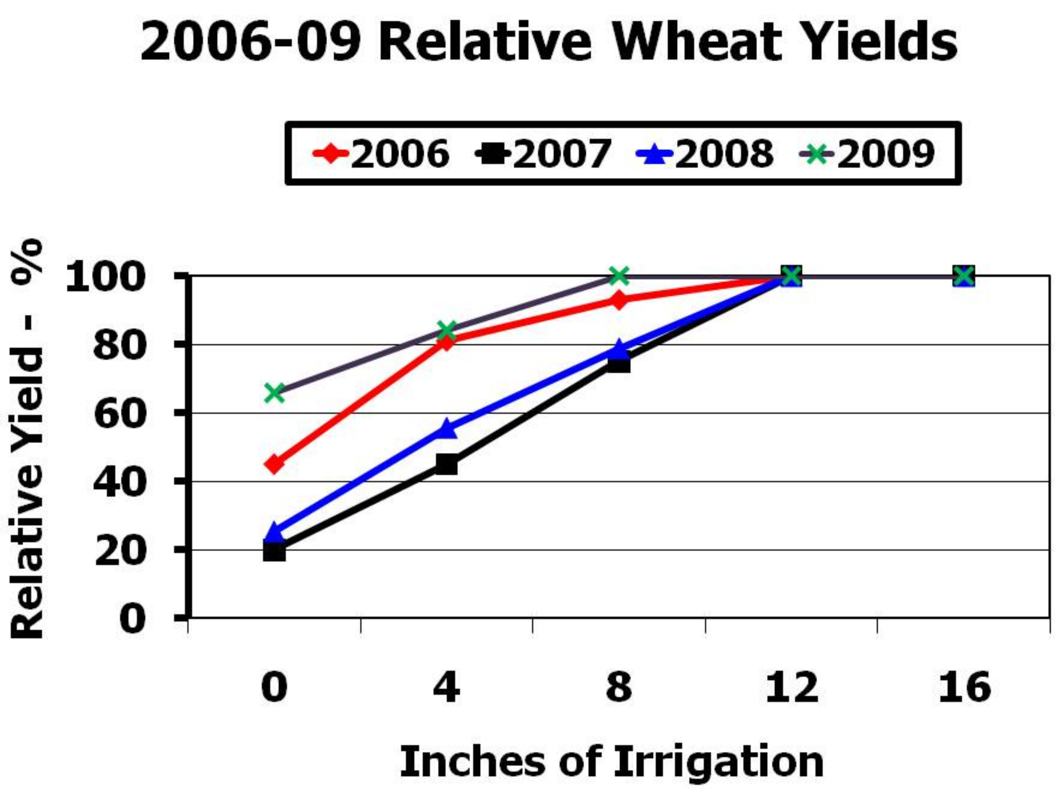

Figure 1. Relative winter wheat yields 2006 through 2009.

Table 2 shows corn yields for the five years. During 2007, a late freeze on June 8 caused severe damage, but plants did recover. Maturity was not affected, but overall yield potential was decreased.

Table 2. Corn grain yields at Scottsbluff.

Irrigation	2005	2006	2007	2008	2009
	----------------Bushels per acre----------------				
0 in	81	30	30	60	90
5 in	133	139	97	115	149
10 in	153	172	139	165	185
15 in	174	188	172	183	194

The average relative yields over five years were 69% for the low irrigation treatment and 90% for the medium treatment. Good yield increases were obtained for the last increment of water for corn which is why most producers try to fully irrigate. Relative corn grain yields are shown in Figure 2.

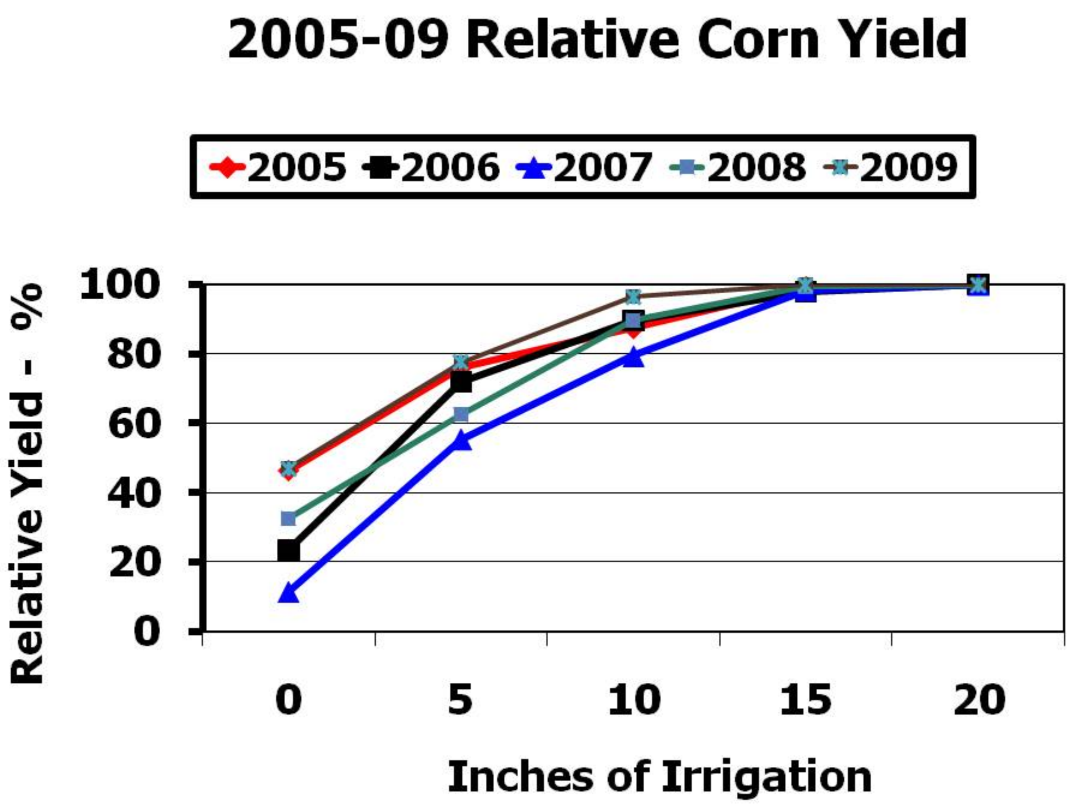

Figure 2. Relative corn grain yields 2005 through 2009.

Dry bean yields are shown in Table 3. During 2006, herbicide damage decreased plant vigor and delayed maturity but because of a warm and late fall beans did mature before frost. Maturity was not affected, but overall yield potential was decreased compared to other years.

Table 3. Dry bean yields at Scottsbluff.

Irrigation	2005	2006	2007	2008	2009
	----------------Pounds per acre----------------				
0 in	1,000	400	300	300	1500
4 in	2,140	1,310	1,050	1562	2280
8 in	2,580	1,560	1,640	1783	2660
12 in	2,560	1,800	2,265	2160	2950

For dry beans, average relative yields over five years were 71% for the 4 in treatment and 87% for 8 in irrigation. As with winter wheat, in more normal years, the 8 in application would normally produce 90% of maximum yields. Relative yields are shown in Figure 3.

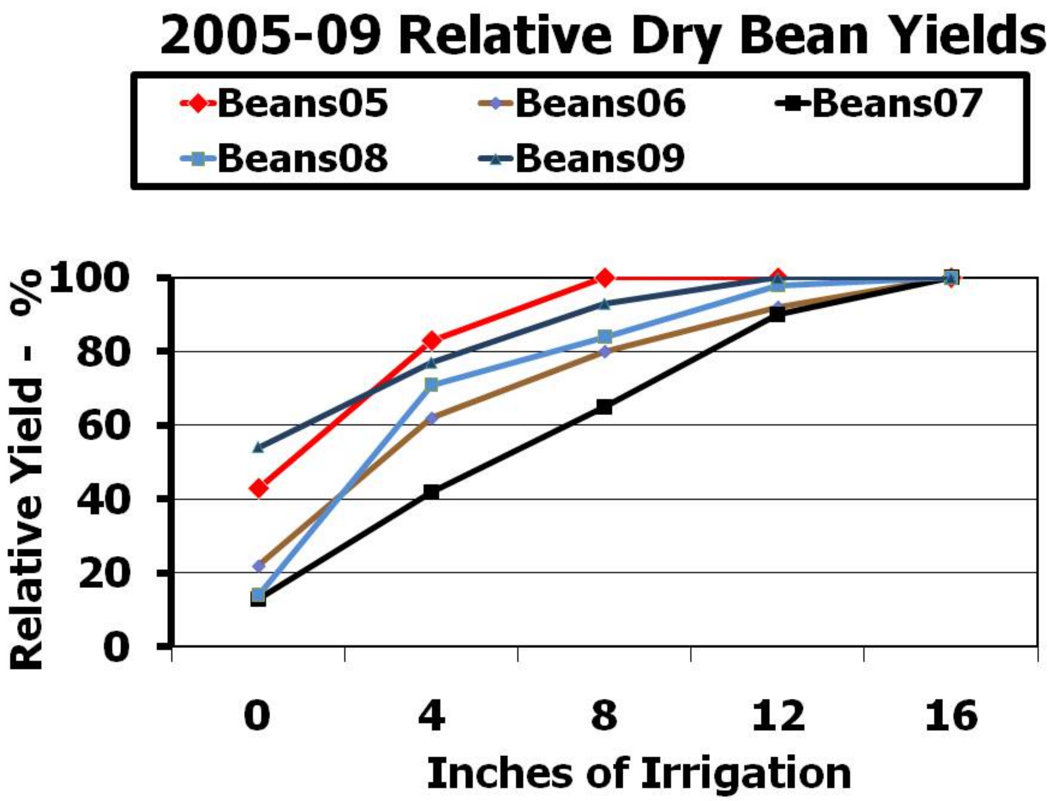

Figure 3. Relative dry bean yields for 2005 through 2009.

Spring canola yields are shown in Table 4. Canola was not grown until 2006. Canola is a new crop for the area and yields did improve after our first learning year determining appropriate cultural practices, especially planting date and irrigation. Yield levels are good for this area and compared to major canola regions in the southern Canadian provinces and the Northern Great Plains but are not as high as could be obtained with winter canola grown in climates with less extreme winters. The problem with winter canola is that it does not fit these rotations well. The only crop it can follow is winter wheat as it must be planted in mid-August. It also is subject to winter-kill about 50% of the time in this area.

Table 4. Spring canola yields.

Irrigation	2006	2007	2008	2009
	----------------Pounds per acre----------------			
0 in	1,000	1,000	300	2450
4 in	2,050	2,040	1562	2650
8 in	2,110	2,485	1783	2630
12 in	2,140	2,740	2160	2650

The average relative yields for canola over four years were 82% for the low irrigation treatment and 92% for the medium treatment. These higher yields reflect the ability of canola to use residual soil moisture from the 3 to 4 foot depths not used by the previous dry bean crop. Soil water data shows that canola effectively roots to 5 feet at this site. Canola has the potential to fit in limited irrigated rotations and is a viable oil seed crop for this region as it produces about twice as much oil per acre than soybean. Relative yields are shown in Figure 4.

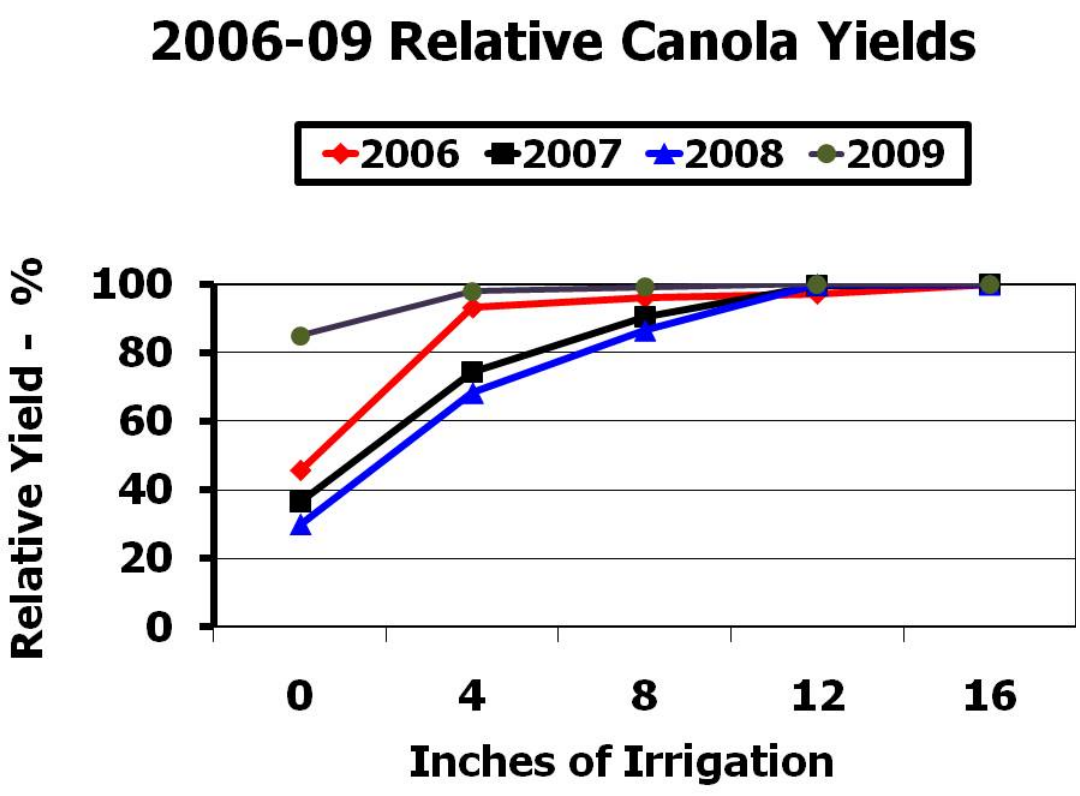

Figure 4. Relative canola yields for 2006 through 2009.

Conclusions

The data confirm much of the previous research on limited irrigation in higher rainfall regimes (Hergert et al, 1993). The shape of the irrigation response functions (relative yield versus irrigation) was generally curvilinear but they were much steeper than those at North Platte. Because three of the five years of this experiment received precipitation that was on average only 66% of the 30-year average, it was a severe test and there were much higher responses between the medium and high irrigation level than in the North Platte research. Winter wheat is a drought tolerant crop, but in this environment (higher elevation than North Platte) it has a 20% higher yield potential and will respond to additional water to reach that maximum yield level. At the lowest irrigation levels, most crops yields were only 45-50% of maximum yield except canola which produced at 76%. At the medium irrigation level corn, dry beans and wheat produced 70-75% of maximum yield whereas canola produced 90%. The data provide an excellent basis for determining the economic value of irrigation water and show the potential of no-till limited irrigated systems to sustain higher levels of productivity than most producers would deem possible with much less water than they have become accustomed to.

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DOES DEFICIT IRRIGATION GIVE MORE CROP PER DROP?

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Past studies have shown that the reduction in yield with deficit irrigation is usually less than the reduction in irrigation water applied - for example, a 30% reduction in irrigation results in only a 10% reduction in yield. This means the marginal productivity of irrigation water applied tends to be low when water application is near full irrigation. This results either from increased efficiency of water applications (less deep percolation, runoff, and evaporation losses from irrigation and better use of precipitation) with deficit irrigation, or from a physiological response in plants that increases productivity per unit water consumed when water is limited. Economically managing limited water supplies will often involve deficit irrigation rather than reducing acreage. Likewise, if water supplies can be transferred or sold for other uses and the value is higher than the value of using the water to produce maximum yields, selling the water can increase the farm income.

In Colorado, there is continuing need for additional water supplies for growing cities, groundwater augmentation, and environmental restoration. This water is usually purchased from agriculture through “buy and dry” – purchasing the water rights and fallowing the land. Limited irrigation may be an alternative way to provide for other water needs while sustaining productive agriculture. However, in fully allocated basins where one farmer’s return flows becomes water supplies for downstream users, only the consumed portion of irrigation supplies – that lost to evapotranspiration - can be sold and the return flows must be maintained. Thus, it becomes critical to evaluate limited irrigation based on reductions in water consumptive use (CU) or equivalently, evapotranspiration (ET) rather than irrigation applications.

Improved irrigation efficiency is not likely to produce much transferable water because it results primarily in a reduction of return flows rather than a reduction in ET. If significant transferable water is to be produced by deficit irrigation, it must result from reduced ET. For deficit irrigation to provide economic benefits to growers, it must result in improved efficiency of the crop to convert ET to yield. Thus, the “maximize crop per drop” slogan must in reality be to maximize crop per consumptively used drop.

Although many limited irrigation studies have been carried out in the high 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 high plains crops – corn, dry beans, wheat, and sunflower - under a wide range of irrigation levels from fully irrigated to rainfed. We are measuring ET of the crops under each of these conditions. 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.

The Limited Irrigation Research Farm - LIRF

A 50 acre research farm northeast of Greeley, CO was developed to enable the precision water control and field measurements required to accurately measure ET of field crops. The farm, originally known as the Potato Research Farm and later as the Northern Colorado Research and Demonstration Center had been operated collaboratively by CSU and ARS for many years (in the 1980s, Harold Duke and students conducted surge irrigation trials there), but had not been in active research for over 20 years. The predominately sandy-loam soils and good groundwater well are ideal for irrigation research.

Four crops – winter wheat, field corn, sunflower (oil), and dry beans (pinto) are 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 only 40% of the fully irrigated amount. Deficit irrigations are timed to maximize production – usually by allowing relatively higher stress during early vegetative and late maturity stages and applying extra water to reduce stress during reproductive stages.

We apply irrigation water with drip irrigation tubes placed on the soil surface in each row. In this way we can accurately measure applications and know that the water is applied uniformly. This is essential to be able to complete the water balance. Water applied to each irrigation plot is measured with flow meters. Four crops, six irrigation levels, and 4 replications results in 96 individual plots.

A CoAgMet (Colorado Agricultural Meteorological Network) automated weather station is located on the farm near the center of a one acre grass plot. Hourly weather data from the station are used to calculate ASCE Standardized Penman-Monteith alfalfa reference evapotranspiration (ETr). Soil water content between 6 inches and 6 ft depth is measured by a neutron probe from an access tube in the center of each plot. Soil water content in the surface 6 inches is measured with a portable TDR system. Irrigations are scheduled using both predicted soil water depletions based on ETr measurements, and measured soil water depletion.

Plant measurements are taken periodically to determine crop responses to the water levels. We record plant growth stage and measure canopy cover with digital cameras. The digital cameras along with spectral radiometers and an infrared thermometer are mounted on a “high boy” mobile platform and driven through the plots weekly. Indicators of crop water stress such as stomatal conductance, canopy temperature, and leaf water potential are measured periodically. At the end of the season, seed yield and quality as well as total biomass are measured from each plot. On one field on the farm, crop ET is measured with energy balance instruments (Bowen Ratio method) for well watered crops. These measurements allow crop coefficients to be estimated for the crops. On other fields on the farm, we are cooperating with CSU faculty to test wheat and dry bean varieties under varying irrigation levels.

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.

RESULTS

This project began in 2008. We will summarize the first two years of corn results in this article. Figure 1 shows the yield:water relationship for corn for each year. Irrigation applications (the irrigation data and lines on the left side in the figure) varied from about 430 mm (17”) for the fully irrigated crop down to 120 mm (5”). When precipitation is added in (about 230 mm (9”) each growing season), deep percolation below the root zone is subtracted out, and depletion of stored soil water is included, the evapotranspiration for the crops varied from about 590 mm (23”) down to 380 mm (15”). Of that ET, about 60 – 90 mm was evaporation from the soil surface and the remainder was transpiration through the plants. Soil evaporation would be higher with sprinkler or furrow irrigation. 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 top (red) data in the figure are total above ground biomass (dry weight) and the bottom lines (blue) are grain yields. Grain yields varied from 13 Mg/ha (200 bu/ac) at full irrigation down to 6 Mg/ha (100 bu/ac) and biomass was about double grain yields. Hail damage in 2009 resulted in about 15% lower grain yields but little difference in total biomass. Harvest index (the portion of total biomass that is grain) ranged from 50 – 60% and did not vary with irrigation level.

The water production function for grain (blue lines) based on applied irrigation water curves downward as the water application decreases, showing that the decrease in yield for each unit decrease in water applied is relatively small when the deficit is small, but the rate of yield decrease gets larger as the deficit

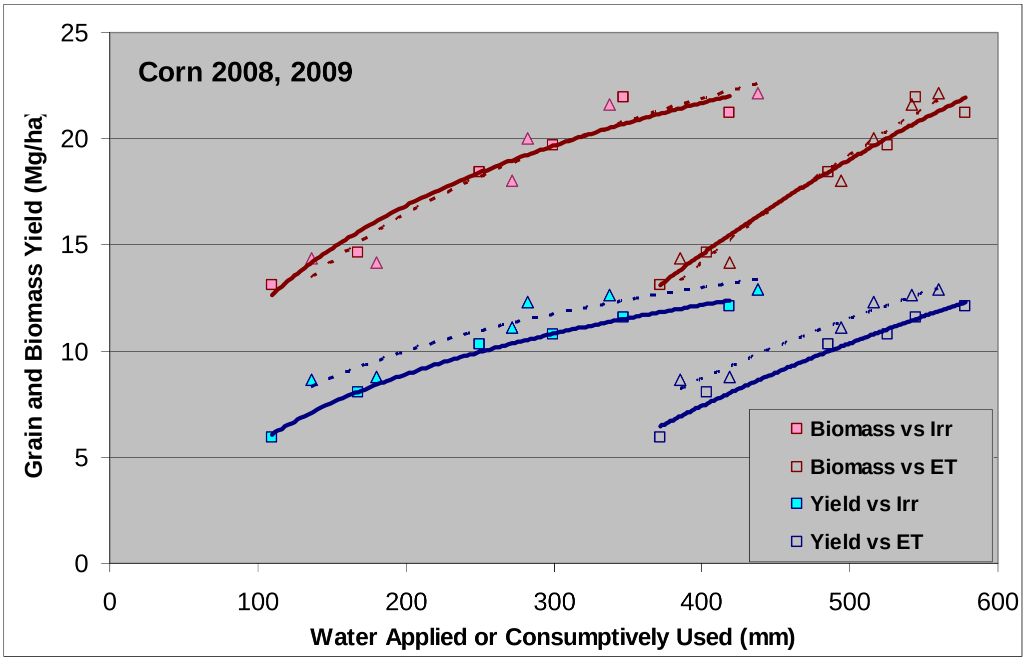

Figure 1. Water production functions for 2008 and 2009 corn. Red lines (top two lines) are total biomass (dry wt.). Blue lines (bottom two lines) are grain yield (15.5% moisture content). Yields are plotted relative to irrigation amount (Irr) and crop ET. Triangles and dashed lines are 2008 data. Squares and solid lines are 2009 data.

