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WATER LOSSES ASSOCIATED
WITH CENTER PIVOT NOZZLE PACKAGES

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INTRODUCTION

Sprinkler packages that are available and used in the Great Plains of the United States are widely varied from older impact heads to more modern spray heads or various rotator designs and have an assortment of application and/or placement modes. This paper will address common sprinkler packages in use on center pivot sprinklers. Sprinkler packages are designed and selected (purchased) for a variety of reasons. Often high irrigation uniformity and application efficiency are cited as priority goals in selecting a particular sprinkler package or sprinkler application method. In practice, many sprinkler packages can achieve the desired design and operational goals equally well at or near the same costs. Management, maintenance, and even installation factors can be as important as the selection of a package or application method.

This paper discusses the desired traits of various sprinkler packages and sprinkler application modes and discusses the anticipated water losses that might impact both irrigation uniformity and efficiency. In most cases “generic” descriptions are used rather than individual commercial names of sprinkler manufacturers. End-gun effects are not discussed or addressed to a significant degree.

TYPES OF SPRINKLER PACKAGES

Sprinkler Spacing

The first sprinklers used on center pivots were impact heads adopted from hand-move, portable sprinkler lines that had a large angle (~23 degrees from horizontal) of discharge to maximize the water jet trajectory. Many of these were single nozzle types, but some used double nozzles to improve the uniformity for the pattern. Early center pivot design sprinkler spacing was about 32 ft (9.8 m) with impact sprinklers while some later designs used a variable spacing (closer towards the outer end of the pivot). Two principal design modes were commonly used for these packages – 1) constant (uniform) spacing with variable nozzle diameters along the center pivot to vary the sprinkler discharge or 2) almost constant nozzle discharge and head selection with variable spacing (e.g., farther apart near the pivot point and closer together on the outer lengths of the pivot). It was common to mount larger sprinklers on the ends of the pivot (end guns) to cover more land area with a fixed pivot length. A third design mode – called the semiuniform spacing (Allen et al., 2000) is a combination of these two other design modes. The variable spacing mode is easier to apply to rotator-spinner-spray heads but greatly complicates the center pivot pipeline design and the sprinkler package installation and maintenance.

The constant outlet spacing is quite common, particularly for closely spaced systems (~5 ft or 1.5 m) used with LEPA (low energy, precision application), LESA (low elevation, spray application), or LPIC (low pressure, in-canopy) methods of application. The sprinkler outlet spacing for non LEPA/LESA type systems with the constant spacing are often spaced up to 10 ft (3 m) apart. This spacing type is still used for pipeline mounted low angle impact sprinklers or spray heads on drops (typically mounted just below the truss rods). One concern with this spacing design can be the larger sprinkler discharge rate at the outer end requiring large nozzles with larger droplets. Additionally, it can result in the requirement for higher operating pressures in some cases. These two factors — larger nozzles and higher operating pressures — can cause infiltration problems due to soil crusting and/or runoff difficulties from the high instantaneous application rates.

When LEPA and LESA are not used, the semiuniform spacing can rather conveniently be used with a 10 ft (3 m) outlet spacing uniformly along the pivot pipeline. Allen et al. (2000) suggested that the first third of the pivot length might use a 40 ft (12 m) sprinkler spacing, the middle third might use a 20 ft (6 m) sprinkler spacing, and the outer third might use a 10 ft (3 m) sprinkler spacing with the unused outlets plugged. This concept would also work with a 5 ft (1.5 m) outlet sprinkler spacing along the pipeline that might offer conversion options to LEPA, LESA, or LPIC application methods. This semiuniform spacing mode avoids many of the problems with larger nozzles.

The application uniformity will depend on many factors of the design and several operational factors (e.g., wind speed, pivot alignment and the wind direction, topography (tilt of the sprinkler axis in relation to the ground slope), effect on pressure at the outlet, etc., soil type, etc.) The main sprinkler factors affecting uniformity are the sprinkler spacing, the sprinkler device type –its diameter of throw, application pattern type, operating pressure, nozzle and spray plate design, the elevation of the application device above the ground, and any crop canopy interference.

Sprinkler Types

Center pivot sprinklers can be classified generally into two broad types –impact sprinklers and spray heads. Within the impact type, nozzle angles can vary from the older type heads with higher trajectory angles (~23 degrees) to lower angle impact sprinklers (~6-15 degrees) that are typically mounted on top of the center pivot pipeline. Impact sprinklers are usually constructed using brass or plastic materials. They operate with a spring and heavy jet deflector arm with each arm return (from the spring) imparting a momentum to rotate the nozzle jet slightly. It might take up to 100 or more deflector arm returns to cause the impact sprinkler head to make a full rotation. The rotation speed depends on several design factors of the deflector arm; its mass and the bearing in which the sprinkler rotates. Nozzles can be simple "straight bore" types (that operate according to basic orifice principles where discharge depends on the nozzle diameter and the operating pressure) or various design types that provide flow controls by compensating the nozzle discharge –pressure relationship to provide a more constant discharge independent of the operating pressure. The operating pressure of most impact sprinklers is in the range of 25 to 40 psi (170 to 280 kPa), but the operating pressure is higher for larger sized nozzles. Impact sprinklers typically have a 3/4 in. NPT male end (18 mm), but some larger nozzles may require a 1 in. NPT (25 mm) size to reduce pressure losses across the pipeline mounting coupling.

Impact sprinklers have an advantage because they typically have a large radius of "throw", thereby having a larger wetted area and smaller instantaneous application rate (equivalent to the "precipitation" intensity) that can nearly match the soil infiltration rate with fewer runoff and erosion difficulties. Because they must rely on the hydrodynamics of the water jet and its breakup for the irrigation application, transport mechanism, they are affected to a greater degree by winds and subject to greater pattern distortions because of their higher application elevation above the ground or crop. Also, they might have a higher pumping cost due to their greater operating pressure.

Spray heads are a much more diverse classification. They can range from simple nozzles and deflector plates to more sophisticated designs involving moving plates that slowly rotate or types with spinning plates to designs that use an oscillating plate with various droplet discharge angles and trajectories. The rotator types are similar to small, low angle impacts sprinklers, except the sprinkler rotation is controlled by the nozzle jet with a hydraulic "motor." Most spray heads have a near 360 degree coverage and can have deflector plates designed with differing groove sizes to affect the spray streams (deeper grooves with fewer jets to have larger diameter streams in windier cases, shallower grooves with more streams to have smaller droplets, or flat to have a greater droplet diameter range), and they can have streams that are ejected almost horizontal (flat), upward (concave) and/or downward (convex) with downward orientated spray heads. They can be designed with plates that direct water streams upward at various angles for chemigation of tall or short crops. Spray heads can have partial coverage (i.e., not a complete 360 degree pattern), which are often used near towers to minimize track wetting. Spray heads can be mounted upward on the center pivot pipeline itself. Typically, spray heads are mounted on “drops” from “goose-neck” fittings that make a 180-degree bend from the upper side of the center pivot pipeline and longer “goose-necks” (also referred to as furrow arms) may be used to allow matching LEPA or LESA drops to the rows. The drops are usually flexible hoses. For longer drops (LEPA, LESA, or LPIC), the drop hose will typically have a weight (1-2 lb or 1/2 to 1 kg) to minimize swaying from the wind. Usually, the “goose-necks” and drops are installed on alternating sides of the center pivot pipeline (Figure 2).

Figure 1. Typical example of a LESA system with spray heads on drops spaced 5 ft (1.5 m) apart). Note that the furrow arms and drop hoses alternate from one side to the other along the truss.

Spray heads typically operate at pressures from 10 to 30 psi (70 to 200 kPa), but some LEPA or LESA systems operate at pressures as low as 6 psi (40 kPa). Lower pressure systems or ones with significant elevation changes are usually equipped with pressure regulators to achieve higher uniformities. Spray heads are often constructed from plastic, and the various nozzle sizes are color-coded (varies by manufacturer).

Allen et al. (2000) describes many of the common types of spray heads from several manufacturers and their characteristics. Table 1 provides a summary of some of the typical sprinkler heads used on center pivots. The list of advantages and disadvantages is intended solely as a guide, and individual situations may have unique situations not characterized here. Readers are encouraged to seek local advice from technical advisors (e.g., county extension agents, USDA-NRCS specialists, irrigation dealers, irrigation extension specialists, consultants, etc.) before making any sprinkler design selection or changes. Figure 2 conceptually illustrates the relative application rates under various sprinkler types after (King and Kincaid (1997). The peak application rate linearly increases along the center pivot radius and is a maximum at the outer end. The X-axis presented as a distance scale in Fig. 2 can be converted to a time scale based on the speed of the center pivot at that point (e.g., divide the distance wetted by the speed (ft/hr) to achieve the time course of the application as the pivot passes a particular point). The area under each of the transformed curves will be a constant along the center pivot's length representing the application amount (in. or mm).

Sprinkler Application Modes

The application modes for center pivot "sprinkler packages" can be described as either 1) overhead or over-canopy methods or 2) near-canopy or in-canopy methods. The sprinkler type selected is influenced by the mode of the desired application method. The mode and sprinkler type may influence the required spacing. So these are not independent alternatives. Hence, they have been called "sprinkler packages" because all aspects of design, installation, maintenance, and management affect the "package" performance.

The overhead or over-canopy methods are those application types mounted on the center pivot pipeline itself or those mounted on drops that are typically just below the truss rod elevation above ground. Of course these descriptions are still arbitrary depending on the system height and the crop height. One of the main decision factors for this mode is whether only overhead or over-canopy chemigation is desired or if no chemigation option is desired. Impact sprinklers, spray heads, and rotators are typically considered for this application mode. This mode and application method is well suited to rolling topography, low intake soil types, and crops tolerant of overhead wetting.

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Table 1. Characteristics of common center pivot sprinkler types

Sprinkler Type	Pressure Range psi (kPa)	Typical Height ft (m)	Advantages	Disadvantages
Impact, high angle	25-50 (170-300)	6-15 (1.8-4.5)	Low application rate.	High energy requirement. Exposure to wind effects.
Impact, low angle	25-35 (170-250)	6-15 (1.8-4.5)	Low application rate.	High energy requirement. Still impacted by winds.
360° spray head, rotator, spinner; high location	10-30 (70-200)	6-15 (1.8-4.5)	Lower energy requirement. Closer spacing.	High application rate. Only over canopy chemigation.
360° spray head, low location LESA or LPIC	10-30 (70-200)	1-6 (0.3-1.8)	Lower energy requirement. Less wind effect. Close spacing. Some have LEPA drag hose adapters. Under canopy chemigation.	High application rate.
Low drift and multiplate spray heads	10-30 (70-200)	Varied Pipeline Truss Level. LPIC	Lower energy requirement. Lower drift and wind effects. Many configurations. Some have LEPA drag hose adapters and chemigation plates.	High application rate.
Rotators	15-50 (100-300)	Varied. Pipeline. Truss Level. LPIC	Larger wetted diameter, lower application rate. Good resistance to wind effects.	Can have higher energy requirement. Limited in-canopy chemigation applications.
Spinners	10-20 (70-150)	Varied. See Rotators	Low energy requirement. Gentler droplet applications.	Limited in-canopy chemigation applications.
Oscillating/Rotating Spray Plates	10-20 (70-150)	3-6 (0.9-1.8)	Low energy requirement. Low misting from small droplets. Low application rate and gentler applications.	Limited in-canopy chemigation applications.
LEPA Bubble	6-10 (40-70)	1-3 (0.3-0.9)	Low energy requirement. Usually, alternate furrow applications and less evaporation. Multi purpose (convertible from spray to bubble to drag sock). Excellent in-canopy chemigation options.	Extremely high application rate. Requires furrow dikes or surface storage (~1-2 in., 15-50 mm of water volume).
LEPA Drag Sock	6-10 (40-70)	0 (0)	See LEPA Bubble. Less erosion of furrow dikes.	See LEPA Bubble.

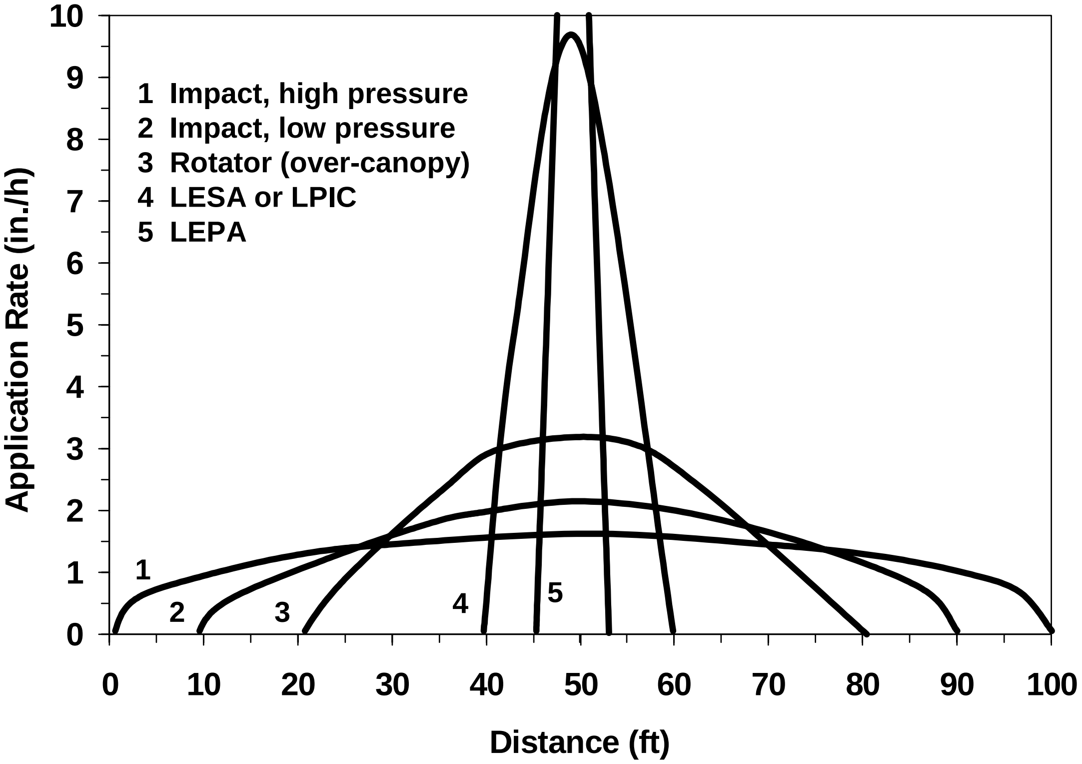

Figure 2. Illustration of the relative application rates for various sprinkler types under a center pivot. Modified and adopted from King and Kincaid (1997). The LEPA application rate is difficult to show because it is essentially a "point" discharge, and its peak was illustrated to exceed the rate range of this graph.

The near- canopy or in-canopy application methods are always mounted on drop tubes from the center pivot pipeline. The main difference is whether the sprinkler devices are mounted near the ground (LEPA or LESA), within the crop canopy or the mature crop canopy (LPIC), or just above the maximum height of the crop. Of course, a LPIC system designed for a tall crop may not be a LPIC system in a shorter crop (e.g., a corn LPIC system will not be a LPIC system in cotton, peanut, or soybean crops; Figure 3). For that reason, we (USDA-ARS Bushland) have preferred to use the names — LESA for a system with the spray heads mounted 1-2 ft (0.3-0.6 m) above the ground or MESA (mid elevation spray application) for a system with spray heads mounted 5-8 ft (1.5-2.4 m) above the ground. The name LEPA should only be used for a system with bubblers (e.g., an adjustable multi-purpose head) or drag socks mounted on a flexible hose. LEPA hoses can be attached with commercial adapters to many types of spray heads whether the spray heads are mounted low near the ground like LESA or at a higher elevation like a LPIC or MESA system. Although Lyle and Bordovsky (1981) originally used LEPA in every furrow, subsequent research (Lyle and Bordovsky, 1983) demonstrated the superiority for alternate furrow LEPA. The reasons aren't always evident, but they may result from the deeper irrigation penetration (twice the volume of water per unit wetted area compared with every furrow LEPA), possible improved crop rooting and deeper nutrient uptake, and less surface water evaporation (~30-40% of the soil is wetted). LEPA and LESA work best with either LEPA heads or 360° spray heads. Some of these systems (LEPA or LESA) also have flexibility to chemigate either a tall crop (e.g., corn) or shorter crops (e.g., soybean, wheat, cotton, or peanut). LPIC and MESA systems have the conversion potential to LEPA, but they don't have the under canopy chemigation potential of LEPA or LESA systems. LEPA and LESA systems are typically located in or above alternate furrows or between alternate rows if furrows are not used. LEPA requires a furrow with furrow dikes according to the concepts described by Lyle and Bordovsky (1981) while LESA can be effective without furrows in no-till or conservation till systems. This doesn't imply LEPA heads cannot be used without furrow dikes, but it shouldn't be described as "LEPA". LPIC or MESA systems are typically spaced for a desired uniformity and may not be bound by the row spacing. LPIC systems may require a narrower spacing to compensate for crop interference (Spurgeon et al., 1995).

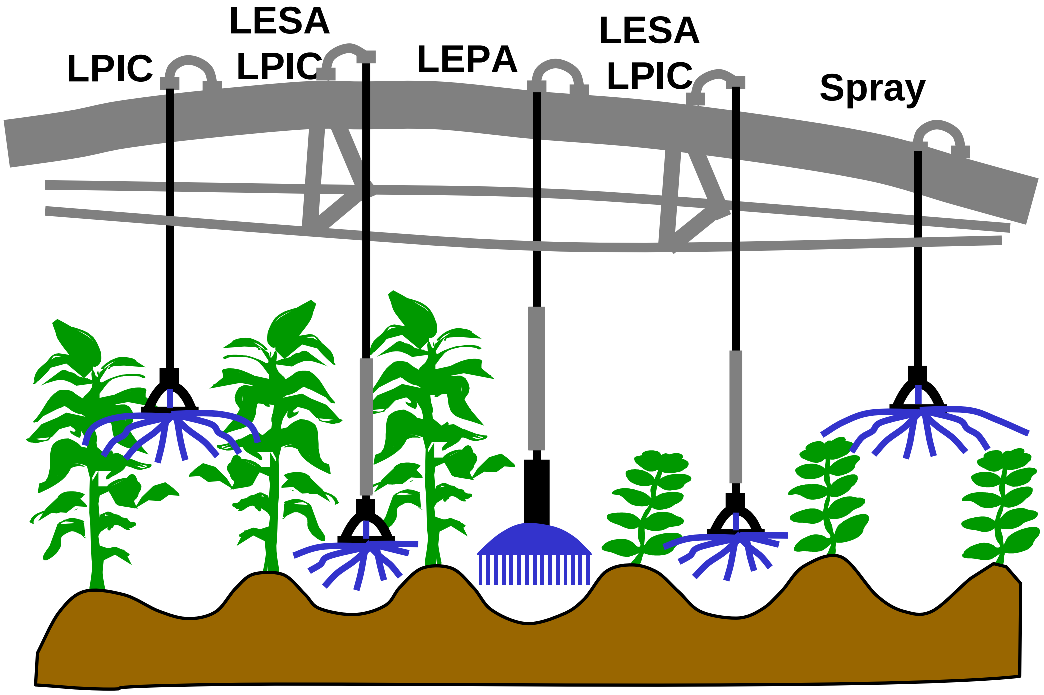

Figure 3. Illustration of the LEPA, LESA, LPIC, and spray application concepts in tall and short crops. The illustration has drops in each furrow to conserve space while actual systems typically use drops in alternate furrows either 60-in. or 80-in. (1.5-m or 2-m) apart depending on the crop row spacing.

Lyle and Bordovsky (1981) developed the LEPA concept as a “system” comprising irrigation combined with furrow diking (basin tillage). In fact, all advanced center pivot sprinkler application packages need to be incorporated into a complete agronomic package involving tillage, controlled traffic, residue management, fertility, harvesting, etc. (Figure 4). Table 2 summarizes several of the typical center pivot “sprinkler packages” and their “system” components.

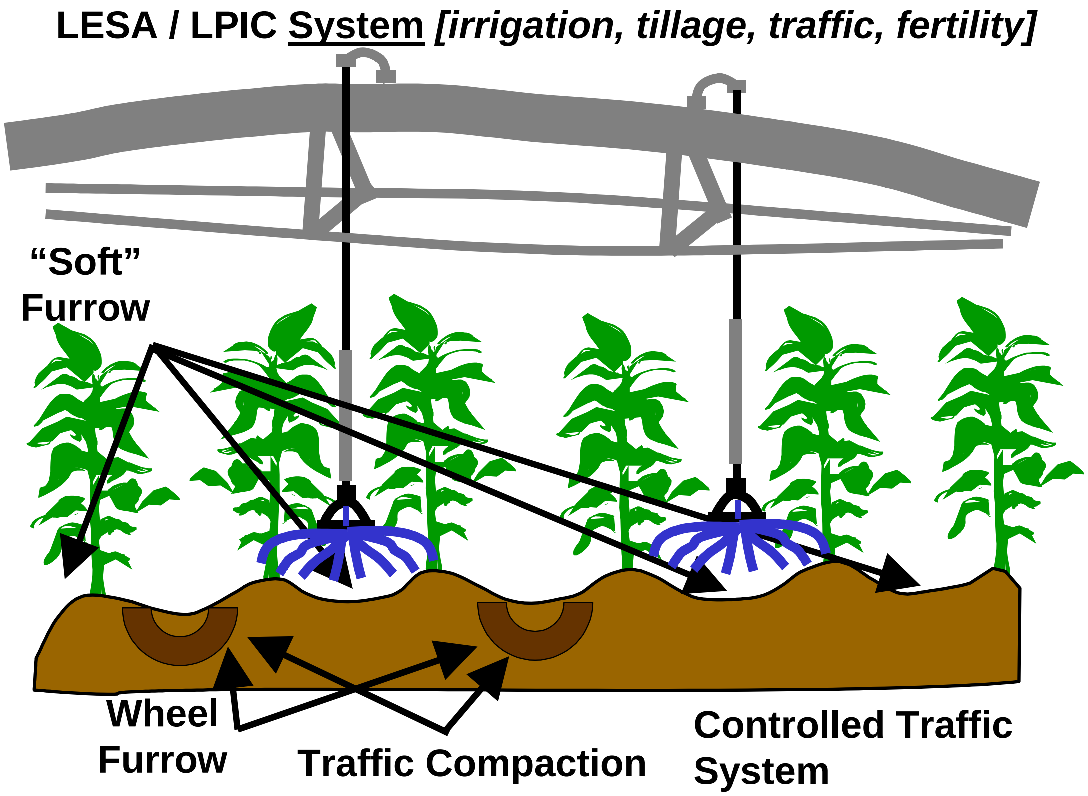

Figure 4. Illustration of the "agronomic system” concept involving irrigation, controlled tillage, fertility, etc.

WATER LOSS COMPARISONS

The efficiency of an irrigation application depends on many factors. The water losses depend on the application technology and operation and include other agronomic cultural aspects. The interpretation and characterization of water loss estimates or measurements involves the conservation of mass applied to sprinkler irrigation as outlined by Kraus (1966). He presented the components as

$$Q_s = Q_{ae} + Q_{ad} + Q_{fi} + Q_{gi} \qquad \text{...[1]}$$

where Q_s is the sprinkler discharge, Q_{ae} is the droplet evaporation during travel from the nozzle to the target surface, Q_{ad} is the water drift outside the target area, Q_{fi} is the intercepted water on the foliage, and Q_{gi} is the water reaching or intercepting the ground. The units for these components can be expressed on a rate, mass, or volume basis. Q_{fi} represents the sum of water evaporated from the foliage during the irrigation (Q_{fe}) and the amount of water remaining on the foliage at the end of then irrigation (Q_{fs}). The water reaching the ground (a defined unit area) can be partitioned into its components characterized as

$$Q_{gi} = Q_{si} + Q_{ge} + Q_{gs} + Q_{gwe} + Q_{gri} + Q_{gro} \qquad \text{...[2]}$$

where Q_{si} is the infiltrated water, Q_{ge} is the water evaporated from the ground during the irrigation, Q_{gs} is the water stored on the ground during the irrigation, Q_{gwe} is the water evaporated from the water stored on the ground prior to infiltration during irrigation, Q_{gri} is the water that runs onto the unit area, and Q_{gro} is the water that runs off the unit area. In its simplest case, irrigation application efficiency is equivalent to the ratio Q_{si}/Q_s because percolation beneath the root zone can usually be ignored. Percolation beneath the root zone depends on irrigation scheduling and other water management issues. Percolation can be significant in low lying areas in the field that accumulate runoff from upland areas.

Generally for a center pivot, drift outside the area is small and is often ignored; however, it could be more significant with systems equipped with end guns or in extremely high wind situations. Typically, irrigation application efficiency can only be measured after the water application has been completed and after the evaporative processes that affect the Q_{ae}, Q_{fe}, and Q_{ge} components. For methods that wet the foliage, transpiration will decline, and generally the “net” evaporation (evaporative loss offset by the reduced transpiration) is the component of interest. Also, the movement of the water vapor downwind humidifies the drier air reducing the crop evapotranspiration rates, even before the area is wetted by the irrigation. In addition evaporation continues after the completion of the irrigation event from the foliage intercepted water (Q_{fi}) and surface storage water (Q_{gs}) and the evaporation from the ground during the irrigation (Q_{ge}) and following the event (Q_e, total evaporation of water from the ground surface). At the typical observation time, the intercepted water on the foliage and the ground will already have evaporated and these amounts are largely unknown, except by some inference methods (qualitative comparisons; e.g., estimating Q_{ge} from evaporation from an “open” water body near the site). Table 3 outlines the possible water loss components common for various sprinkler packages.

Table 2. Example sprinkler packages with desired tillage and agronomic systems.

Sprinkler Package	Tillage System	Agronomic System
Overhead		
Impact sprinklers rotators, spinners	Any	Any
MESA or spray	Any. Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with or without beds. No-till, ridge-till, or conservation till compatible.	Any
Within canopy		
LPIC 360° Spray head Low drift head Spinner Oscillating plate	Any. Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with or without beds. No-till, ridge-till, or conservation till compatible.	Any
LESA 360° Spray head Low drift head Spinner	Any. Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with or without beds. No-till, ridge-till, or conservation till compatible.	Any, circular rows desired
LEPA (bubble)	Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with beds.	Circular rows
LEPA (drag socks)	Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with beds. (basin tillage is more effective)	Circular rows

Howell et al. (1991) reviewed many of the studies that had measured evaporative losses from sprinkler systems, especially those using lysimeters. They noted the great difficulty in making measurements of evaporative losses, but they found major differences in the application losses for differing sprinkler methods – low angle impacts, LEPA, and over canopy spray (MESA or LPIC) due to their different wetted times, differing wetted surfaces (e.g., LEPA only wetted a small portion of the soil surface with minimal or no canopy wetting). Tolk et al. (1995), using measured corn transpiration, found net canopy evaporation of intercepted water was 5.1 to 7.9% of applied water for a one-inch (25-mm) application volume. McLean et al. (2000) reviewed several past evaporation studies and evaluated above canopy evaporation losses from center pivots using the change in electrical conductivity of sprinkler catch water as an indicator of evaporation. They reported impact and spray losses from –1 to 3%. The negative losses were attributed to atmospheric condensation on the droplets due to the cool groundwater temperatures that were less than the atmospheric dew point temperature. Schneider (2000) reviewed the evaporation losses from LEPA and spray systems (LESA, LPIC, and MESA types). He summarized the limited studies reporting “net” canopy evaporation that had values ranging from 2 to 10% (some of these were simulated and/or based on a theoretical model). Evaporation from LEPA systems ranged from 1 to 7% of the applied amounts with application efficiencies ranging from 93 to 100%. His review of evaporation losses from spray irrigation studies had values that ranged from 1 to 10%, while their mean application efficiencies ranged from 85 to 100%.

Table 3. Water loss components associated with various sprinkler packages.