Figure 2. Comparison of corn growth condition on July 31, 2008 just before tasseling. Rows at the left and background are fully irrigated; rows at right are the lowest irrigation level.

increases. This means that the marginal value of irrigation water is relatively low near full irrigation, showing the potential benefit to the farmer of transferring water to higher-valued uses. The marginal value of water increases from about 1.3 kg/m^3 (60 bu/ac-ft) of water applied near full irrigation to 3 kg/m^3 (150 bu/ac-ft) at the lowest irrigation level.

However, the water production function for grain yield based on ET is relatively straight. This implies that the corn is equally efficient in it's 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 3 kg/m^3 (150 bu/ac-ft).

These results imply that nearly all 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 and deep percolation.

These results also imply that, based on consumptive use, there would be little or no yield benefit to deficit irrigation compared to fully irrigating only a portion of the land. In fact, fully irrigating less land would likely provide the highest economic returns due to lower production costs.

These preliminary results show the importance of developing water production functions based on the correct 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. However, for the purpose of transferring consumptive use savings, the productivity must be based on water consumed. The value of limited irrigation based on CU savings will likely be less, and if the crop is efficient at converting increased CU to yield, there may be no economic benefit to limited irrigation.

This limited irrigation study will be continued to confirm these initial results for each of the four crops.

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REDUCING THE COST OF PUMPING IRRIGATION WATER

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Energy Use in Irrigation

Irrigation accounts for a large portion of the energy used in Nebraska agriculture. Analysis of data from the 2003 USDA Farm and Ranch Irrigation Survey shows that the average energy use for irrigating crops in Nebraska was equivalent to about 300 million gallons of diesel fuel annually. A number of irrigation wells have been installed since 2003, thus energy use today is even higher. While use varies depending on annual precipitation, average yearly energy consumption is equivalent to about 40 gallons of diesel fuel per acre irrigated.

The cost to irrigate a field is determined by the amount of water pumped and the cost to apply a unit (acre-inch) of water (Figure 1). Factors that determine pumping costs include those that are fixed for a given location (in the ovals in Figure1) and those that producers can influence. The four factors that producers can influence include: irrigation scheduling, application efficiency, efficiency of the pumping plant, and for center pivots the pumping pressure required for the system. Pumping costs can be minimized by concentrating on these factors.

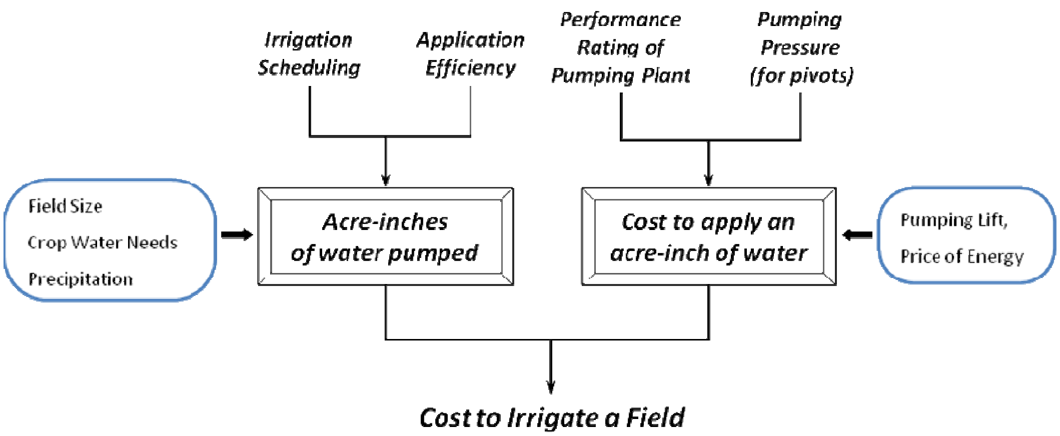

Figure 1. Diagram of factors affecting irrigation pumping costs

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

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

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

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

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

Energy Requirements

The cost to pump irrigation water depends on the type of energy used to power the pumping unit. Electricity and diesel fuel are used to power irrigation for about 75% of the land irrigated in Nebraska (Figure 2). Propane and natural gas are used on about 8 and 17% of the land respectively. Very little land is irrigated with gasoline powered engines.

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

- The amount of work that can be expected from a unit of energy.
- The distance water is lifted from the groundwater aquifer or surface water.
- The discharge pressure at the pump,
- The efficiency of the pumping plant, and
- The cost of a unit of energy.

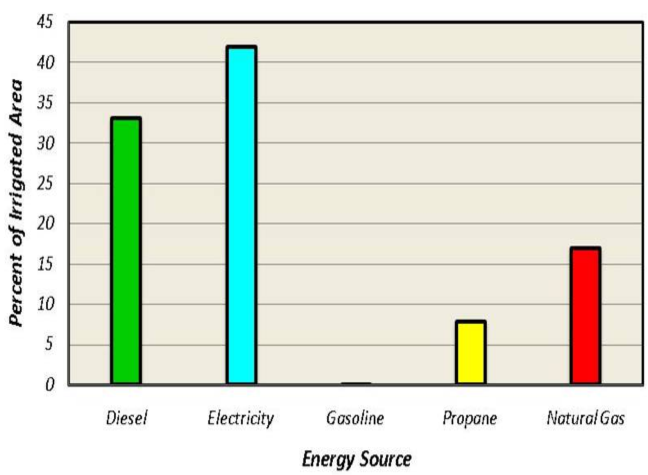

Figure 2. Percent of land irrigated in Nebraska by type of energy source (from USDA Farm and Ranch Irrigation Survey, 2003).

The amount of work produced per unit of energy depends on the source used to power the pump. For example one gallon of diesel fuel provides about 139,000 BTUs while propane provides about 95,500 BTUs/gallon. Clearly, more propane would be required to pump an acre-inch of water even if diesel and propane engines were equally efficient.

The Nebraska Pumping Plant Performance Criteria was developed to provide an estimate of the amount of work that can be obtained from a unit of energy by a well designed and managed pumping plant (Table 1). Values were developed from testing engines and motors to determine how much work (expressed as water horsepower hours) could be expected from a unit of energy for pumping plants that were well designed and maintained. The values reflect the amount of energy available per unit and how efficiently engines, motors and pumps operate.

Table 1. Amount of work produced per unit of energy used for a well designed and maintained pumping plant.

Energy Source	Value	Work Per Unit of Energy
Diesel	12.5	whp-hours / gallon
Gasoline	8.66	whp-hours / gallon
Propane	6.89	whp-hours / gallon
Natural Gas	61.7	whp-hours / 1000 ft^3
Electricity	0.885	whp-hours / kilowatt hour

whp stands for water horsepower

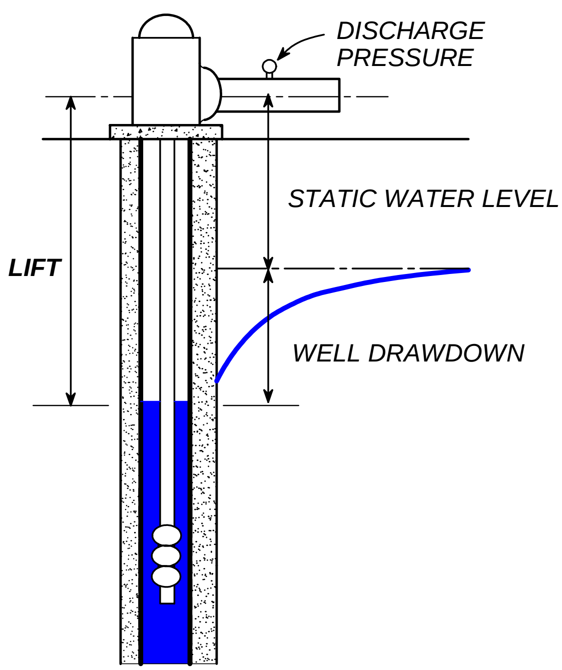

Figure 3. Diagram of pumping lift and discharge pressure measurements needed to assess pumping plant efficiency.

The pumping lift depends on the location of the water source relative to the elevation of the pump discharge. For groundwater the lift depends on the distance from the pump base to the water level when not pumping (static water level) plus the groundwater drawdown as shown in Figure 1. Note that the lift is not the depth of the well or the depth that the pump bowls are located in the well. The lift may increase over time if groundwater levels decline during the summer or over the years. It is best to measure the pumping lift directly but the value can be estimated from well registration information for initial estimates. Well registration information can be obtained from the Nebraska Department of Natural Resources at http://dnrdata.dnr.ne.gov/wellssql/

The discharge pressure depends on the pressure needed for the irrigation system, the elevation of the inlet to the irrigation system relative to the pump discharge, and the pressure loss due to friction in the piping between the pump and the irrigation system. It is best to measure the discharge pressure with a good gage near the pump base.

Pumping Plant Efficiency

The amount of energy required for a properly designed and maintained pumping plant to pump an acre-inch of water can be determined from Tables 2 and 3. For example, a producer who has a system with a pumping lift of 150 feet and

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

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

Table 3. Conversions for other energy sources.

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

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

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

operates at a pump discharge pressure of 60 pounds per square inch (psi) would require 2.63 gallons of diesel fuel to apply an acre-inch of water. If the producer uses electricity the value of 2.63 should be multiplied by the factor in Table 3 to convert energy units. So, (2.63 x 14.12) = 37 kilowatt-hours would be needed per acre inch of water.

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

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

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

Table 5. Volume of water pumped per hour.

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

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

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

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

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

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

For this case the performance rating is 85 meaning that the system uses about 17% more diesel fuel than required for a system at the Nebraska Criteria. The multipliers in Table 2 can also be used with the hourly method for other energy sources.

Paying for Repairs

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

Table 6. Series Present Worth Factor

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

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

Examples

Some examples will illustrate the procedure to estimate potential from improving a pumping plant.

Example 1

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

The analysis of this example is illustrated in the worksheet in Figure 4. An efficient pumping plant would require about 3843 gallons of diesel fuel for the year (*i.e.,* 2.19 gallons/acre-inches times 1755 acre-inches of water). If a producer's records show that 5500 gallons were used to pump the water, then the performance rating would be (3843 / 5500) x 100 = 70%. This shows that 1657 gallons of diesel fuel could be saved if the pumping plant performance was improved. The annual savings in pumping costs would be the product of the energy savings times the cost of diesel fuel; *i.e.,* $3/gallon times 1657 gallons/year = $4971/year. If a 5-year repayment period and 9% interest were used, the series present worth factor would be 3.89. The breakeven repair cost would be $4971 × 3.89 = $19,337. If repair costs were less than $19,337 then repairs would be feasible. If costs were more than $19,337 the repairs may not be advisable at this time.

Example 2

This example represents a center-pivot field irrigated with a pump powered by electricity. Details of the system are also included in Figure 4. In this case the pumping lift is 175 feet which is not listed in Table 2. The lift of 175 feet is half way between 150 and 200 feet so the amount of diesel fuel per acre-inch of water is estimated as 2.44 gallons per acre-inch (*i.e.,* halfway between 150 and 200 feet). Since electricity is used to power the pumping plant the multiplier of 14.12 is used in row M of Figure 4. The calculations for the second example are similar to the first example for the rest of the information in Figure 4. This pumping plant has a performance rating of 88% and given the cost of electricity only about $3,770 could be spent for repairs.

Example 3

This example illustrates the application of the hourly method for a propane powered pumping plant. This system has a performance rating of 88% and based on Table 4 13% of the annual energy cost could be saved if the pumping plant was brought up to the Nebraska Criteria.

Summary

This publication demonstrates a method to estimate the potential for repairing pumping plants to perform at the Nebraska Pumping Plant Performance Criteria. Producers frequently have several questions regarding the procedure.

First they want to know ***"Can actual pumping plants perform at a level equal to the Criteria"***. Tests of 165 pumping plants in the 1980s indicated that up to 15% of the systems actually performed at a level above the Criteria. So producers can certainly achieve the standard.

The second question is ***"What level of performance can producers expect for their systems?"*** Tests on 165 systems in Nebraska during the 1980s produced an average performance rating of 77% which translates to an average energy savings of 30% by improving performance. Tests on 200 systems in North

Dakota in 2000 produced very similar results. These values illustrate that half of the systems in the Great Plains could be using much more energy than required. The simplified method can help determine if your system is inefficient.

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

Sometimes the system is simply not operated properly. An example occurred where a center-pivot sprinkler package was installed that used pressure regulators with a pressure rating of 25 psi. However, the end gun on the pivot was not equipped with a booster pump so the main pump was operated at a pressure of 75 psi to pressurize the entire system just to meet the needs of the end gun. Since end guns only operate about half of the time the pump was actually pumping against the pressure regulators half of the time, wasting a significant amount of energy. The problem here was not the pump or the power unit but the sprinkler design and its operation.

We recommend that you periodically arrange with a well drilling company to test the efficiency of your pump. They conduct a test that determines pumping lift, discharge pressure and the efficiency of the pump for a range of conditions that you would expect for your system. They also use equipment to measure the power output of your engine or electric motor. While they don't usually measure the energy consumption rate the results of the test will tell you if the pump is performing efficiently. This provides an excellent reference for future analysis.

Figure 4. Pumping Cost Worksheet

		Pump/Field						
1. Known Information		*Annual Diesel Example*	*Annual Electric Example*	*Hourly Propane Example*				
A	Pumping lift, feet	***125***	***175***	***250***				
B	Pressure at pump discharge, psi	***50***	***40***	***55***				
C	Size of the irrigated field, acres	***130***	***128***	***130***				
D	Depth of irrigation applied, inches	***13.5***	***13***					
E	Amount of energy used to irrigate the field for the year	***5500***	***65,000***					
F	Type of energy source used to pump water	***Diesel***	***Electric***	***Propane***				
G	Cost of a unit of energy ($/gallon, $/kwh, etc.)	***$3.00***	***$0.07***	***$1.80***				
H	Annual interest rate, %	***9***	***7***					
I	Repayment period, years	***5***	***10***					
2. Annual Performance								
J	Gallons of diesel fuel @ standard to pump an acre-inch (from Table 2)	***2.19***	***2.44***	***3.44***				
K	Volume of water pumped, acre-inches: (multiply row C x row D)	***1755***	***1664***					
L	Gallons of diesel fuel needed at 100% Performance Rating (J x K)	***3843***	***4060***					
M	Multiplier for energy source (from Table 3)	***1***	***14.12***	***1.814***				
N	Energy used if at 100% pump rating (L x M)	***3843***	***57,327***					
O	Performance rating of pump (100 x N / E)	***70***	***88***					
P	Potential energy savings with repair, gallons, kWh, etc.: (E - N)	***1657***	***7673***					
Q	Annual cost savings, $ (G x P)	***$4,971***	***$537***					
R	Series present worth factor (Table 6)	***3.89***	***7.02***					
S	Breakeven repair investment (Q * R)	***$19,337***	***$3,770***					
3. Hourly Performance								
T	Pump discharge, gallons per minute			***700***				
U	Volume of water pumped per hour (Table 5), acre-inches/hour			***1.55***				
V	Energy use per hour if at 100% Performance Rating (J x M x U)			***9.65***				
W	Actual energy use rate (gallons/hour, 1000 cubic feet/hr, or kWh/hr)			***11.0***				
X	Pumping plant performance rating (100 x V /W)			***88***				

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Updating the Nebraska Pumping Plant Performance Criteria

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INTRODUCTION

Irrigation water is removed from groundwater storage using deep well turbine pumps powered by electric motors or diesel, gasoline, propane, ethanol, or natural gas internal combustion engines. For best operating efficiency irrigation power units are selected to specifically meet the requirements of the irrigation system that include how deep the water in the well is under pumping conditions, the water pressure required at the pump outlet, and the system flow rate. Since each component of the irrigation pumping plant (pump, motor, and right angle gear drive) is a mechanical device, wear and tear can reduce its operating efficiency making the motor use extra power to pump the water. As some components of the irrigation system are replaced, such as replacing a sprinkler package, the original pumping plant may no longer match the new requirements. These factors cause the energy use efficiency of irrigation pumping plants to be lower than optimum.

The evaluation of pumping plants to establish pumping plant performance dates back into the 1950's when researchers at the University of Nebraska were unable to directly compare the operation of an electrically powered pump installation to that powered by a diesel or other internal combustion engine. The solution to this issue was to develop performance criteria for each energy source that would be based upon the amount of work (water horsepower-hours) operators could expect if the system were well-designed and well-maintained. This performance criterion was referred to as the Nebraska Pumping Plant Performance Criteria (NPPPC) that is cited by irrigation design engineers worldwide (Scheusener and Sulek, 1959). Defining the original criteria involved manufacturer's and Nebraska Tractor Test data and field evaluations of pumping installations. Since 1959, the diesel fuel standard was updated by Fischbach and Dorn, (1981).

The 3-state area has approximately 110,000 active irrigation wells (2008 Ag Census). The University of Nebraska conducted a statewide pumping plant efficiency study in the late 1970's. In this study, they tested 180 farmer-owned pumping plants. When the performance ratings of all pumping plants tested were

tallied, the average pumping plant in the study was found to be operating at 77% of the NPPPC . Some pumping plants were found to be very efficient, and 15% of the systems tested actually exceeded the NPPPC.
Engineers from Minnesota, North Dakota and South Dakota were involved in irrigation pumping plant efficiency tests during 1978, 1979 and 1980. Performance characteristics were determined for 249 electric powered installations. The average performance rating was 77% of the NPPPC.

More recent tests confirm that pumping plant performance ratings remain well below the NPPPC. Pumping plant evaluations conducted on 244 units in Texas during the early 1990's (Fipps and Neal, 1995). In their work, diesel powered units averaged 80.4%, natural gas engines averaged 87.5% and electric motors averaged 72.5% of the NPPPC. Hla and Scherer, (2000) reported on 37 units tested in North Dakota and found the average performance rating for center pivot based systems was about 80% of the NPPPC.

Based on Nebraska Tractor Test data, significant improvement has been made in the brake horsepower output per unit of fuel for internal combustion engines. However, pumping costs continue to increase due to rising fuel costs which have overshadowed improvements in pumping plant components. That said, more efficient irrigation pumping plants still could save an average of 25-30 percent of the energy used to pump irrigation water through properly matching and adjusting the pump and motor to current operating conditions. In Nebraska alone, improvement in pumping plant performance will reduce energy costs by up to $40 million per year.

Frequently cited causes of pumping plant inefficiency are the following:

1. The pipeline is valved back at the well to meet pressure requirements;
2. Well screen is plugged due to mineral incrustation and/or iron bacteria resulting in extra pumping lift;
3. Worn pump impeller due to wear from pumping sand or extended use;
4. Improper impeller adjustment on deep well turbine pumps;
5. Alteration of the irrigation application system without redesigning the pumping plant;
6. Mismatched system components such power unit too large ;
7. The power source may not be operating at the specified speed (rpm) for maximum efficiency;
8. The engine may need a tune-up; and
9. Improperly sized discharge column.

Nebraska survey results indicate that 32.7% of the power units used to pump irrigation water are diesel engines, 42.6% are electric motors, 17% are natural gas engines, 7.6% are powered by propane and 0.02% are powered by gasoline engines (USDA, 2004). The average irrigation system in Nebraska operates for 774 hours, pumping water at a rate of 839 gallons per minute, from a depth of 143 feet, with a pump outlet pressure of 42 pounds per square inch. Based on the NPPPC, the average system would require 57.4 kilowatt-hours of electricity per hour of operation or 44,464 kilowatt-hours per year. The equivalent annual energy use would be 3149 gallons of diesel fuel, 5,712 gallons of propane, or 6,380 MCF of natural gas. Assuming an average performance rating of 80% of the NPPPC, if the performance rating were improved by 10% percent, the average annual energy savings would be equivalent to 5,560 kilowatt-hours of electricity. When multiplied by 92,000 wells in Nebraska, the potential savings could reach nearly $100 million per year in energy savings.

The NPPPC is based upon the assumption that the pump efficiency is 75% and on the energy contained in fuel for internal combustion engines. Likewise, the assumed efficiency of an electric motor is 88%. Other assumptions are included in the footnotes in Table 1. Based on these assumptions, the existing pumping plant performance criteria are listed in Table 1.

Table 1. The current Nebraska Pumping Plant Performance Criteria (NPPPC).

Energy Source	**Energy Unit**	**Bhp-hr/unit [1]**	**Whp-hr [2]/unit [3]**
Electric	Kilowatt-hr	1.18[5]	0.885
Diesel	Gallon	16.6	12.5[4]
Natural Gas	1000 cu. Ft.	88.9[7]	66.7
Propane	Gallon	9.2	6.89
Gasoline[6]	Gallon	11.5	8.66

1 Horsepower hours (bhp-hr) is the work accomplished by the power unit including drive losses

2 Water horsepower hours (whp-hr) is the work produced by the pumping plant per unit of energy at the NPPPC

3 The NPPPC are based on 75% pump efficiency

4 Criteria for diesel revised in 1981 to 12.5 whp-hr/gal

5 Assumes 88% electric motor efficiency

6 Taken from Test D of Nebraska Tractor Test Reports. Drive losses are accounted for in the data. Assumes no cooling fan

7 Manufacturers' data corrected for 5 percent gear-head drive loss and no cooling fan. Assumes natural gas energy content of 1000Btu per cubic foot.

PERFORMANCE TESTING

The key factors affecting pumping plant performance are typically recorded using a procedure developed by the University of Nebraska (Schroeder and Fischbach, 1982). The test involves accurate measurement of pump discharge pressure, pumping water level, water flow rate, and fuel consumption. These data are entered into Equation 1 to determine the water horsepower-hours produced by the pumping plant. When divided by the fueled consumed during the testing period, the outcome is the pumping plant performance.

$$\text{WHP} - \text{HR} = \frac{[(\text{Pressure} * 2.31) + (\text{Lift})] * \text{Flow Rate}}{3960} \qquad 1)$$

where:	WHP-HR	=	water horsepower-hours of work produced by the pumping plant
	Pressure	=	pump outlet pressure, psi
	Lift	=	water level in the well during pumping, ft.
	Flow Rate	=	pump flow rate measured at the outlet, gpm

Figure 1 shows a schematic of a pumping plant with some performance variables that are recorded during a pumping plant test.

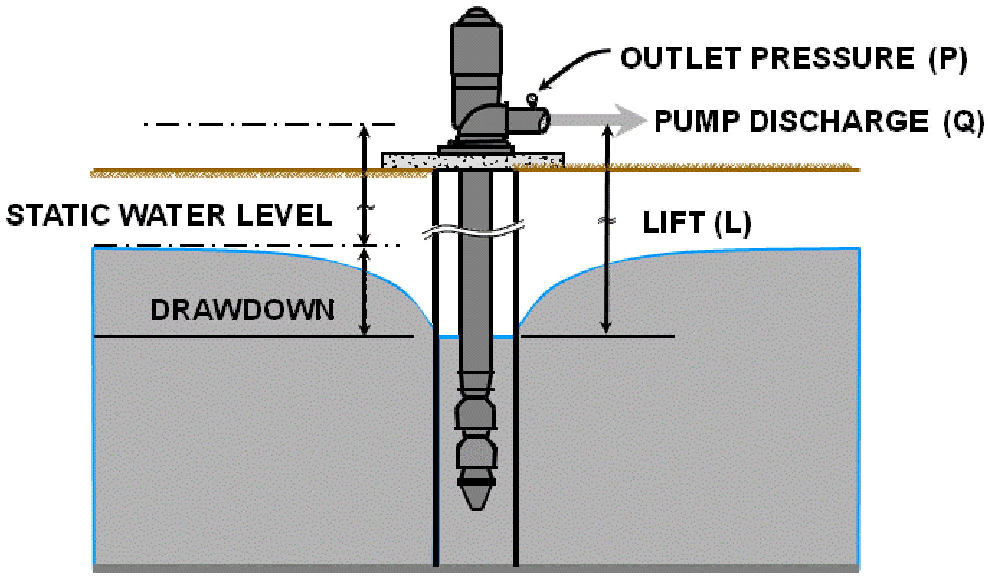

Figure 1. Schematic of factors affecting the pumping plant performance of a deep well turbine pump powered by an electric motor.

Additional information recorded during the test include the number and type of impellers, pump speed of rotation, power-take-off torque, motor manufacturer, and motor model number. Where necessary, an electric current meter is used to record incoming power in each leg of 3-phase power line. Recent Nebraska tests have included monitoring gas emissions from the engine exhaust to gain additional insight into how well the engine is adjusted.

In the winter of 2008-2009, we received a grant through the Water Energy and Agriculture Initiative to conduct pumping plant evaluations across the state of Nebraska with the overall goal of helping to reduce the energy consumption by irrigation pumping plants powered by electricity, natural gas, propane, gasoline, ethanol, and diesel fuel.

Specific objectives are to:

1) Identify pumping plant components that do not match current operating requirements;
2) Determine the potential maximum brake-horsepower output per unit of energy for new irrigation power plants;
3) Develop a revised Nebraska Pumping Plant Performance Criteria for diesel, natural gas, propane, electricity, ethanol, and gasoline power units.

Testing protocol varied slightly depending on the type of power unit and the ability to install instrumentation to the system. However, the general protocol is listed below.

Irrigation Pumping Plant Test Sequence:

1. Record information about pump and motor on the data sheet that was not available via the well registration or producer. Contact well driller if necessary to identify pump impellers.
2. Record static water level in the well if system has been shut down for several hours.
3. Install monitoring equipment including: engine/motor and pump speed, engine exhaust gas analyzer, pump outlet pressure, ultrasonic flow meter, and fuel use with scale or electric meter.
4. Start the pumping plant and bring the system to normal operation speed. Allow to run for a minimum of 30 minutes.
5. Switch engine fuel source to the test can on the scale.
6. Manually record all data onto data sheet to start the test sequence. During the test period record the outlet pressure, motor and pump rpm, flow rate (instantaneous and totalizer), fuel use rate, pumping water level and exhaust gas concentrations a minimum of once every 5 minutes for a minimum of 30 minutes.
7. Manually calculate system performance to ensure the accuracy of recorded data.
8. Save data files in separate file folder on the laptop.
9. If the test is acceptable, turn off the motor/engine and remove equipment.

Special Considerations:

1. The pumping plant evaluation must be conducted with all conditions nearly constant throughout the testing sequence. Recorded information during the test sequence should change less than the following:

Pump speed	± 0.5%
Pumping water level	± 1%
Fuel use rate	± 0.5%
Pump flow rate	± 1%

2. Pumping water level, flow meter, fuel use, and engine exhaust gases should be recorded nearly simultaneously.

3. Engine speed should not be changed once the test has been initiated since engine speed impacts flow rate, outlet pressure, and fuel use rates.
4. At least one test sequence should be conducted with and without power use by the center pivot, volume gun, or other irrigation system components.

Initial year testing began in July of 2009 and the results of the tests are presented in Table 2. Nearly all of the units tested were less than 3 years old. Though at least one unit in each of the energy sources was above the NPPPC, overall results indicated that extra energy is still being used to pump irrigation water in Nebraska. The electric units were the closer to the NPPPC than the other power types.

Table 2. Average test results for pumping plant tests conducted in 2009.

Energy Type	Flow Rate gpm	Pumping Level feet	Outlet Pressure psi	Energy Use Rate Unit/hr	Performance Whp-hr/unit	% of NPPPC %
Electric	794	146	37	46.1	0.84	95
Diesel	668	105	46	35.6	10.8	82
Propane	513	39.5	52	3.58	5.77	84
Ethanol	1689	191	1	9.3	8.89	??

SUMMARY

A new pumping plant testing program is under way to update the Nebraska Pumping Plant Performance Criteria for all energy types. Average pumping plant test results conducted previously in Nebraska and elsewhere have been near 80% of the NPPPC. Tests conducted on relatively new installations in 2009 produced results that ranged from 82% for Diesel powered units to 92% for electric units. The project will continue in 2010 and the update of the NPPPC will be based on data collected by the UNL and other entities across the country.

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EVALUATION OF PRESSURE REGULATORS FROM CENTER PIVOT NOZZLE PACKAGES

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Abstract: *Performance evaluations of center pivot nozzle packages for uniformity have been conducted as part of the Mobile Irrigation Lab program for a number of years. These evaluations were performed using a catch can system. Later the evaluation expanded to spot checking pressure and flow for in-canopy nozzle packages that could not be tested with catch cans. However, the latter procedure did not measure the pressure drop across the pressure regulator and approximately 80 per cent of Kansas center pivot irrigation systems are pressure regulated. This study tested pressure regulator performance of regulators from existing center pivot nozzle packages.*

Keywords: Center pivot irrigation, pressure regulators

INTRODUCTION

Center pivot irrigation systems are the dominant irrigation system type in use within Kansas (Rogers et. al., 2007). Irrigation is also the dominant use of water supplies for the state, but in many areas of the state, water supplies are diminishing. However, irrigated agriculture makes significant contributions to the economy so improving irrigation water utility has long term benefits to the region. The Mobile Irrigation Lab (MIL) project previously developed a procedure to performance evaluate center pivot nozzle packages for uniformity (Rogers et. al., 2002). Later, the performance evaluation was expanded to include an evaluation procedure for in-canopy (low to the ground) nozzle packages (Rogers et. al., 2005), although, the performance evaluations did not focus on individual components. Approximately 80 percent of the nozzle packages were equipped with pressure regulators (Rogers et. al., 2007); however, the pressure drop across the regulator was not measured in the previous performance evaluation procedure. By observation, pressure regulator failure has appeared to be either excessive leaking at the regulator or clogging with no water passing, but otherwise the regulators were assumed to be functioning. In this study, pressure regulators from existing systems were collected and laboratory tested for performance.

PROCEDURES

Two sets of 10 pressure regulators each were initially intended to be removed from various systems in southwest Kansas. Older nozzle packages were selected. The samples were normally collected from the third and last span of the system. In one case, all the pressure regulators from the system were evaluated. The regulators were subsequently brought to the hydraulics laboratory at the Department of BAE, Kansas State University. Each regulator was tested at two input pressures (20 and 30 psi) and three nozzles sizes appropriate to the flow rating of the pressure regulator.

RESULTS AND DISCUSSION

Three hundred and nine pressure regulators were collected and tested. Only one regulator was recorded as failed. In this case, excessive leakage through the regulator body occurred, which was a part of the GFS3 test. The average results of this collection are based on the averages of the remaining 9 in the collection sample. In another case, a regulator had no flow passing through the regulator when it was initially installed on the test stand. It was removed, at which time debris was noted in the intake side which was then removed by tapping the regulator on a hard surface. This dislodged the debris, so the regulator was re-installed and tested.

An example of a pressure regulator performance chart is shown in figure 2. For the design output pressure or pressure rating, the downstream or output pressure will be slightly less than line (input) pressure due to friction losses through the regulator. Once the internal friction loss is overcome, the device will begin to output the approximate design rating. This value will generally be slightly elevated with increasing input pressure. The amount of flow through a pressure regulator will also affect the output pressure, with decreasing output pressure with increasing flow.

A summary of the results are in Table 1, where the average output pressure of the collected set are shown as well as the highest and lowest reading from the test set. The size of the nozzle is also noted in the table. Pressure regulators were collected from 8 different systems. On two systems only the outer span regulators were collected and on one system the S3 span had different pressure rated (6 psi) regulators than the LS span (10 psi); making 14 data sets. Based on figure 2 discussion, it would be expected that as nozzle size (higher flow) increased, the average output pressure would decrease. This was the case in 9 of the 14 sets for the 20 psi test. RKS3, RKLS, GFS3, MGLS, and RBLS did not follow the pattern of decreasing output pressure with increasing flow. At 30 psi, 8 of 14 followed the expected pattern with the same sets above and also GFLS breaking pattern. When comparing test results between 20 and 30 psi pressure tests, only RKS3, RKLS and TLLS did not have higher output pressure at 30 psi input pressure as compared to 20 psi, which would be different than the expected result. Overall, performance of the regulators seemed very good.

Figures 3 and 4 show the results of Test SFGF S3 and LS which are 6 psi rated regulators and, as noted previously, follow the expected pattern of performance. For example at 20 psi input pressure, the average S3 output pressure changes from 6.25 to 5.73 to 5.53 psi for the respective nozzle sizes. Figure 3 shows individual data points to indicate the range of values. Most test values are relatively close, although in the 20 psi LS test, one regulator had a test value of nearly 8 psi, which is an outlier as compared to the others. Figure 4 shows a different data presentation. In this figure, S3 and LS test results were averaged into a combined set. Note that flow through the nozzle has more impact on the output pressure than does the input pressure.

Figures 5 and 6 show the results of Test UB S3 and LS which are 10 psi rated pressure regulators. The S3 and LS models are the same but the former is a low flow model while the latter is a high flow model. As noted previously, they follow the expected pattern of performance. For example at 20 psi input pressure, the average S3 output pressure changes from 10.25 to 9.74 to 9.20 psi for the respective nozzle sizes. Figure 5 shows individual data points to indicate the range of values. Most test values are relatively close, although in the 30 psi LS test, the range of data points was larger than the other ranges. Figure 6 shows the data presented by nozzle size and the results show the decreasing output pressure with increasing nozzle size. The output pressures for the 20 and 30 psi input pressures were not as tight as in the SFGF example but still similar; with the average 20 psi LS test was slightly lower than the other average values

Figures 7 and 8 show the test results from 169 pressure regulators. These regulators were collected from one center pivot irrigation system in position order and tested at the two pressure and three flow rates as described previously. The most remarkable feature of either figure 7 or 8 is that the variability of results of the first thirty regulators as compared to the rest of the regulators from the position. At higher flows (figure 7), the regulators performed better, although still at higher output pressure as compared to higher numbers of position. The regulators also performed better at 30 psi (figure 8) than at 20 psi. No notable differences in appearance of the regulators during collection or during test installation were noted. S3 regulators as discussed previously would have been downstream of the variable area noted in this full system analysis.

CONCLUSION

Pressure regulators collected from a variety of center pivot systems located in SW Kansas were laboratory tested. Older nozzle packages were targeted. Although additional analysis of the data is planned, it appears the regulators performed well under the variety of conditions experienced in the region. One full system analysis was completed. Regulator performance in the inner part of this system was more variable than the outer part of the system, however no conclusions should be drawn from a single test.

ACKNOWLEDGEMENTS

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Table 1: Average, highest, and lowest Output Pressure of various pressure regulators for two input pressures and three flow rates.

Pressure Regulator ID	Nozzle Size	Ave Output Pressure PSI	High Pressure PSI	Low Pressure PSI	Ave Output Pressure PSI	High Pressure PSI	Low Pressure PSI
		Upstream Test Pressure = 20 psi			Upstream Test Pressure = 30 psi		
RKS3	15	10.21	11	9.5	9.86	10.9	8.4
10 psi	20	9.63	10.4	9.1	9.68	10.7	9.2
	24	10.26	11.6	9.4	10.47	12	9.1
RKLS	15	10.34	11.1	9.8	10.13	10.7	9.6
10 psi	20	9.93	10.5	9.6	9.78	10.7	8.4
	24	10.45	11.7	9.7	10.76	11.2	10.3
GFS3	15	5.28	6.3	4.2	5.73	6.70	4.60
6 psi	20	5.6	7.9	4.2	5.67	7.30	3.70
	24	5.47	8.50	4.20	5.51	7.50	3.60
GFLS	15	5.73	7.6	5.2	5.83	7.1	5.1
6 psi	20	5.73	7.2	4.9	5.97	7.2	4.7
	24	5.65	7.8	4.6	5.89	7.4	4.8
MGLS	7	8.91	11.1	7.1	10.09	12.5	6.2
10 psi	12	7.84	11.1	4.6	7.84	10	5
	15	8.33	10.4	4.8	7.98	11.3	6.5
RBLS	7	5.79	7.5	5	6.16	7.1	5
6 psi	12	4.77	6.7	3.6	4.77	6.9	4.1
	15	4.92	6.3	4.2	5.32	6.3	3.7
SFGFS3	7	6.25	6.6	6	6.54	7	6.1
6 psi	12	5.73	6.1	5.2	5.98	6.3	5.4
	15	5.53	5.9	4.8	5.6	6.1	5.1
SFGFLS	7	6.51	7.9	6	6.6	7	6.2
6 psi	12	6.13	6.7	5.6	6.05	6.5	5.8
	15	5.79	6.3	5.3	5.52	5.9	5.2

Pressure Regulator ID	Nozzle Size	Ave Output Pressure PSI	High Pressure PSI	Low Pressure PSI	Ave Output Pressure PSI	High Pressure PSI	Low Pressure PSI
UBS3	7	10.25	11.1	8.9	10.43	11.5	9.8
10 psi	12	9.74	10.5	9.2	9.86	10.7	9.2
	15	9.2	10.1	8.1	9.02	9.7	8.1
UBLS	15	9.7	11	7.7	10.32	12	8
10 psi	20	8.59	9.8	7.5	9.42	10.5	7.8
	24	8.55	9.7	7.3	8.64	9.2	7.7
TLS3	7	10.85	11.5	10.3	11.05	11.5	10.5
10 psi	12	10.24	10.6	9.6	10.39	10.7	10
	15	9.72	10.3	8.7	10.09	10.6	9.6
TLLS	15	6.51	7.6	5.2	6.34	7.1	5.8
6 psi	20	6.09	7.5	5.4	5.91	6.7	4.7
	24	5.88	8.2	4.7	5.54	6.6	4.7
ALS3	7	10.68	11.1	10.2	10.91	11.5	10.1
10 psi	12	10.21	10.5	9.9	10.12	10.6	8.6
	15	9.97	10.5	9.5	9.97	10.3	9.6
ALLS	7	10.48	11.1	9.9	10.6	11.3	9.9
10 psi	12	9.97	10.5	9.6	10.19	11	9.3
	15	9.7	10.1	8.8	9.66	10.1	8

Figure 1. Picture of Pressure Regulator Test Stand, including manifold, pressure regulator, pressure shunt, water meter, pressure shunt and flow nozzle.

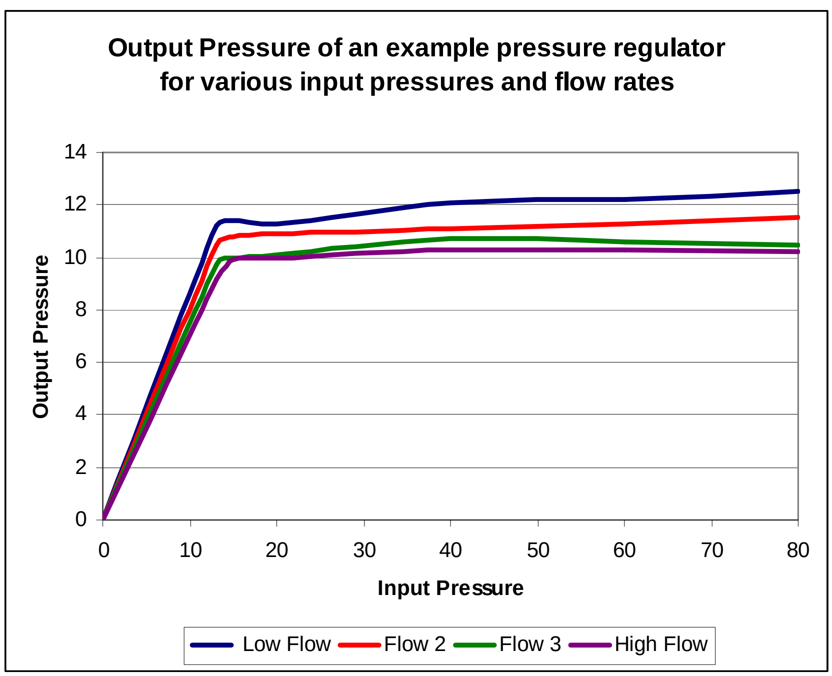

Figure 2. Example of Output Pressure verses Input Pressure for a Pressure Regulator.

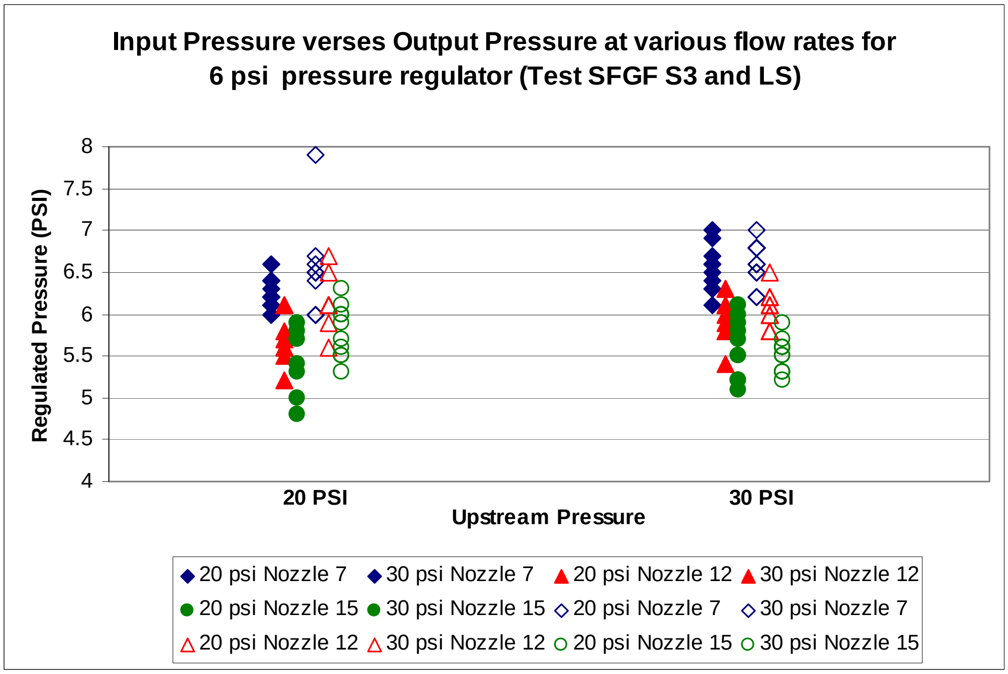

Figure 3. Input pressure verses output pressure at various flow rates for 10 6 psi pressure regulators for Tests SFGF S3 and LS.