	Sprinkler Package			
Water Loss Component	**Overhead**	**MESA or Spray**	**LESA LPIC**	**LEPA**
Droplet evaporation	Yes	Yes	Yes	No
Droplet drift	Yes	Yes	No	No
Canopy evaporation	Yes	Yes	Yes, (not major)	No, (chemigation mode only)
Impounded water evaporation	No	Yes	Yes	Yes, (major)
Wetted soil evaporation	Yes	Yes	Yes	Yes, (limited)
Surface water movement	No, (but possible)	Yes, (not major)	Yes	Yes, (not major)
Runoff	No, (but possible)	Yes	Yes	Yes, (not major unless surface storage is not used)
Percolation	No	No	No	No

Surface water redistribution (runoff from one area to a lower area but not perhaps leading to runoff leaving the field) and field runoff should not occur in most cases. Yet, they regularly happen and affect the infiltration uniformity, deep percolation, and ultimately the efficiency of the application. Spray systems (LESA, LPIC, or MESA) or LEPA systems (despite the use of surface tillage designed to enhance surface water storage volume) are most prone to runoff problems. Soil type and slope play a central role in the surface water redistribution and runoff potential of a particular site in addition to the sprinkler package and system capacity (system flow rate per unit area) (Figure 5). Either surface storage (basin or reservoir tillage) or crop residues from no-till or profile modification tillage (chiseling, para-till, etc.) may be needed to reduce or eliminate surface water redistribution and runoff. Increasing the system speed (decrease the application depth) generally reduces the potential runoff volume. Both water redistribution and field runoff occur from rainfall that can further impact irrigation water requirements. Few studies are published on rainfall runoff from sprinkler-irrigated fields or that have measured the total season water balance components.

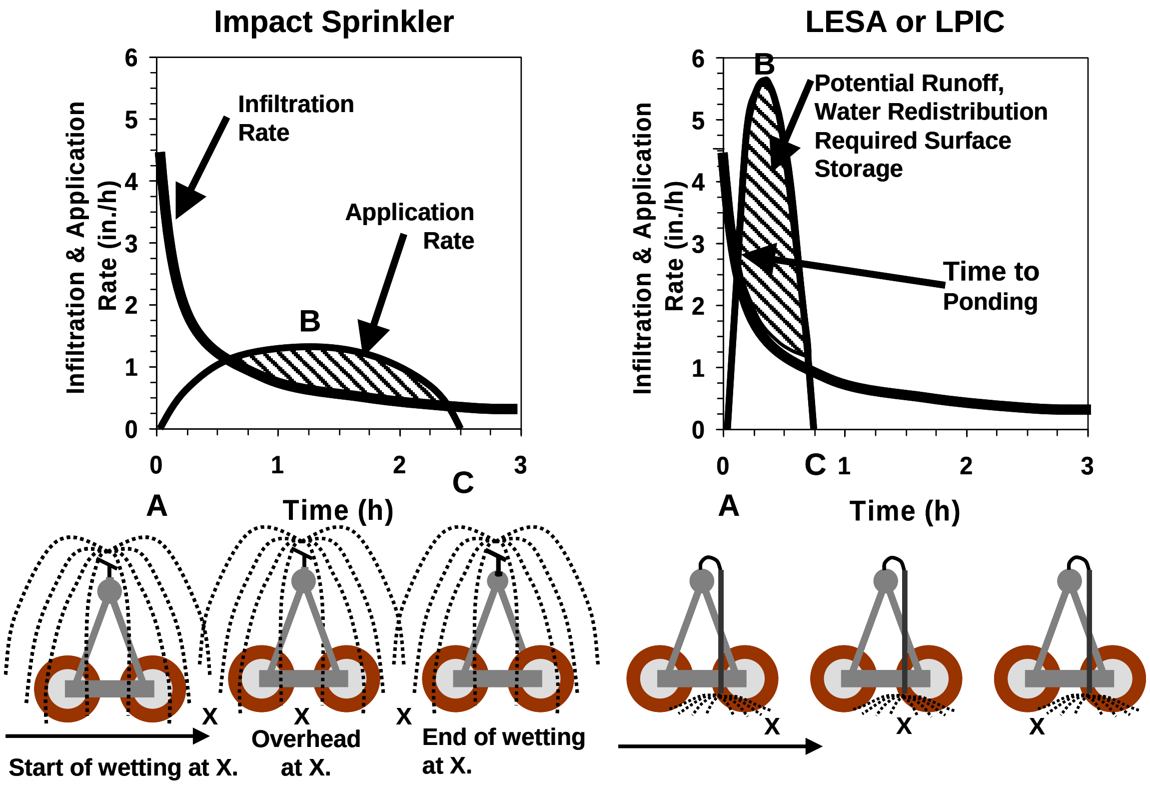

Figure. 5 Illustration of runoff or surface water redistribution potential for impact sprinkler and spray (LESA or LPIC) center application packages for an example soil. (A) represents the start of the irrigation, (B) is the peak application rate (usually when the system is directly overhead), and (C) is the completion of the irrigation**.** The first intersection point of the infiltration curve and the application rate curve represents the first ponding on the soil surface.

Schneider (2000) reviewed many of the previous studies on irrigation runoff and surface storage as influenced by tillage systems for LEPA and spray application methods. Runoff or water redistribution without basin or reservoir tillage ranged from 3 to over 50% in several studies with the greatest runoff losses occurring from LEPA modes without basin tillage (most in the bubble mode). LEPA applications in alternate furrows may require twice the storage volume needed for equivalent LESA or LPIC systems (representing full wetting like rain or

MESA). Runoff from LESA or LPIC systems may be critical on steeper slopes (>1-2%), low intake soils (heavier textures like clay loams), and higher capacity systems (>6 gpm/ac or 0.32 in./d or 8.1 mm/d).

CONCLUSIONS

The sprinkler package is a combination of the sprinkler applicator, the application mode, and the applicator spacing. The system capacity determines the peak application rate of the particular sprinkler application package. The sprinkler package should be designed together with the tillage and agronomic system. The particular soil and slope conditions will define the infiltration rate. The intersection area between the infiltration curve and the application rate curve illustrates the "potential" runoff or surface water redistribution that might require surface storage from basin or reservoir tillage needed to reduce or eliminate runoff from LESA, LESA, or LPIC systems.

The type of sprinkler applicator and the mode of application determine the particular components of water losses. "Net" canopy evaporation may be in the 5-10% range. Overall evaporation losses in several cases were between 10-20%. Irrigation efficiency of LEPA systems without runoff were in the 93 -99% range, but without basin tillage LEPA systems in several cases had large runoff (or surface water redistribution) amounts. LESA or LPIC systems can be efficient with evaporative losses less than 10% in most cases, particularly with basin or reservoir tillage or with a no-till system.

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IMPACT OF VARIABLE WELL YIELD ON CENTER PIVOT PACKAGES

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INTRODUCTION

Irrigation in the Central Plains began in the 1930's and 1940's when farmers began drilling wells. The 1960's saw rapid irrigation development, as the center pivots became a proven technology. The growth has been quite slow since the 1980's when the drilling of wells has been controlled. There is a continual increase in drawdown of the water table in many areas of the Central Plains.

McGuire, 2004 published a Fact Sheet presenting the water-level changes in the High Plains Aquifer. Two periods were highlighted, predevelopment to 2003 and 2002 to 2003. McGuire reported that in 1949 there was 2.1 million irrigated acres compared to 13.7 million acres in 1980. The irrigated area peaked at 13.9 million acres in 1997 and reduced to 12.7 million acres in 2002. Ground water withdrawals increased from 4 to 19 million acre-feet from 1949 to 1974. The withdrawals exceed the recharge and the pumping lifts are continuing to increase. The objective of this paper is to discuss the effect the continuing decrease on water levels have on center pivot irrigation systems. Area weighted average water level changes are -1.0, -1.7, and -1.3 feet in the states of Colorado, Kansas and Nebraska. The 2002-2003 water level changes varied from a rise of 9 feet to a decline of 14 feet. There were significant areas that had ground water declines in excess of 5 feet in a one-year period. Southwest Kansas had areas of greater than 50 feet decline in water levels from the predevelopment to 2003. Obviously, much of this occurred in the later years with the increased irrigation development. Pumping of air is a major problem that is readily observed. It is the gradual decline in the water table and the decrease in irrigation uniformity that is not as easily observed.

ANALYSIS OF INCREASED PUMPING DEPTHS

The analysis of center pivot performance is made using a computer simulation program (CPED). Presentations of the use of CPED were given at the previous two Central Plains Irrigation Conferences. The program simulates the application depths for the center pivot irrigation system. The input to the program includes the pump characteristics, the sprinkler package and lateral dimensions. The pumping level or total dynamic lift (TDL) is input to the program. The program solves the hydraulics of the center pivot system and pumping plant to determine the total discharge and pressure on the center pivot system. The problem of pumping air cannot be analyzed with the simulation analysis. It is assumed that the pump has sufficient net positive suction head to prevent air entrainment as it is lifted from the ground water and pressurized for the center pivot. The increase in TDL is assumed to be at least 10 feet and that it could easily approach 50 feet over just a few years, much less than the life of a center pivot system.

CENTER PIVOT AND PUMP SYSTEMS

Four center pivot systems are used to illustrate the characteristics of various pump and sprinkler packages. Table 1 summarizes the variables of each of the systems simulated. Assuming a change in the number of pump stages are used to illustrate their effect on the adequacy of an existing system All the systems with pressure regulators had big guns with booster pumps at the end of the lateral. Changes in the pressure and operating point on the pump curve with changes in TDL are a function of the unregulated sprinkler head until the pressure was below the regulator pressure. The analysis assumes that the sprinkler packages provide uniform irrigations when adequate pressure is maintained. The data are from systems installed in the Great Plains.

Table 1. A brief description of the systems used for illustrating the effect of changes in the total dynamic lift (TDL).

System	H	P	B	K
Towers	7	7	8	14
Length, ft.	1287	1260	1491	2584
Sprinkler type	Iwob	Impact	Rotator	Spray
No. of Sprinkler	123	42	170	206
Sprinkler spacing, ft	18/9	30	9	18/9
Pressure Regulator	Yes	No	Yes	Yes
Pump stages, no.	3/2	7/3/2	1/2	4/3
Topography, differential ft.	20	0	0	3
TDL, ft	90- 190	90- 350	20-150	78- 128

System H

The first system simulated is a low pressure system with inverted wobbler[1] nozzles. Pressure regulators are installed on all application devices except for

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[1] Mention of reference to a particular model of brand name is not an endorsement but is only for information that may be useful to the reader.

the big gun on the end of the system. There is 20 feet of elevation change along the 1300 foot lateral. The system was installed with a three stage pump that can accommodate a 100 foot increase in TDL and still maintain sufficient pressure. This example demonstrates an over-design where one stage could be removed and still meets the demands with the existing sprinkler package. Figure 1 illustrates the elevation and pressure head distribution at each of the towers. The minimum elevation and pressure head requirements at the end of the system is approximately 213 feet which is at least 10 feet less than provided with a 190 ft. TDL.

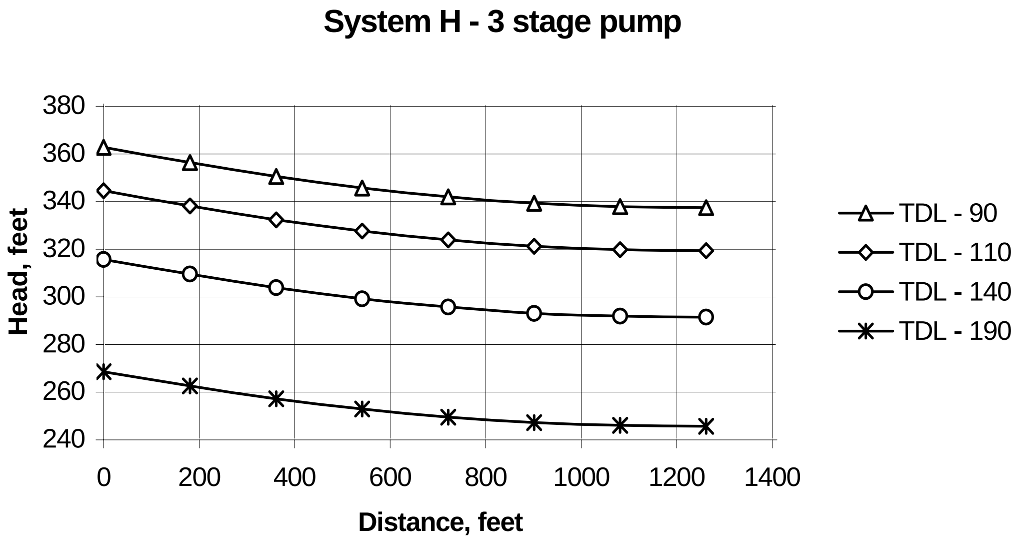

Figure 1. Lateral pressure head curves for System H (three stage pump) as installed with increases in total dynamic lift from 90 to 190 feet. Elevation and pressure head at end of system must equal 231 feet to meet minimum pressure requirements for installed sprinkler package.

Figure 2 is the same center pivot system but with one stage removed from the pump. The lower curve is the elevation of the center pivot pad and each of the towers. The difference between this and the elevation and pressure head distribution in the curves for the different TDL's, demonstrates the need for pressure regulation. The curves for the TDL of 90 and 110 meet the minimum pressure along the entire length of the system. However, with the increase in drawdown of 50 feet (TDL=140), the pressure is no longer sufficient to meet the required minimum.

Table 2 and 3 summarize the operating conditions for the three and two stage pumps, respectively. For the three stage pump the change in total discharge is a result of the big gun without pressure regulation. The reduced application depth is due to the reduced application with the big gun at the outer end of the pivot. The KW demand decreases with an increase in TDL. This is due to a lower pivot pressure and decrease in the big gun discharge. The KW demand and the head/stage is nearly the same for all conditions.

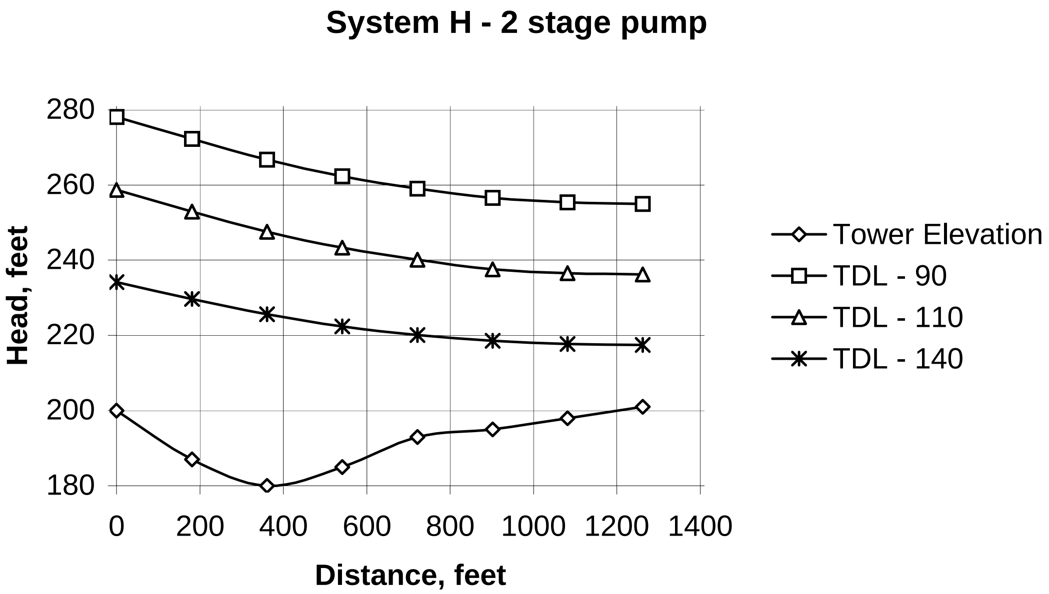

Figure 2. Lateral pressure head curves for System H (two stage pump) with increases in total dynamic lift from 90 to 140 feet. Elevation and pressure head at end of system must equal 231 feet to meet minimum pressure requirements for installed sprinkler package.

Table 2. Simulated operating characteristics for System H with three stage pump as was installed.

TDL, feet	90	110	140	190
Discharge,gpm	829	823	812	793
Pivot Pressure, psi	71	63	50	30
Irrigation depth, in.	0.77	0.77	0.76	0.75
Big gun, gpm	135	129	119	99
Head/stage, feet	88.0	88.5	88.9	89.8
KW	58.9	58.8	58.3	57.5

Table 3. Simulated operating characteristics for System H with two stage pump.

TDL, feet	90	110	140
Discharge,gpm	797	788	692
Pivot Pressure, psi	34	25	15
Irrigation depth, in.	0.75	0.74	0.66
Big gun, gpm	103	94	85
Head/stage, feet	89.6	89.8	92.2
KW	38.4	38.1	34.3

However, when one stage is removed, (Table 3) the big gun discharge is reduced as well as the application depth. A larger booster pump for the big gun could easily correct this. The head/stage is approximately the same as for the three stage pump. The final incremental increase in drawdown of 50 feet to a TDL of 140 does result in the pressure not being met at the outer end of the lateral. The discharge decreased and the application depth decreased from 3/4 inch to 2/3 inch.

The major benefit of the two stage pump is the reduction of power requirements. Assuming a pump efficiency of 70%, the demand is reduced from 59 to 38 KW. Operating with the three stage pump will obviously provide for a larger safety factor that can accommodate a larger increase in TDL. However, the two stage pump can easily accommodate a 20 foot increase in drawdown, with the current design conditions. The irrigator can still consider a change to a three stage pump when water levels decline further

System P

System P is similar in length to System H but the sprinklers are high pressure impact heads. The system is assumed to have no topography change along the lateral. The system is simulated with three pump configurations having 7, 3, and 2 stages. It is the only system in this study that does not have pressure regulators along the lateral. The seven stage pump has TDL range from 300 to 350 feet. The TDL range for the two and three stage pumps is 90 to 100 feet.

Figure 3 illustrates the pump curves for the 3, 4, and 7 stage pumps. The system operating points for the simulation are plotted on the pump curves. The discharge range for all simulations is between 600 to 800 gpm. The system without pressure regulators does exhibit a drop in the irrigation depth even with an increase in TDL by 10 feet (Table 4, 5). The Christiansen uniformity for each of the different pump configurations is 89 to 90%. An increase of 10 feet in the TDL for the four stage pump had a 0.02 in. decrease in application depth with a decrease in CU from 90 to 80%. The decrease in uniformity is primarily caused by the change in discharge and the pattern radius of the big gun. Comparing the three stage pump with TDL=90 and the seven stage pump with TDL=350 illustrates this fact. The pivot pressures are only 2% different but the CU is 11% different. Examining the depth data shows that the big gun has a major influence on the CU. CPEDlite used by the NRCS for EQIP funding does not include the big gun in the uniformity calculations. It is included here only to see the effect of changing TDL on the system performance. The take home message is that the increase in TDL can decrease the application depth by 10 – 15%.

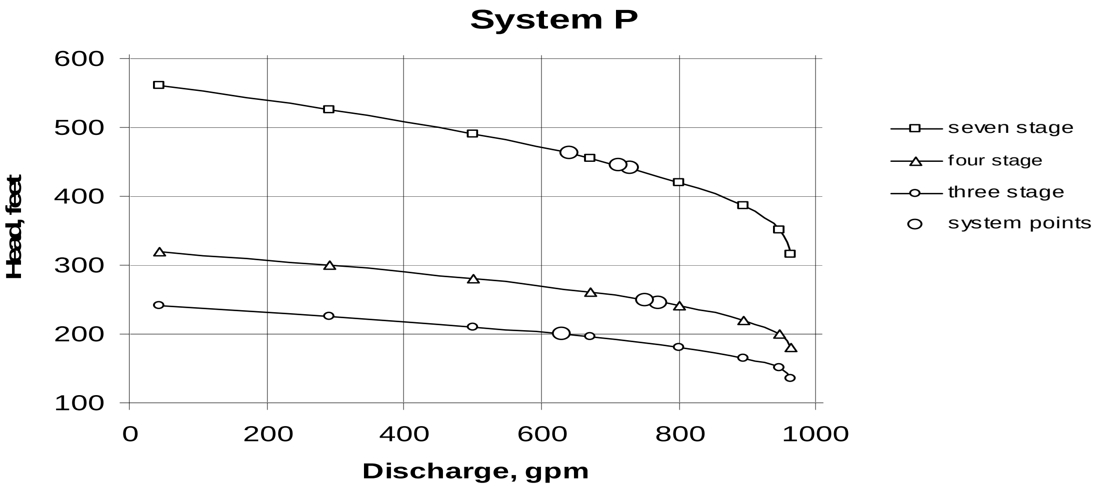

Figure 3. The pump curves for the different number of stages for System P. The operating points are for the one included in the simulation analysis of this system.

Table 4. Simulated operating characteristics for System P with seven stage pump as was installed.

TDL, feet	300	310	350
Discharge,gpm	729	712	642
Pivot Pressure, psi	55	53	43
Irrigation depth, in.	0.77	0.75	0.68
Big gun, gpm	32	31	28
Head/stage, feet	63	63.6	66.1
KW	86.5	85.3	79.9
CU	89	89	78

Table 5. Simulated operating characteristics for System P with three and four stage pump to illustrate the lower power requirement.

Pump stages	3	4	4
TDL, feet	90	90	100
Discharge,gpm	630	769	751
Pivot Pressure, psi	41	61	59
Irrigation depth, in.	0.67	0.81	0.79
Big gun, gpm	27	33	33
Head/stage, feet	66.3	61.4	62.3
KW	33.7	50.8	50.4
CU	89	90	80

System B

System B is a pressure regulated system with a rotator sprinkler package. Both a single and double stage pump are used in the simulations. The system is also assumed to be operating on a level field. Figure 4 shows the pump curves and simulated operating points for the single and double stage pumps. Again the two pump curves are used to illustrate the effect of TDL changes over different ranges. The one and two pumps used a TDL range from 0-50 feet and 90-150 feet, respectively (Table 6). The one stage pump with TDL=0 feet and the two stage pump with TDL=90 are equivalent for the center pivot system. The pivot pressures vary only by 1 psi. In each case the head/stage is equal to 86.7 feet, thus the pressure difference is the difference between the TDL and the head/stage. The simulations demonstrate that a delta change in TDL has the same effect on the center pivot pressures whether the TDL is small or much larger. The increased TDL requires additional stages be added to the pump. The pump head for a two stage pump is double that of the single stage and the KW is linearly related to the number of stages. This conclusion assumes that the same pump characteristic for the single stage is used as stages are added. This is often the case where the discharge is used to select the pump.

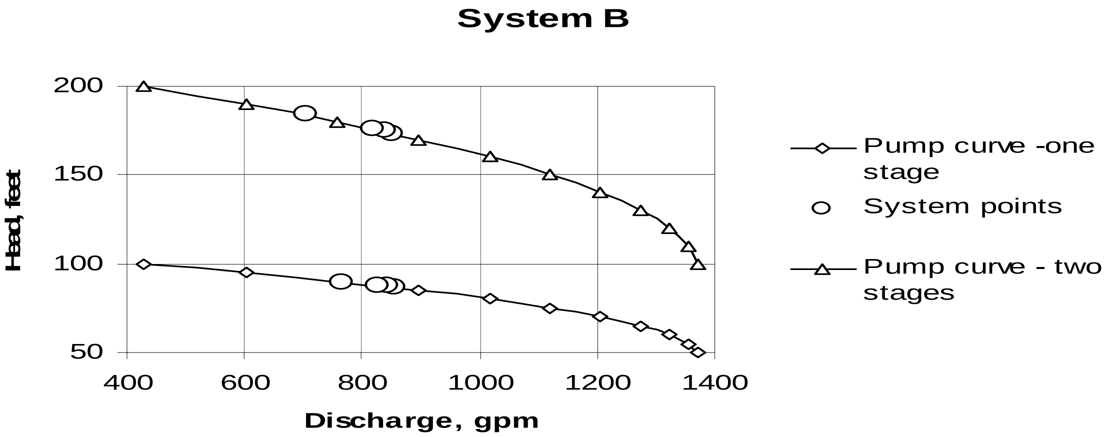

Figure 4. System B operating with single and two stage pump shown with simulated system points.

Table 6. Simulated operating characteristics for System B with a single and two stage pump.

	One stage pump				Two stage pump			
TDL, feet	0	20	40	50	90	110	130	150
Discharge,gpm	855.1	841.8	827.1	767.7	853	840	816.9	704.5
Pivot Pressure, psi	33.9	25.5	17.2	13.7	32.5	24.4	16.3	11.1
Irrigation depth, in.	0.6	0.6	0.6	0.6	0.6	0.6	0.59	0.51
Big gun, gpm	134	121	106	103	132	119	105	100
Head/stage, feet	86.7	87.3	88.1	90	86.7	87.4	88	92
KW	20.0	19.8	19.6	18.6	39.8	39.5	38.7	34.9

Another observation that can be illustrated with this system is the effect of pressure regulators. Figure 5 shows the center pivot hydraulic characteristics for System B assuming there are no pressure regulators with the same sprinkler package. Different pivot pressures were used to simulate the four points on the curve. The regulated system point (Fig. 5) has the same discharge as the first point on the curve. This emphasizes the influence of pressure regulators on a system. Regulators control the nozzle pressure for all heads when the pressure exceeds the regulator pressure along the lateral. The pivot pressure for the unregulated system is one-half that of the regulated system and the application depth decreases with distance from the pivot. The effect of drawdown on a regulated system is best observed by decreased pivot pressure as TDL increases. Systems with big guns are affected by a decrease in discharge as TDL increases. The big gun discharge decreased approximately 10% when the TDL increased 50-60 feet.

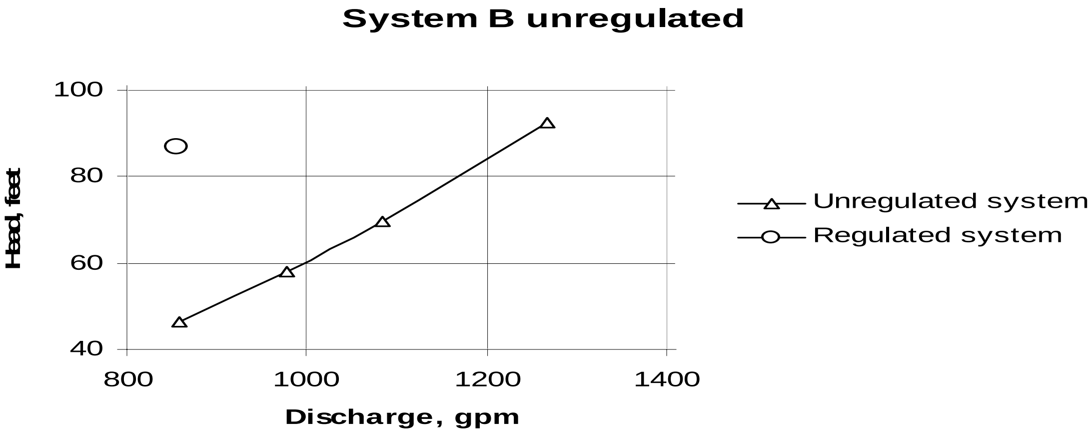

Figure 5. System B center pivot system hydraulic demand curve operating without pressure regulators

System K

System K is an illustration with a much longer lateral length (2584 feet) than previous systems. The topography change is about 3 feet along the entire lateral. Three and four stage pumps were used for the simulations comparing TDL's of 78 and 128 feet. Figure 6 shows the three and four stage pump curves and the simulated operating points. The discharges are almost double from the previous systems to irrigate the larger area. The operating characteristics are show in Table 7. The pivot pressure for the three stage pump and a TDL=128 feet is below that required for the lateral pressure to exceed the pressure regulator settings. The average irrigation depth is reduced by 8%. Figure 7 shows the application depths for each of the simulations. The depth is the same for all simulations to the 1600 feet from the pivot. The reduction in depth results from the smaller depths from this point on to the end of the pivot lateral. The system is not meeting the design but would be difficult to evaluate with catch cans. The application depth is 13% less at the outer end of the system. The best procedure for monitoring systems would be to measure the pivot pressure and compare to minimum pressure required at the time of design.

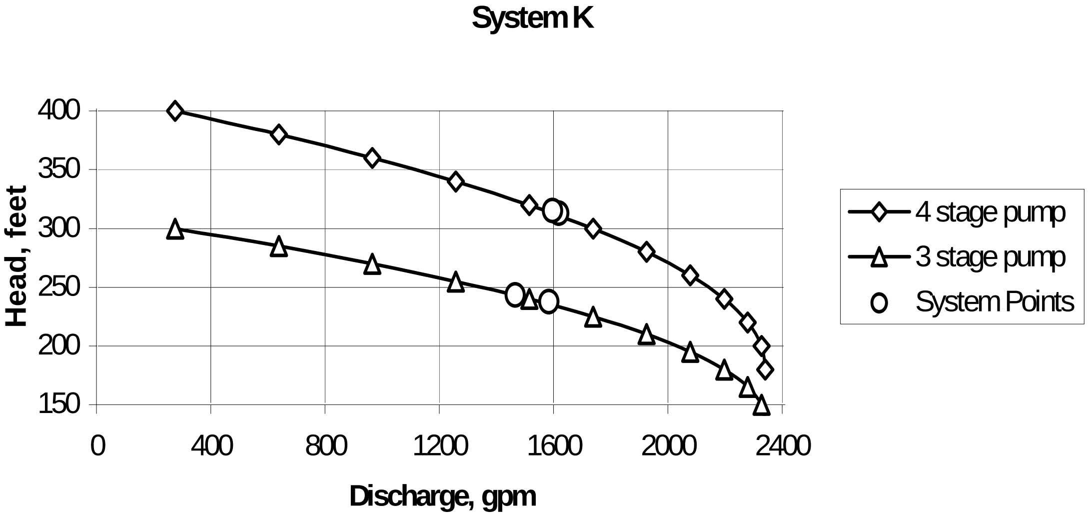

Figure 6. System K operating with three and four stage pumps shown with simulated system points.

Table 7. Simulated operating characteristics for System K with a single and two stage pump.

	four stage pump		three stage pump	
TDL, feet	78	128	78	128
Discharge,gpm	1617	1596	1583	1465
Pivot Pressure, psi	94	73	61	43
Irrigation depth, in.	0.38	0.39	0.39	0.36
Big gun, gpm	156	135	122	105
Head/stage, feet	78.3	78.8	79.3	81.2
KW	136.3	135.4	101.3	96.0

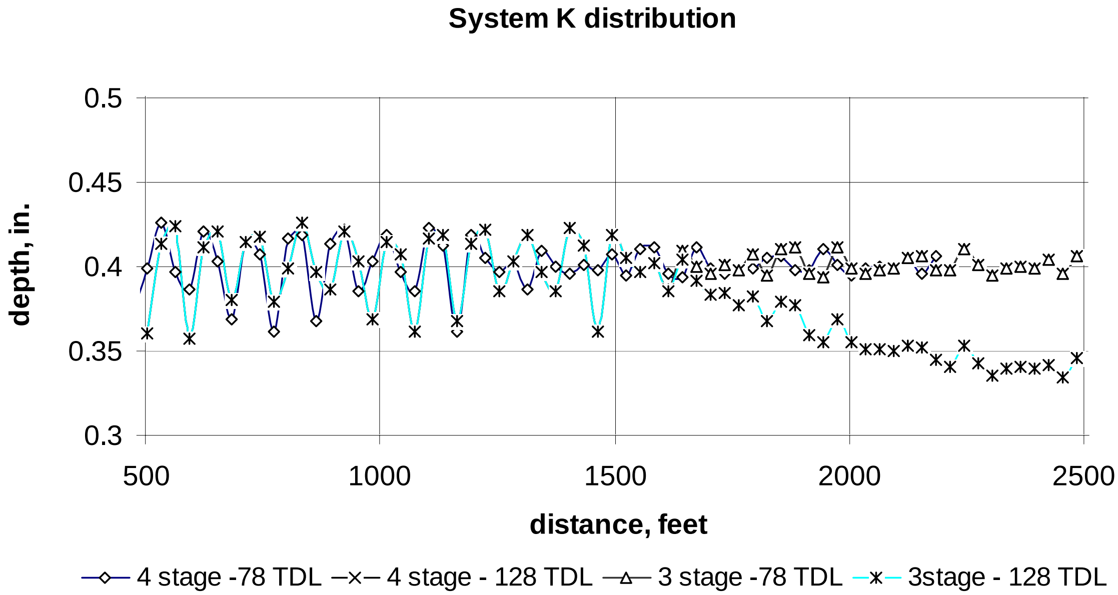

Figure 7. Simulated depths for the System K for the combinations of TDL and pump stages.

SUMMARY

The continual increase in drawdown in the Central Great Plains requires that producers monitor their water table depths and center pivot system operation. The data used for the simulation analysis indicated that many systems are designed to have considerably more pumping capacity than needed. This will automatically provide a factor of safety as the water table drops. The cost of operation of these systems is more expensive since many systems operate with pressure regulators. The excess pressure is dissipated in the regulator before reaching the nozzle and the energy is wasted. It is recommended that each system be analyzed to assure a pumping capacity that meets current needs plus an estimated increase in future water table depths. Monitoring wells in an area provides some guidance for the amount of anticipated increase in TDL requirements.

LITERATURE CITED

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MIL EVALUATION OF CENTER PIVOT IRRIGATION SYSTEMS

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Introduction

The Mobile Irrigation Lab (MIL) project is an educational and technical assistance program focused on enhancing the irrigation water management practices of Kansas irrigators (Clark et. al., 2002 and Rogers et. al., 2002). The MIL has two parts: one part emphasizes irrigation software development and hands-on computer training for producers; the second part has emphasis on field activities, which has included on-farm irrigation demonstrations and center pivot performance evaluations. Center pivot nozzle package evaluations have used IrriGage catch can data to calculate a distribution uniformity coefficient. However in the Ogallala irrigated areas of western Kansas, the most commonly utilized center pivot nozzle package is an in-canopy nozzle placement, which can not be tested using the catch can procedure. The MIL team has worked on to develop an in-canopy nozzle testing procedure that can be done in a time efficient manner to help producers evaluate systems and make adjustments as needed to keep the system distributing irrigation water and chemicals effectively and allow for good irrigation water management. Both evaluation procedures are discussed and examples of test results are shown. MIL computer software programs and materials are available through your local county Research and Extension Office but can also be easily accessed via the MIL website at http://www.oznet.ksu.edu/mil/.

IrriGage Nozzle Package Testing

MIL has an emphasis on field evaluation center pivot sprinkler packages for distribution uniformity. The initial rational for testing was to make certain that water was distributed so that individual plants within a field had equal access to the water. This is particularly important when using irrigation scheduling procedures to minimize irrigation water application depth. If "just in time, just enough" water is applied, then the water must be distributed so that plants have equal access to the water to prevent over- or under-water within the field, which would have yield implications.

Center pivot systems are the dominate irrigation system type in Kansas, representing about 80 percent of the irrigated acres. The sprinkler package design is based on a number of factors with system pressure and flow rate as major considerations. Center pivot irrigation systems have been largely assumed to be properly operating if the pivot point pressure and flow rate are set at the design operating specifications. Routine evaluation of the center pivot sprinkler packages are seldom performed after installation. Testing involves placement of multiple catch containers along the lateral of the system and then measurement of each catch. The catch containers used had to be measured quickly in order to avoid measurement error that would be introduced by evaporation losses. Therefore, a number of individuals had to be present at the test site for quick measurement. Measurement required entry into a very wet field, making for difficult data collection.

Development of a more streamlined testing procedure has been made possible through the use of IrriGages. IrriGages are a non-evaporating collection device as shown in Figure 1. A series of IrriGages are placed along the center pivot or linear lateral and are normally spaced at about 80 percent of the nozzle spacing. The IrriGages are placed so that all water from a complete pass of the center pivot is collected. The data collected includes the volume of catch and the position radius of the IrriGage relative to the center pivot point or the end of the linear system. System operating and package characteristics are also recorded. The catch data is entered into a MIL uniformity evaluation program where the average depth of application and the coefficient of uniformity (CU) value is calculated. The program also plots the catch data, which helps to visually identify the location of package weakness.

Center pivot package evaluations using IrriGages are limited to sprinkler packages that are at least four feet above ground as three feet of clearance is recommended between the top of the collector and nozzle outlet. Another restriction is the need for the top of the collector to be above the crop canopy or be placed in a non-vegetated strip of a width of about three times the height differential between the collector top and the nozzle on each side of the catch container. The height restriction means many in-canopy systems can not be evaluated using IrriGages.

Test Result Examples

Field test results have found a number of center pivot nozzle packages that were not performing to expectations. Some non-uniform system results may be related to the original design where possibly the incorrect well yield and pivot pressure was provided to the designer. Some non-uniformity may be due to incorrect input pressure and flow settings due to well or pump changes or faulty gauge or meter readings. A number of systems have been found that had the package incorrectly installed, while some had performance problems related to nozzle maintenance issues.

The uniformity evaluation results for three systems using IrriGages are shown in Figures 2 through 4. Figure 2 is center pivot system equipped with rotators[1] and tested at a CU of 84 percent. The major spike in application depth in the inner part of this system was due to a leaky tower boot. This catch data for this system extended nearly to the center pivot point. The inner spans of many systems often have an application depth that is greater then the system average due to size limitations on nozzle orifices. There is also a tendency to see some choppiness in the application uniformity, which can also be due to the range of orifice size availability at the lower flow rates but also due to the nozzle spacing configuration.

The results for a new system equipped with I-Wob[1] nozzles in Figure 3 showed an increasing depth of application with increase of radius. Although the CU value is acceptable at 82 percent, the application depth was approximately one-third greater in the outer portion as compared to the inner portion. The cause of this condition is believed to be due to improper flow and pressure conditions at the pivot point. However, independent measurements were not taken at the time of the test. This system was re-tested the following season. When the pivot point pressure and flow was measured and was verified as correct, the average application depth was constant along the lateral. This illustrates the importance of making certain design operating conditions are met for proper performance.

Figure 4 shows the results from another system equipped with rotator nozzles. The CU value of this system was low at 67 percent and there was also decreasing water application depth with increasing distance from the pivot point. The design inflow rate to the nozzle package was below specifications. The field also had a considerable elevation increase at the outer edge at the test location. Some of the major spikes were noted to be several tower boot leaks, goose neck leaks and non-rotating rotators. Remediation for this system would likely be best achieved with a new package design, including consideration of pressure regulators.

While the systems evaluated to date have found many systems to be performing as designed, the evaluation program has found a number of systems not meeting performance expectations. The industry has developed a large number of nozzle options that can perform very well under a wide range of operating conditions, but only if they are properly designed, installed, and operated. The Other tests have revealed installation problems, such as missing drop nozzles and reversal of tower nozzle sequences. Poor performances have also been attributed to changes in operating conditions as compared to original design specifications. Another possible cause of low uniformity could be internal incrustation similar to the material encrusted on nozzles splash types, which would alter friction loss characteristic of the system resulting in loss of design integrity.

In-canopy Nozzle Package Testing

Unlike an above canopy nozzle package, where the uniformity of water distribution is dependent on non-interference by the crop canopy, the in-canopy nozzle package almost always has the water streams from the nozzle being intercepted and/or redirected by the crop stocks and leaves. The primary exception to this would be a LEPA system, utilizing circularly planted rows and bubble mode nozzles or drag tubes. Few of these types of system are utilized in Kansas. However, even these types of systems would have non-uniform water distribution if the design flow rate and pressure requirement were not met. As with above-canopy nozzle packages, in-canopy systems must be properly designed, installed, and operated to perform properly.

The concept of the in-canopy test was to develop a protocol to minimize data collection from a system that would still allow a determination of whether design and operating conditions matched. The intent was to take a number of pressure and flow readings from nozzles along the center pivot lateral and measure total flow and pivot point pressure and compare this information to the design sheet specifications. It was thought that eventually only readings of a few nozzles at the beginning and end of the pivot lateral would be sufficient to verify the system performance in terms of water distribution along the center pivot lateral.

Since the nozzles are near the ground and many are mounted on a flexible drop tube, the installation of a pressure shunt is generally accomplished by crimping off the water flow to an individual nozzle and installing the pressure shunt to determine the nozzle pressure. The flow rate could be determined by volume flow measurement and a stop watch. However before testing began, several small digital flow meters (F-1000-RB flow rate meters from Blue-White Industries[1]) were purchased and configured with the pressure shunt.

This procedure is only effective in determining if the design operating conditions are being met. It will not reveal installation errors, such as tower reversals or mis-sized nozzles. However, these types of problems can be much more easily

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[1] No criticism or endorsement is intended by the use of commercial name. The use is only for clarity of the presentation.

detected for an in-canopy system by visual inspection and comparison to the design chart, since the nozzles are low to the ground

Most irrigation wells are metered in Kansas and flow meter readings were accepted for use in the previous above-canopy evaluations. However, several of the systems that were evaluated had poor performance ratings for no apparent reason. One reason might have been improper flow or pressure at the pivot point. However input flow and pressure readings were not initially independently verified, so this could not be proven. One of the systems was retested at a later date and the performance rating was good and both input flow and pressure were verified independently. To allow this to routinely occur, a non-intrusive flow meter was obtained.

The digital flow meters were lab tested and worked well over the specified flow range. However, during field tests, we have had some difficulty with moisture accumulation in the LED display to the degree that the display can not be read. Although the instrument specifications indicate they can be used in a wet environment, the instruments would also shut down after several readings presumably due to the moisture condensation within the body of the instrument. The instrument bodies can be opened to allow drying without apparent effect on accuracy. Several ideas to prevent condensation have been tried without much success, so this remains an issue for these particular instruments. The back up method for obtaining flow readings is the bucket and stop watch.

Test results from the first in-canopy pivot analysis are shown in Figures 5 and 6. Most of the measurements were taken adjacent to a pivot tower. The test was conducted early in the irrigation season. The center pivot was 1305 feet long and equipped with LDN[1] nozzles using concave grooved by chemigation pads with 6 and 10 psi pressure regulators. The design flow rate was 350 gpm with a top of pivot pressure of 14 psi.

Figure 5 shows the field measured pressure distribution and the design pipe pressure. The field pressures were measured at approximately the nozzle height of 3 feet from the ground. The design pipe pressure would be at an elevation of approximately 12.5 feet, for about a 4 psi pressure differential. The measured values appear to be slightly higher than the design values. However, all nozzles are pressure regulated, so much of the pressure differential would be dampened out through the regulators.

Figure 6 shows measured flow rates and design flow rates. Measured observations appeared to be slightly higher at the end of the center pivot than design values. The test was conducted before the start of the general irrigation season, which could mean the well yield was higher than what it might be after long term pumping. However flow measurements at the beginning of the pivot lateral were matched very closely to the design values. Overall, it appears this system's performance was satisfactory.

Concluding remarks

The obvious improvements needed for the in-canopy test procedure are 1) reliable measurement of the pivot point flow rate and pressure, 2) either a different nozzle flow measurement instrument or a method to better seal the existing instrument, and 3) a standardized data collection routine. The latter comes with multiple testing and analysis. Items one and two are being addressed. In addition to moisture condensation or accumulation within the instrument, the instruments also shut down completely after a number of uses. This was originally thought to be due to the moisture exposure, but an additional suggestion that exposure to cold ground water may be having an effect on the instrument. This will be tested in the lab. During the test, the instruments are not exposed to direct spray from other nozzles, but do get wet from handling.

Acknowledgment:

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Rogers, D.H., G. A. Clark, M. Alam, R. Stratton, and S. Briggeman. 2002. A Mobile Irrigation Lab for Water Conservation: II Education Programs and Field Data. In proceedings of Irrigation Association International Irrigation Technical Conference, October 24-26, 2002, New Orleans, LA, available from I.A., Falls Church, VA.

Figure 1. Series of IrriGages being positioned prior to an above canopy nozzle package evaluation.

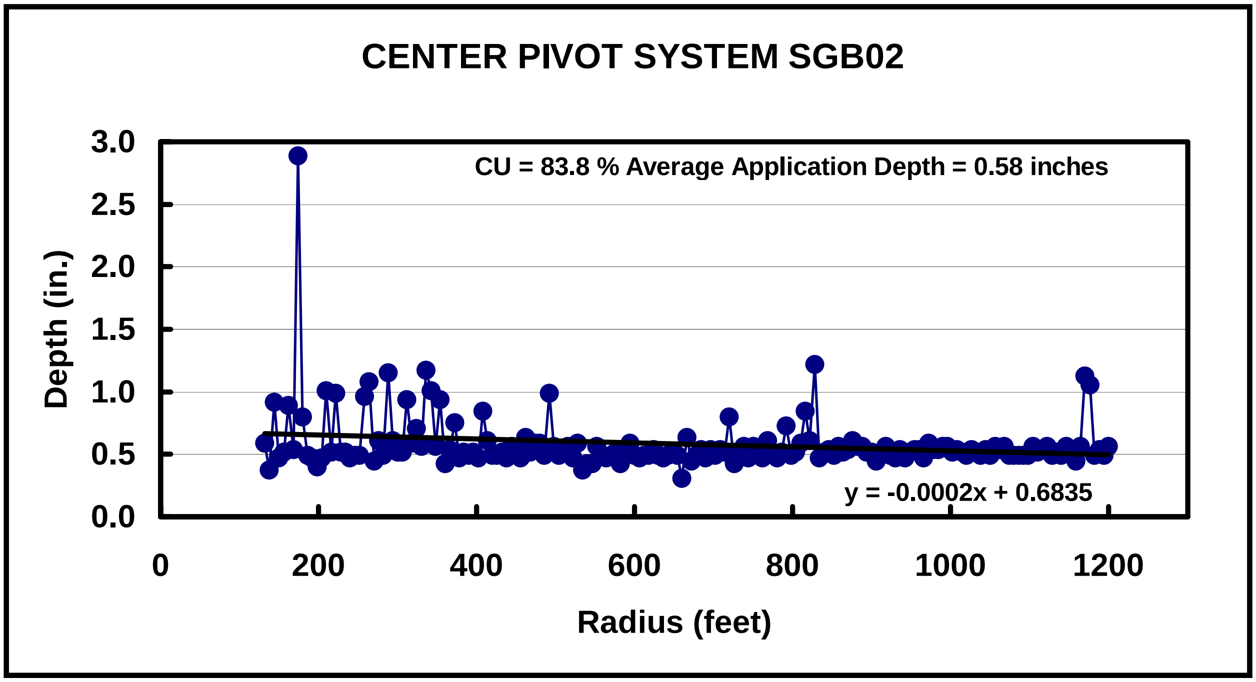

Figure 2. MIL uniformity test results for a center pivot equipped with an above canopy nozzle package of rotator nozzles.

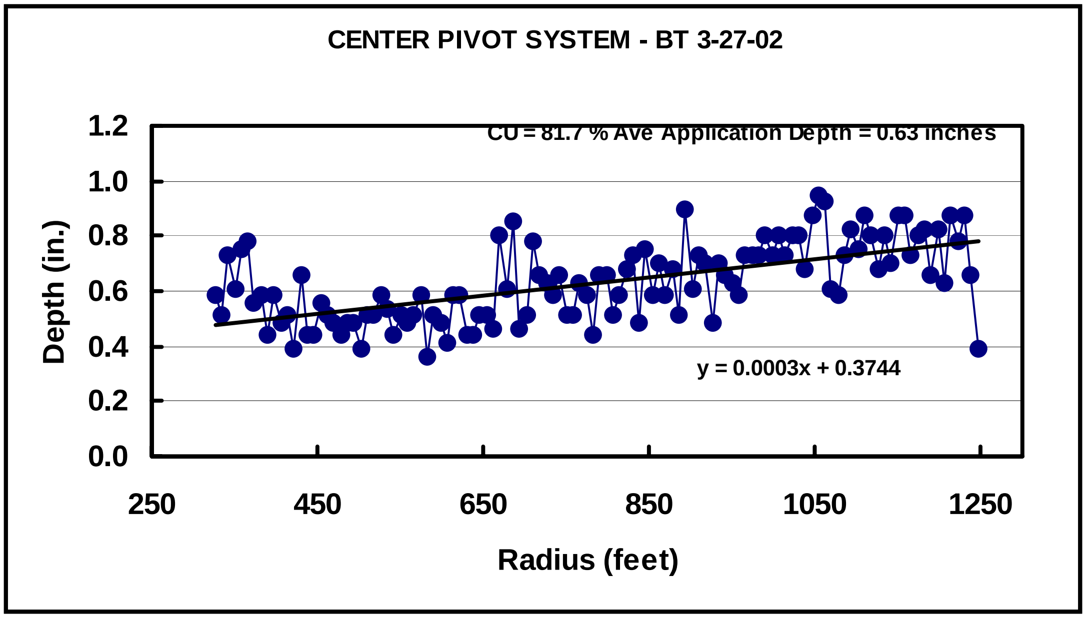

Figure 3. MIL uniformity test results for a center pivot equipped with an above canopy nozzle package of I-wob nozzles.

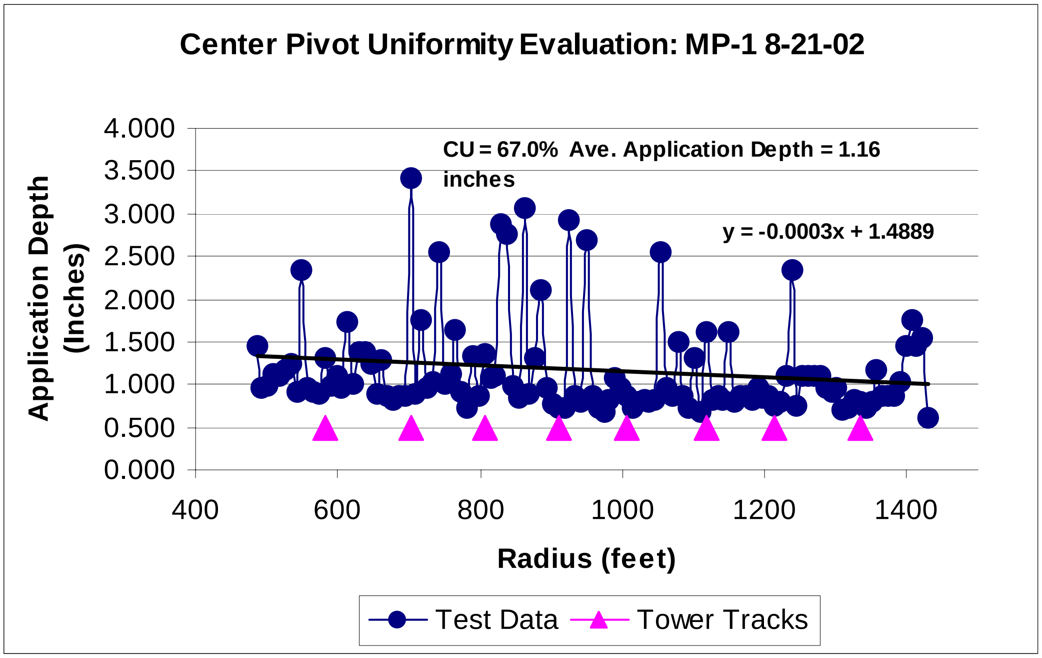

Figure 4. MIL uniformity test results for a center pivot equipped with rotator nozzles.

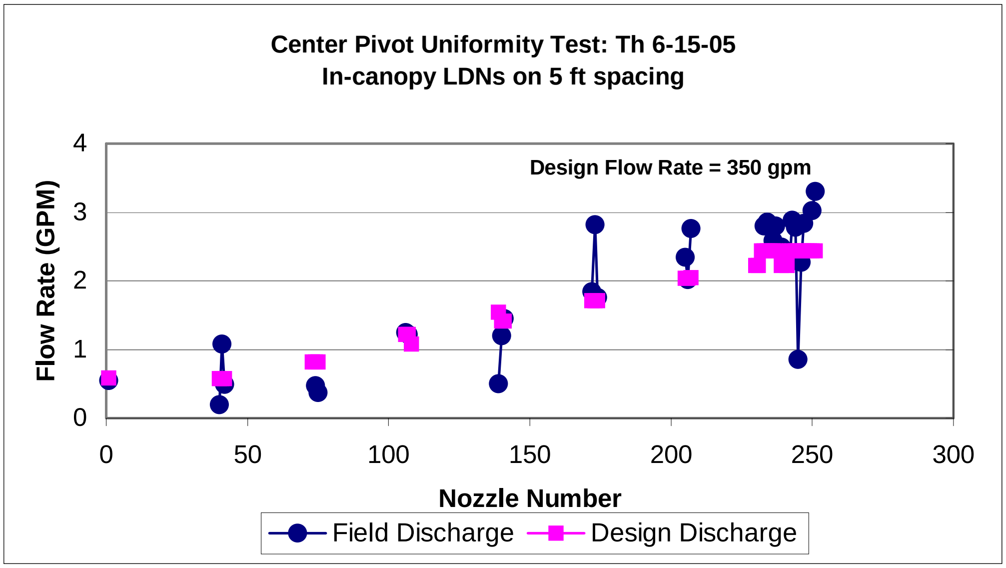

Figure 5. Field measured and design pressure versus nozzle location in-canopy center pivot evaluation.

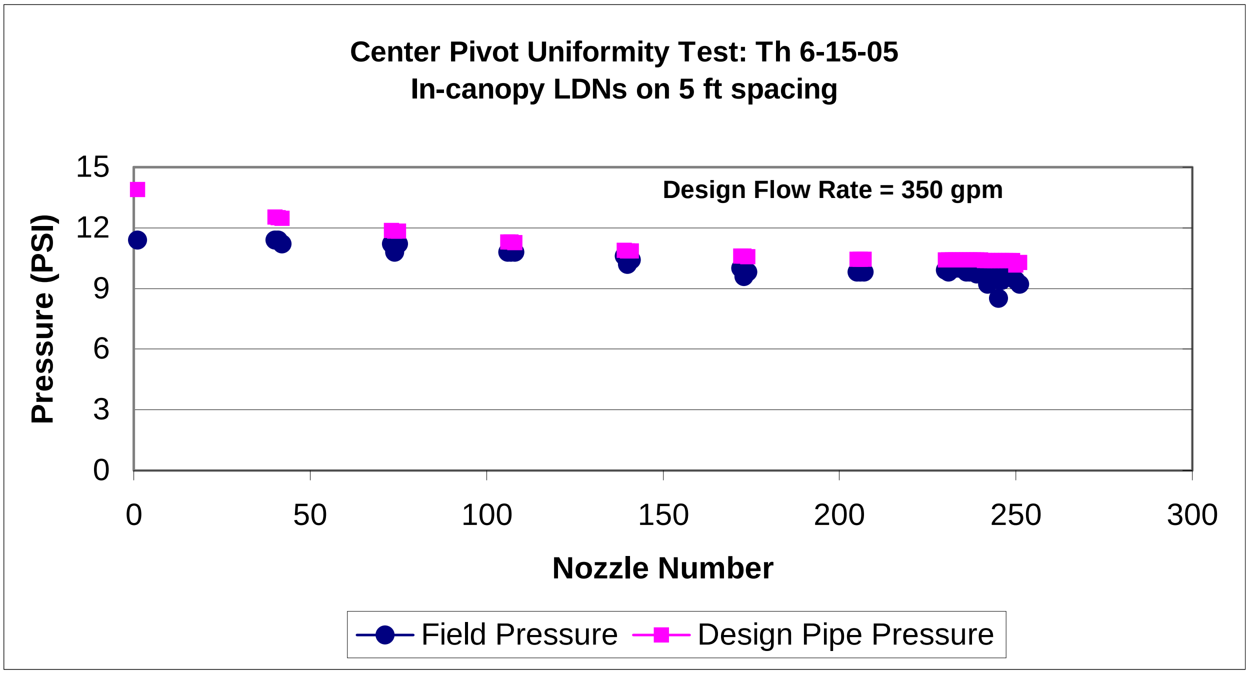

Figure 6. Field measured and design nozzle flow rates verses nozzle location on an in-canopy center pivot evaluation.