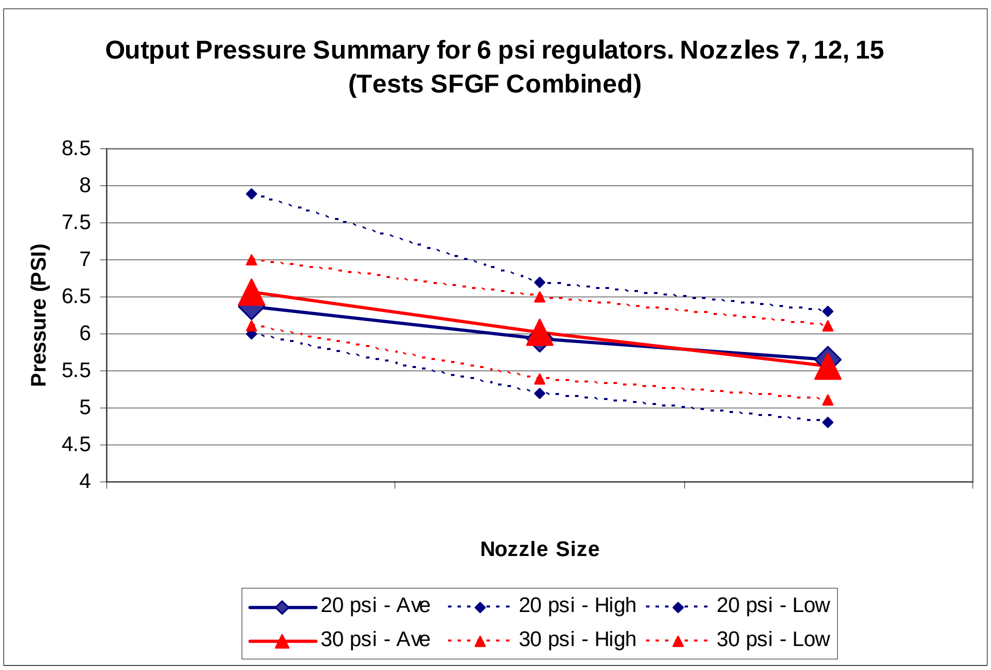

Figure 4. Average, high and low output pressures for 6 psi pressure regulators for Test SFGF S3 and LS.

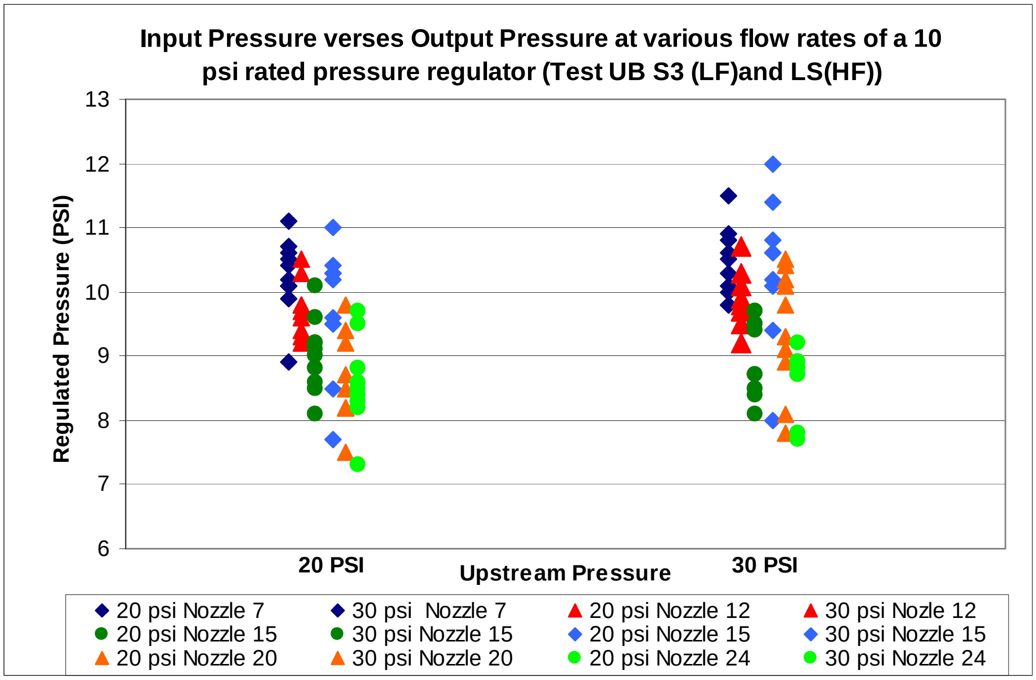

Figure 5. Input pressure verses output pressure at various flow rates for 10 psi pressure regulators for Tests UB S3 and LS.

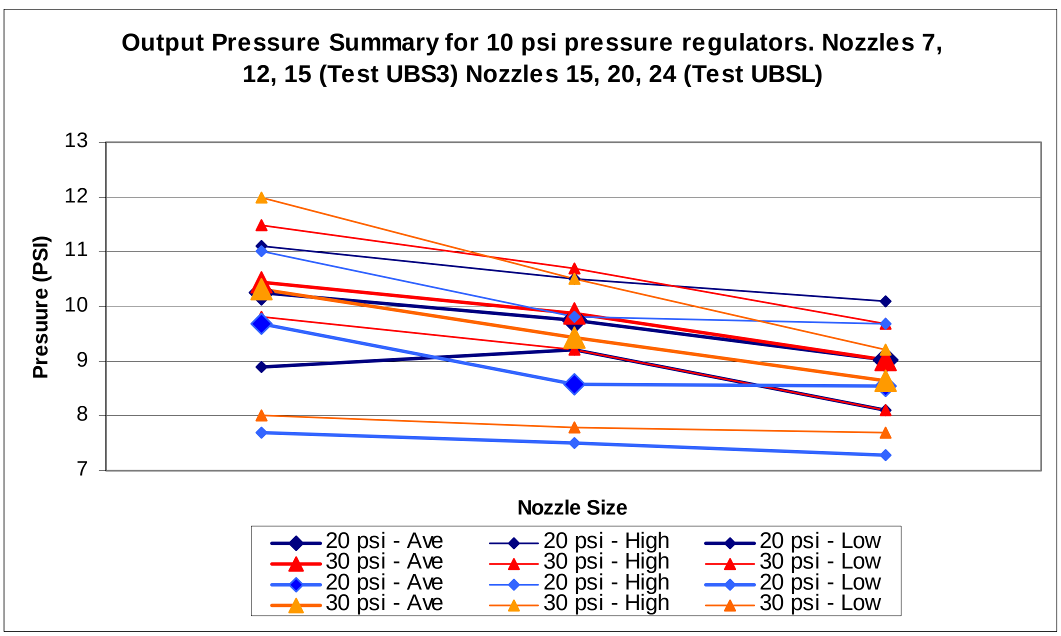

Figure 6. Average, high and low output pressures for 10 psi pressure regulators for Tests UB S3 and LS.

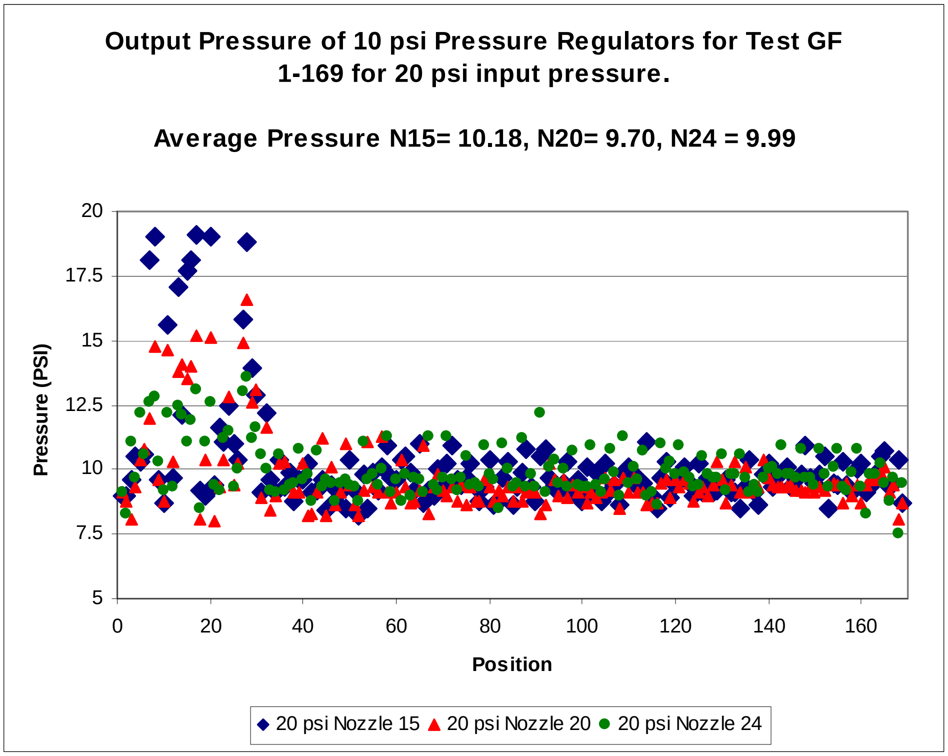

Figure 7. Output pressure of 169 pressure regulators tested at three nozzle sizes. Tests GF 1-169.

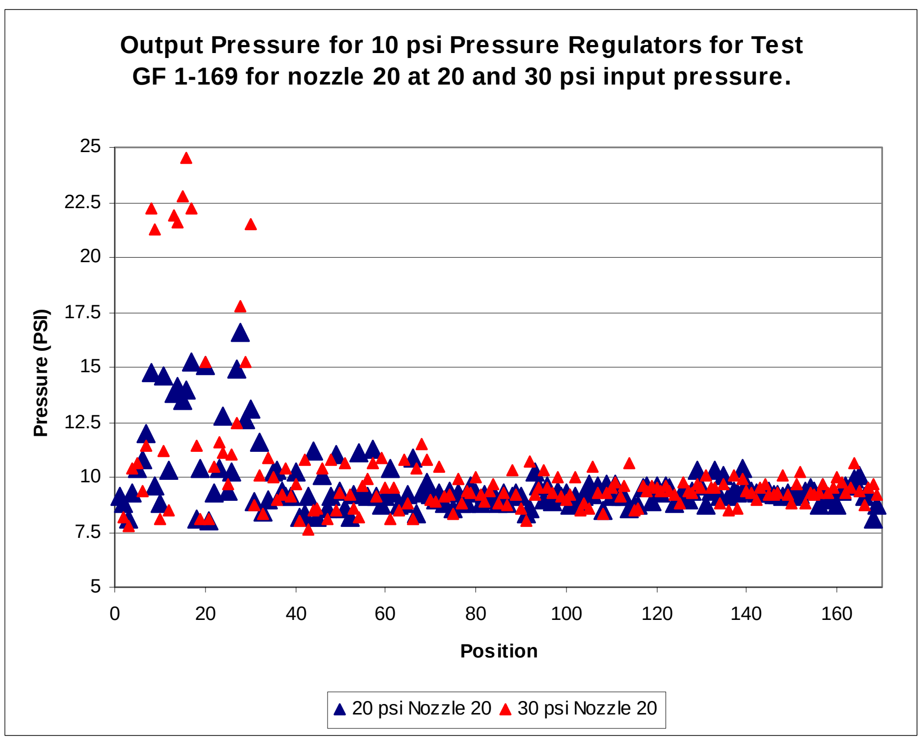

Figure 8. Output pressure of 169 pressure regulators tested at 20 and 30 psi input pressure. Tests GF 1-169.

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Integrated Controls, Distributed Sensors and Decision Support Systems for Wireless Site-specific Sprinkler Irrigation

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INTRODUCTION

Traditional uniform water applications by self-propelled center pivot and linear move sprinkler irrigation systems ignore within field variations that cause varying crop yield and quality across most fields. This variability may include topographic relief, changes in soil texture, tillage, fertility and pests as well as various irrigation system characteristics. These effects on management can be additive and interrelated. Excessive applications potentially lead to drainage, soil erosion and disease problems as well as excessive energy use, whereas under applications can reduce yields and/or quality with the severity level often depending on management. Typical management objectives would be to optimize yield and quality goals while maintaining environmental health (reduced water and agrichemical use) and reduce chemical leaching.

Microprocessor controlled center pivot and linear move irrigation systems are particularly amenable to site-specific management approaches because of their current level of automation and large area coverage with a single lateral pipe. These technologies provide a unique control and sensor platform for economical and effective ways to vary agrichemical and water applications to meet the specific needs of a crop in uniquely defined zones within a field.

Advances in communications and microprocessors have enabled the implementation of site-specific water applications by self-propelled center pivot and linear move sprinkler irrigation systems. Site-specific irrigation usually involves some type of variable rate application method in combination with geo-referenced maps or tables. These decision maps specify the amount of water applied to each pre-defined management area within a field and are generated using some type of rule base predefined by the producer or a consultant. Ideally, these management maps or tables are frequently updated based on real time, spatially distributed data on field conditions. Management areas may be different for irrigation than for chemigation applications, and each may have its own maps.

Recent innovations in low-voltage sensor and wireless radio frequency technologies combined with advances in Internet technologies offer tremendous opportunities for development and application of real-time management systems for agriculture. Integration of these technologies into the irrigation decision making process can determine when, where how much water to apply in real time; which enables implementation of advanced state-of-the-art water conservation measures for economically viable production with limited water supplies.

Researchers at the USDA-ARS research laboratory in Sidney, Montana have developed and tested an automated closed-loop irrigation system for automated variable-rate linear move sprinkler irrigation system. This research integrated in-field sensor stations distributed across the field, an irrigation control station on the linear move system, and a decision support system on a base computer station.

INTEGRATION OF SYSTEMS

Variable-Rate Irrigation System

A site-specific controller and hardware were developed with the capability to switch between either mid-elevation spray application (MESA) or low energy precision application (LEPA) methods as well as to simultaneously vary water application depths by plot as the machines traveled down the field. The machine was converted to make groups of individual sprinkler nozzles electronically controllable by attaching a programmable logic controller (PLC), solenoids, air valves, and a low cost WAAS enabled GPS system. The linear move irrigation system was modified so that every plot could be irrigated using either MESA or LEPA methods. The control system was used on fifty-six 15 m × 24.4 m (50 ft × 80 ft) plots as well as several other smaller research projects in which there were a mix of crops and a prescribed set of management experiments in a single field for a total area of about 12 ha (28 ac).

All plots were irrigated with an 244 m (800 ft), 5 span, Valley[1] self-propelled linear move sprinkler irrigation system (Valmont Industries, Inc., Valley, NE) including the cart, which was installed in the spring of 2003. A diesel engine powered an electrical generator set (480 v, 3 phase) on the cart that provided electricity for the tower motors, cart motors, pump, air compressor and control valves. A buried wire alignment system was used with antennas located in the middle of the machine. The linear move machine used a screened floating pump intake in a level ditch as its water supply. Nominal operating pressure was about 250 kPa

[1] Mention of a trademark, vendor or proprietary product does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products that may also be suitable. This type of information is solely provided to assist the reader in better understanding the scope of the research and its results.

(36 psi). Two double direction boom backs were installed at each of the towers (although not at the cart). Spans were 48.8 m (160 ft) in length except for the center span with the guidance system which was a 47.5 m (156 ft) span. The machine moved at about 2.1 m min^{-1} (7 ft min^{-1}) at the100% setting. Equivalent depths of water were applied for both irrigation methods for the same crop.

The PLC-based control system activated grouped networks of electric over air-activated control valves. Thirty 15-meter (50 ft) wide banks of sprinklers were controlled with this system (15 MESA banks, 15 LEPA banks.) Both the depth and method of irrigation were varied depending on the location of each plot in the field. When not being used, low-cost pneumatic cylinders lifted the LEPA heads above the MESA heads to avoid spray interference when the MESA is operating over a given plot width and length. Water application depths were varied by modulating pulses of water through the sprinkler nozzles on and off to achieve targeted, variable application amounts on each predefined area (or plot) as the machine moved down the field. The controller, communications and modifications to the water application methods utilized off-the-shelf components as much as possible

The amount of water applied was adjusted by pulsing nozzle heads on and off to achieve a targeted, variable depth based on a predefined digital map stored in the PLC (or in a base computer) of depths for each nozzle location as the machine moved down the field. As was the case with other site-specific controllers in the literature, machine speed was set by the Valley panel, which established the maximum application depth and the PCL controller managed the sprinkler heads. Treatments were a percentage of maximum by varying on times in a 60 second cycle time. However, our software allowed us to easily change the cycle time if we needed to make adjustments.

Distributed Sensor Systems and Control

A distributed wireless sensor network (WSN) was integrated into the existing site-specific linear move sprinkler irrigation system described above. Field conditions were monitored by six in-field sensor stations with Campbell CR200 dataloggers (Campbell Scientific, Inc, Logan, UT) distributed across the field based on a soil property map and monitored soil moisture, soil temperature, and air temperature. WaterMark soil water sensors (Irrometer Company, Inc., Riverside, CA) were used in the decision support process and were calibrated with a neutron probe and individually identified for their response ranges at each zone. All in-field sensory data were sampled on 1 second intervals. A nearby weather station monitors micrometeorological information on the field, i.e., air temperature, relative humidity, precipitation, wind speed, wind direction, and solar radiation. Communication signals from the sensor network, weather station and PLC irrigation controller to the base station were successfully interfaced using low-cost Bluetooth wireless radio communication.

Decision Support System

A Windows based decision making program was developed with a simple click-and-play menu using graphical user interface (GUI), and optimized to adapt changes of crop design, irrigation pattern, and field location. This system offered stable remote access to field conditions and real-time control and monitoring of both inputs (field data) and outputs (sprinkler controls). In-field micrometeorological information was displayed on a geo-referenced field map at the base station screen. The PLC on the machine provided the current geo-referenced location of the machine from an on-board differential GPS. The base computer recalculated the position of individual sprinkler heads, analyzed soil water status, calculated crop water needs, updated machine instructions and sent control commands to the irrigation controller to site-specifically operate each individual sprinkler group and apply a specified depth of water for every time step (1 sec) based on criteria in a predetermined management map. An algorithm for nozzle sequencing was developed as part of the decision support software to stagger nozzle-on operations so as evenly distribute irrigation system flow rates over the 60-sec cycle to avoid hydraulic surges. Sensor-based closed-loop irrigation was highly correlated to catch can water with r^2=0.98.

CONCLUSIONS

Automated site-specific sprinkler irrigation system can save water and maximize productivity, but implementing automated irrigation is challenging in system integration and decision making. Irrigation decisions can be implemented site-specifically based on feedback from soil water and environmental conditions from distributed in-field sensor stations using wireless radio communications. The performance of the system was evaluated with the measurement of water usage and soil water status throughout the growing season.

Integration of the decision making process with the controls is a viable option for determining when and where to irrigate, and how much water to apply. Distributed in-field sensors offer a major advantage in supporting site-specific irrigation management that allows producers to maximize water productivity while enhancing overall profitability.

There are many reasons why site-specific sprinkler irrigation has not generally been a commercial success to date. These include the fact that servicing hardware and software on advanced, integrated systems can be difficult. Much hardware troubleshooting could be done via the internet from a central location and defective parts, computer cards or chips changed by on-site technicians, but the support infrastructure is not developed. Another reason is the lack of decision support applications (software) that is needed to take full advantage of the capabilities of these systems. This is likely due to the potential liability inherent in any decision support system, which has delayed their implementation. Every decision support application would have to be tailored to fit each individual field and even simple mistakes can have costly consequences. Growers usually do not have the interest, knowledge or the time to fuss with software; thus, dealers or consultants would likely have to provide this service. Specialized, continual training on the hardware, software and advanced agronomic principles would also be needed for dealers, technicians and other personnel to service these systems.

Additional Information

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Twenty-One Years of SDI Research in Kansas

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Abstract

This paper will summarize research efforts with subsurface drip irrigation in Kansas that has occurred during the period 1989 through 2009. Special emphasis will be made on brief summaries of the different types of research that have been conducted including water and nutrient management for the principal crops of the region, SDI design parameters and system longevity and economics. Annual system performance evaluations have shown that dripline flowrates are within 5% of their original values. Economic analysis shows that systems with such longevity can be cost competitive even for the lower-valued commodity crops grown in the region.

Introduction and Brief History

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

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

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

Over the course of the past 21 years, additional significant funding has been obtained to conduct SDI research from the USDA, the Kansas Water Resources Research Institute, special funding from the Kansas legislature, the Kansas Corn Commission, Pioneer Hi-Bred Inc., the Mazzei Injector Corporation and Syngenta. Funding provided by the Kansas legislature through the Western Kansas Irrigation Research Project (WKIRP) allowed for the expansion of the NWREC site by an additional 1 acres and 46 additional research plots in 1999. An additional 22 plots were added in 2000 to examine swine wastewater use through SDI and 12 plots were added in 2005 to examine emitter spacing. Three research block areas originally used in a 1989 dripline spacing study have been refurbished with new 5 ft spaced driplines to examine alfalfa production and emitter flowrate effects on soil water redistribution. The NWREC SDI research site comprising 19 acres and 201 different research plots is the largest facility devoted expressly to small-plot row crop research in the Great Plains and is probably one of the largest such facilities in the world.

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

General Study Procedures

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

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

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

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

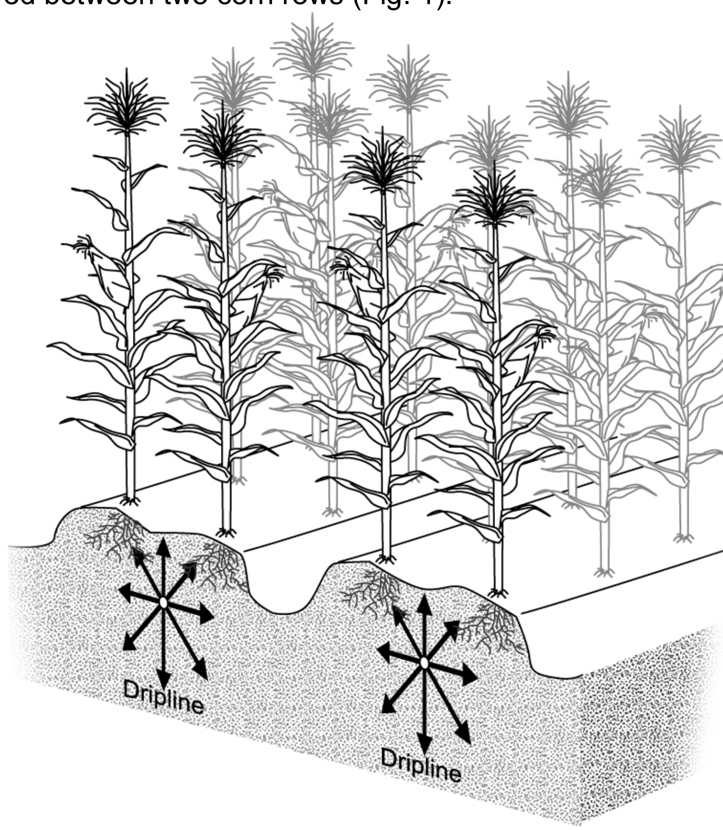

Figure 1. Physical arrangement of the subsurface dripline in relation to the corn rows.