PMDI FIELD TEST RESULTS FROM SHERIDAN COUNTY

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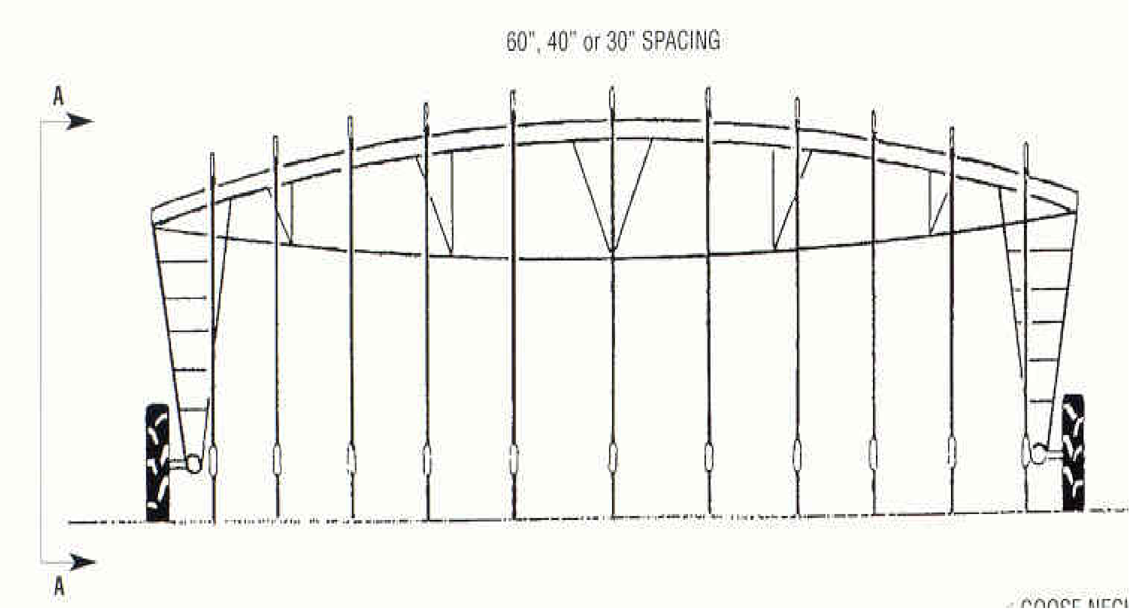
INTRODUCTION

Precision mobile drip irrigation is an irrigation system where drip hoses are attached to a center pivot sprinkler and drug on top of the ground. The placement of water by the hoses on the ground could potentially increase irrigation efficiency over a standard drop nozzle system. In addition, problems associated with wet wheel tracks should be reduced. However, drag hoses lying on the ground could cause more management concerns for farmers. One example would be animal damage to the drip hoses which disrupts uniform water distribution. The objectives of this study were to compare yield from corn irrigated using precision mobile drip irrigation (PMDI) to sprinkler irrigation with drops (drop nozzle). The second objective was to discern if the emitters have a reduction in water flow over the season due to clogging. Figure 1 is a sprinkler with the drag hoses attached.

Figure 1



PROCEDURE

The study was initiated on a center pivot sprinkler located seven miles north and three miles west of Hoxie, KS. Cooperation from DLS Farms was very important to evaluating these two application methods. Three spans, spans 4, 5, and 7, of an eight span center pivot sprinkler were divided into two sections. Each section had either the PMDI system installed or the standard drop nozzle system. With this configuration, three replications of each method were achieved for a total of six plots. The center pivot sprinkler is nozzled to apply 300 gpm. Drag hose spacing on the PMDI system was 60 inches while the spacing on the drop nozzle system was 120 inches. The entire flow to the center pivot was screen filtered to 50 mesh.

For the 2004 growing season, the farmer strip-tilled the field the previous fall and applied 75 lbs/A of N as anhydrous ammonia and 7-25-0 lbs/A as 10-34-0. The field was planted on May 2, 2004 in circular rows with Mycogen 2E685 treated with Cruiser at 26,000 seeds/A with 50 lbs/A of N as 32% UAN applied in a 2x2. Appropriate pest management measures were taken to control weeds and insects.

For the 2005 growing season, manure was applied to the field, and then the field was strip-tilled in the fall. On April 28, 2005 Mycogen 2E762 treated with Cruiser was seeded in straight noncircular rows at 26,000 seeds/A. Appropriate pest management measures were taken to control weeds and insects.

Emitter water flow at the end emitter and then the 5, 10, and 15 emitter from the end of two drag hoses from each plot were captured for one minute on May 26, August 4, and September 13 in 2004 and May 27, July 29, and September 8 in 2005. Water flow for the entire drag hose was also collected for the two drag hoses along with the water flow from two drop nozzles on the same span.

Corn yield was collected in two ways. First, samples were hand harvested from forty feet of each plot. Samples were then dried, threshed, weighed, and yield was calculated on a bu/a basis. Yield was also collected at harvesting using a Green Star yield monitoring system for the entire field.

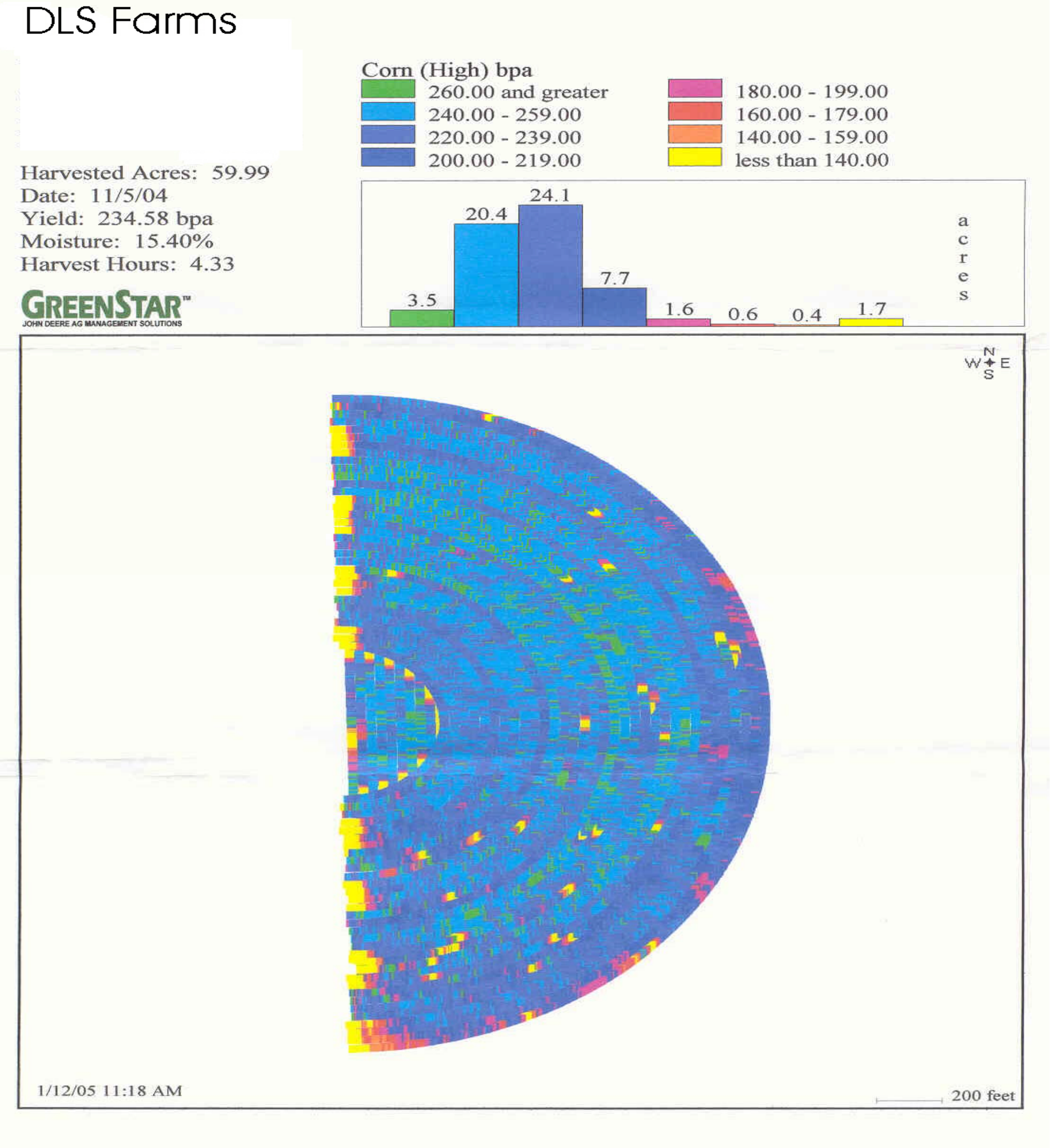
RESULTS

Weather conditions over the summer brought supplemental rainfall which allowed for respectable yields to be achieved at the site for both years. When comparing hand harvest yields, there was no significant difference between the PMDI treatment and the drop nozzle treatment in either year or when combined across years (Table 1). When looking at the 2004 field map (Fig. 2) or the 2005 field map (Fig. 3) generated by a yield monitor, no discernable pattern was evident between the two systems.

Table 1. Yield (bu/a) as influenced by irrigation treatment (Data from hand harvest)

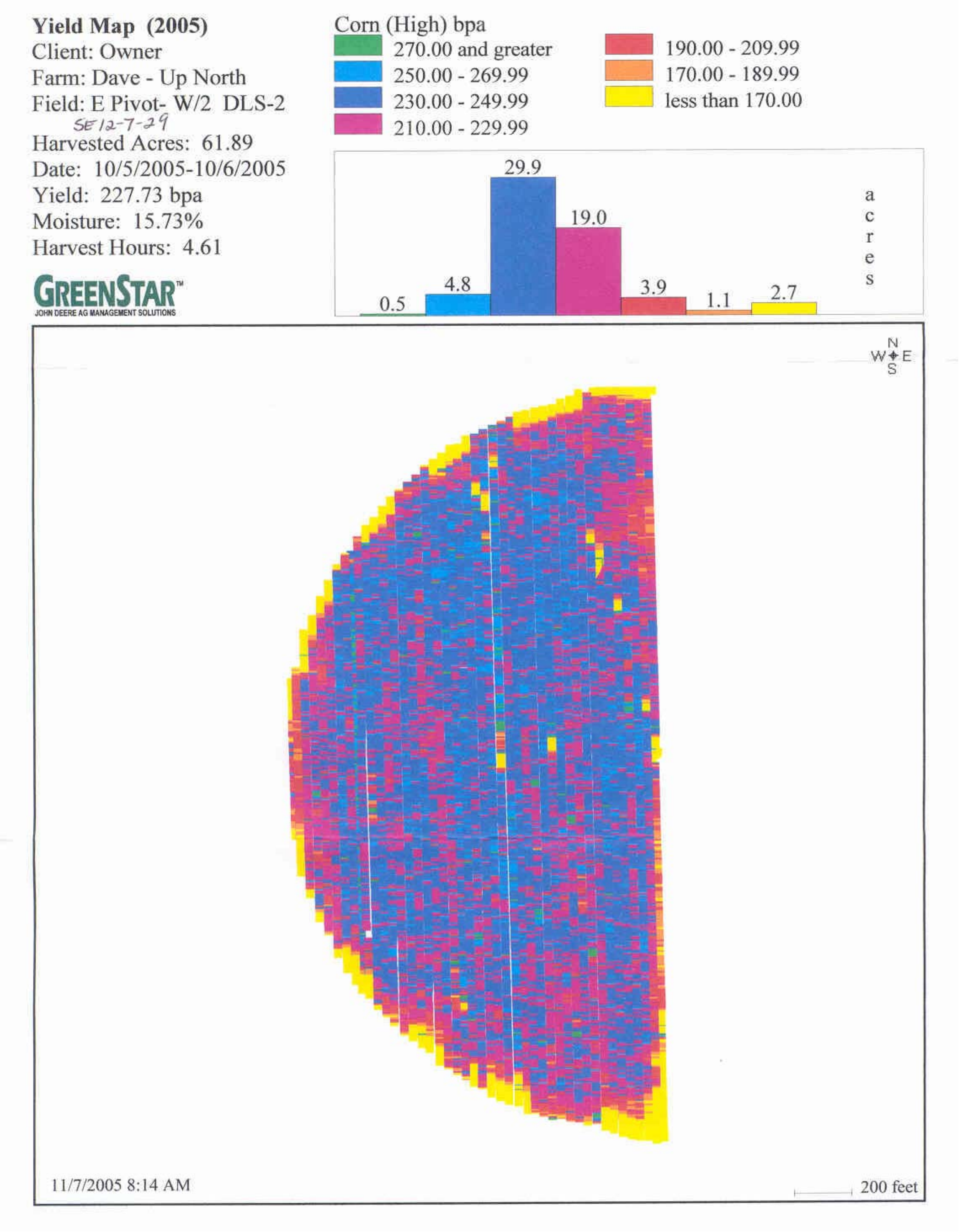
Treatment	2004	2005	Combined Results
PMDI	233	239	236
Drop Nozzle	236	236	236
LSD (0.05)	NS	NS	NS

Fig. 2 – 2004 Field Map


DLS Farms

Harvested Acres: 59.99
Date: 11/5/04
Yield: 234.58 bpa
Moisture: 15.40%
Harvest Hours: 4.33

Fig. 3 – 2005 Field Map



Yield Map (2005)
Client: Owner
Farm: Dave - Up North
Field: E Pivot- W/2 DLS-2
SE 12-7-29
Harvested Acres: 61.89
Date: 10/5/2005-10/6/2005
Yield: 227.73 bpa
Moisture: 15.73%
Harvest Hours: 4.61

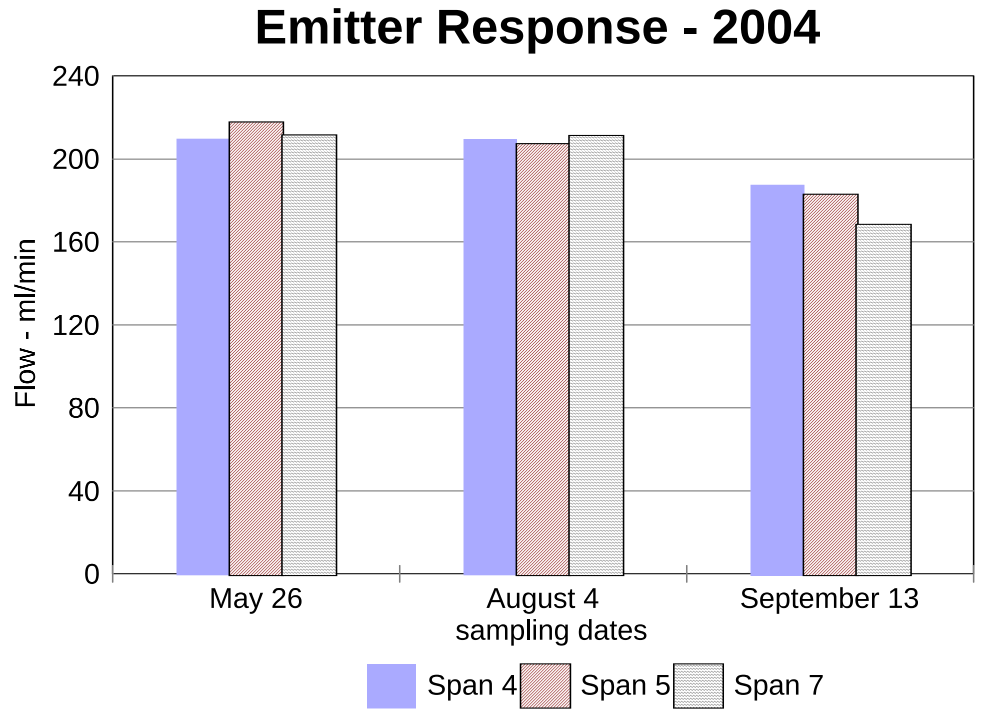
In 2004, the average emitter output over the summer declined from 214 ml/min. on May 24 to 209 ml/min on August 4 to 180 ml/min on September 13. Output from the emitters decreased by an average of 16% through the summer (Fig. 5). Output from the nozzles from span 4, 5, and 7 also decreased from an average of 2.51 gpm on May 26 to 2.48 gpm on August 4 to 2.28 gpm on September 13 (Fig. 4). The average reduction in flow was 9%. The 9% reduction in flow indicates that the overall pumping capacity of the well was reduced. However, the additional 7% reduction in flow rate from the emitters is likely due to emitter clogging.

In 2005, the average emitter output over the summer declined from 180 ml/min. on May 27 to 168 ml/min on July 29 to 158 ml/min on September 8. Output from the emitters decreased by an average of 14% through the summer (Fig. 5). Output from the nozzles from span 4, 5, and 7 actually increased from an average of 2.13 gpm on May 27 to 2.17 gpm on July 29 to 2.49 gpm on September 8. The average increase in flow was 17%. Why there was an increase in flow over this time is difficult to explain, but it may be related to a difference in field evaluation for the locations where the sampling was conducted. However, there was a greater difference in 2005 compared with 2004 in the flow between the average output of the emitters and the average output of the nozzles which implies increased clogging of the emitters.

Summary

In conclusion, as with any field evaluation, variability is inherently higher due to factors outside of the parameters that can be controlled by the investigators. However, there was no positive or negative impact on yield from those plots that were irrigated with the PMDI system versus a standard drop nozzle system. Emitter flow was decreased in both years when compared with nozzle flow which was likely due to emitter clogging. Clogging of the emitters over the life of the system along with puncturing of the hoses from wildlife appear to be two negatives of the system, while one benefit of the system was the reduced wheel pivot tracks when the PMDI system is used to water crops near the pivot wheel. The authors of this paper would again like to thank DLS farms for their cooperation on this project.

Fig. 5. Emitter response from 2004 and 2005



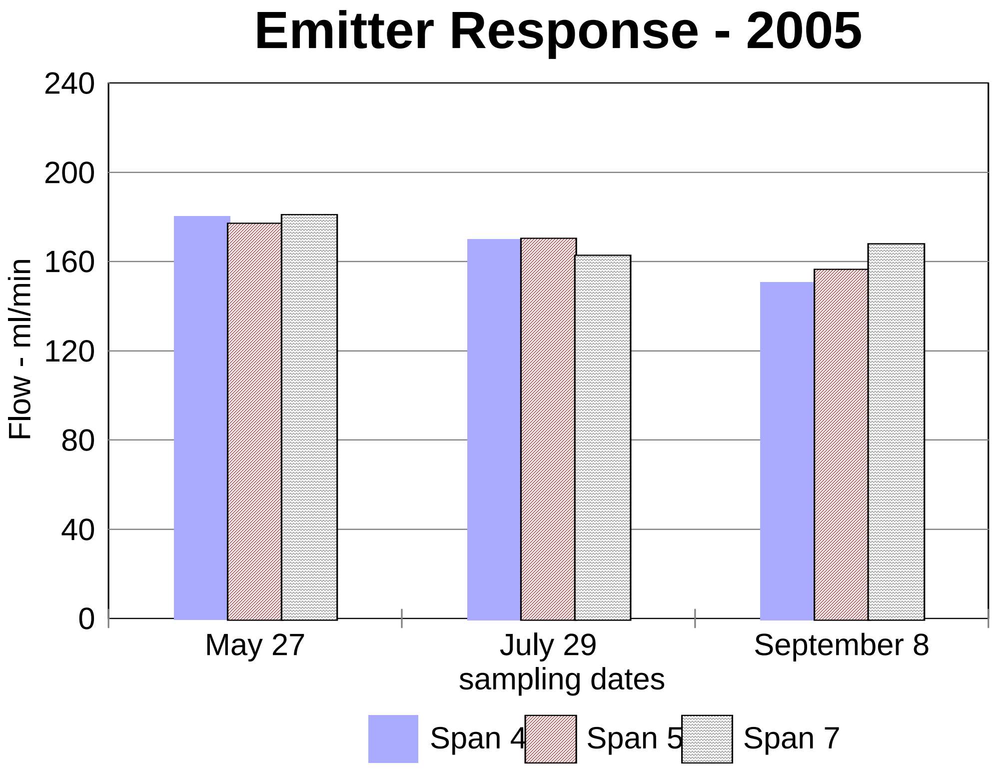
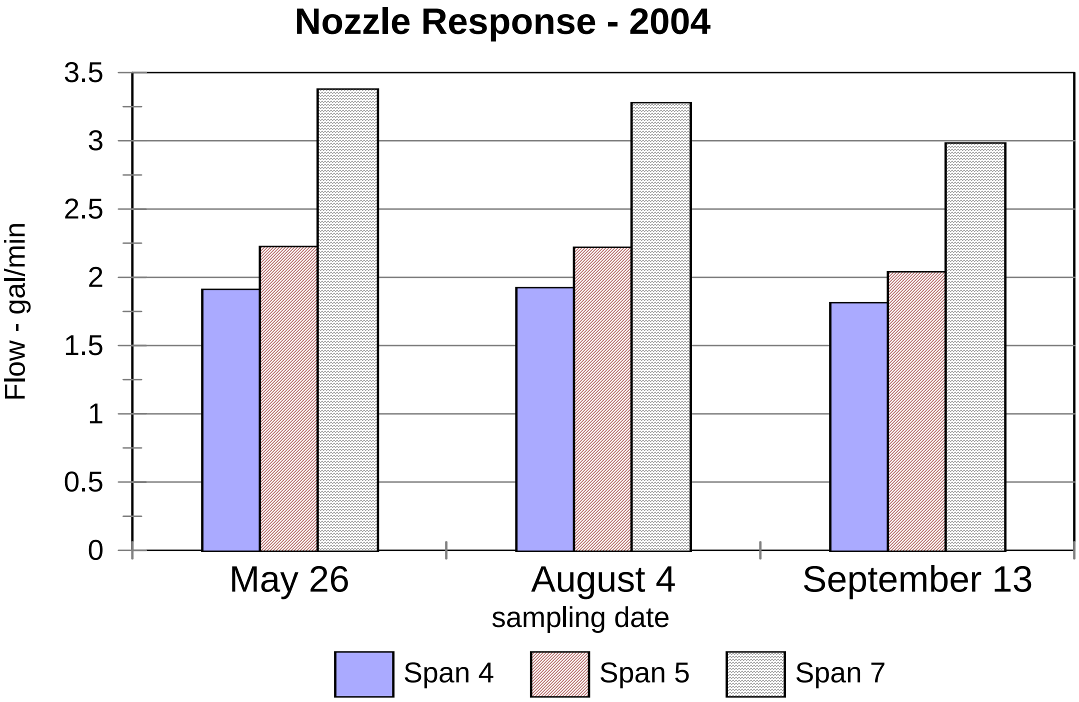
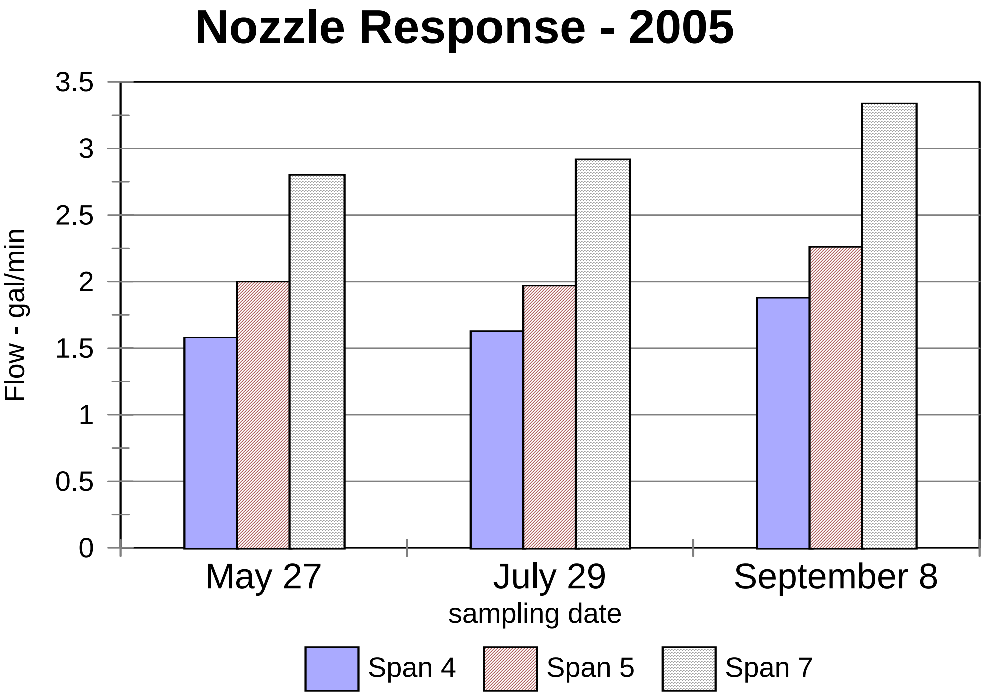


Fig. 6. Nozzle Response from 2004 and 2005





INFLUENCE OF NOZZLE PLACEMENT ON CORN GRAIN YIELD, SOIL MOISTURE AND RUNOFF UNDER CENTER PIVOT IRRIGATION

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Maximizing irrigation efficiency is of enormous importance for irrigators in the Central Great Plains to conserve water and reduce pumping costs. High temperatures, frequently strong winds and low humidity increase the evaporation potential of water applied through sprinkler irrigation. Thus, many newer sprinkler packages have been developed to minimize water losses by evaporation and drift. These systems have the potential to reduce evaporation losses as found by Schneider and Howell (1995). Schneider and Howell found that evaporation losses could be reduced by 2-3% as compared to above canopy irrigation. Many producers and irrigation companies have promoted placing sprinklers within the canopy to conserve water by reducing the exposure of the irrigation water to wind. However, runoff losses can increase due to the reduced wetted diameter which increases the application rate greater than soil infiltrate capacity. Schneider and Howell (2000) found that furrow dikes were necessary to prevent runoff with in-canopy irrigation.

In 2003 and 2004, a study was conducted comparing sprinkler nozzle placement near Burlington, Colorado in cooperation with a local producer. The objective of this study was to determine the impact of placing the sprinkler devices within the canopy upon soil moisture, runoff and crop yield. A secondary objective was to determine the usefulness of in-season tillage on water intake and preventing runoff.

METHODS

For this study, the current configuration of a center pivot irrigation system owned by our cooperating farmer was utilized. This configuration included drops with spray heads at approximately 1.5 feet (in-canopy) above the ground surface. The sprinkler heads on the seventh and outside span of the center pivot were raised to approximately 7 feet above ground level (above canopy). This nozzle height allowed for an undisturbed spray pattern for a majority of the growing season. The sprinkler heads on the sixth span of the center pivot remained at the original height (in-canopy). In 2003, the nozzles were raised by attaching the flexible drop hose using truss rod slings. Because the farmer decided not to irrigate this field in 2004, the study was moved to an adjacent pivot in 2004. The pivot nozzles were raised by replacing the drop hoses and ‘j-tubes’ on this system. In 2004 the nozzle heights in the outside span were left at 1.5 feet above ground level and the next span into the field were raised to 7 feet. Spacing was 5-feet between nozzles for both site-years.

For the 2003 growing season, three in-season tillage treatments were replicated three times under each of the sprinkler heights. The three tillage treatments were cultivation, inter-row rip and basin tillage. The cooperating farmer implemented the tillage treatments when the corn was at the V6 growth stage. The tillage treatments were implemented in strips running the length of the field. The field was planting perpendicular to the sprinkler direction. In 2004, the cooperating farmer chose to use grow the corn crop using no-till and planted in a circular pattern. In-season tillage was was to be implemented, inter-row rip and basin tillage operations, it was prevented by wet weather in June.. Thus, the only tillage in 2004 was no-till. The cooperating farmer conducted all field operations (planting, fertilization, pest control, irrigation, etc.) during 2003 and 2004.

Runoff was measured on cultivation and basin tillage for 2 replications and both sprinkler heights in 2003. Four-inch, V-notch furrow weirs installed at the bottom of the 8-row plots. The runoff for two 30-inch rows for the entire length of the pivot span (plot) was directed into the weir by the tillage treatment and soil berms where needed. The water level height in the stilling-wells of the weirs was recorded using auto-logging pressure transducers. Because the cooperating farmer chose no-till for the 2004 season, two 10-foot by 38-foot runoff plots using landscape edging were installed. Furrow weirs were installed on the lower end of the plots to measure runoff.

The soil type at both sites was Kuma Silt Loam. The slope was approximately 1 to 1.5 percent and was fairly uniform across treatments. We measured soil moisture from mid-June through early September using a Troxler neutron probe at one-foot increments to five feet of soil depth. A neutron access tube was installed in each tillage and nozzle height treatment in 2003 and six access tubes were installed in each nozzle height treatment in 2004. The study was repeated in 2005 but the results are not published. Problems associated with the bowls created surging and resulted in sections of sprinklers not outputting water. These sprinklers were generally the above canopy sprinklers.