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

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

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

Results and Discussion

Water Requirement and Irrigation Capacity Studies

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

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

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

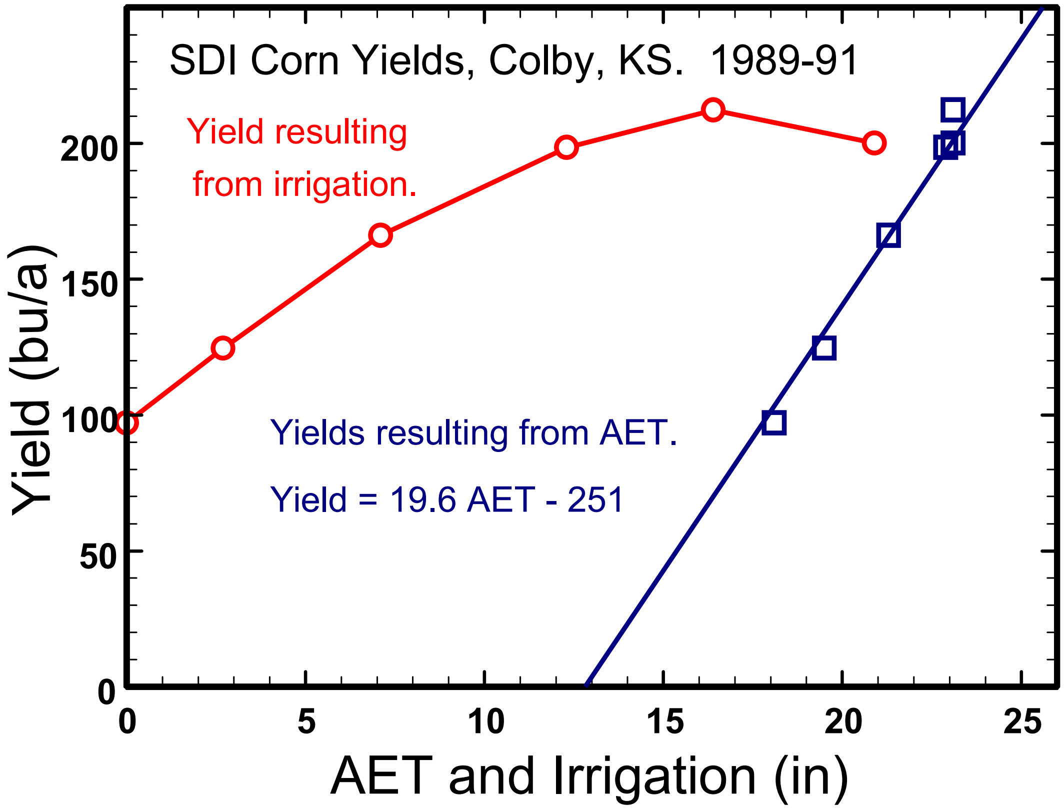

Figure 2. Corn yield as related to irrigation and calculated evapotranspiration (AET) in a SDI water requirement study, Colby, Kansas, 1989-1991.

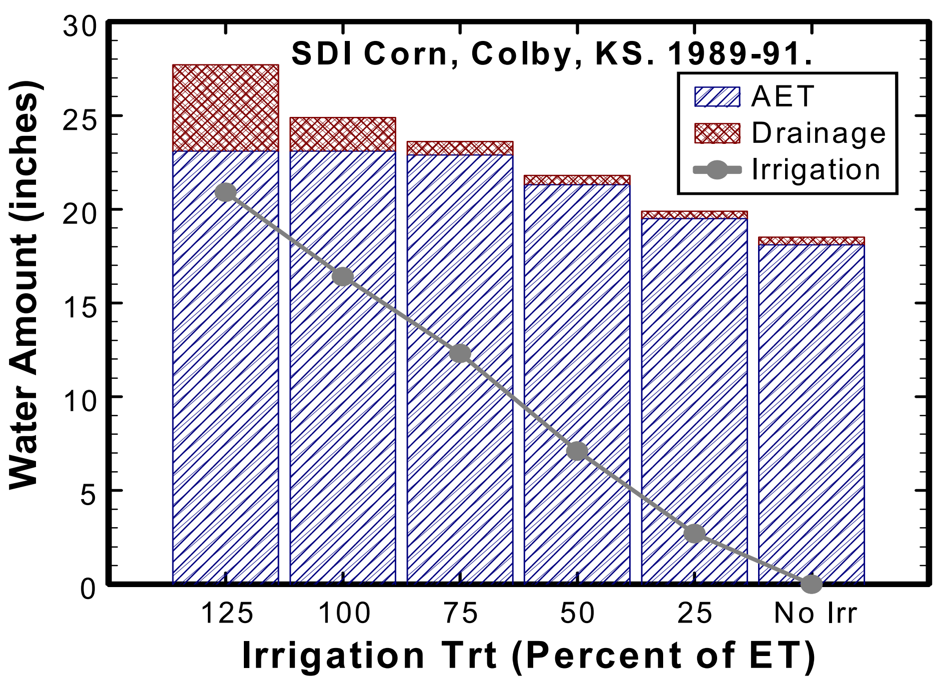

Figure 3. Calculated evapotranspiration (AET) and seasonal drainage as related to irrigation treatment in a SDI water requirement study, Colby, Kansas, 1989-1991.

The results from four SDI studies on corn water use were summarized by Lamm, 2005. Relative corn yield reached a plateau region at about 80% of full irrigation and continued to remain at that level to about 130% of full irrigation (Figure 4). Yield variation as calculated from the regression equation for this plateau region is less than 5% and would not be considered significantly different. The similarity of results for all four studies is encouraging because the later studies included the effect of the four extreme drought years of 2000 through 2003.

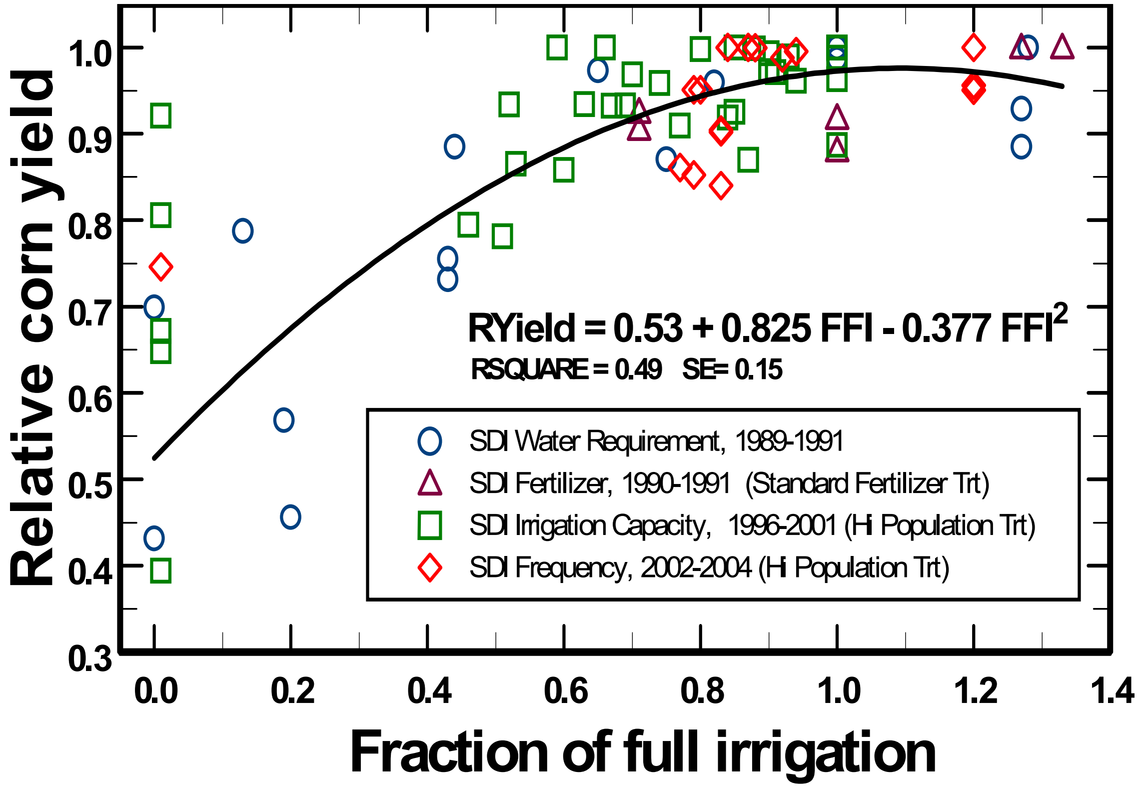

Figure 4. Relative corn grain yield for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

An examination of water productivity (WP) for the same four studies indicates that water productivity plateaus for levels of full irrigation ranging from 61% to 109% with less than 5% variation in WP (Figure 5). The highest WP occurs at an irrigation level of approximately 82% of full irrigation. This value agrees with results summarized by Howell, (2001) for multiple types of irrigation systems. The greatest WP (82% of full irrigation) also occurred in the plateau region of greatest corn yield (80 to 130% of full irrigation). This suggests that both water- and economically-efficient production can be obtained with SDI levels of approximately 80% of full irrigation across a wide range of weather conditions on these soils in this region.

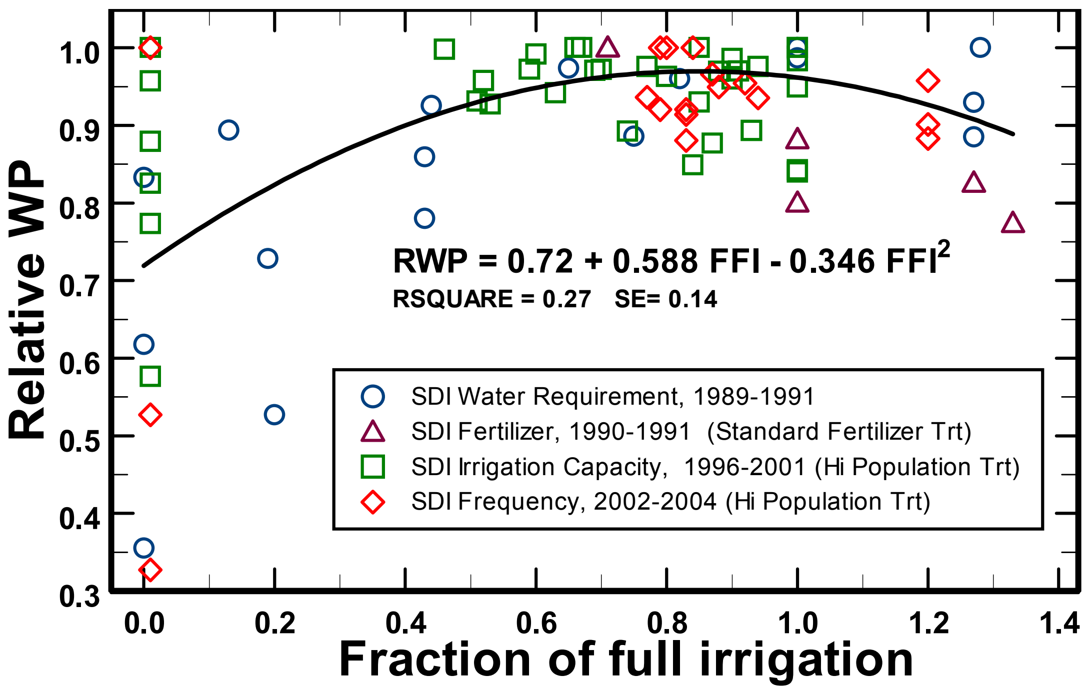

Figure 5. Relative water use productivity (WP) of corn for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

SDI Frequency

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

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

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

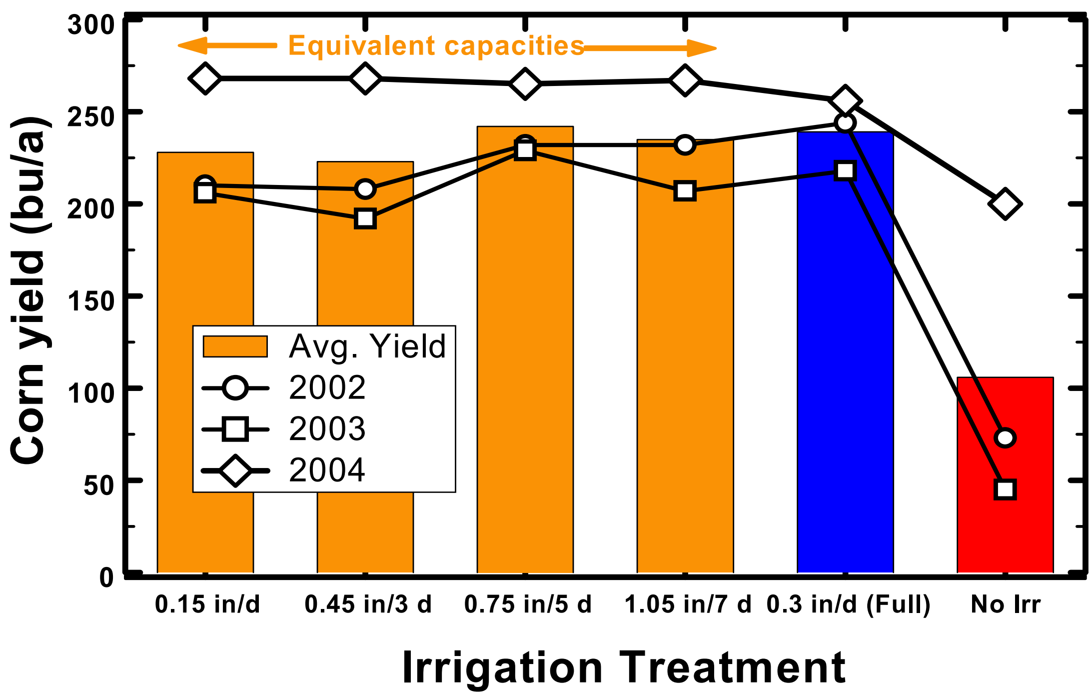

Figure 6. Corn grain yields as affected by irrigation treatment in a study examining SDI frequency under limited irrigation, Colby, Kansas, 2002 to 2004.

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

Optimal Dripline Spacing

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

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

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

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

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

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

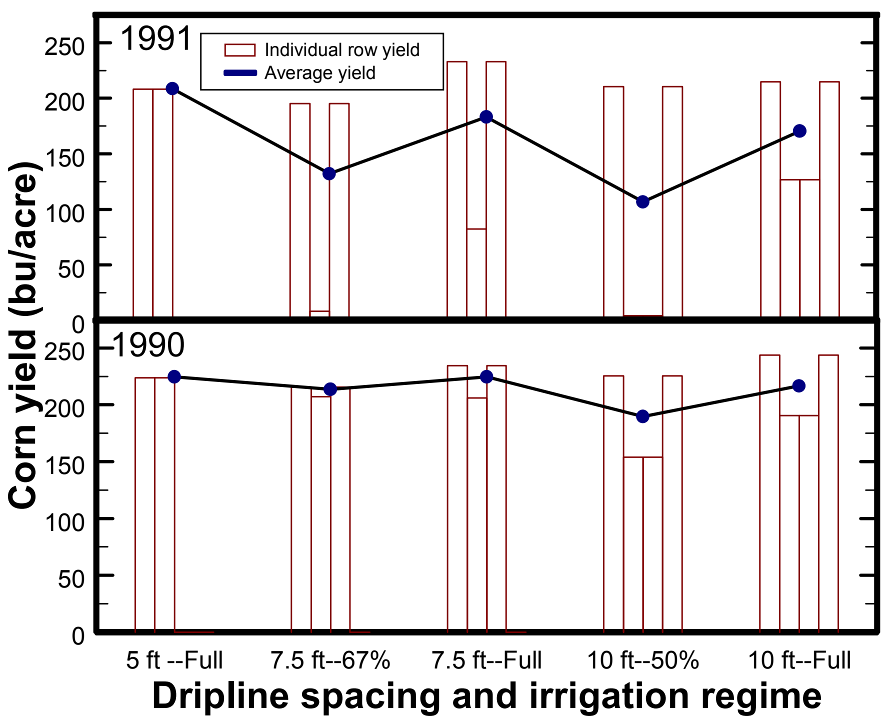

Figure 7. Corn yield distribution as affected by dripline spacing and irrigation regime, Colby, Kansas, 1990-1991. Note: Individual row yields are mirrored about a centerline half way between two adjacent driplines for display purposes.

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

Dripline Depth Study

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

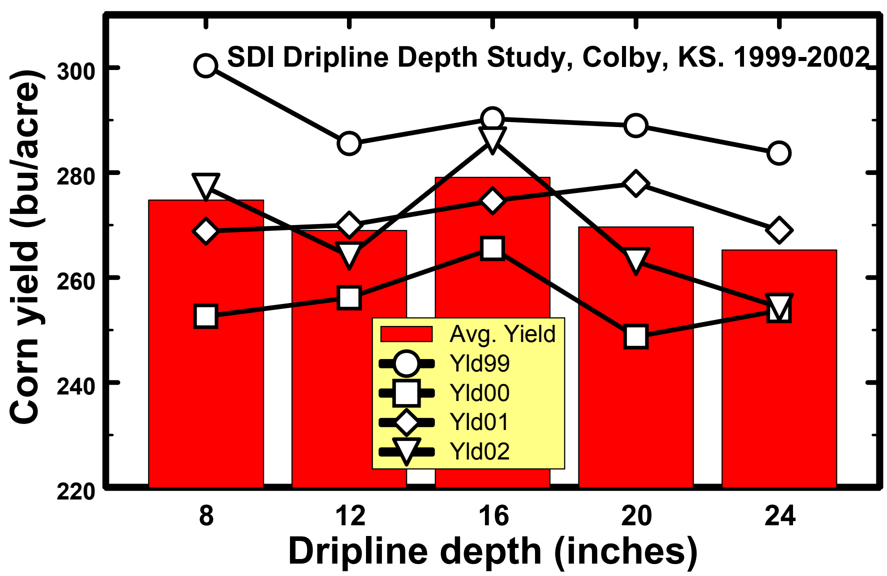

Figure 8. Corn grain yields as affected by dripline depth, 1999-2002, Colby, Kansas.

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

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

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

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

Nitrogen Fertilization with SDI

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

In a study conducted at the KSU Northwest Research-Extension Center at Colby, Kansas from 1990-91, there was no difference in corn grain yields between preplant surface-applied nitrogen and nitrogen injected into the driplines throughout the season. Corn yields averaged 225 to 250 bu/acre for the fully irrigated and fertilized treatments. Water use was increased (P=0.05) in 1991 and for the two year average by injection of N fertilizer with the SDI system. The additional in-season fertigation allowed for healthier and more vigorous plants that were better able to utilize soil water. The results suggest that a large portion of the applied N could be delayed until weekly injections begin with the first irrigation provided there is sufficient residual soil N available for early growth. In both years, nearly all of the residual nitrate nitrogen measured after corn harvest was located in the upper 12 inches of the soil profile for the preplant surface-applied nitrogen treatments, regardless of irrigation level. In contrast, nitrate concentrations increased with increasing levels of nitrogen injected with SDI and migrated deeper in the soil profile with increased irrigation (Lamm et. al., 2001). Nitrogen applied with SDI at a depth of 16 to 18 inches redistributed differently in the soil profile than surface-applied preplant nitrogen banded in the furrow (Figure 9*).* *Since residual soil-nitrogen levels were higher* *where nitrogen was injected using SDI, it may be possible to obtain similar high corn yields using lower amounts of injected nitrogen.*

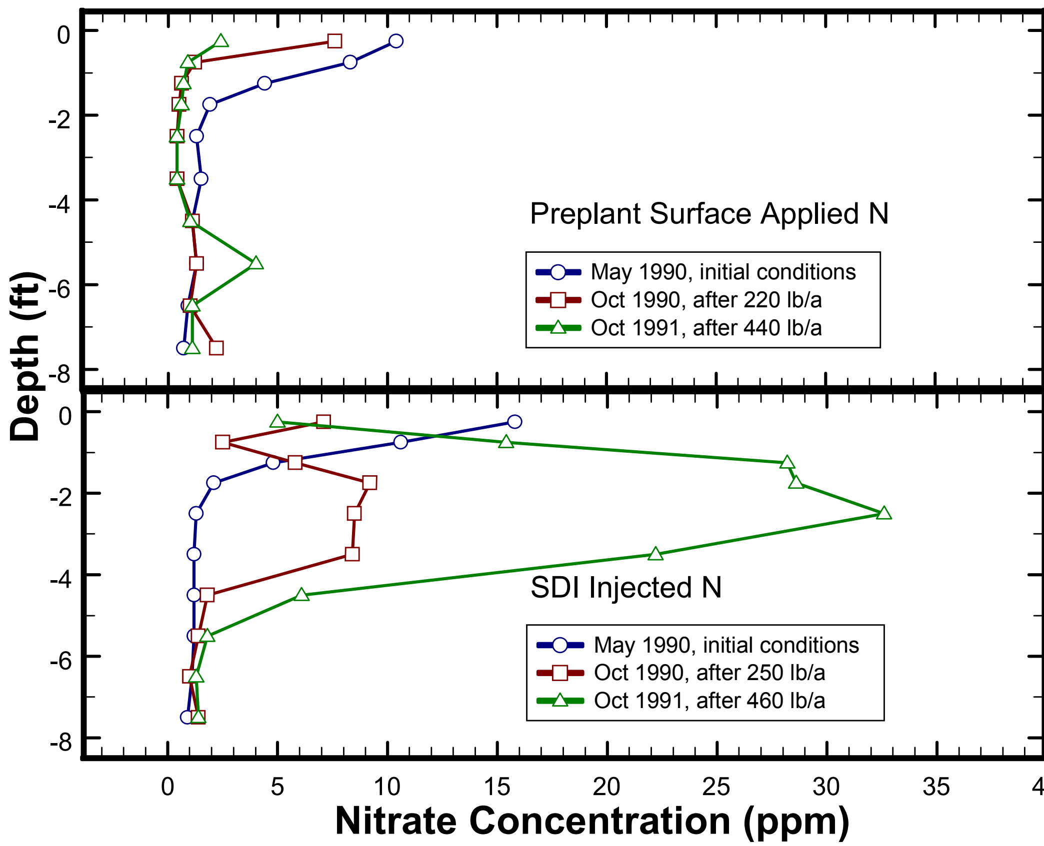

Figure 9. Nitrate concentrations in the soil profile for preplant surface-applied and SDI injected nitrogen treatments, Colby, Kansas, 1990-91. Data is for selected nitrogen fertilizer rate treatments with full irrigation (100% of AET).