RESULTS

Grain Yield

Grain yields in 2003 were not significantly different for in-canopy and above canopy irrigation (Tables 1 and 2). Statistically significant difference between tillage treatments were not found. However the yields for above canopy irrigation were consistently 4 bushels per acre greater than in-canopy irrigation within each tillage treatment. This would indicate that moisture stress did not occur under either above canopy or in-canopy irrigation. Grain yields for above canopy sprinkler placement were not statistically greater than in-canopy placement in 2003 as well. However, grain yields averaged across tillage treatments over the two-year period suggest that a potential trend where above canopy placement of sprinklers has greater yields than that of in-canopy placement. We plan to continue measuring grain yield and soil moisture at this site in 2005 to determine if this potential yield trend continues.

Soil Moisture

Soil moisture was measured for both above canopy and in-canopy sprinklers during the 2003 growing season. When comparing above canopy to in-canopy irrigation, changes in soil moisture were greater for in-canopy irrigation than above canopy (Figure 1). The depletion of soil moisture was significantly higher for the in-canopy sprinkler placement than with above canopy sprinklers. With similar yields, this would indicate that greater runoff losses occurred with in-canopy irrigation since soil moisture usage offset reduced infiltration. The greatest difference in change in soil moisture between above and in canopy irrigation occurred during early August when the difference was greater than 3 inches of soil moisture between the two sprinkler placements. Differences in soil moisture usage at physiological maturity were 1.7 inches greater for in-canopy irrigation than above canopy irrigation.

Changes in soil moisture between tillage treatments in 2003 were not significantly different from each other within a sprinkler height during the growing season. This would indicate that sprinkler height was the dominant factor in soil moisture content.

Contrary to 2003, soil moisture initially increased early in the 2004 growing season, declining after drier weather and higher ET rates began in July. Soil moisture content initially showed a greater increase for in-canopy placement as compared to above canopy placement (Figure 2). Much of this was due to the in-canopy placement being drier at the beginning of the season and above canopy placement reaching field capacity in mid-July. Most likely, deep percolation occurred in the above canopy placement while stored soil moisture increased for the in-canopy placement. Changes in soil moisture for both in-canopy and above canopy placement were similar after July 27. This was after the above canopy and in-canopy placement reached maximum stored soil moisture during the growing season.

Runoff

Due to inconsistent and unreliable readings from one replication of the data loggers installed on the weirs recording runoff, only one replication of the 2003 measurements was used for this paper. Runoff was greater with in-canopy irrigation than above canopy for the conventional cultivation and basin tillage treatments (Table 3). Changes in soil moisture between sprinkler placement treatments agree with runoff results collected for each placement. Greater amounts of runoff between sprinkler packages were offset by greater soil moisture loss. Runoff amounts were less for basin tillage as compared to cultivation. The reduction in runoff was due to the increase in surface storage created by the implanted basins. Although not measured, no or little runoff or signs of runoff was observed in the inter-row ripping tillage plots.

Only two significant runoff events due to irrigation, 1.1 and 0.89 inches of runoff, were recorded in 2004. This was due to management changes made by the producer. Irrigation depths in 2003 were 1.5 to 2 inches per application. In 2004, application amounts were reduced to 0.7 inches per application. This reduction in application depth reduced runoff in all but two irrigations where the producer applied higher amounts (at least 2 inches) per application.

Conclusions

Results from this study suggest that above canopy irrigation was more efficient at increasing stored soil moisture and reducing runoff as compared to in-canopy irrigation. Less runoff from above canopy irrigation in 2003 resulted in more stored soil moisture and similar to slightly more grain yield than in-canopy irrigation. In-season tillage such as basin tillage decreased runoff as compared to conventional cultivation. Yields between tillage treatments were not significantly different, but a trend of yield increases was observed when soil intake rates were modified by tillage.

No statistically significant yield differences were observed when irrigation sprinkler nozzles were placed above the canopy and soil moisture differences between above canopy and in-canopy placement reflected the differences in runoff. The results of this project suggest that sprinkler placement above a corn canopy would be preferable to placing sprinklers in-canopy unless significant changes in irrigation management practices occur.

References:

1995. Schneider, A. D. and Howell, T. A. Reducing sprinkler water losses. In Proc. 1995 Central Plains Irrigation Short Course & Equipment Exposition. Kansas Cooperative Extension Service, Manhattan, KS. pp. 60-63.

2000. Schneider, A. D. and Howell, T. A. Surface runoff due to LEPA and spray irrigation of a slowly permeable soil. Trans. ASAE 43(5):1089-1095.

Table 1. Average grain yields for sprinkler placement and tillage treatment (2003).

	Above Canopy		In-Canopy	
	Yield*	Moisture	Yield	Moisture
Tillage Treatment	(bu/acre)	(%)	(bu/acre)	(%)
Cultivation	187	15.2	182	17.5
Basin Tillage	188	14.5	184	18.1
Inter-row Rip	193	14.9	189	18.7
Average	189	14.9	185	18.1

*Grain yields adjusted to 15.5% grain moisture.

Table 2. Grain yields for sprinkler placement averaged across tillage treatments for 2003 and 2004.

	Grain Yield*		
	Above Canopy	In-Canopy	
Year	--------- bu/acre ---------		P>F
2003	189	185	0.33
2004	253	246	0.3
Average	221	216	0.17

*Grain yields adjusted to 15.5% grain moisture.

Table 3. Estimated runoff from July 4 to August 30 for sprinkler nozzle placement and tillage treatment in 2003. Runoff represents 15 irrigation events.

	--- Nozzle Placement ---	
	Above Canopy	In-Canopy
Tillage Treatment	--------- Inches Runoff ---------	
Cultivation	5.8	9.3
Basin Tillage	0.0	2.0

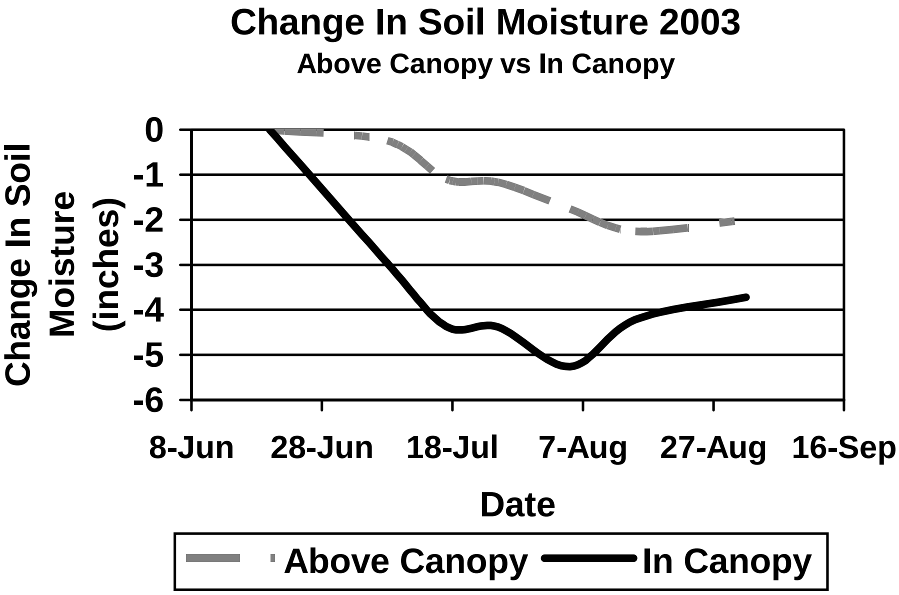

Figure 1. Change in soil moisture (from initial values) during the 2003 growing season for above canopy and in-canopy placement of sprinklers.

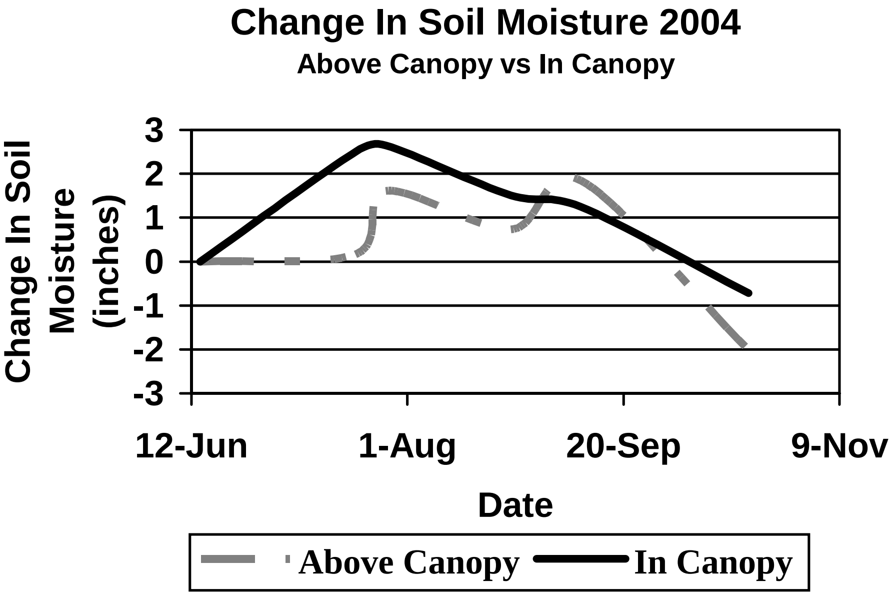

Figure 2. Change in soil moisture (from initial values) during the 2004 growing season for above canopy and in-canopy placement of sprinklers.

CRITERIA FOR SUCCESSFUL ADOPTION OF SDI SYSTEMS

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INTRODUCTION

Subsurface drip irrigation (SDI) systems are currently being used on about 15,000 acres in Kansas. Research studies at the NW Kansas Research and Extension Center of Kansas State University begin in 1989 and have indicated that SDI can be adapted for efficient, long-term irrigated corn production in western Kansas. This adaptability has been demonstrated on other deep-rooted irrigated crops grown in the region by demonstration plots and producer experience. Many producers have had successful experiences with SDI systems; however most experienced at least some minor technical difficulties during the adoption process. However, a few systems have been abandoned or failed after a short use period due to problems associated with inadequate design, inadequate management, or a combination of both.

Both research studies and on-farm producers experience indicate SDI systems can result in high yielding crop and water-conserving production practices, but only if the systems are properly designed, installed, operated and maintained. SDI systems in the High Plains must also have long life to be economically viable when used to produce the relatively low value field crops common to the region. Design and management are closely linked in a successful SDI system. A system that is not properly designed and installed will be difficult to operate and maintain and most likely will not achieve high irrigation water application uniformity and efficiency goals. However, proper design and installation does not ensure high SDI efficiency and long system life. An SDI system must be operated at design specifications and utilize good irrigation water management procedures to achieve high uniformity and efficiency. An SDI is also destined for early failure without proper maintenance. This paper will review important criteria for successful adoption of SDI for Kansas irrigated agriculture.

MINIMUM SDI SYSTEM COMPONENTS FOR WATER DISTRIBUTION AND EFFICIENT SYSTEM OPERATION

Design considerations must account for field and soil characteristics, water quality, well capabilities, desired crops, production systems, and producer goals. It is difficult to separate design and management considerations into distinct issues as the system design should consider management restraints and goals. However, there are certain basic features that should be a part of all SDI systems, as shown in Figure 1. Omission of any of these minimum components by a designer should raise a red flag to the producer and will likely seriously undermine the ability of the producer to operate and maintain the system in an efficient manner for a long period of time. Minimum SDI system components should not be sacrificed as a design and installation cost cutting measure. If minimum SDI components cannot be included as part of the system, serious consideration should be given to an alternative type of irrigation system or remaining as a dryland production system.

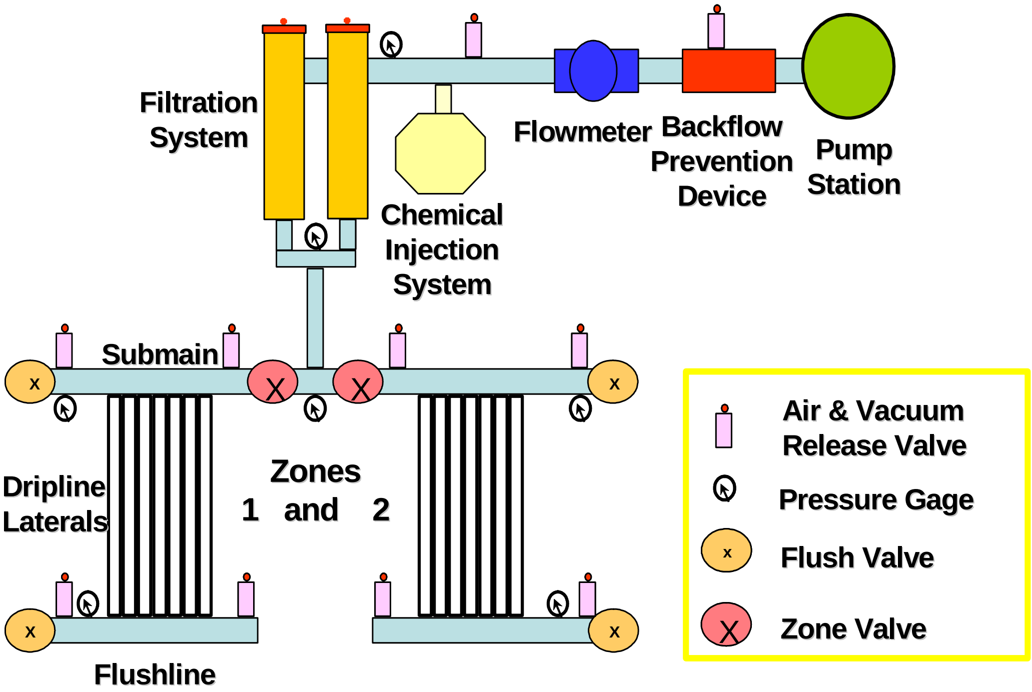


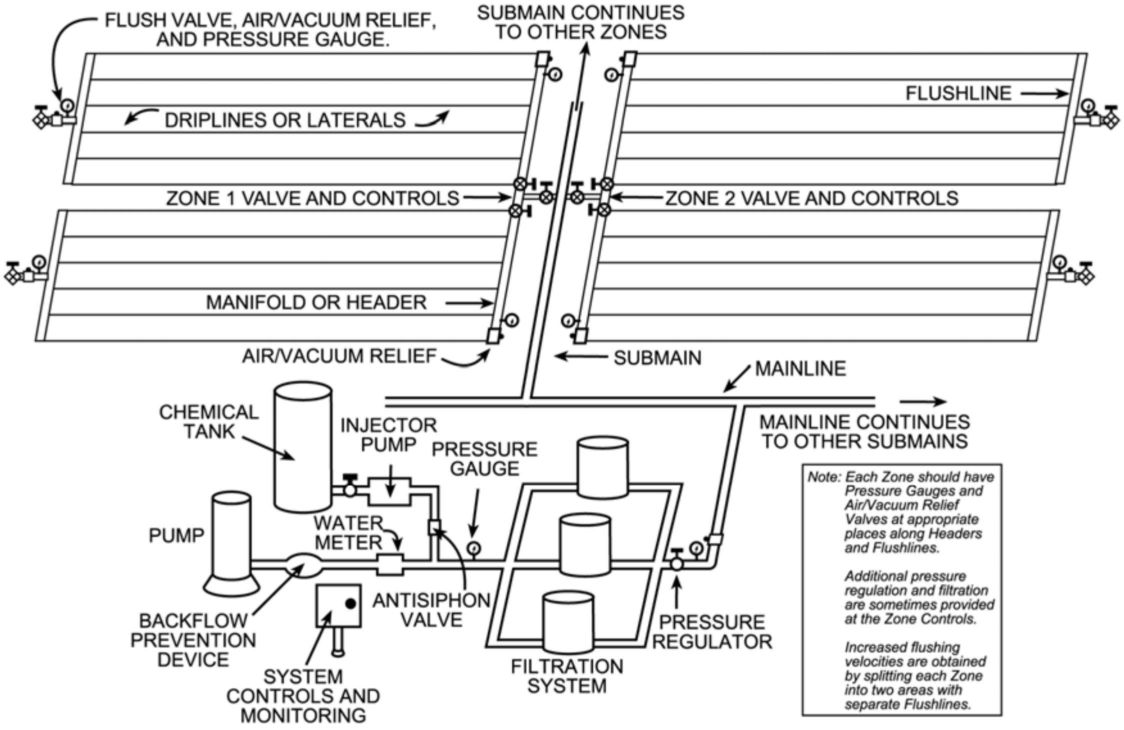
Figure 1. Minimum components of an SDI system. (Components are not to scale) K-State Research and Extension Bulletin MF-2576, Subsurface Drip Irrigation (SDI) Component: Minimum Requirements.

The water distribution components of an SDI system are the pumping station, the main, submains and dripline laterals. The size requirements for the mains and submains would be similar to the needs for underground service pipe to center pivots or main pipelines for surface flood systems. Size is determined by the flow rate and acceptable friction loss within the pipe. In general, the flow rate and acceptable friction loss determines the dripline size (diameter) for a given dripline lateral length. Another factor is the land slope. An SDI system consisting of only the distribution components would have no method to monitor system performance and the system would not have any protection from clogging or any methods to conduct system maintenance. Clogging of dripline emitters is the primary reason for SDI system failure.

The actual characteristics and field layout of an SDI system will vary from site to site, but often irrigators will want to add additional capabilities to their system. For example, the SDI system in Figure 2 shows additional valves that allow the irrigation zone to be split into two flushing zones. The ability to flush SDI systems is essential. Filter systems are generally sized to remove particles that are approximately 1/10 the diameter of the smallest emitter passageway. However, this still means small particles pass through the filter and into the driplines. Overtime, they can clump together and/or other biological or chemical processes can produce materials that need removal to prevent emitter clogging. The opening of the flushline valves and allowing water to pass rapidly through carrying away any accumulated particles flushes the driplines. A good design should allow flushing of all pipeline and system components. If the well or pump does not have the capacity to provide additional flow and pressure to meet the flushing requirements for the irrigation zone, splitting of the zone into two parts may be an important design feature. The frequency of flushing is largely determined by the quality of the irrigation water and to a degree, the level of filtration. A good measure of the need to flush is to evaluate the amount of debris caught in a mesh cloth during a flush event. If little debris is found, the flushing interval might be increased but heavy accumulations might mean more frequent flushing is needed.

The remaining components, in addition to the water distribution components of Figure 1, are primarily components that allow the producers to monitor the SDI system performance, to protect or maintain performance by injection of chemical treatments, and to allow flushing. The injection equipment can also be used to provide additional nutrients or chemicals for crop production. The backflow preventive device is a requirement to protect the source water from accidental contamination should a backflow condition occur.

The flow meter and pressure gauges are essentially the operational feedback cues to the manager. In SDI systems, all water application is underground. In most properly installed and operated systems, no surface wetting occurs during irrigation, so no visual cues are available to the manager concerning the system operating characteristics. The pressure gauges at the control valve of each zone allow the measurement of the inlet pressure to driplines. Decreasing flow and/or increasing pressure can indicate clogging is occurring. Increasing flow with decreasing pressure can indicate a major line leak. The pressure gauges at the distal ends of the dripline laterals are especially important in establishing the baseline performance characteristics of the SDI system. Flowrate and pressure measurement records can be used as a diagnostic tool to discover operational problems and determine appropriate remediation techniques (Figure 3).



Note: Each Zone should have Pressure Gauges and Air/Vacuum Relief Valves at appropriate places along Headers and Flushlines.

Additional pressure regulation and filtration are sometimes provided at the Zone Controls.

Increased flushing velocities are obtained by splitting each Zone into two areas with separate Flushlines.

Figure 2. An example layout for a well designed SDI system.

Anomaly A: The irrigator observes an abrupt flowrate increase with a small pressure reduction at the Zone inlet and a large pressure reduction at the Flushline outlet. The irrigator checks and finds rodent damage and repairs the dripline.

Anomaly B: The irrigator observes an abrupt flowrate reduction with small pressure increases at both the Zone inlet and the Flushline outlet. The irrigator checks and finds an abrupt bacterial flare-up in the driplines. He immediately chlorinates and acidifies the system to remediate the problem.

Anomaly C: The irrigator observes an abrupt flowrate decrease from the last irrigation event with large pressure reductions at both the Zone inlet and Flushline outlet. A quick inspection reveals a large filtration system pressure drop indicating the need for cleaning. Normal flowrate and pressures resume after cleaning the filter.

Anomaly D: The irrigator observes a gradual flowrate decrease during the last four irrigation events with pressure increases at both the Zone inlet and Flushline outlet. The irrigator checks and find that the driplines are slowly clogging. He immediately chemically treats the system to remediate the problem.

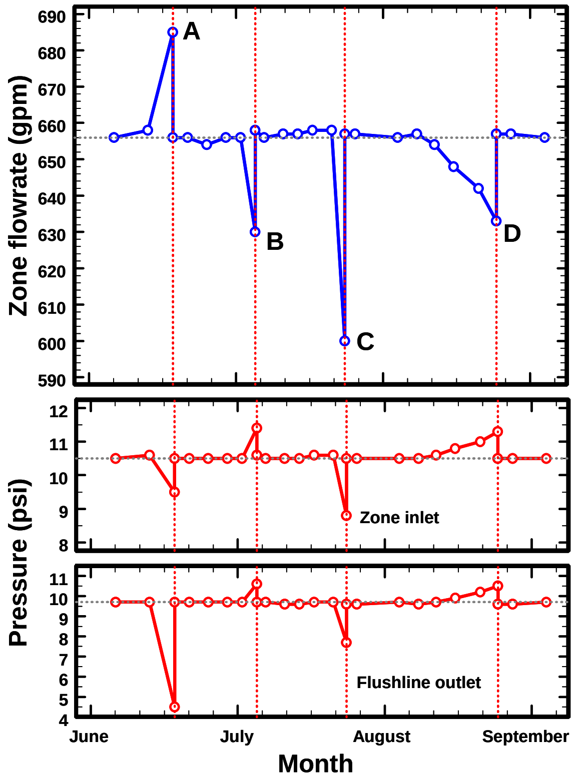


Figure 3. Hypothetical example of how pressure and flowrate measurement records could be used to discover and remediate operational problems.

The heart of the protection system for the driplines is the filtration system. The type of filtration system needed will depend on the quality characteristics of the irrigation water. Clogging hazards are classified as physical, biological or chemical. The illustration in Figure 1 depicts a pair of screen filters, while Figure 2 shows a series of sand media filters. In some cases, the filtration system may be a combination of components. For example, a well that produces a lot of sand in the pumped water may require a cyclonic sand separator in advance of the main filter. Sand particles in the water would represent a physical clogging hazard. Another common type of filtration system is the disc filter.

Biological hazards are living organisms or life by-products that can clog emitters. Surface water supplies may require settling basins and/or several layers of bar screen barriers at the intake site to remove large debris and organic matter. Sand media filtration systems, which consist of a bank of two or more large tanks with specially graded filtration sand, are considered to be well suited for surface water sources. Water sources that have a high iron content, can also be vulnerable to biological clogging hazards, such as when iron bacteria flare-up in a well. Control of bacterial growths generally requires water treatment in addition to filtration.

Chemical clogging hazards are associated with the chemical composition or quality of the irrigation water. As water is pulled from a well and introduced to the distribution system, chemical reactions can occur due to changes in temperature, pressure, air exposure, or also by the introduction of other materials into the water stream. If precipitants form, they can clog the emitters.

The chemical injection system is often considered to be a part of the filtration system but it can also be used to inject nutrients or chemicals to enhance plant growth or yield. There are a variety of types of injectors that can be used; the choice of unit depends on the desired accuracy of injection of a material, the rate of injection, and the agrochemical being injected. There are also state and federal laws that govern the type of injectors, required safety equipment (Figure 4), appropriate agrochemicals and application amounts that can be used in SDI systems. Always follow all applicable laws and labels when applying agrochemicals. Many different agrochemicals can be injected, including chlorine, acid, dripline cleaners, fertilizers, and some pesticides. Producers should never inject any agrochemical into their SDI system without knowledge of the agrochemical compatibility with the irrigation water. For example, many phosphorus fertilizers are incompatible with many water sources and can only be injected using additional precautions and management techniques. If a wide variety of chemicals are likely to be injected, then the system may require more than one type of injection system. The injection systems in Figures 1 and 2 are depicted as a single injection point, located upstream of the main filter. Some agrochemicals might require an injection point downstream from the filter location to prevent damage to the filter system. However, this should only be done by experienced irrigators or with an expert consultant, since the injection bypasses the protection of the filter system.

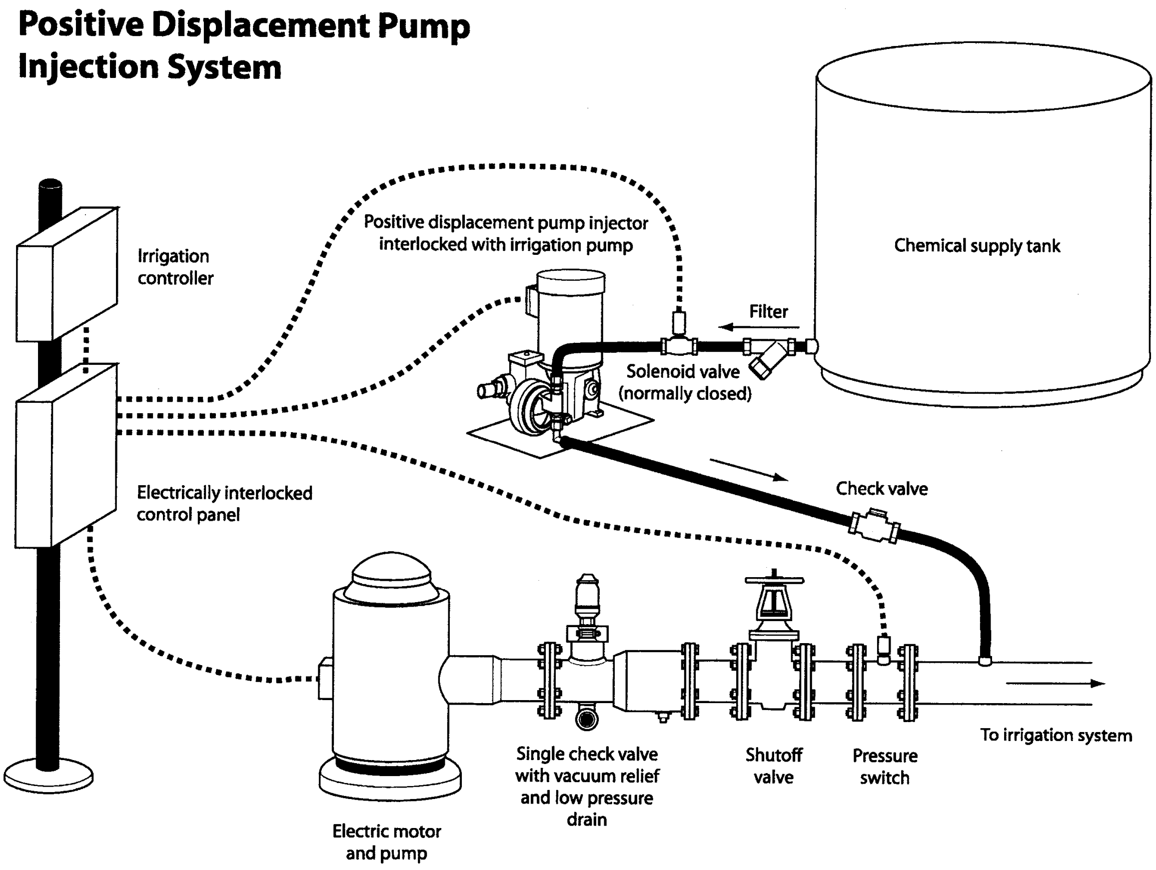


Figure 4. Typical layout for an injection system showing many of the safety interlocks and backflow prevention devices required to prevent contamination of the environment. (Courtesy of L.J. Schwankl, Univ. of California-Davis).

Chlorine is commonly injected to disinfect the system and to minimize the risk of clogging associated with biological organisms. Acid injection can also lower the pH chemical characteristic of the irrigation water. For example, high pH water may have a high clogging hazard due to a mineral dropping out of solution in the dripline after the filter. The addition of a small amount of acid to lower the pH to slightly acidify the water might prevent this hazard from occurring.

Water quality can have a significant effect on SDI system performance and longevity. In some instances, poor water quality, such as high salinity, could cause soil quality and crop growth problems. However, with proper treatment and management, water with high mineral loading, water with nutrient enrichment or water with high salinity can be used successfully in SDI systems. However, no system should be designed and installed without first assessing the quality of the proposed irrigation water supply.

WATER QUALITY ANALYSIS RECOMMENDATIONS

Prevention of clogging is the key to SDI system longevity and prevention requires understanding of the potential problems associated with a particular water source. Information on water quality should be obtained (Table 1) and made available to the designer and irrigation manager in the early stages of the planning process so that suitable system components, especially the filtration system, and management and maintenance plans can be selected.

Table 1. Recommended water quality tests

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1. Electrical Conductivity (EC) - measured in ds/m or mmho/cm - a measure of total salinity or total dissolved solids;

2. pH - a measure of acidity -
   where 1 is very acid, 14 is very alkali, and 7 is neutral;

3. Cations - measured in meq/L, (milliequivalent/liter), includes;
   Calcium (Ca),
   Magnesium (Mg), and
   Sodium (Na);

4. Anions - measured in meq/L, includes:
   Chloride (Cl),
   Sulfate (SO_4),
   Carbonate (CO_3), and
   Bicarbonate (HCO_3);

5. Sodium Absorption Ratio (SAR) - a measure of the potential for sodium in the water to develop sodium sodicity, deterioration in soil permeability and toxicity to crops. SAR is sometimes reported as Adjusted (Adj) SAR. The Adj. SAR value better accounts for the effect on the HCO_3 concentration and salinity in the water and the subsequent potential damage by sodium to the soil.

6. Nitrate nitrogen (NO_3 - N) - measured in mg/L(milligram/liter);

7. Iron (Fe),
   Manganese (Mn), and
   Hydrogen Sulfide (H_2S) - measured in mg/L;

8. Total suspended solids - a measure of particles in suspension - in mg/L;

9 Bacterial population - a measure or count of bacterial presence in # / ml, (number per milliliter);

10. Boron* - measured in mg/L;

11. Presence of oil**

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* The boron test would be for crop toxicity concern.

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

Results for Tests 1 through 7 are likely to be provided in a standard irrigation water quality test package. Tests 8 through 11 are generally offered by water labs as individual tests. The test for presence of oil may be a test to consider in oil producing areas of the state or if the well to be used for SDI has experienced surging, which may have mixed existing drip oil in the water column into the pumped water. The fee schedule for Tests 1 through 11 will vary from lab to lab and the total cost for all recommended tests may be a few hundred dollars. This is still a minor investment in comparison to the value offered by the test in helping to determine proper design and operation of the SDI system.

PRODUCER RESPONSIBILITIES

As with most investments, the decision lies with the investor. Good judgments generally require a good understanding of the fundamentals of the particular opportunity and/or the recommendations from a trusted and proven expert. While the microirrigation (drip) industry dates back over 40 years now and its application in Kansas as SDI has been researched since 1989, a network of industry support is still in the early development phase in the High Plains region. Individuals considering SDI should spend time to determine if SDI is a viable systems option for their situation. They might ask themselves:

What things should I consider before I purchase a SDI system?

1. Educate yourself before contacting a service provider or salesperson by
    a. Seeking out university and other educational resources. Good places to start are the K-State SDI website at http://www.oznet.ksu.edu/sdi/ and the Microirrigation forum at http://www.microirrigationforum.com/. Read the literature or websites of companies as well.
    b. Reviewing minimum recommended design components as recommended by K-State. http://www.oznet.ksu.edu/sdi/Reports/2003/mf2576.pdf
    c. Visit other producer sites that have installed and used SDI. Most current producers are willing to show them to others.
2. Interview at least two companies.
    a. Ask them for references, credentials (training and experience) and sites (including the names of contacts or references) of other completed systems.
    b. Ask questions about design and operation details. Pay particular attention if the minimum SDI system components are not met. If not, ask why? System longevity is a critical factor for economical use of SDI.
    c. Ask companies to clearly define their role and responsibility in designing, installing and servicing the system. Determine what guarantees are provided.
3. Obtain an independent review of the design by an individual that is not associated with sales. This adds cost but should be minor compared to the total cost of a large SDI system.

SUMMARY AND CONCLUSIONS

Subsurface drip irrigation offers a number of agronomic production and water conservation advantages but these advantages can only be achieved with proper design, operation, and maintenance, so that the SDI system can have an efficient, effective, and long life. One management change from current irrigation systems is the need to understand the SDI system sensitivity to clogging by physical, biological and/or chemical agents.

Before designing or installing an SDI system, be certain a comprehensive water quality test is conducted on the source water supply. Once this assessment is complete, the system designer can alert the manager of any potential problems that might be caused by the water supply. The old adage “an ounce of prevention is worth a pound of cure” is very appropriate for SDI systems. Early recognition of developing problems and appropriate action can prevent larger problems. While this may seem daunting at first, as with most new technology, most managers quickly will become familiar with the system and its operational needs.

The SDI operator/manager also needs to understand the function and need for the various components of an SDI system. There are many accessory options available for SDI systems that can be included during the initial design and installation phases, and even added at a later time, but more importantly, there are minimum design and equipment features that must be included in the basic system. SDI can be a viable irrigation system option, but should be carefully considered by producers before any financial investment is made.

The SDI operator/manager should monitor and record zone flowrates and pressures during ever irrigation event so that through observation of short and long term performance trends, operational problems can be discovered and remediated immediately.

OTHER AVAILABLE INFORMATION

The above discussion is a very brief summary from materials available through K-State. The SDI related bulletins and irrigation-related websites are listed below:

MF-2361	*Filtration and Maintenance Considerations for Subsurface Drip Irrigation (SDI) Systems* *http://www.oznet.ksu.edu/sdi/Reports/2003/mf2361.pdf*
MF-2576	*Subsurface Drip Irrigation (SDI) Components: Minimum Requirements* *http://www.oznet.ksu.edu/sdi/Reports/2003/mf2576.pdf*
MF-2578	*Design Considerations for Subsurface Drip Irrigation* *http://www.oznet.ksu.edu/sdi/Reports/2003/mf2578.pdf*

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

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

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

Related K-State Research and Extension Irrigation Websites:

Subsurface Drip Irrigation http://www.oznet.ksu.edu/sdi/

General Irrigation http://www.oznet.ksu.edu/irrigate/

Mobile Irrigation Lab http://www.oznet.ksu.edu/mil/

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PROGRESS WITH SDI RESEARCH AT KANSAS STATE UNIVERSITY

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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 25 acres of SDI research facilities and nearly 220 separately controlled plot areas.

Over the course of the past 17 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., and the Mazzei Injector Corporation. 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 5.5 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. Two 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 19.5 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 use efficiency, 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.

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 16-18 inches with a 5-ft 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).

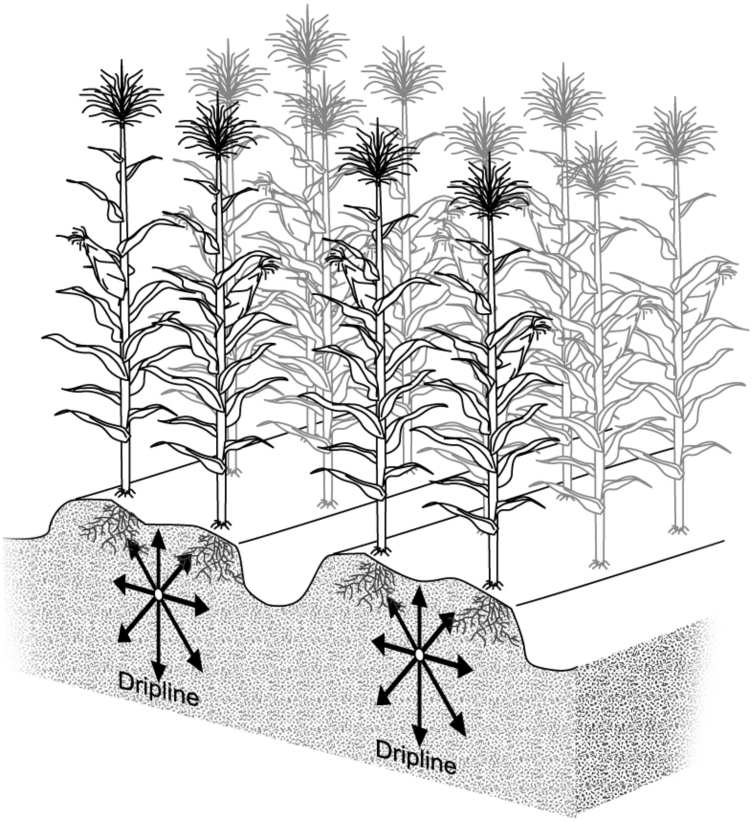

Figure 1. Physical arrangement of the subsurface dripline in relation to the corn rows.

A modified ridge-till system was used in corn production with two corn rows, 30 inches apart, grown on a 5-ft 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) was calculated using a modified Penman combination equation similar to the procedures outlined by Kincaid and Heerman (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.

WATER REQUIREMENT AND IRRIGATION CAPACITY STUDIES

Research studies were conducted at Colby and Garden City, Kansas 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/a of grain for each mm 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).

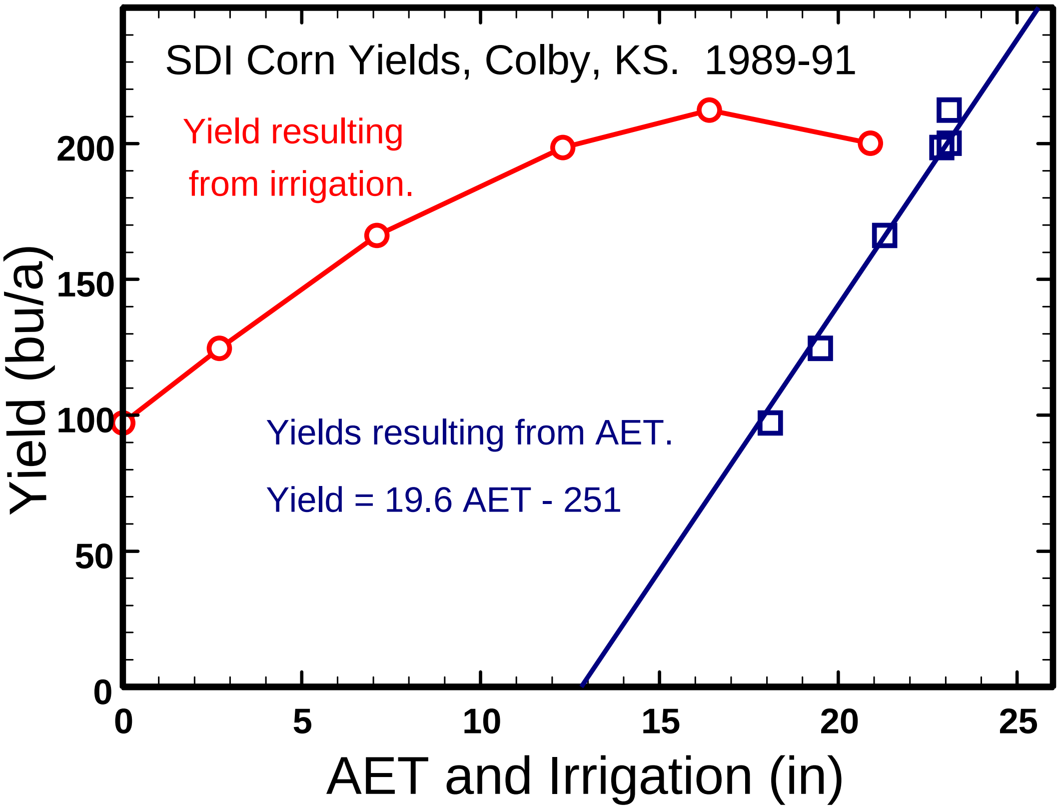

Figure 2. Corn yield as related to irrigation and calculated evapotranspiration (AET) in a SDI water requirement study, Colby, Kansas, 1989-1991.

SDI technology can make significant improvements in water use efficiency 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.

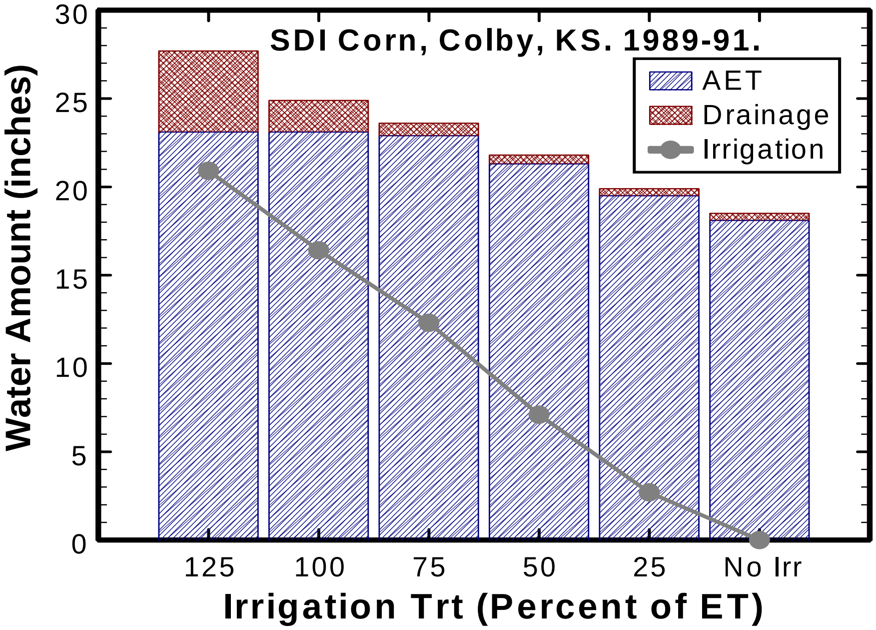

Figure 3. Calculated evapotranspiration (AET) and seasonal drainage as related to irrigation treatment in a SDI water requirement study, Colby, Kansas, 1989-1991.

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 populations (33100, 29900, 26800, and 23700 plants/acre). Daily SDI application of even small amounts of water (0.10 inches) doubled corn grain yields from 93 to 202 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 weight is established by grain filling conditions between the reproductive period and physiological maturity (last 50-60 days of crop season). Thus the extent of mining of the soil water reserves during this period will have a large effect on final kernel weight and ultimately, corn grain yield. Increasing plant population from approximately 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 population even when irrigation was severely limited or eliminated.

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.

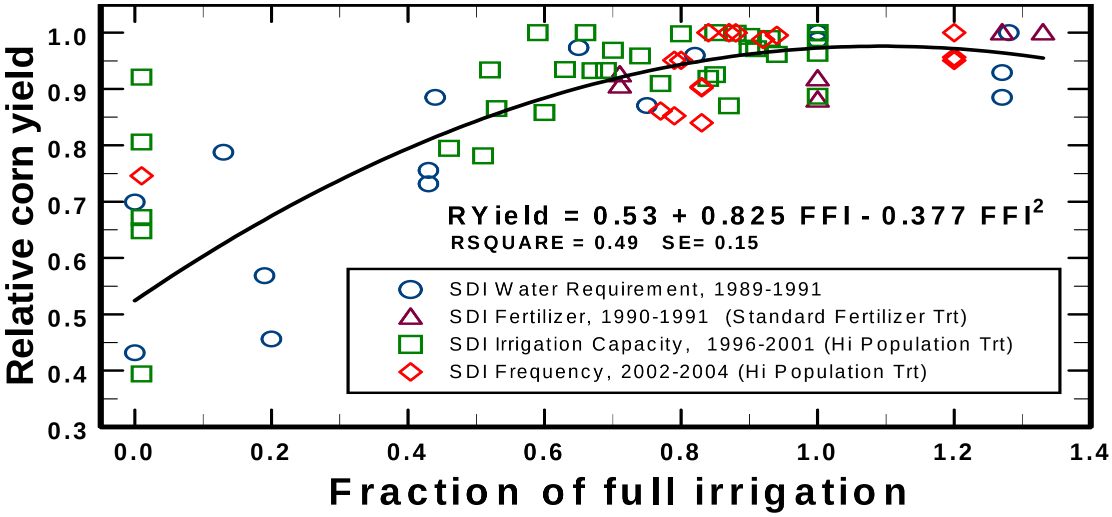

Figure 4. Relative corn grain yield for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

An examination of water use efficiency for the same four studies indicates that water use efficiency plateaus for levels of full irrigation ranging from 61% to 109% with less than 5% variation in WUE (Figure 5). The highest WUE 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 highest WUE (82% of full irrigation) also occurred in the plateau region of highest 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.

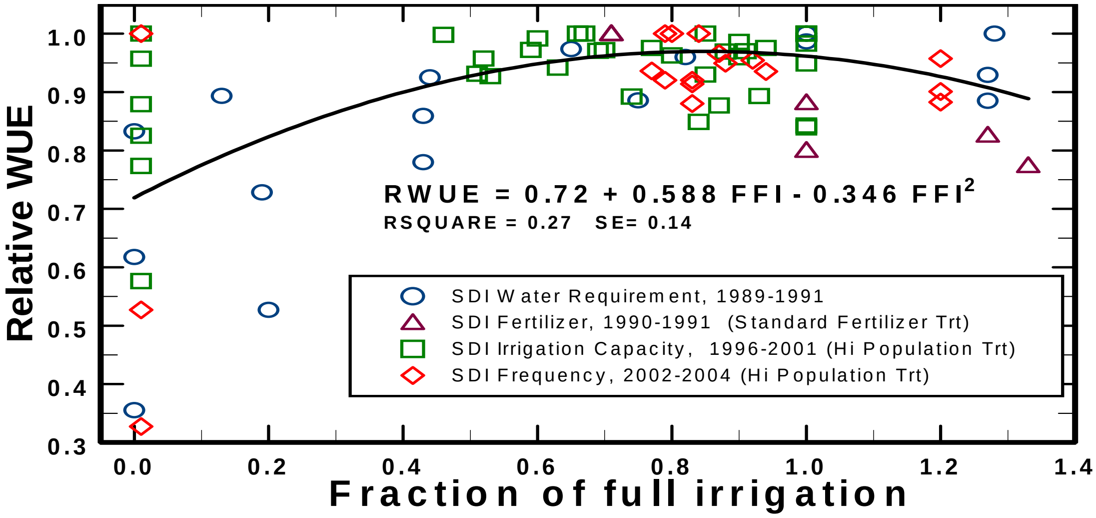

Figure 2. Relative water use efficiency of corn for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

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/a) 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 <u>fully-irrigated corn on the deep silt loam soils</u> 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 longer irrigation frequencies had 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 diminished. The four irrigation frequencies were 0.15 inches/day, 0.45 inches/3 days, 0.75 inches/5 days and 1.05 inches/7days which are equivalent but limited capacities. As a point of reference, a 0.25 inch/day irrigation capacity will match full irrigation needs for corn for center pivot sprinkler irrigation in most years. The fully irrigated treatment was limited to 0.30 inches/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.) 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 inches/5 days and 1.05 inches/7 days) resulted in yields approximately 10 to 20 bushels/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 24-36 inches high), 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.

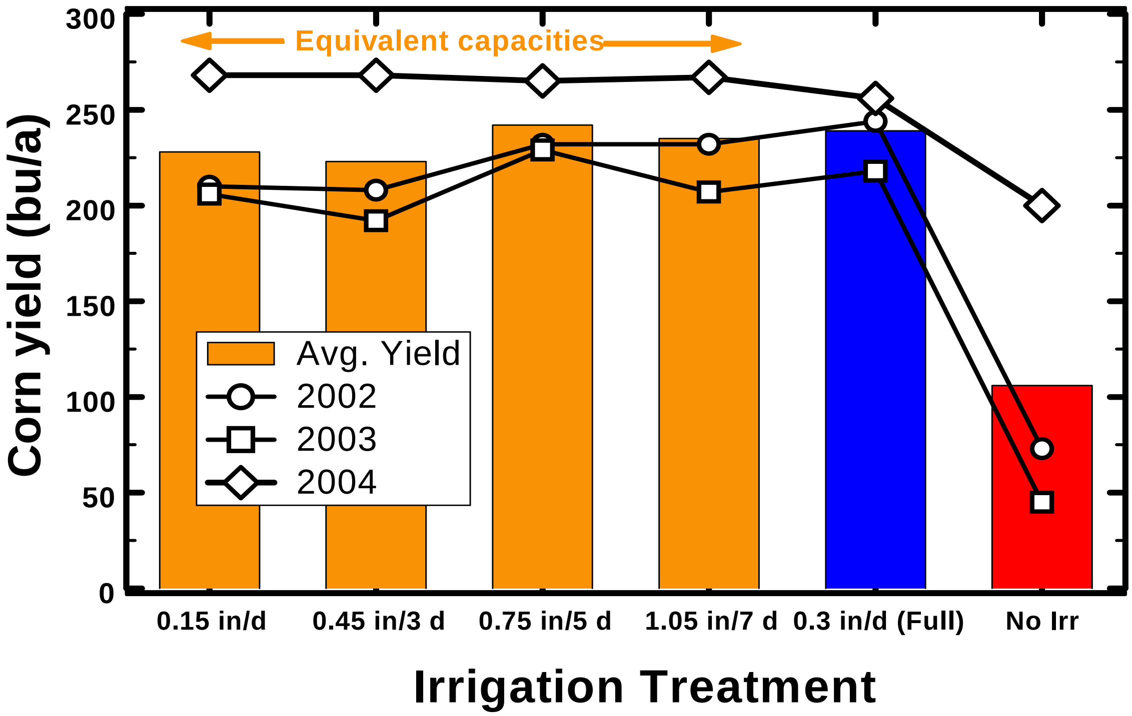

Figure 6. Corn grain yields as affected by irrigation treatment in a study examining SDI frequency under limited irrigation, Colby, Kansas, 2002 to 2004.

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 16-18 inches) for corn production on deep, silt-loam soils (Lamm et al., 1997a, Manges et al., 1995). The first study at the KSU Southwest Research-Extension Center at Garden City, Kansas evaluated 4 spacings (2.5, 5, 7.5, and 10 ft) with corn planted in 30 inches 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 rows parallel to the driplines. Average yields for corresponding treatments were similar between sites even though row orientation was different (Table 1).

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 10 ft.) 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.)

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

Spacing treatment	Irrigation treatment	Dripline ratio in relation to 5 ft. trt.	Corn yield (bu/a) Garden City 1989-91	Corn yield (bu/a) Colby 1990-91
2.5 ft.	Full irrigation	2.00	230	----
5.0 ft	Full irrigation	1.00	218	216
7.5 ft	Full Irrigation	0.67	208	204
7.5 ft	Reduced irrigation (67%)	0.37	----	173
10.0 ft	Full irrigation	0.50	194	194
10.0 ft	Reduced irrigation (50%)	0.50	----	149

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 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/a (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 use efficiency (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).

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 60 inches 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.

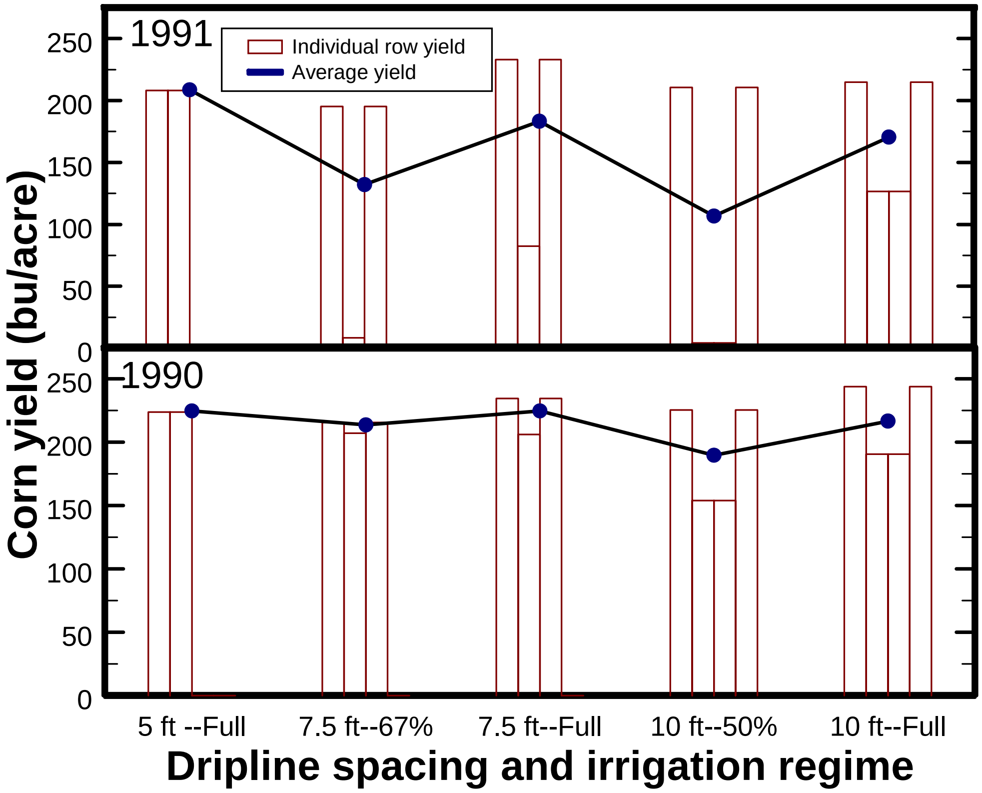

Figure 7. Corn yield distribution as affected by dripline spacing and irrigation regime, Colby, Kansas, 1990-1991. Note: Individual row yields are mirrored about a centerline half way between two adjacent driplines for display purposes.

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 depth (8, 12, 16, 20 or 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.). However, it is still too early to answer questions about how depth affects longevity (chemical and biological clogging, pests, and tillage practices). The study area has not been used to examine the effects of dripline depth on germination in the spring, but studies in this regard may be conducted in the future. 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 great. 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 have been no instances thus far of tillage tool damage to the shallow 8-inch depth driplines.

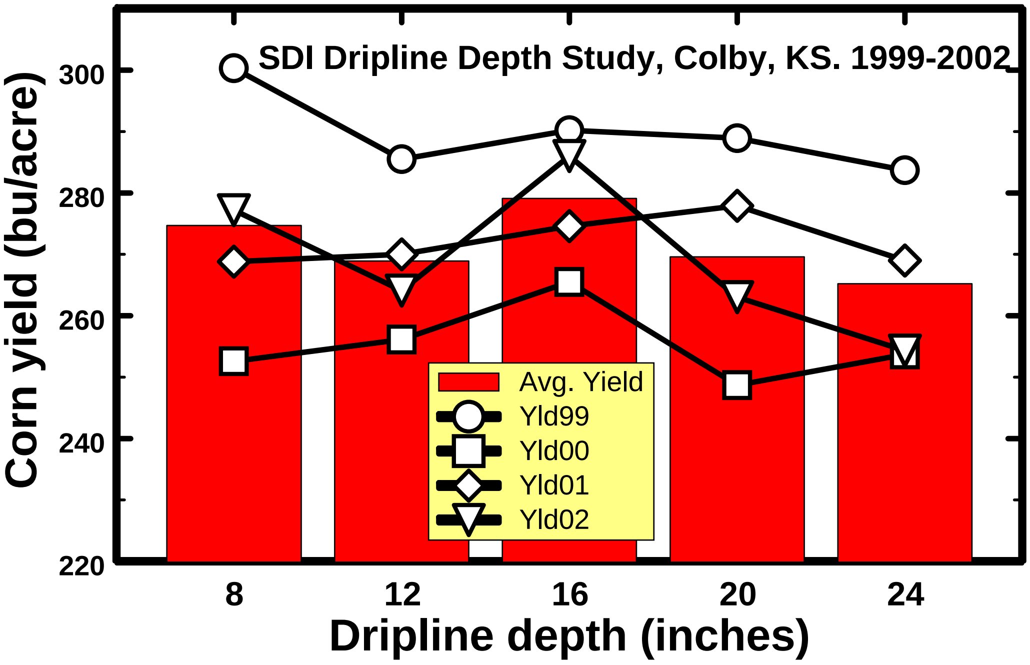

Figure 8. Corn grain yields as affected by dripline depth, 1999-2002, Colby, Kansas.