A follow-up four year study was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas on a deep Keith silt loam soil to develop a Best Management Practice (BMP) for nitrogen fertigation for corn using SDI. Residual ammonium- and nitrate-nitrogen levels in the soil profile, corn yields, apparent nitrogen uptake (ANU) and water productivity (WP) were utilized as criteria for evaluating six different nitrogen fertigation rates, 0, 90, 135, 180, 225, and 270 kg/ha. The final BMP was a nitrogen fertigation level of 180 kg/ha with other non-fertigation applications bringing the total applied nitrogen to approximately 215 kg/ha (Lamm et. al., 2004). The BMP also states that irrigation is to be scheduled and limited to replace approximately 75% of ET. Corn yield, ANU, and WP all plateaued at the same level of total applied nitrogen which corresponded to the 180 kg/ha nitrogen fertigation rate (Figure 10). Average yields for the 180 kg/ha nitrogen fertigation rate was 13.4 Mg/ha. Corn yield to ANU ratio for the 180 kg/ha nitrogen fertigation rate was a high 53:1. The results emphasize that high-yielding corn production also can be efficient in nutrient and water use.

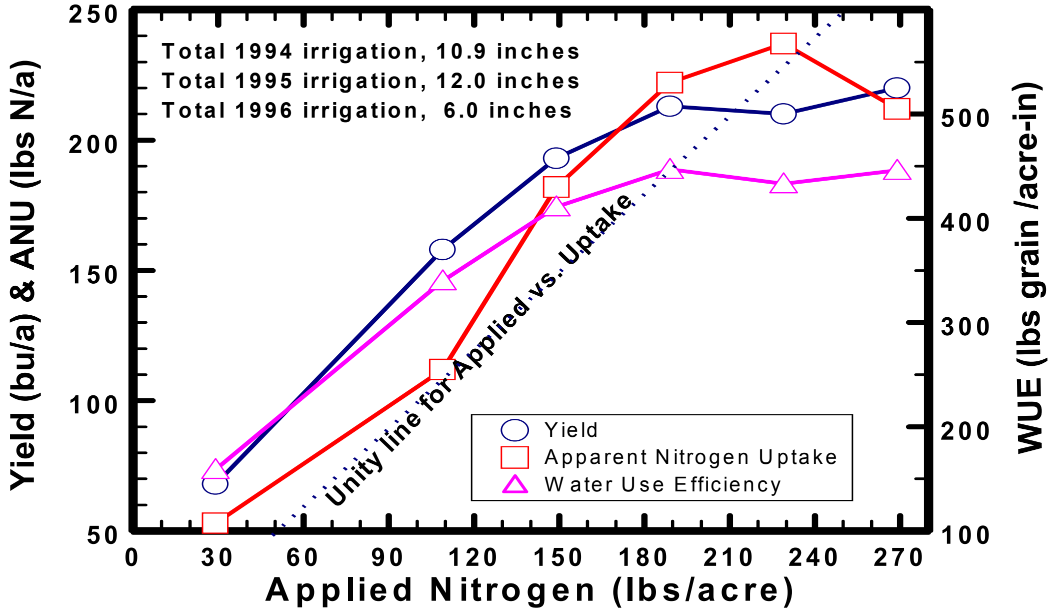

Figure 10. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water productivity as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded fertigation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

Comparison of SDI and Simulated LEPA Sprinkler Irrigation

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

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

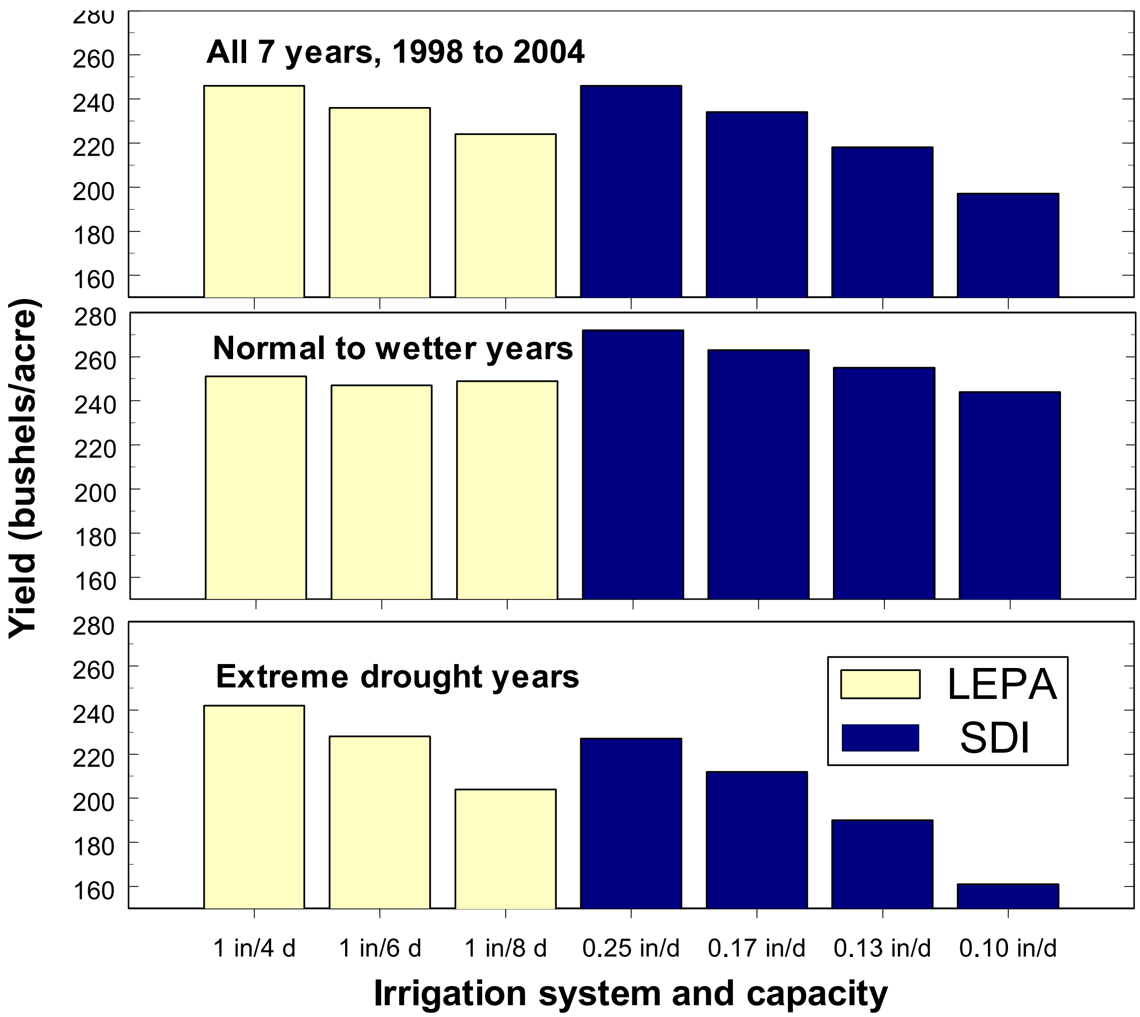

Figure 11. Variation in corn yields across years and weather conditions as affected by irrigation system type and capacity, Colby Kansas.

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

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

Table 3. Crop yield of soybean, grain sorghum and sunflower as affected by irrigation method and irrigation treatment, KSU Northwest Research-Extension Center, Colby Kansas, 2004-2008.								
Irrigation method	**Irrigation Treatment**	**Soybean yield bu/a**	**Grain Sorghum bu/a**			**Sunflower yield bu/a**		
		2005	**2006**	**2008**	**Mean**	**2004**	**2007**	**Mean**
SDI	100% ET	73	169	154 b*	161	3098	2824	2961
	80% ET	70	175	144 b	159	3442	3292	3367
	60% ET	70	155	131 c	143	3346	3273	3309
	Mean SDI	71	166	143	155	3295	3130	3212
LEPA	100% ET	75	179	170 a	174	3694	3354	3524
	80% ET	71	180	169 a	175	3285	2929	3107
	60% ET	63	175	160 a	167	3125	2729	2927
	Mean LEPA	69	178	167	172	3368	3004	3186
	LSD 0.05	NS	NS	13	-	NS	NS	-

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

Alfalfa Production with SDI

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

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

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

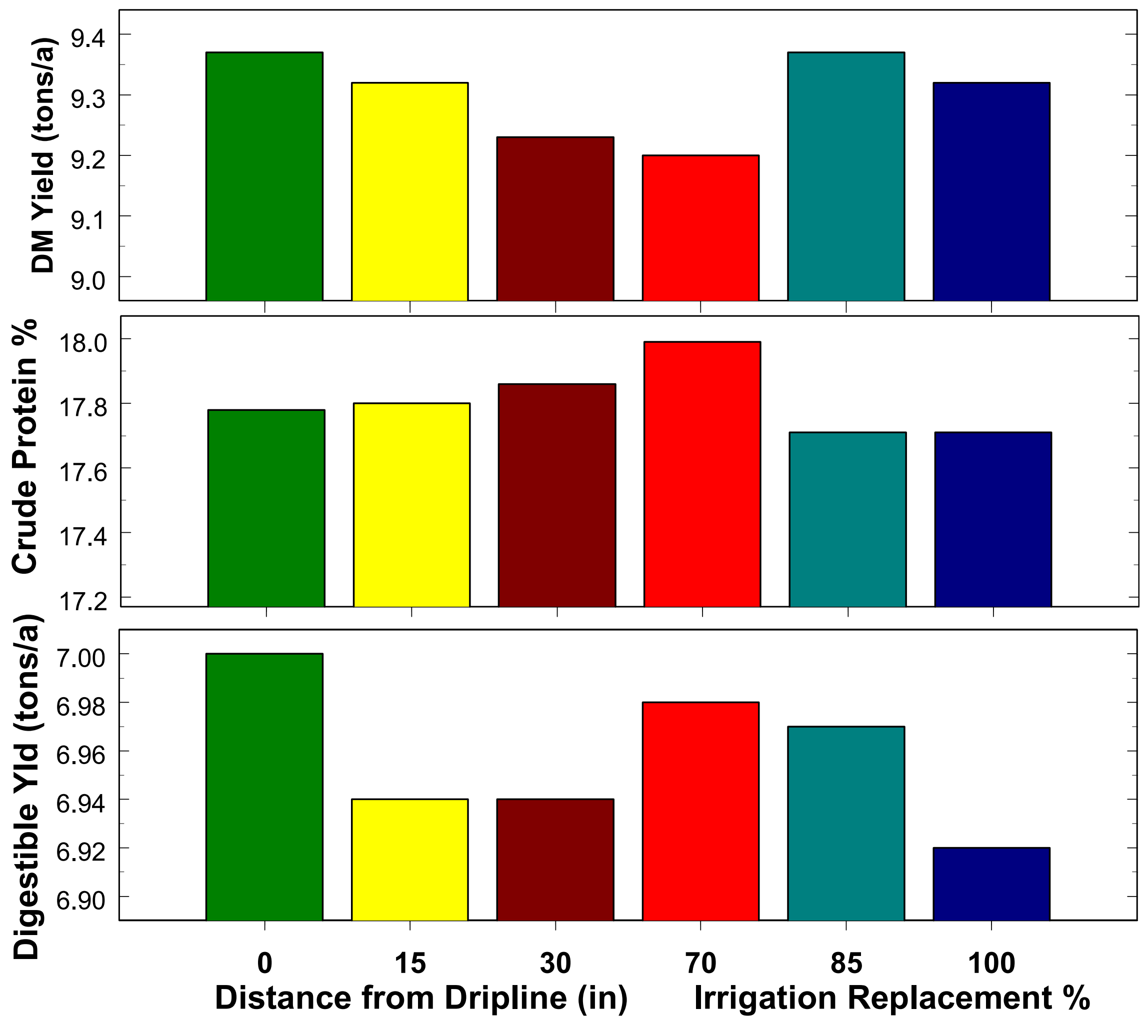

Figure 12. Dry matter yield, percentage crude protein and digestible dry matter yield as affected by perpendicular horizontal distance from dripline and irrigation level, KSU Northwest Research-Extension Center, Colby Kansas. Data is averaged over the years, 2005 through 2007.

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

Application of Livestock Effluent with SDI

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

An engineering feasibility study (1998 to 2002, commercial beef feedlot in Gray County, Kansas) conducted by Kansas State University with beef feedlot effluent has indicated that driplines with discharge of 0.4 to 1 gal/hr-emitters can be used successfully with little clogging. However, the smaller emitter sizes normally used with high quality groundwater in the Central Great Plains may be risky for use with beef feedlot effluent. The discharge of the two smallest emitter sizes, 0.15 and 0.24 gal/hr-emitter decreased approximately 40% and 30%, respectively, during the four seasons, indicating considerable emitter clogging (Figure 13). The three driplines with the highest flow rate emitters (0.4, 0.6, and 0.92 gal/hr-emitters) have had approximately 7, 8, and 13% reductions in flow rate, respectively. Following an aggressive freshwater flushing, acid and chlorine injections in April of 2002, the flowrates of the lowest two emitter sizes (0.15 and 0.24 gal/hr-emitter) were restored to nearly 80 and 97% of their initial flowrates, respectively.

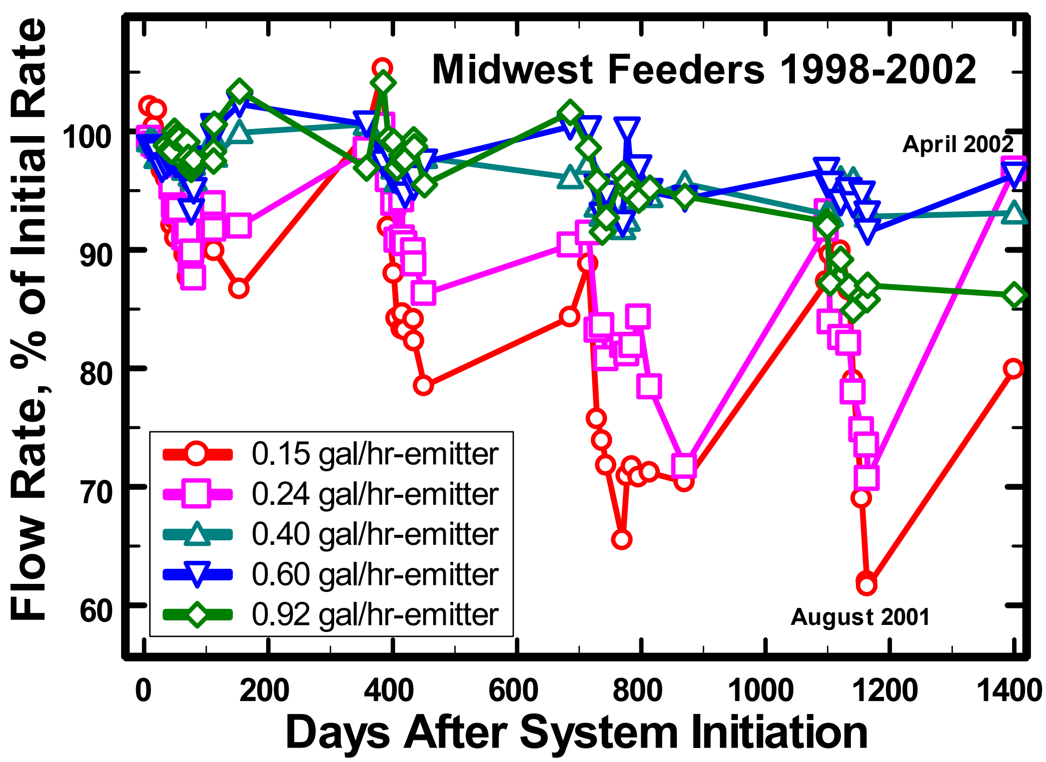

Figure 13. Decrease in emitter discharge during four seasons of operation of an SDI system with biological effluent at Midwest Feeders, Ingalls, Kansas, 1998 to 2002.

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

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

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

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

2 Total of seasonal change of soil water storage in the 8-ft profile plus irrigation and precipitation.

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

Economics of SDI

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

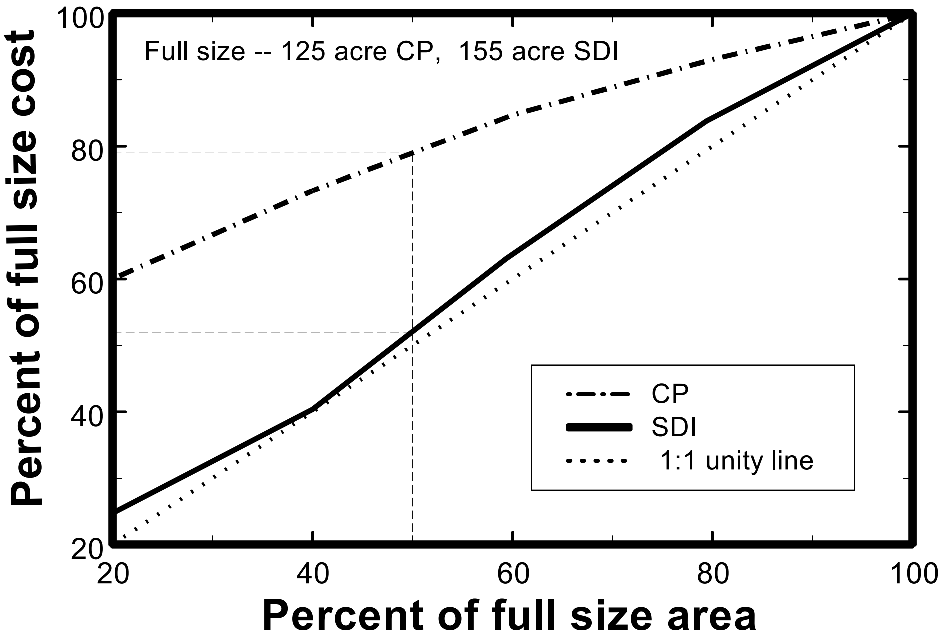

Figure 14. Center pivot sprinkler (CP) and SDI system costs as related to field size. (after O'Brien et al., 1997)

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

System life of SDI

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

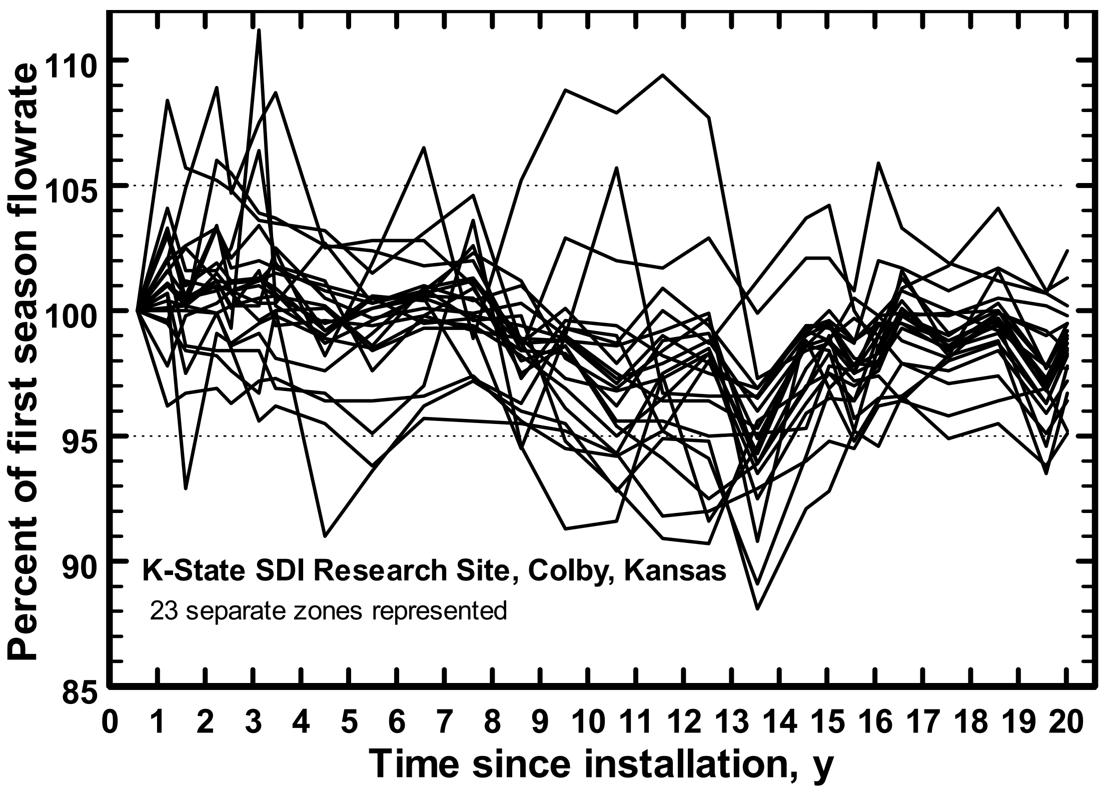

Figure 15. Stability in zone flowrates from the initial first season as related to time for an SDI system installed at Kansas State University, Colby, Kansas, 1989-2009.