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 Colby, Kansas from 1990-91, there was no difference in corn yields between preplant surface-applied nitrogen and nitrogen injected into the driplines throughout the season. Corn yields averaged 225 to 250 bu/a for the fully irrigated and fertilized treatments. 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 16-18 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.*

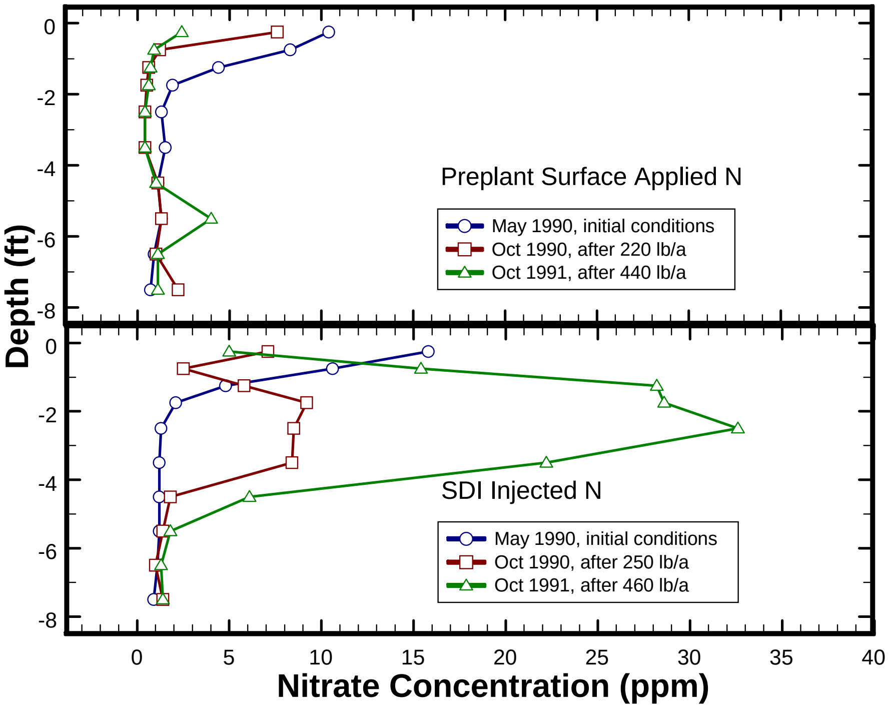

Figure 9. Nitrate concentrations in the soil profile for preplant surface-applied and SDI injected nitrogen treatments, Colby, Kansas, 1990-91. Data is for selected nitrogen fertilizer rate treatments with full irrigation (100% of AET).

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 use efficiency (WUE) were utilized as criteria for evaluating six different nitrogen fertigation rates, 0, 80, 120, 160, 200, and 240 lbs/acre. The final BMP was a nitrogen fertigation level of 160 lbs/acre with other non-fertigation applications bringing the total applied nitrogen to approximately 190 lbs/acre (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 WUE all plateaued at the same level of total applied nitrogen which corresponded to the 160 lbs/acre nitrogen fertigation rate (Figure 10). Average yields for the 160 lbs/acre nitrogen fertigation rate was 213 bu/acre. Corn yield to ANU ratio for the 160 lbs/acre 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.

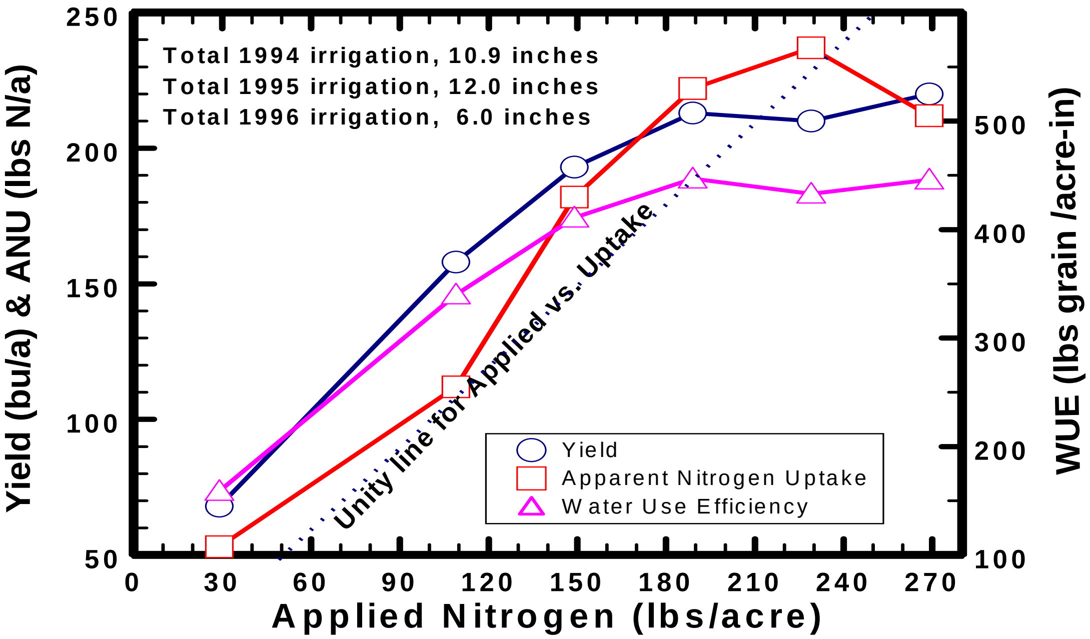

Figure 10. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water use efficiency as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded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

COMPARISON OF SDI AND SIMULATED LEPA SPRINKLER IRRIGATION

A seven-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 bushels/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 bushels/acre) and SDI had higher yields in 3 normal to wetter years (approximately 15 bushels/acre).

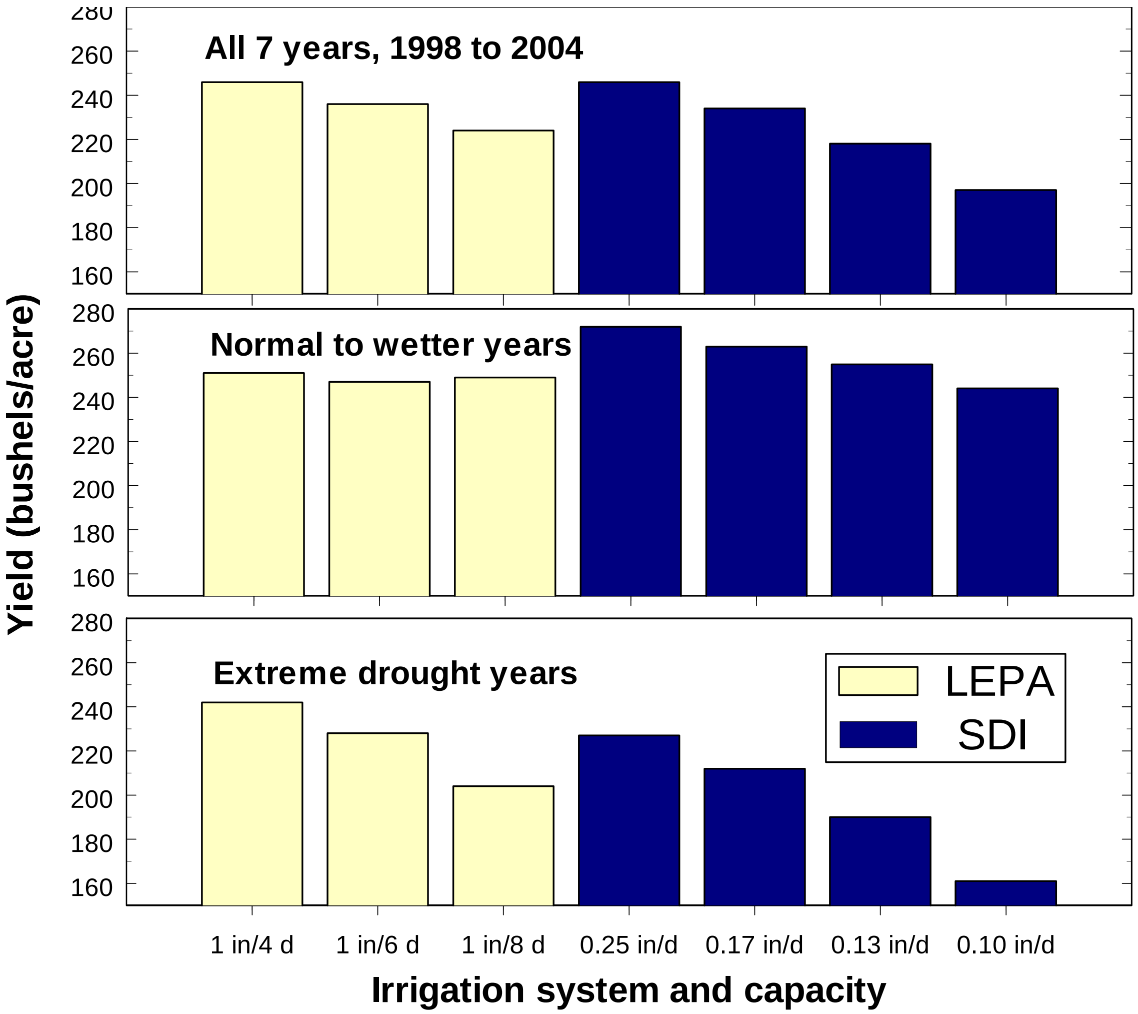

Figure 3. Variation in corn yields across years and weather conditions as affected by irrigation system type and capacity, Colby Kansas.

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 weight at harvest as compared to LEPA (34.7 vs. 33.2 grams/100 kernels 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 weight) between irrigation systems as climatic conditions vary.

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 acres (Figure 13). Small and irregular shape fields may be ideal candidates for SDI.

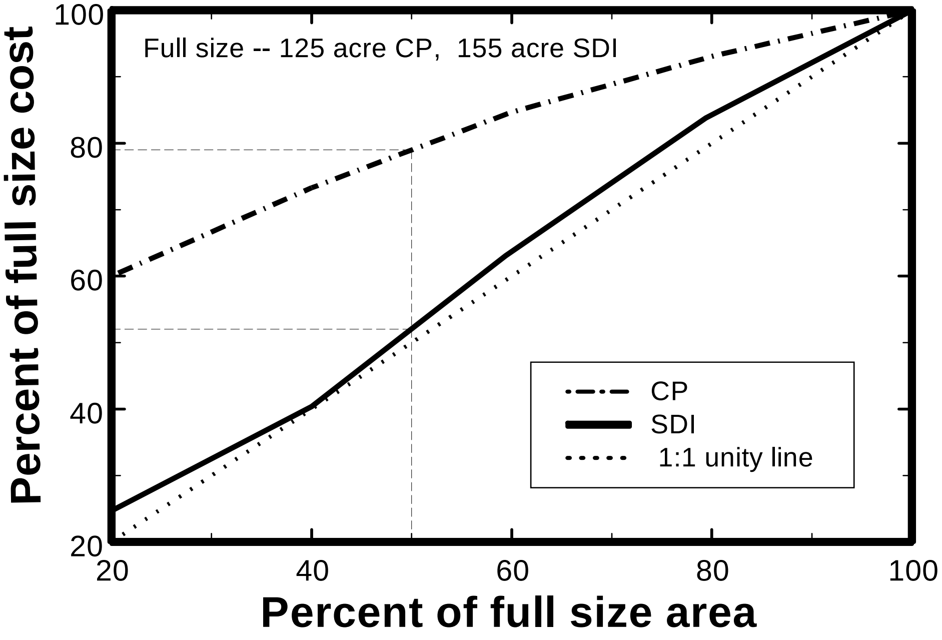

Figure 12. Center pivot sprinkler (CP) and SDI system costs as related to field size. (after O'Brien et al., 1997)

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 to make CP and SDI economic comparisons is available for downloading from the internet for free at http://www.oznet.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 12). 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 (16-18 inches) has reduced the chemical clogging hazards due to less temperature fluctuations and negligible evaporation directly from the dripline.

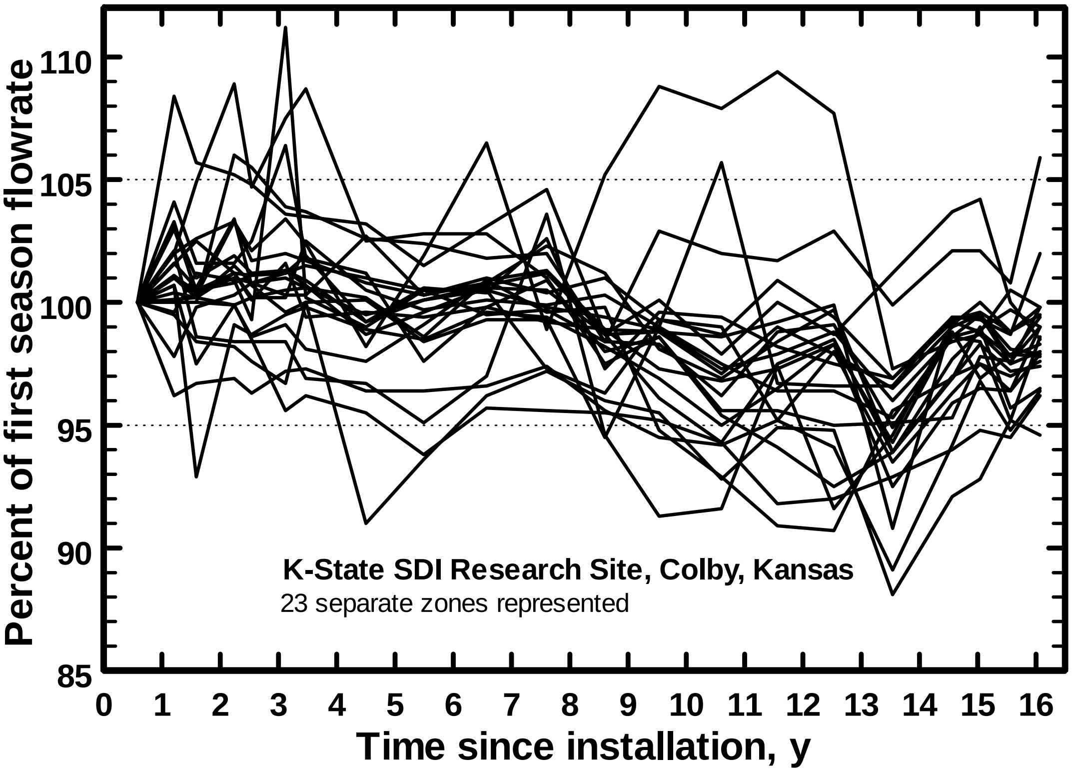

Figure 12. Stability in zone flowrates from the initial first season as related to time for an SDI system installed at Kansas State University, Colby, Kansas, 1989-2005.

CONCLUDING STATEMENTS

Research progress has been steady since 1989. Much of K-State's SDI research is summarized at K-State's SDI Website at http://www.oznet.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.

ACKNOWLEDGEMENTS

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

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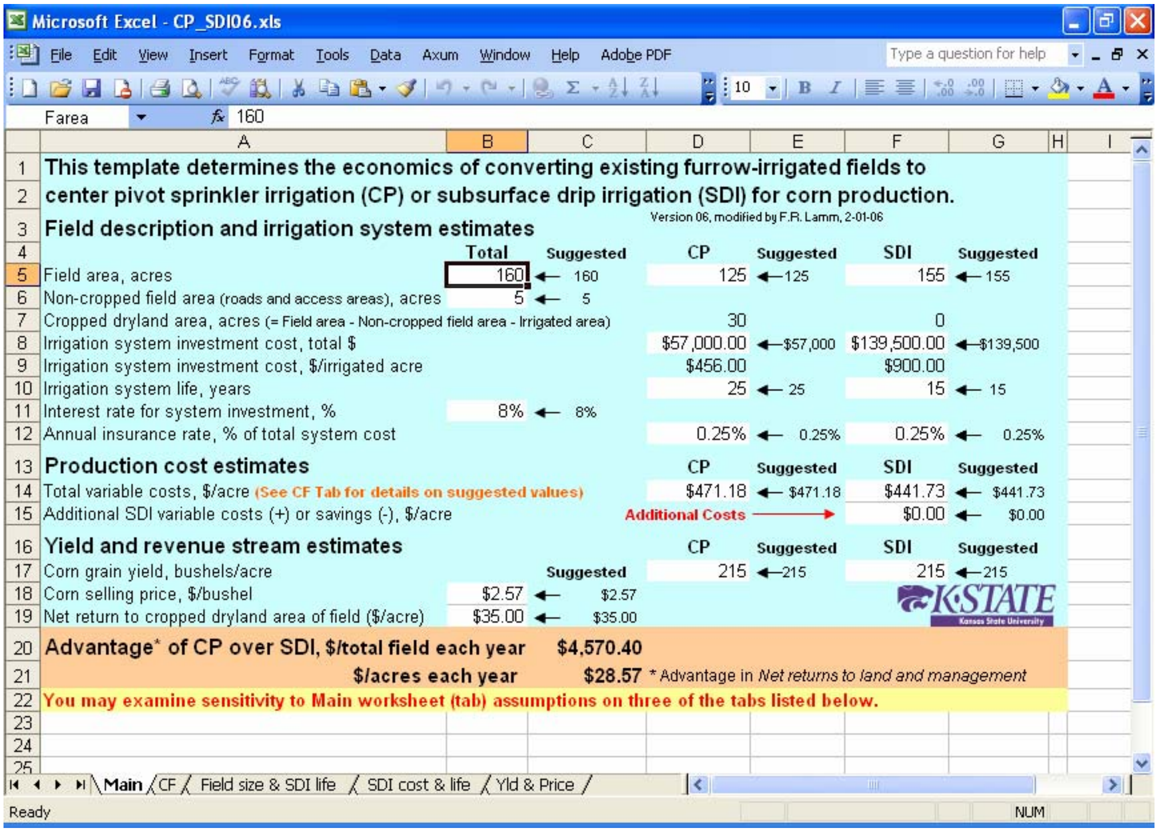
INTRODUCTION

In much of the Great Plains, the rate of new irrigation development is slow or zero. However, as the farming populace and irrigation systems age, there has been a continued momentum for conversion of existing furrow-irrigated systems to modern pressurized irrigation systems. These systems, including center pivot sprinkler irrigation (CP) and subsurface drip irrigation (SDI), can potentially have higher irrigation efficiency and irrigation uniformity while at the same time reducing irrigation labor. SDI is a relatively new irrigation system alternative for corn production on the Great Plains. Corn producers converting from furrow-irrigated systems to a pressurized system are faced with economic uncertainty about whether to convert to center pivot sprinklers (CP) or SDI. In the spring of 2002, a free Microsoft Excel[1] spreadsheet template was introduced by K-State for making economic comparisons of CP and SDI. Since that time, the spreadsheet has been periodically updated to reflect changes in input data, particularly system and corn production costs. The spreadsheet also provides sensitivity of these comparisons to key factors. Efforts are underway to expand the spreadsheet capabilities to other crops and regions within the Great Plains, but those templates are not ready for distribution at this time. This paper will discuss how to use the spreadsheet and the key factors that most affect the comparisons. The template has five worksheets (tabs), the Main, CF, Field size & SDI life, SDI cost & life, Yield & price tabs. Most of the calculations and the result are shown on the Main tab (Figure 1.).

ANALYSES METHODS AND ECONOMIC ASSUMPTIONS

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



	A	B	C	D	E	F	G
1	**This template determines the economics of converting existing furrow-irrigated fields to**						
2	**center pivot sprinkler irrigation (CP) or subsurface drip irrigation (SDI) for corn production.**						
3	**Field description and irrigation system estimates**			Version 06, modified by F.R. Lamm, 2-01-06			
4		**Total**	**Suggested**	**CP**	**Suggested**	**SDI**	**Suggested**
5	Field area, acres	160	← 160	125	←125	155	←155
6	Non-cropped field area (roads and access areas), acres	5	← 5				
7	Cropped dryland area, acres (= Field area - Non-cropped field area - Irrigated area)			30		0	
8	Irrigation system investment cost, total $			$57,000.00	←$57,000	$139,500.00	←$139,500
9	Irrigation system investment cost, $/irrigated acre			$456.00		$900.00	
10	Irrigation system life, years			25	← 25	15	← 15
11	Interest rate for system investment, %	8%	← 8%				
12	Annual insurance rate, % of total system cost			0.25%	← 0.25%	0.25%	← 0.25%
13	**Production cost estimates**			**CP**	**Suggested**	**SDI**	**Suggested**
14	Total variable costs, $/acre **(See CF Tab for details on suggested values)**			$471.18	← $471.18	$441.73	← $441.73
15	Additional SDI variable costs (+) or savings (-), $/acre			**Additional Costs**	→	$0.00	← $0.00
16	**Yield and revenue stream estimates**			**CP**	**Suggested**	**SDI**	**Suggested**
17	Corn grain yield, bushels/acre		**Suggested**	215	←215	215	←215
18	Corn selling price, $/bushel	$2.57	← $2.57				
19	Net return to cropped dryland area of field ($/acre)	$35.00	← $35.00				
20	**Advantage* of CP over SDI, $/total field each year**		**$4,570.40**				
21	**$/acres each year**		**$28.57**	* Advantage in *Net returns to land and management*			
22	**You may examine sensitivity to Main worksheet (tab) assumptions on three of the tabs listed below.**						
23							
24							
25							

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.

Field & irrigation system assumptions and estimates

It is assumed that an existing furrow-irrigated field with a working well and pumping plant is being converted to either center pivot sprinkler irrigation or SDI. The pumping plant is located at the center of one of the field edges and is at a suitable location for the initial SDI distribution point (i.e. upslope of the field to be irrigated). Any necessary pump modifications (flow and pressure) for the CP or SDI systems are assumed to be of equal cost and thus are not considered in the analysis.

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

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

Irrigation system costs are highly variable at this point in time due to rapid fluctuations in material and energy costs. Cost estimates for the 125 acre CP system and the 155 acre SDI system are provided on the current version of the spreadsheet template, but since this is the overall basis of the comparison, it is recommended that the user apply his own estimates for his conditions. In the base analyses, the life for the two systems are assumed to be 25 and 15 years for the CP and SDI systems, respectively. No salvage value was assumed for either system. This assumption of no salvage value may be inaccurate, as both systems might have a few components that may be reusable or available for resale at the end of the system life. However, with relatively long depreciation periods of 15 and 25 years and typical financial interest rates, the zero salvage value is a very minor issue in the analysis.

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

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

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

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

The annual interest rate can be entered as a variable, but is currently assumed to be 8%. The total interest costs over the life of the two systems were converted to an average annual interest cost for this analysis. Annual insurance costs were assumed to be 0.25% of each total system cost, but can be changed if better information is available. It is unclear whether insurance can be obtained for SDI systems and if SDI insurance rates would be lower or higher than CP systems. Many of the SDI components are not subject to the climatic conditions that are typically insured hazards for CP systems. However, system failure risk is probably higher with SDI systems which might influence any obtainable insurance rate.

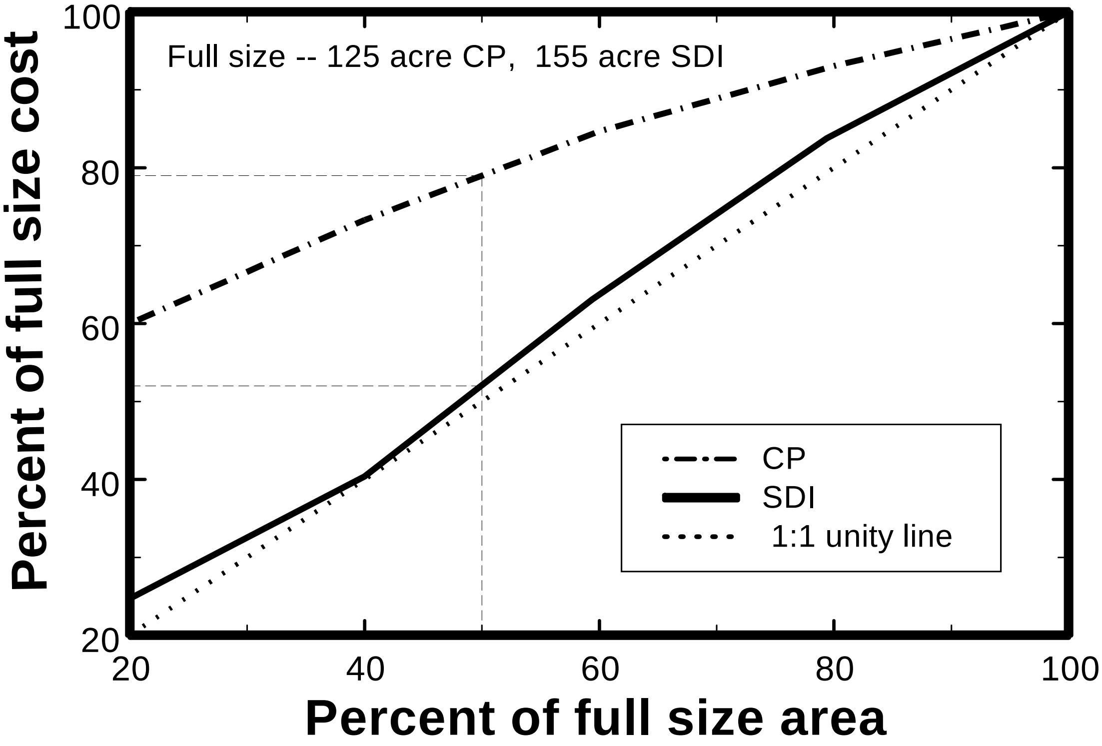
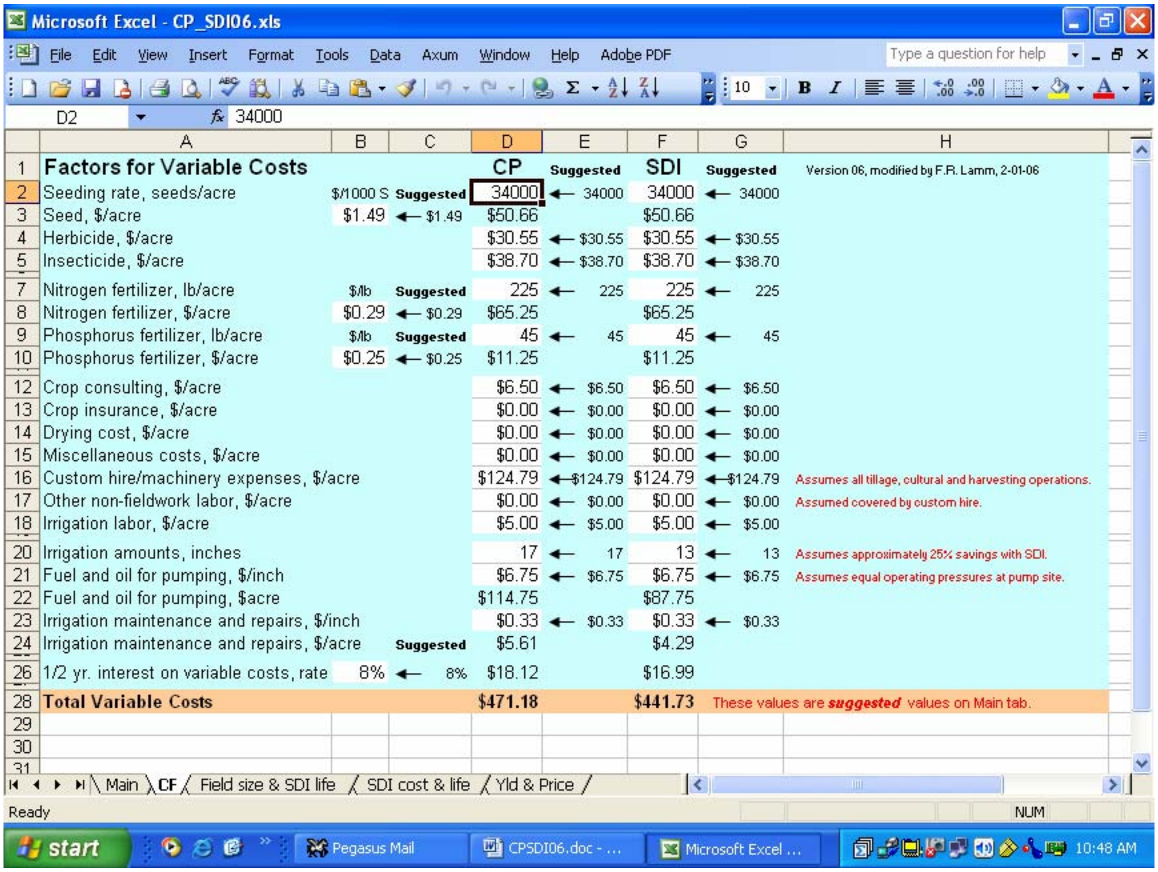


Figure 2. CP and SDI system costs as related to field size. (O'Brien et al., 1997)

Production cost assumptions and estimates

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

Production costs were adapted from KSU estimates (Dumler and Thompson, 2005). A listing of the current costs is available on the CF worksheet (tab) (Figure 3) and the user can enter new values to recalculate variable costs that more closely match their conditions. This sum would become the new suggested Total Variable Costs on the Main worksheet (tab), but the user must manually change the input value on the Main worksheet (White input cell box) for the economic comparison to take effect. *The user may find it easier to just change the differential production costs between the systems on the Main tab rather than changing the baseline assumptions on the CF tab. This will help maintain integrity of the baseline production cost assumptions.* The reduction in variable costs for SDI is attributable to an assumed 25% net water savings that is consistent with research findings by Lamm et al. (1995). This translates into a 17 and 13 inch gross application amount for CP and SDI, respectively. The current estimated production costs are somewhat high considering the gross revenues are only approximately $550/irrigated acre. This may be reflecting the overall profitability issue during these trying economic conditions, but producers might also try to reduce these variable costs somewhat to cope with low crop prices. This fact is pointed out because a lowering of overall variable costs favors SDI, since more irrigated cropped acres are involved, while higher overall variable costs favors CP production. The variable costs for both irrigation systems represent typical practices for western Kansas.