Concluding Statements

Research progress has been steady since 1989. Much of K-State's SDI research is summarized at K-State's SDI Website, SDI in the Great Plains at http://www.ksre.ksu.edu/sdi/. Irrigators are watching the results of K-State closely. Some irrigators have begun to experiment with the technology and most appear happy with the results they are obtaining. It is K-State's hope that by developing a knowledge base in advance of the irrigator adoption phase that the misapplication of SDI technology and overall system failures can be minimized. Economics of the typical Great Plains row crops will not allow frequent system replacement or major renovations. Irrigators must carefully monitor and maintain the SDI system to assure a long system life. Continued or new areas of research are concentrating on optimizing allocations of water, seed, and nutrients, utilizing livestock wastewater, developing information about SDI use with other crops besides corn, soil water redistribution, water and chemical application uniformity, and finally system design characteristics and economics with a view towards system longevity.

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

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

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How Economic Factors Affect the Profitability of Center Pivot Sprinkler and SDI Systems

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In much of the Great Plains, the rate of new irrigation development is slow or zero. Since the 1970s there has been a dramatic shift in irrigation methods in the Great Plains region, as center pivot sprinkler irrigation systems have become the predominant technology, having replaced much of the furrow- irrigated base. In addition, a small yet increasing amount of subsurface drip irrigation (SDI) has been installed. Although SDI systems represent less than 1 percent of the irrigated area, producer interest still remains high because of their greater irrigation efficiency and irrigated water application uniformity. As irrigation systems need to be upgraded or replaced, available irrigated water sources become more scarce, and farm sizes become larger, there will likely be a continued interest in and momentum toward conversion to modern pressurized irrigation systems.

Irrigation system investment decisions will be affected by both the physical characteristics of the irrigation systems being considered and the economic environment that irrigated crop enterprises are operating within. Key assumptions about the physical characteristics of the irrigation systems include input-output efficiencies, life span, and system investment costs. Key economic factors include commodity prices, costs of key crop inputs, irrigation energy costs, interest rates on operating expenses, the opportunity cost of capital investments, and overall inflation in production costs. The economic factors affecting irrigation system choices can be strongly influenced by broader macroeconomic conditions and trends in the United States and world economies. To the degree that the volatile patterns in agricultural, energy and financial markets since the early 1970s continue or even become more pronounced, economic decisions about irrigation system investments will become more risk-prone and uncertain.

This paper will discuss how volatile economic conditions in key agricultural and financial markets affect expected relative profitability of center pivot sprinkler and subsurface drip irrigation systems under crop production conditions in the Great Plains. This analysis will use a K-State center pivot sprinkler (CP) and subsurface drip irrigation (SDI) comparison spreadsheet (Lamm, et al., 2009) to estimate the affect of various key economic factors upon investment decisions.

CP-SDI Comparison Spreadsheet

K-State Research and Extension introduced a free Microsoft Excel[1] spreadsheet template for making economic comparisons of CP and SDI in the spring of 2002. The spreadsheet has been periodically updated since that time to reflect changes in input data, particularly system and corn production costs. The spreadsheet also provides sensitivity analyses for key factors. Lamm, et al., (2009) explains how to use the spreadsheet and the key factors that most strongly affect the returns comparisons. The online accessible 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.). Critical field and irrigation system assumptions are illustrated.

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 09, modified by F.R. Lamm, D. M. O'Brien, D. H. Rogers, T. J. Dumler, 1-27-09

Field description and irrigation system estimates	**Total**	**Suggested**	**CP**	**Suggested**	**SDI**	**Suggested**
Field area, acres	160	← 160	125	← 125	155	← 155
Non-cropped field area (roads and access areas), acres	5	← 5				
Cropped dryland area, acres (= Field area - Non-cropped field area - Irrigated area)			30		0	
Irrigation system investment cost, total $			$73,450	← $73,450	$186,000	← $186,000
Irrigation system investment cost, $/irrigated acre			$587.60		$1,200.00	
Irrigation system life, years			25	← 25	21	← 20
Interest rate for system investment, %	7.5%	← 8.0%				
Annual insurance rate, % of total system cost			1.60%	← 1.60%	0.60%	← 0.60%
Production cost estimates			**CP**	**Suggested**	**SDI**	**Suggested**
Total variable costs, $/acre (See CF Tab for details on suggested values)			$517.90	← $517.90	$499.85	← $499.85
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	$3.50	← $4.00				
Net return to cropped dryland area of field ($/acre)	$38.55	← $36.00				
Advantage of Center Pivot Sprinkler over SDI *				$/total field each year		$876
* Advantage in net returns to land and management				$/acres each year		$5

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

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

The scenario analyzed in this research is a comparison of whether a center pivot sprinkler irrigation system (CP) is more or less profitable than a subsurface drip irrigation system on 160 acres of farmland. The CP system would irrigate 125 acres of the 160 acres of farmland, with the remaining 35 acres divided between 30 acres of non-irrigated or "dryland" cropping systems and 5 acres of non-cropped area (i.e., roads and access areas). The SDI system would irrigate 155 acres of the 160 acres of farmland, with the remaining 5 acres used for non-cropped roads and access areas. Irrigation system design and cost information is available from the authors and the K-State Research and Extension publication Irrigation Capital Requirements and Capital Costs, MF-836. Only information that is relevant to the comparison of returns for CP and SDI systems is included in this analysis. This excludes such factors as cost of irrigated cropland which will not vary for those acres that are irrigated under either irrigation system investment scenario. Non-irrigated cropland returns are included because of the inclusion of dryland acreage under the CP scenario. Average cash rental rates are included as a market-based proxy for the returns expected from farming non-irrigated cropland. For further discussion of the assumptions used in this analysis see Lamm, et al. (2009).

Actual values used in this analysis may vary from suggested values in the Main tab of the worksheet where current prices and market conditions warrant. Key information from the Main tab for the following analysis is as follows.

1. Corn selling price, $/bushel = $ 3.50 /bushel
2. Interest rate for system investment, % = 7.5%
3. Total variable costs, $/acre: CP = $517.90
4. Total variable costs, $/acre: SDI = $499.85
5. Net return to cropped dryland area of field ($/acre) = $ 38.55

Production cost estimates and assumptions represented in the CF tab are based on K-State Research and Extension crop enterprise budget estimates for irrigated corn in western Kansas (Figure 2.).

Factors for Variable Costs			CP	Suggested	SDI	Suggested	Version 09, modified by F.R. Lamm, D. M. O'Brien, D. H. R
Seeding rate, seeds/acre	$/1000 S	Suggested	34000	← 34000	34000	← 34000	
Seed, $/acre	$2.49	← $2.24	$84.66		$84.66		
Herbicide, $/acre			$31.06	← $28.68	$31.06	← $28.68	
Insecticide, $/acre			$35.64	← $35.30	$35.64	← $35.30	
Nitrogen fertilizer, lb/acre	$/lb	Suggested	242	← 242	242	← 242	
Nitrogen fertilizer, $/acre	$0.24	← $0.40	$58.08		$58.08		
Phosphorus fertilizer, lb/acre	$/lb	Suggested	50	← 50	50	← 50	
Phosphorus fertilizer, $/acre	$0.44	← $0.35	$22.00		$22.00		
Crop consulting, $/acre			$6.50	← $6.50	$6.50	← $6.50	
Crop insurance, $/acre			$37.00	← $37.00	$37.00	← $37.00	
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			$143.79	← $150.14	$143.79	← $150.14	Assumes all tillage, cultural and harvesting operations.
Other non-fieldwork labor, $/acre			$0.00	← $0.00	$0.00	← $0.00	Assumed covered by custom hire.
Irrigation labor, $/acre			$6.50	← $6.50	$6.50	← $6.50	
Irrigation amounts, inches			17	← 17	13	← 13	Assumes approximately 25% savings with SDI.
Fuel and oil for pumping, $/inch			$3.75	← $5.80	$3.75	← $5.80	Assumes equal operating pressures at pump site.
Fuel and oil for pumping, $acre			$63.75		$48.75		
Irrigation maintenance and repairs, $/inch			$0.60	← $0.60	$0.60	← $0.60	
Irrigation maintenance and repairs, $/acre		Suggested	$10.20		$7.80		
1/2 yr. interest on variable costs, rate	7.5%	← 8.0%	$18.72		$18.07		
Total Variable Costs			**$517.90**		**$499.85**		These values are ***suggested*** values on Main tab.

Figure 2. CF worksheet (tab) of the economic comparison spreadsheet template and the current production cost variables. Sums at the bottom of the CF worksheet are the suggested values for total variable costs on the Main worksheet (tab).

Corn enterprise cost of production information is available from the authors and the K-State Research and Extension publication Center Pivot Irrigated Corn Cost Return Budget in Western Kansas, MF-585. Actual values may vary from suggested values in the worksheet where current prices and market conditions warrant.

Key assumptions represented on the CF tab that are relevant to this economic analysis are listed below.

1.	Nitrogen fertilizer, $/pound of 82-0-0	= $ 0.24 /pound
2.	Phosphorus fertilizer, $/pound of 18-46-0	= $ 0.44 /pound
3.	Fuel and oil for pumping, $/acre inch inch	= $ 3.75 /acre
4.	½ yr. Interest on variable costs, rate	= 7.5% interest
5.	Total variable costs, $/acre: CP	= $517.90
6.	Total variable costs, $/acre: SDI	= $499.85

Lamm, et al. (2009) provides a further explanation of sensitivity analysis of physical production factors critical to the CP versus SDI investment decision in spreadsheet tabs on a) Field size & SDI life, b) SDI cost & life, and c) Yield & Price tabs.

Economic Factors Affecting CP versus SDI Investments

The key economic factors in this decision framework which are hypothesized to have an impact upon CP versus SDI investments include commodity prices, costs of key crop inputs, irrigation energy costs, interest rates on operating expenses, the opportunity cost of capital investments, and overall inflation in production costs.

Economic analysis typically relies upon “ceteris paribus” assumptions to determine the marginal impact of any particular factor in isolation (i.e., with "all other things being equal or held constant"). The following analysis will first focus on the impacts of variability of key factors separately (i.e., “ceteris paribus”). A final broader analysis will be conducted in which “low” versus “high” market product price and production cost regimes are examined to understand the systematic impact of these key factors. This systematic perspective reflects the integrated, interdependent nature of agricultural, energy and financial markets.

Corn Price Variability Impact

Over the October 2000-December 2009 period U.S. corn prices have exhibited great variability, with corn upfront corn futures contract prices ranging from approximately $1.90 to $7.50 per bushel (Figure 3.). In this analysis, CP versus SDI investment returns will be analyzed for the base budget corn price ($3.50 per bushel), a low price ($1.95) and a high price ($6.00). The low price of $1.95 per bushel represents the current U.S. average commodity marketing loan program price for corn. The high price of $6.00 per bushel represents a basis-adjusted estimate of cash prices that would be typically available to crop producers at the high end of the 2000-2009 corn futures trading range.

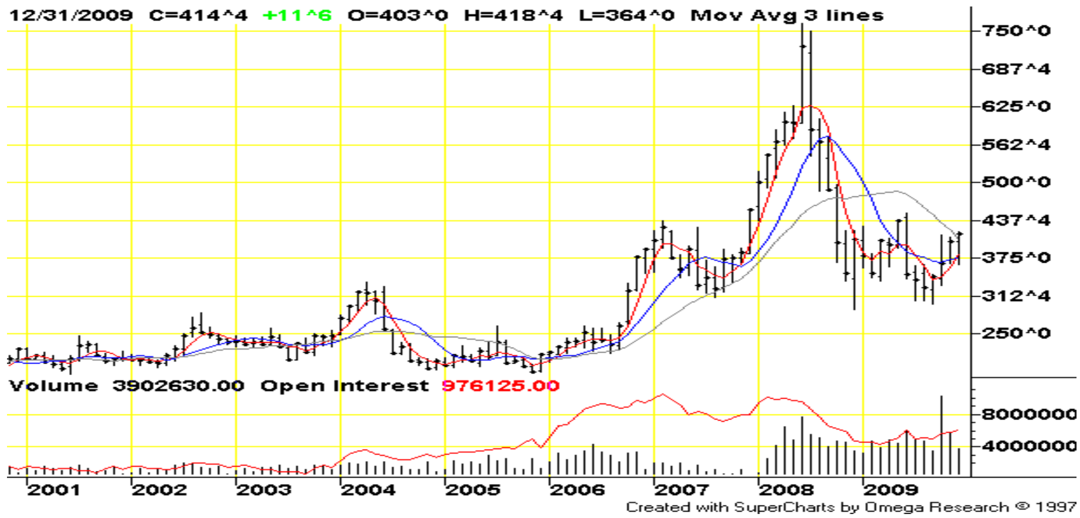

Figure 3. CBOT Corn Futures Continuation Chart: October 2000-December 2009. Online source: www.futures.tradingcharts.com

In this analysis, higher corn prices tended to favor SDI systems, while lower corn prices tended to favor CP systems (Table 1). These results can also be derived from the Yield and Price tab of the K-State spreadsheet.

Table 1. Corn Price Variation Impact on SDI versus CP Returns

Corn Price Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: $3.50 per bu.	$517.90	$499.85	($876)	($5)
Low: $1.95 per bu.	$517.90	$499.85	($11,106)	($69)
High: $6.00 per bu.	$517.90	$499.85	$15,624	$98

Natural Gas – Pumping Cost Variability Impact

Just as for other agricultural and energy-related commodities, over the October 2000-December 2009 period U.S. natural gas prices have exhibited great variability. Lead contract natural gas futures contract prices have ranged from approximately $2.00 to nearly $16.00 per mcf. (Figure 4.).

In the irrigated crop enterprise budgets developed by K-State Research and Extension, natural gas is the energy source used to calculate irrigation pumping costs. Center pivot sprinkler versus SDI investment returns will be analyzed for a base budget natural gas price of $5.53 per mcf., leading to a cost of $3.75 per acre inch of water applied for pumping-related fuel and oil. The low natural gas price to be considered is $2.00 per mcf., leading to a cost of $1.55 per acre inch of water applied for pumping-related fuel and oil. The high natural gas price is $12.00 per mcf., leading to a cost of $7.78 per acre inch of water applied for pumping-related fuel and oil.

Figure 4. NYMEX Natural Gas Futures Continuation Chart: October 2000-December 2009. Online source: www.futures.tradingcharts.com

Natural gas price variation does not have a large impact on net returns in this analysis, causing a variation of $2 to $3 per acre in the advantage of CP over SDI systems from the base scenario (Table 2.).

Table 2. Natural Gas Price Variation Impact on SDI versus CP Returns

Natural Gas Price Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: $5.53 per mcf. $3.75 per acre inch	$517.90	$499.85	($876)	($5)
Low: $2.00 per mcf. $1.55 per acre inch	$479.10	$470.17	($1,126)	($7)
High: $12.00 / mcf. $7.78 per acre inch	$588.98	$554.20	($416)	($3)

Nitrogen and Phosphorous Fertilizer Cost Variability Impact

Fertilizer prices for anhydrous ammonia or NH3 (82-0-0 N-P-K) and di-ammonium phosphate or DAP (18-46-0 N-P-K) have also been extremely variable in the most recent decade. Over the 1999-2008 period U.S. fertilizer prices have trended higher, with 82-0-0 prices ranging from $211 to $755 per ton of nitrogen on average per year. During the summer of 2008 anhydrous ammonia prices reached over $1,050 per ton of nitrogen. During 1999-2008 di-ammonium phosphate prices ranged from $227 to $850 per ton, reaching up to $1,200 per ton in the summer months of 2008.

Although the prices for these two fertilizer products are not perfectly correlated in real world markets, the low and high price scenarios for anhydrous ammonia and di-ammonium phosphate will be analyzed together. The base 82-0-0 price is $0.24 per pound of nitrogen, and the base price for 18-46-0 is $0.44 per pound. The low 82-0-0 price is $211 per ton or $0.13 per pound of nitrogen, and $0.11 per pound for 18-46-0. The high 82-0-0 price is $950 per ton or $0.57 per pound of nitrogen, and $0.85 per pound for 18-46-0.

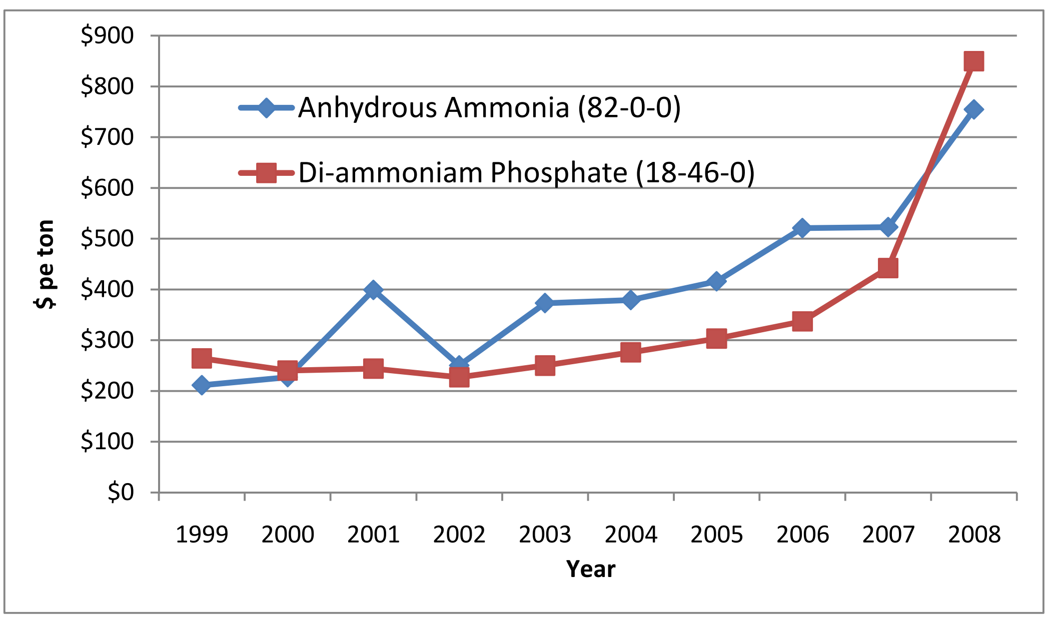

Figure 5. United States Annual Average Fertilizer Prices: 1999-2008. Source: USDA Economic Research Service

Fertilizer price variation does have some impact on net returns in this analysis, favoring SDI systems when fertilizer prices decline, and Center Pivot Irrigation systems when fertilizer prices increase. High-low N and P fertilizer price variation in this analysis accounted for a $19 per acre change in the profitability of SDI and CP systems (Table 3.).

Table 3. Fertilizer Price Variation Impact on SDI versus CP Returns

Fertilizer Price Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: $0.24 / lb 82-0-0 $0.44 / lb 18-46-0	$517.90	$499.85	($876)	($5)
Low: $0.13 / lb 82-0-0 $0.11 / lb 18-46-0	$473.16	$455.11	$466	$3
High: $0.37 / lb 82-0-0 $0.85 / lb 18-46-0	$571.81	$553.76	($2,494)	($16)

Interest Rate Variability Impact

Interest rates in the United States have varied from almost 0% up to 20% since 1950 (Figure 6.). Large swings in interest rates can have sizable impacts on the cost of borrowing money. In this analysis interest rates affect variable operating costs and the cost of borrowing money for irrigation system investments. Even if irrigation investments are paid for without credit and associated interest expenses on borrowed money, the opportunity cost of having capital invested in one enterprise as opposed to another are relevant to an investor's decision.

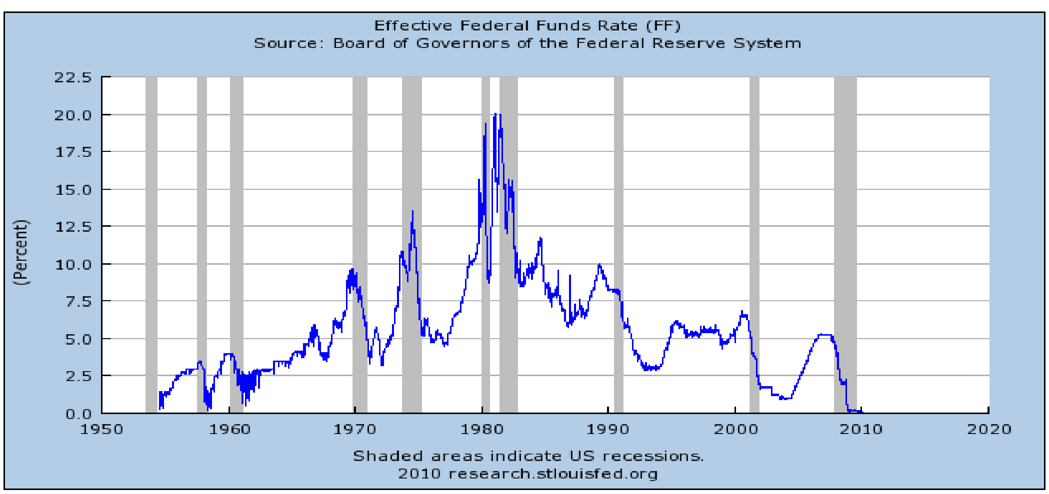

Figure 6. United States Interest Rates: 1955-2010. Source: St. Louis Federal Reserve Bank.

In this analysis the base interest rate used is 7.5%. The low interest rate scenario is calculated using a 5% rate on operating funds and capital investments. The high interest rate was set equal to 75% of the top rate of 20% charged during the period of the late 1980s – early 1990s, i.e., 15%.

Interest variation does have a large impact on relative returns in this analysis. Low interest rates near 5% benefit SDI over CP systems by $4 per acre, while historically high 15% interest rates cause CP systems to become more profitable than SDI systems by approximately $35 per acre (Table 4.).

Table 4. Interest Rate Variation Impact on SDI versus CP Returns

Interest Rate Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: 7.5% Interest	$517.90	$499.85	($876)	($5)
Low: 5.0% Interest	$511.66	$493.82	$685	$4
High: 15.0% Interest	$536.62	$517.91	($5,556)	($35)

Cost Inflation Variability Impact

Since the early 1900s, inflation rates in the United States have varied from a negative 1.94% (i.e., deflation) during 1920-29 to a positive 8.7% during the 1913-1919 period (Figure 7.). Since World War II, the decade of the 1970s had the highest annual average rate of inflation at 7.09% per year. Periods of high inflation in the cost of consumer goods raise consumer's cost of living and tend to diminish their real inflation-adjusted buying power and personal wealth. In the same way, inflation in agricultural production costs tend to increase cost of production and diminish crop enterprise profitability if not accompanied by increases in agricultural product prices.