	A	B	C	D	E	F	G	H
1	**Factors for Variable Costs**			CP	**Suggested**	SDI	**Suggested**	Version 06, modified by F.R. Lamm, 2-01-06
2	Seeding rate, seeds/acre	$/1000 S	**Suggested**	34000	← 34000	34000	← 34000	
3	Seed, $/acre	$1.49	← $1.49	$50.66		$50.66		
4	Herbicide, $/acre			$30.55	← $30.55	$30.55	← $30.55	
5	Insecticide, $/acre			$38.70	← $38.70	$38.70	← $38.70	
7	Nitrogen fertilizer, lb/acre	$/lb	**Suggested**	225	← 225	225	← 225	
8	Nitrogen fertilizer, $/acre	$0.29	← $0.29	$65.25		$65.25		
9	Phosphorus fertilizer, lb/acre	$/lb	**Suggested**	45	← 45	45	← 45	
10	Phosphorus fertilizer, $/acre	$0.25	← $0.25	$11.25		$11.25		
12	Crop consulting, $/acre			$6.50	← $6.50	$6.50	← $6.50	
13	Crop insurance, $/acre			$0.00	← $0.00	$0.00	← $0.00	
14	Drying cost, $/acre			$0.00	← $0.00	$0.00	← $0.00	
15	Miscellaneous costs, $/acre			$0.00	← $0.00	$0.00	← $0.00	
16	Custom hire/machinery expenses, $/acre			$124.79	← $124.79	$124.79	← $124.79	Assumes all tillage, cultural and harvesting operations.
17	Other non-fieldwork labor, $/acre			$0.00	← $0.00	$0.00	← $0.00	Assumed covered by custom hire.
18	Irrigation labor, $/acre			$5.00	← $5.00	$5.00	← $5.00	
20	Irrigation amounts, inches			17	← 17	13	← 13	Assumes approximately 25% savings with SDI.
21	Fuel and oil for pumping, $/inch			$6.75	← $6.75	$6.75	← $6.75	Assumes equal operating pressures at pump site.
22	Fuel and oil for pumping, $acre			$114.75		$87.75		
23	Irrigation maintenance and repairs, $/inch			$0.33	← $0.33	$0.33	← $0.33	
24	Irrigation maintenance and repairs, $/acre		**Suggested**	$5.61		$4.29		
26	1/2 yr. interest on variable costs, rate	8%	← 8%	$18.12		$16.99		
28	**Total Variable Costs**			**$471.18**		**$441.73**	These values are ***suggested*** values on Main tab.	
29								
30								
31								

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

Yield and revenue stream estimates

Corn grain yield is currently estimated at 215 bushels/acre in the base analysis with a corn price of $2.57/bushel (See values on Main worksheet). Net returns for the 30 cropped dryland acres for the CP system (corners of field) were assumed to be $35.00/acre which is essentially the current dryland crop cash rent estimate for Northwest Kansas. Government payments related to irrigated crop production are assumed to be spread across the overall field size, and thus, do not affect the economic comparison of systems.

Sensitivity analyses

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

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

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

The results are very sensitive to

- any additional production cost savings with SDI.

The results are moderately sensitive to

- corn yield
- corn price
- yield/price combinations

and very sensitive to

- higher potential yields with SDI

with advantages favoring SDI as corn yields and price increase.

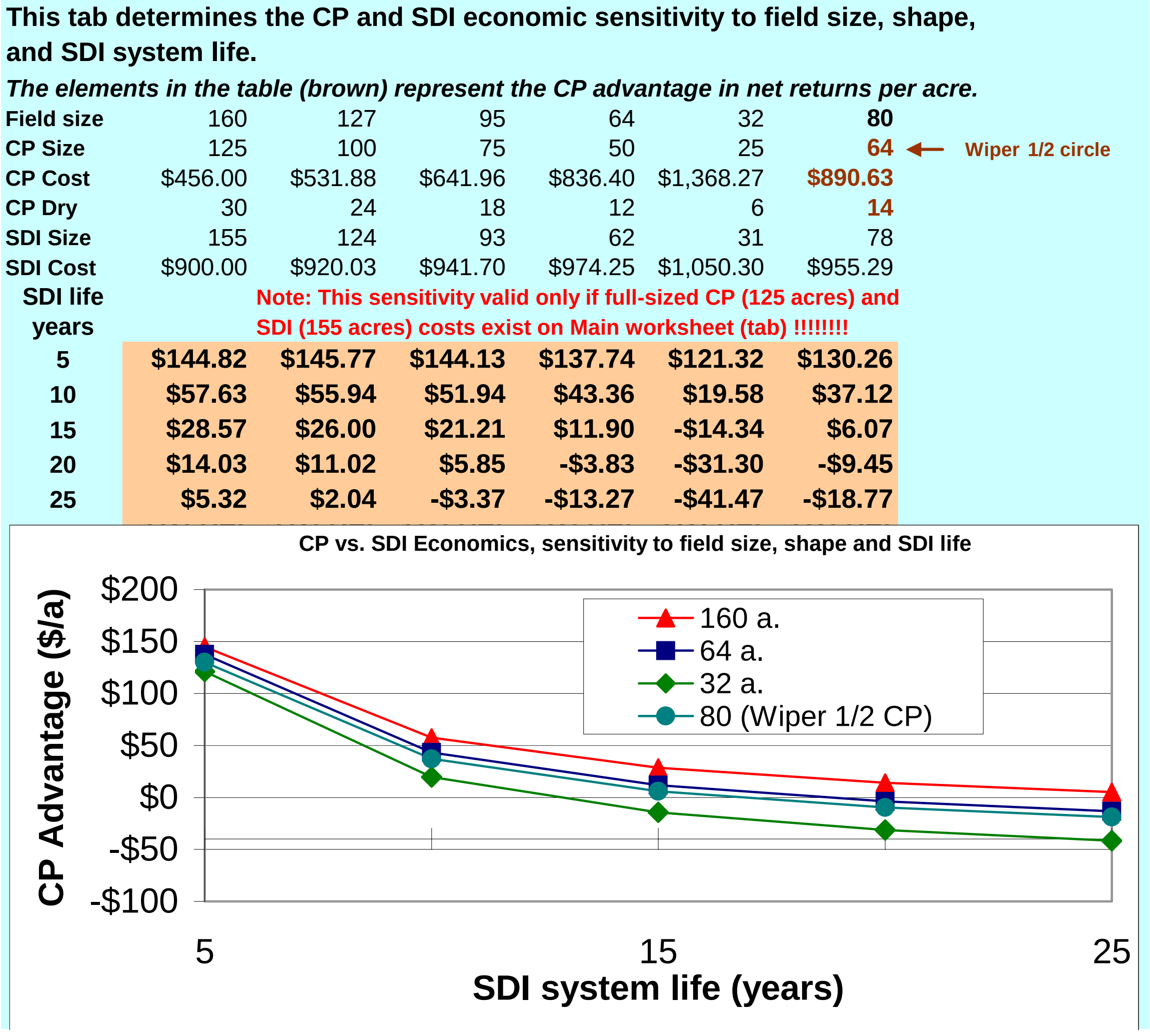
The economic comparison spreadsheet also includes three worksheet (tabs) that display tabular and graphical sensitivity analyses for field size and SDI system life, SDI system cost and life, and corn yield and selling price (Figure 4). These sensitivity analysis worksheets automatically update when different assumptions are made on the Main worksheet.

SOME KEY OBSERVATIONS FROM PREVIOUS ANALYSES

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

Smaller CP systems and systems which only complete part of the circle are less competitive with SDI than full size 125 acre CP systems This is primarily because the CP investment costs ($/ irrigated acre) increase dramatically as field size decreases (Figure 2 and 4) or when the CP system cannot complete a full circle.

Increased longevity for SDI systems is probably the most important factor for SDI to gain economic competitiveness with CP systems. A research SDI system at the KSU Northwest Research-Extension Center has been operated for 17 years with very little performance degradation, so long system life is possible. However, a short SDI system life that might be caused by early failure due to clogging, indicates a huge economic disadvantage that would preclude nearly all adoption of SDI systems (Figure 4). The sensitivity of CP system life and cost is much less because of the much lower initial CP cost and the much longer assumed life. In areas where CP life might be much less than 25 years due to corrosive waters, a sensitivity analysis with shorter CP life is warranted.



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

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

Field size	160	127	95	64	32	**80**	
CP Size	125	100	75	50	25	**64**	← **Wiper 1/2 circle**
CP Cost	$456.00	$531.88	$641.96	$836.40	$1,368.27	**$890.63**	
CP Dry	30	24	18	12	6	**14**	
SDI Size	155	124	93	62	31	78	
SDI Cost	$900.00	$920.03	$941.70	$974.25	$1,050.30	$955.29	
SDI life years		**Note: This sensitivity valid only if full-sized CP (125 acres) and SDI (155 acres) costs exist on Main worksheet (tab) !!!!!!!!**					
5	**$144.82**	**$145.77**	**$144.13**	**$137.74**	**$121.32**	**$130.26**	
10	**$57.63**	**$55.94**	**$51.94**	**$43.36**	**$19.58**	**$37.12**	
15	**$28.57**	**$26.00**	**$21.21**	**$11.90**	**-$14.34**	**$6.07**	
20	**$14.03**	**$11.02**	**$5.85**	**-$3.83**	**-$31.30**	**-$9.45**	
25	**$5.32**	**$2.04**	**-$3.37**	**-$13.27**	**-$41.47**	**-$18.77**	

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

The present baseline analysis already assumes a 25% water savings with SDI. There are potentially some other production cost savings for SDI such as fertilizer and herbicides that have been reported for some crops and some locales. Small changes in the assumptions can make a sizable difference.

Combining a higher overall corn yield potential with an additional small yield advantage for SDI can allow SDI to be very competitive with CP systems.

AVAILABILITY OF FREE SOFTWARE

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

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

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SALT THRESHOLDS FOR LIQUID MANURE APPLICATIONS THROUGH A CENTER PIVOT

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INTRODUCTION

Application of liquid manure to growing crops is often a convenient and agronomically acceptable means of land application. Center pivots have been adapted to apply a broad range of fertilizers and pesticides. Development of large animal production facilities has added manure application to the list of materials that can be applied via center pivots. Al-Kaisi, et al. (2002) reported on the impact of using a center pivot to apply dilute swine lagoon water to cropland in Colorado. However, some producers have learned the hard way that manure contains some good and some bad materials. Occasionally, crop damage occurs as a result of application of concentrated manure presumably because of high salt concentrations.

Sprinkler application of animal manure to growing crops is a different issue than most of the salinity research that has been conducted across the country. Soluble salt levels in liquid manures are often higher than in the saline water used for irrigation in the western U.S. When irrigating with saline irrigation water the major problem is buildup of salt over time due to removal of the water by the crop leaving the salts behind. However, application of manure occurs at relatively low rates per acre and the annual rainfall or irrigation tends to leach the undesirable salts from the profile between applications. An additional concern with center pivot application of concentrated swine manure is the potential for plant damage (phytotoxicity) due to high ammonia levels.

Crop damage due to sprinkler application of manure with high EC levels occurs because of the direct contact of the salt with plant leaves and potentially the roots. Early research reporting the salinity thresholds for induced foliar injury concluded that since damage was caused by salt absorption into plant tissues, foliar application should be avoided in hot, dry, windy conditions that produce high potential evapotranspiration (PET). It was noted that species varied in the rate of foliar absorption of salts, such as: sorghum < cotton = sunflower < alfalfa = sugar beet < barley < potato. However, the susceptibility to injury was not related to salt absorption, as injury varied as: sugar beet < cotton < barley = sorghum < alfalfa < potato (Maas, et al., 1985; Maas, 1982). They found that leaf absorption of salts may be affected by leaf age, with generally less permeability in older leaves, and by angle and position of the leaf, which may affect the time and amount of leaf salt exposure. Producers need to know what the safe levels are and the effect of timing on potential plant damage for corn and soybeans.

The goal of the project was to establish the safe level of salt that could be applied to corn and soybean at different stages of growth. To accomplish this goal, a range of swine manure concentrations was applied to a growing crop in a manner that simulated application via a center pivot.

METHODS

Salt and ammonia concentration data from over 2700 manure samples were obtained from a private laboratory to determine the range in concentrations that should be evaluated in the field research. The EC level is an indication of the salt concentration in the manure sample. Figure 1 is a summary of the samples analyzed where the median EC level was 6.7 dS m^{-1} with a range from 0.1 to 70 dS m^{-1}. The median ammonia concentration was 497 ppm NH_4-N with a range from 0.03 to 12646 ppm NH_4-N.

The field research was conducted at the Haskell Agricultural Laboratory of the University of Nebraska located near Concord, Nebraska. The soil was a Kennebec silt loam with a pH of 7.3, and 3.5% soil organic matter. Corn (cv. Pioneer Brand 34N43) was planted on 16 May 2003 at 27,000 seeds per acre. Soybean (cv. Garst 2502) was planted on 28 May 2003 at 189,000 seeds per acre. Field plots were 8-30 inch rows wide and 35 feet long randomly arranged with three replications. The experimental area was irrigated with a lateral-move sprinkler irrigation system equipped with low-pressure spray nozzles mounted on top of the pipeline. The EC of the irrigation water was 0.6 dS m^{-1}. Irrigation was applied as needed to maintain greater than 50% available water in the rootzone. Irrigation supplied 8 inches of irrigation water to both crops, and precipitation supplied 14.4 inches between 1 May and the end of the season.

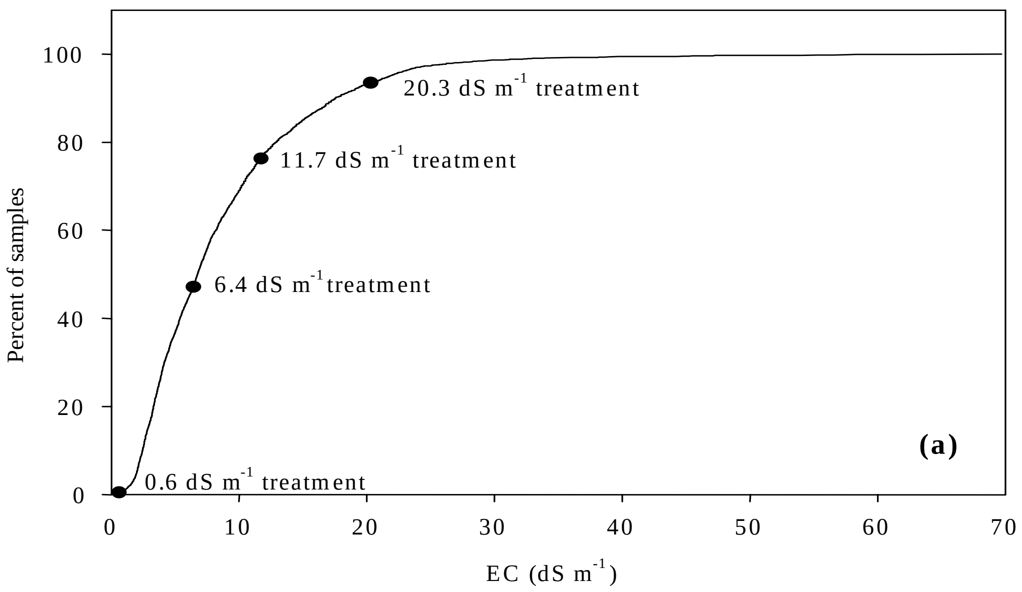

Figure 1. Cumulative distribution of electrical conductivity of liquid manure submitted for analysis to a commercial laboratory in Nebraska. The concentrations used in this study are also presented.

Swine manure from a commercial confined feeding operation was pumped from an under-building storage pit through a 2 mm screen to remove large solids. The liquid manure was passed through a 0.4 mm screen and then pumped to transfer tanks equipped to continuously agitate the liquid. Multiple screening was necessary to prevent the applicator nozzles from plugging during application. The EC of the solutions was determined using a conductivity meter (ATI Orion model 130, Analytical Technology, Inc., Boston, Mass.) calibrated with either a 1 or 10 dS m^{-1} solution. Liquid manure samples for both applications were collected from the supply tank outlet between the tank and the applicator and sent to Ward Laboratories to determine EC and nutrient concentration (Table 1).

The screened manure was diluted with fresh water to create four levels of EC in the liquid manure. The original manure had an EC level of 20.3 dS m^{-1}. Fresh water was added to dilute the manure down to 6.4 and 11.7 dS m^{-1}. Fresh water with an EC of 0.6 dS m^{-1} was used as a control treatment.
A portable applicator was developed and attached to the boom of a Hi-Boy sprayer (Figure 2). The applicator consisted of 21 nozzles arranged in a 3-nozzle wide by 7-nozzle long grid with a spacing of 3 feet between nozzles in each direction. The liquid manure application treatments consisted of a single application of four soluble salt concentrations applied at one of two selected

Table 1. Chemical analysis of liquid manure applied to corn and soybean at Concord, Nebraska, in 2003 (all values in lb/ac except where noted).

	EC Level (dS m^{-1})[1]							
	0.6		6.4		11.7		20.3	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Organic N	0.04	0.04	23.8	3.1	63.6	22.0	179.2	41.0
Ammonium N	0.5	0.1	78.6	9.6	170.4	6.0	365.7	15.9
P as P_2O_5	0.6	0.4	33.7	4.6	112.8	61.3	301.0	72.9
K as K_2O	0.9	0.1	60.7	5.6	130.6	8.8	281.5	26.3
S	3.5	0.5	12.2	1.8	25.5	4.5	53.4	7.1
Ca	8.9	1.0	19.4	1.6	57.9	36.2	131.6	33.0
Mg	2.0	0.1	8.9	0.9	23.2	10.6	57.9	13.4
Na	2.5	0.1	13.8	1.2	27.7	1.2	59.7	3.6
Soluble salts	37.0	1.3	412.4	43.6	753.5	24.2	1303.1	65.0
EC (dS m^{-1})	0.60	0.00	6.4	0.67	11.7	0.38	20.3	1.01
pH	7.87	0.72	6.9	0.12	6.6	0.06	6.2	0.12
Dry matter (%)	0.05	0.01	0.5	0.05	1.8	0.97	4.2	0.86

[1] Mean EC levels for the fresh water used as a control treatment and liquid manure dilutions applied to corn and soybean.

growth stages of corn and soybean. The first application was applied on July 2when corn was at the V7 growth stage and soybean was in the V3 stage (Ritchie, et al., 1996; Ritchie and Hanway, 1984). Air temperatures during application were in the upper 80’s. The second application was applied on July 24 when corn was at the V14 stage and soybean was at the R1 stage. Air temperatures during application were again in the upper 80’s. Approximately 0.5 inches of liquid manure was applied over a 10-minute period to corn and soybeans at each EC level.

Figure 2. Applicator used to apply liquid swine manure to corn and soybean.

RESULTS

Soybean

Each of the production indices was decreased by the 20.3 dS m^{-1} liquid manure for both application times (Table 2). Soybean plant population at harvest was less with the V3 application of 20.3 dS m^{-1} liquid manure than with the 0.6, 6.4, or 11.7 dS m^{-1} treatments, but the R1 application did not affect plant population. Leaf area was damaged by the V3 application but the plants recovered due to less inter-plant competition from a reduced plant population. Thus, the final plant LAI was not significantly different between application dates except for the 20 dS m^{-1} application.

Table 2. Effects of EC level of liquid manure and application time on soybean plant populations, leaf area, dry matter production, and grain yield for the 2003 growing season.

	EC Level (dS m^{-1})				Analysis of Variance[1] (P > F)		
	0.6	6.4	11.7	20.3	Time	EC Level	T × R[2]
Harvest population (pl/ac)							
V3[3]	93800	102700	92000	24300	0.001*	0.003*	0.26
R1 (V7)[3]	100900	106200	102700	104400			
P > F	0.67	0.82	0.55	<0.0001*			
LAI							
V3	4.6	4.5	2.2	0.3	0.85	0.0001*	0.03*
R1 (V7)	3.5	4.1	2.5	1.5			
P > F	0.06	0.46	0.48	0.03*			
Whole-plant dry matter at maturity (lb/ac)							
V3	7447	7893	7395	1071	0.52	< 0.0001*	0.07
R1 (V7)	6760	7400	7044	3909			
P > F	0.50	0.63	0.73	0.01*			
Grain yield (bu/ac)							
V3	43	39	40	5	0.12	< 0.0001*	0.02*
R1 (V7)	42	41	38	23			
P > F	0.57	0.40	0.32	<0.0001*			

[1] Statistical significance of ANOVA main effects are given by the probability of the F-test ($\alpha = 0.05$); significant differences are indicated by *.

[2] T × R is the timing × rate interaction.

[3] V3 and V7 are leaf stage at the time of application. R1 is the stage of growth, but V7 indicates that seven trifoliates were on the plant at the time of application.

When averaged over both application timings, grain yields were the same for the 0.6, 6.4, and 11.7 dS m^{-1} manure applications, averaging 41 bu/ac, as compared to 14 bu/ac for the 20.3 dS m^{-1} application. Soybean with the 20.3 dS m^{-1} application at R1 had much higher grain yield (23 bu/ac) than with the 20.3 dS m^{-1} application at V3 (5 bu/ac). Thus, swine manure applied at EC levels less than 11.7 dS m^{-1} have little impact on final yield despite causing plant damage at lower concentrations early in the growing season.

Corn

Corn growth was less affected than soybean, and damage was detected only with the V8 application at the 20.3 dS m^{-1} concentration (Table 3). The V14 application caused even less damage, likely due to salt tolerance of the fully developed cuticle on the corn leaves. The V8 application of 20.3 dS m^{-1} concentration caused some stunting of plants but no plant death. Overall, the manure increased the corn yields when applied at V14 (178 bu/ac) compared to V8 (165 bu/ac).

Table 3. Effects of EC level of liquid manure and application time on corn plant populations, leaf area, dry matter production and grain yield for the 2003 growing season.

	EC Level (dS m^{-1})				Analysis of Variance[1] (P > F)		
	0.6	6.4	11.7	20.3	Time	EC Level	T × R[2]
Mature plant population (pl acre)							
V8[3]	23522	24103	22216	24684	0.12	0.11	0.04*
V14[3]	22506	25410	25555	24394			
P > F	0.33	0.22	0.005*	0.78			
Leaf area (cm^2 plant^{-1})							
V8	5161	5211	5149	4428	0.09	0.41	0.17
V14	4899	5667	5326	5543			
P > F	0.53	0.29	0.67	0.02*			
Whole plant dry matter at maturity (lbs/ac)							
V8	6987	7800	6883	5784	0.15	0.04*	0.35
V14	6894	7654	7944	6874			
P > F	0.89	0.82	0.11	0.11			
Grain yield (Mg ha^{-1})							
V8	175	181	154	149	0.02*	0.08	0.02*
V14	164	186	179	185			
P > F	0.28	0.65	0.02*	0.003*			

[1] Statistical significance of ANOVA main effects are given by the probability of the F-test ($\alpha = 0.05$); Significant differences are indicated by *.

[2] T × R is the Timing × Rate statistical interaction.

[3] V8 and V14 are leaf stages at the time of application.

Weather conditions following liquid manure application may be important to crop tolerance. Crop damage is expected to be more severe under dry, hot, and windy conditions (Nielson and Cannon, 1975; Maas et al., 1982) with more foliar absorption of salts at higher temperatures (Busch and Turner, 1967). Although this study was conducted during one growing season, the weather conditions were within the range of most likely conditions for the time of application.

The liquid manure applications in this study were greater than typically applied by farmers in order to induce measurable damage. Application through a center pivot may keep the foliage wet and the salts soluble longer than the approximate 10 min in our study, especially near the center of the pivot circle. Our application rate was 0.5 ac-inches, but some pivots can apply as little as 0.2 ac-in), reducing the total amount of soluble salts applied and the potential for leaf damage.

SUMMARY

Producers can use inexpensive EC meters to estimate the potential for damage with liquid manure application. Application of liquid manure to corn and soybean through a sprinkler system is feasible with proper management. The results support the hypothesis that growth stage and liquid manure soluble salt concentration (EC levels) influence plant damage. Based on the conditions of this study, liquid manure with EC levels greater than 6.4 dS m^{-1} should not be applied to soybean during early vegetative growth. Liquid manure with EC levels less than 11.7 dS m^{-1} can be applied to corn and to soybean after flowering. If the soybean plants are not defoliated as a result of liquid manure application, yield is not likely to be reduced. Crop tolerance to soluble salt application is greater during the reproductive growth stages of the season than during the early vegetative stages. Applications of liquid manures that keep the foliage wet for longer periods than used in this study should be done on an experimental basis to make sure phytotoxicity is not increased by increased wetting periods.

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LAND APPLICATION OF ANIMAL WASTE ON IRRIGATED FIELDS

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ABSTRACT

Animal wastes are routinely applied to cropland to recycle nutrients, build soil quality, and increase crop productivity. This study evaluates established best management practices for land application of animal wastes on irrigated corn. Swine (effluent water from a lagoon) and cattle (solid manure from a beef feedlot) wastes have been applied annually since 1999 at rates to meet estimated corn P or N requirements along with a rate double the N (2xN) requirement. Other treatments were N fertilizer (60, 120, and 180 lb N/a) and an untreated control. Corn yields were increased by application of animal wastes and N fertilizer. Over-application of cattle manure has not had a negative effect on corn yield. For swine effluent, over-application has not reduced corn yields except for 2004, when the effluent had much greater salt concentration than in previous years, which caused reduced germination and poor early growth. All animal waste and N fertilizer treatments increased soil solution NO_3-N concentration (5-ft depth) compared with the untreated control. Application of animal wastes on a N requirement basis resulted in similar NO_3-N concentrations as fertilizer N applied at 180 lb/a (approximate recommended rate). The 2xN application caused NO_3-N concentrations to about double for both swine and cattle wastes. Application of swine effluent based on P requirement produced similar NO_3-N concentrations as the 2xN rate because of the relatively low P content in the effluent.

INTRODUCTION

This study was initiated in 1999 to determine the effect of land application of animal wastes on crop production and soil properties. The two most common animal wastes in western Kansas were evaluated; solid cattle manure from a commercial beef feedlot and effluent water from a lagoon on a commercial swine facility.

MATERIALS AND METHODS

The rate of waste application was based on the amount needed to meet the estimated crop