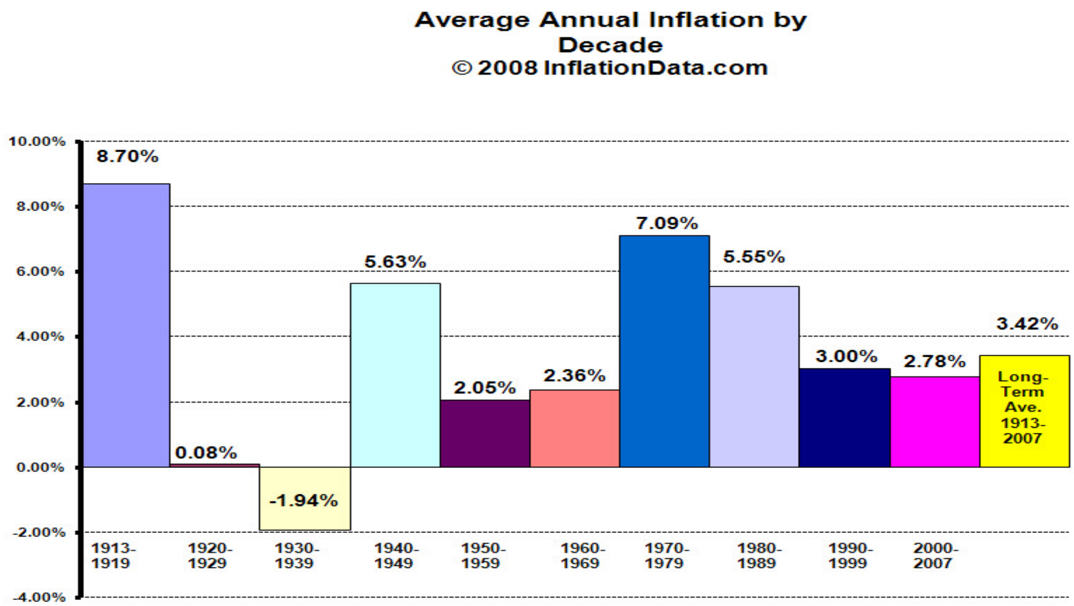

Figure 7. United States Inflation Rates by Decade: 1913-2007. Source: www.InflationData.com.

In this analysis, the impacts of one time inflations of 3% and 9% in the level of crop production costs are analyzed in comparison to the base scenario of no differential cost inflation. For this scenario, the impact of inflation in seed, herbicide, insecticide, crop consulting, crop insurance, custom hire / machinery expenses, labor costs, irrigation maintenance and repair, and non-irrigated cropland rental rates are examined. A more thorough multi-period analysis of inflation impacts over time is called for in future research.

Increasing inflation does not have a large impact on net returns in this analysis, causing increases of $3 to $8 per acre in the advantage of CP over SDI systems from the base scenario (Table 6.).

Table 6. Interest Rate Variation Impact on SDI versus CP Returns

Inflation Rate Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: 0% Inflation	$517.90	$499.85	($876)	($5)
Low: 3% Inflation	$533.44	$514.84	($1,292)	($8)
High: 9% Inflation	$564.51	$544.83	($2,126)	($13)

Broader “Low versus High” Price Cost Scenario Impact

Given the interrelated nature of agricultural and financial markets, it is judicious to examine the impact of broader “low price-low cost” and “high price-high cost” scenarios upon the profitability of SDI versus CP systems. The various inputs into these two scenarios are given in Table 7.

Whether the “low” price – cost or the “high” price – cost regime is in effect has a large impact on the relative returns of a subsurface drip irrigation system as opposed to a center pivot sprinkler irrigation system. “Low” prices and costs strongly favor CP systems while “high” price – cost scenarios strongly favor SDI systems (Table 8.).

Table 7. “Low” and “High” Price-Cost Scenario Inputs

Key Crop Inputs	“Low” Price-Cost Scenario	“High” Price-Cost Scenario
1. Corn Price, $/ bu.	$1.95	$6.00
2a. Natural Gas $, $/mcf.	$2.00	$12.00
2b. Pumping Cost, $/acre in.	$1.55	$7.78
3. Fertilizer Cost		
NH3 (82-0-0), $/lb. N.	$0.13	$0.37
DAP (18-46-0), $/lb.	$0.11	$0.85
4. Interest Rates	5.0%	15.0%
5. Inflation Rate in Crop Production Costs	3.0%	9.0%

Table 8. “Low”-“High” Price-Cost Impact on SDI versus CP Returns

Price Regime Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
“Low” Price - Cost Scenario	$442.00	$433.23	($8,965)	($56)
“High” Price - Cost Scenario	$726.07	$686.60	$8,374	$52

Summary and Conclusions

Variability in United States' agricultural and financial markets impacts irrigation investment decisions in general, and the decision to purchase a center pivot sprinkler or subsurface drip irrigation system in particular. The levels of economic variability observed in U.S. grain, energy, crop input and financial markets have been particularly heightened in recent years. If the recent past is a reasonable predictor of the future, then volatility in these markets is likely to continue to add risk and uncertainty to irrigation investment decisions for the foreseeable future.

This analysis was based on a decision tool developed by Kansas State University to assist farmers in their irrigation system investment decisions – particularly as they consider whether to invest in center pivot sprinkler or subsurface drip irrigation systems.
This analysis focused on the impact of broader economic factors whereas earlier efforts (Lamm, et al, 2009) focused more so on system physical efficiencies, design and life span in determining the most profitable system investment.

These results indicate that economic factors and forces that tend to either increase irrigated crop income or that tend to increase costs equally between the irrigation system alternatives tend to either favor subsurface drip irrigation or are neutral to the investment decision between the two options. Higher corn prices distinctly favor subsurface drip irrigation system returns, while lower corn prices favor center pivot irrigation systems. Changes in fertilizer prices, natural gas prices and associated irrigation pumping costs, and inflation in crop production costs tend to have neutral or small impacts upon the relative returns to each irrigation system.

Because of the higher investment cost required for subsurface drip irrigation systems, increases in interest rates on either borrowed capital or the on the opportunity cost of invested capital in irrigation systems tend to favor investment in center pivot sprinkler irrigation systems with their lower costs of initial investment.

When grouping economic factors into "low price – cost" and "high price – cost" scenarios, it turns out that "low price – cost" scenarios tend to favor center pivot sprinkler irrigation cost investments. Conversely, "high price – cost" scenarios of economic factors favors subsurface drip irrigation investments.

Future analysis should focus on the multi-period impacts of inflation, interest, and variability in product revenues and crop input costs. If farmers believe the hypothesis that higher levels of volatility will continue to exist in agricultural, energy and financial markets in the future, then their irrigation investment decisions will need to be all that much more informed in regards to the physical and economic uncertainties they are dealing with.

This is a contribution of the Kansas State University, Manhattan, Kansas. Contribution No. 10-229-A from the Kansas Agricultural Experiment Station.

This paper is also part of a two-yearlong 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 Project. To follow other activities of this educational effort, point your web browser to http://www.ksre.ksu.edu/sdi/. Watch for this logo.

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Proceedings of the 22nd Annual Central Plains Irrigation Conference, Kearney, NE., February 23-24, 2010
Available from CPIA, 760 N. Thompson, Colby, Kansas

ALTERNATIVE ENERGY SOURCES FOR IRRIGATION POWER UNITS

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Evaluation of Biofuel Driven Irrigation Pumps and/or Electric Generators for Use during Peak Electricity Demand

Project Abstract

The goal of this research is to support the development of a biofuel power unit industry in Nebraska to increase the use of agricultural resources, crops and the resulting biofuels that are produced in the region. Nebraska companies have developed systems to utilize denatured ethanol and other biofuels in industrial power-units. The successful validation and demonstration of these systems will support their adaptation in water pumping and electrical generation plant applications. It also will document exhaust emissions and compare operating costs with traditional engines and fuels. These systems could reduce peak load electrical energy demand resulting from electrical powered irrigation pumping stations, improve emissions compared to petroleum power irrigation pumping stations or peak load electrical generating stations, and may reduce production costs for irrigated farming operations.

Acknowledgements

This project is funded by the Water, Energy and Agriculture Initiative, which funds research to maximize the efficiency with which water and energy resources are used to sustain economic development and water conservation in Nebraska agriculture. The Nebraska Center for Energy Sciences Research administers the initiative, which was created in 2008 through a partnership of the center, the Nebraska Public Power District, the Nebraska Corn Board, the Nebraska Soybean Board and UNL's Agricultural Research Division.

The project team includes University of Nebraska researchers representing the Industrial Agricultural Products Center, the Nebraska Tractor Testing Laboratory, and the Biological Systems Engineering Department. Industrial partners are Amerifuels Energy Solutions of Kearney, NE, CleanFlex Power Systems of Lincoln, NE, Kamterter of Lincoln, NE, and Industrial-Irrigation of Hastings, NE.

Project Goals

The goals of this two year research project (2009 and 2010) are to: support the development and adoption of biofuel-driven stationary power units by: 1) providing third party evaluations, field demonstrations, and educational materials, 2) identifying current constraints and limitations to acceptance, and 3) outlining potential statewide impacts.

Description of Systems

Amerifuels Energy Solutions supplies an 8.1 L GM spark ignition engine equipped with port injectors to electronically inject denatured ethanol in place of traditional fuels such as natural gas or liquid petroleum (LP) gas. In some cases a dual fuel system provides ethanol to supplement natural gas when supplies are limited in the natural gas distribution lines. Further information regarding this system is available directly from the supplier at http://www.amerifuels.com/ or 877-756-1117 (toll free).

CleanFlex Power Systems uses an aftermarket modification for compression ignition (diesel) engines to fumigate hydrated denatured ethanol (60% alcohol by weight) into the air intake after the turbo charger and intercooler, but just before the manifold. The system uses a computer controlled injection spray nozzle and boost pump to replace approximately 20% of the energy normally supplied by diesel fuel with hydrated denatured ethanol. Compression continues to provide the ignition source for the fuels. Further information regarding this system is available directly from the supplier by contacting Ronald Preston at rpreston@vsrfin.com or 402-480-0346.

Kamterter uses an aftermarket modification for compression ignition (diesel) engines to fumigate hydrated denatured ethanol (60% alcohol by weight) into the air intake before the turbo charger and intercooler, but after the air filter. The system uses a very low pressure atomization nozzle and volumetric pump to replace approximately 20% of the energy normally supplied by diesel fuel with hydrated denatured ethanol. Compression continues to provide the ignition source for the fuels. Further information regarding this system is available directly from the supplier by contacting John Eastin at http://www.kamterter.com/ or 402-466-1224.

Key Findings in Year 1

Evaluations compared traditional systems and fuels with the modified systems and fuels. Key comparisons were fuel consumption per hp-hr, energy or Btu consumption per hp-hr, overall thermal efficiency and estimated grams of emissions (CO, CO_2, O_2, NO_x, and total hydrocarbons) per hp-hr.

Key observations regarding the use of denatured ethanol in place of LP gas in the spark ignition engine is that denatured ethanol increases power output, lowers energy (Btu) consumption per hp-hr, dramatically reduces CO and CO_2

emissions per hp-hr, and shows potential to reduce HC and NOx emissions per hp-hr as well.

Key observations regarding fumigation of hydrated denatured ethanol with diesel fuel injection in compression ignition engines are that hydrated denatured ethanol fumigation shows potential to reduce NOx emissions while increasing power output per energy consumed. However, as of the time of testing (summer 2009), further development of the systems may improve control of fuel delivery volumes, atomization, and timing.

Key observations regarding the comparison of B5 biodiesel and #2 diesel fuel revealed that both fuels provided essentially the same fuel efficiency and emission profiles when evaluated with the available testing equipment.

A field demonstration was intended to provide some insight to long term operations and durability in the commercial application environment. The spark ignition system from Amerifuels Energy Solutions was selected for field demonstration in July and August 2009. The system was operated at the University of Nebraska Southwest Research Farm near Curtis, NE for 95.4 hours over the period, consuming 970 gallons of denatured ethanol to pump 7,895,000 gallons of water and gave no indication of engine wear beyond typical engine break-in. This system from Amerifuels Energy Solutions also was in commercial use at numerous irrigation pumping plants in south-central Nebraska.

Further Research – Year 2

The second year of this project will allow for:

- further evaluation as the systems continue to develop;
- further field demonstrations;
- opportunities to identify constraints to the adoption of the systems, for example “Who will be regulating what?”;
- opportunities to access statewide impact of adopting the systems, for example “How much ethanol could be consumed and what energy sources would the systems most likely replace?”; and
- further development and dissemination of educational materials and programs.

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ENERGY SAVINGS USING VARIABLE FREQUENCY DRIVES ON CENTRIFUGAL PUMPING APPLICATIONS

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Modern Electric Motor Starting Means

There are three primary methods used to start and operate induction AC motors: Full voltage direct across the line starters, reduced voltage soft starts, and Variable frequency drives (VFD's). The three methods all have distinctly different effects on both the mechanical system but also the power distribution networks. Both the full voltage and reduced voltage starting means are only capable of running AC motors at the motor's synchronous speed of 60Hz. Full voltage cross the line starters allows the utility's full wave form to start the motor. This method will see a 600% to 800% of full load current in-rush during the starting of the motor. Many utility providers have begun to limit this starting means to only smaller motor loads due to the effects of the high in-rush current required to start the motor. Reduced Voltage soft starts will allow for more control of starting ramp rates of the system, but will have a typical in-rush current during starting of 350% to 450% of the motor's full load current and not allow for speed control. Both of these starting means do not allow for power factor correction within an induction AC motor system.

However, a variable frequency drive allows an induction AC motor to have virtually no in-rush current and is capable of reduced operating speeds of the motor. As a mode of operation, a variable frequency drive rectifies the incoming AC power to a DC bus first. It then switches the DC bus power to create a modified AC waveform to the motor. This technology allows for smoother starts, infinite control of a pump's flow, and significant avoidance of water hammer. A variable speed drive is also capable bringing an oversized system closer to unity power factor as well.

Affinity's Law Effects on Power consumption

Affinity's law is the phenomena that a centrifugal pump typically follows as the system's speed is reduced to control flow rather than throttling. A cubed root relationship allows for significant reductions in energy consumption as the system's speed is lowers. Typically a reduction in speed by 10% can net an energy saving of 27%. These savings often justifies the additional cost of the more sophisticated variable frequency drives.

Comparing the Cost to Traditional Engines

The three popular power sources for irrigation today are Natural Gas fired internal combustion engines, Diesel cycle engines, and Electric AC induction motors. The more traditional methods of power are far less energy efficient than an AC motor. These typically run at 50% or less efficient. Their efficiency will dramatically decrease as their operating speeds are reduced which can negate the benefit of running a system at slower speeds. However, an AC motor with an applied variable frequency drive system is capable of reducing its energy consumption at slower speeds while maintaining the system's efficiency in excess of 90%.

During this session we will cover the basic calculations for power consumption, speed's effects on a centrifugal pumping system, and a look at the total cost of ownership comparing traditional power means versus AC motors applying variable frequency technology.

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PRECISION WATER MANAGEMENT

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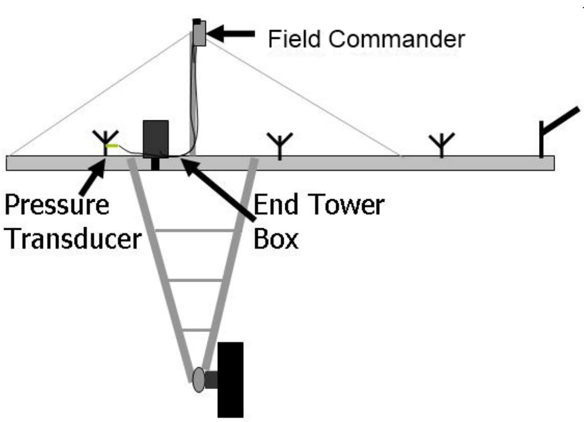
PRECISION WATER MANAGMENT

Remote Pivot Monitor/Control

In regards to the center pivot irrigation system, the ability to remotely monitor position, speed, pressure and flow are essential to precision water management. The ability to remotely control the pivot also assists producers in timely and accurate operation of the pivot.

The Field Commander remote pivot controller mounts on the rabbit ears of the pivot and is equipped with a GPS to track the pivot and perform pivot control operations based on position. The Field Commander utilizes the Digital cell network to transport data across the Internet to the WagNet.net web portal.

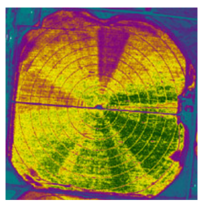
However, other field data must be remotely captured in order to capture a timely, complete picture of what is going on in the field. This data is critical in successfully implementing a precision water management program.



Remote Field Management

In addition to monitoring and controlling the pivot, the Field Commander can be optionally equipped with a 900 MHz radio with meshing technology to communicate with multiple sensors, meters and pumps located in the field via the AgSense Crop Link device, which is also equipped with a 900MHz radio.

Crop Link has built-in hardware and software that enables it to work as a multi-purpose device, allowing it to be programmed and configured in the field, via the Internet.

Crop Link enables AgSense to partner with other agricultural companies to deliver customers a broad range of field data and proprietary solutions. AgSense serves as a gateway to the Internet for a number of applications. However, AgSense does not charge for the additional data transported.

Through collaboration and data sharing, end users enjoy lower annual service cost, as well as timely data that is displayed in coordinated formats, to maximize productivity, efficiency and profitability.

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The Use of Technology in Mechanized Irrigation

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Overview

The development of electronic technology has impacted all of us. It allows better communication, better access to information, and innumerable things that make our lives easier.

It is only natural that these new tools are being put to use to enhance the operation of irrigation equipment as well. As in other applications this manifests itself primarily in two ways. First, as a means to improve the ability to monitor and control equipment. Second, as way to improve the performance and efficiency of the equipment itself.

Monitoring and Control

Unlike most other farm equipment, irrigation systems typically operate unattended. Most farming operations have multiple irrigation installations and often times these are distributed over a large area. In the critical growing season timely management is very important. Interrupted operation at a time of high crop stress can be costly.

Monitoring used to require an individual visual checking each system. This required a lot of time and if a system failed just after being checked it would set idle until the next scheduled “drive by”, wasting valuable time.

Satellite and cell phone networks are now available to us for communication with systems regardless of their accessibility. Devices have been developed that are easily retrofitted to pivots in the field. In their simplest form they can be used for monitoring the system only. More sophisticated units add the ability to control at least the basic functions of the system.

Improved performance and efficiency

To improve the efficiency with which water is applied it is often desirable to "program" a pivot or linear move system to alter its operation either by time of day or location in the field. For instance half of a pivot might be planted to corn and the other half to soybeans, or the operator might want to irrigate only at night.

Early computerized control panels allowed these things to be accomplished but with a marked increase in the complexity of operation. Alpha numeric displays manipulate by a key pad could be very confusing resulting in limiting the utilization of the systems capability. Touch screen technology provides a much more intuitive and efficient operator interface. Visual representation of the system as programmed is one facet. Another is the ease of moving through several screens that provide direct feed back to the operator.

One of the main bits of information needed for effective management of an irrigation system and its functions is location. For center pivots, several devices have been used to mechanically measure the angular location of the pivot center. The accuracy and reliability of such devices is suspect because relatively small angle changes represent large displacement of the out end of a system. A GPS device located on or near the end of a system provides the accuracy needed.

Pivot Control Tools Providing Efficiency to Preserve, Conserve and Protect

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Monitoring and Control of Center Pivots

The ability for producers to monitor and control center pivots has been available since the early 1990's. This technology started with a direct access to the pivot through a land line phone connection on analog cell phone. The technology has continued to evolve. Today pivots and pumps can be controlled from the internet and phone anywhere in the world.

FieldNET

FieldNET was introduced by Lindsay Corporation three years ago. FieldNET provides growers the ability to monitor and control center pivots from a secure user web site or via any telephone. A key feature of FieldNET is that it can work for monitoring and start/stop controls on any brand of pivot. The pivots are connected to the internet through cellular telemetry units or radio telemetry units, which connect to the internet through an internet bridge.

With this web based solution tool growers are able to create a network with all of their pivots and manage them at all times no matter where they are. The user friendly web portal provides quick view of every pivot, providing information on pivot location, pivot status and water usage. This encompassing view enables quick, effective decision making. The portal provides a complete history log and the ability to create reports on water and chemical application.

FieldNET provides growers updates and alerts via phone, text message and email. These notifications are set based upon the users information needs. With this immediate information growers are able to react to various statuses when they occur rather than only when they are at the machine in the field. This leads to greater efficiency and time resource savings.

FieldNET Pump Control

Lindsay Corporation has just added FieldNET for pump controls. Now FieldNET, with pump control, integrates the entire water delivery system from the well or surface water source to the center pivot. It allows the industry-leading pumping solutions by Watertronics and Zimmatic center pivots to work together to automatically monitor and control the system to achieve maximum efficiency.

FieldNET Pump Control lets growers monitor and control several devices such as; pumps, pivots, and sensors. Visual pressure settings on pumps with Variable Frequency Drives allow for management of pressure and flow for efficient energy savings. Linking pump devises compares pump station capacity with pivot demand for informed irrigation decisions and alerts of any detected disparity. Reports and charting allow for record keeping of total gallons pumped and electricity used.

FieldNET Irrigation Management Advantages

There are many advantages to remote monitoring of pivots and pumps. These include:

- Reduced energy costs
- Significant labor savings
- Convenience
- Flexibility for current equipment
- Effective tool for professional service providers
- Development and use of Knowledge:
- Reporting and Diagnostics:
- Reduced risk and less downtime
- Enhanced best practices and stewardship: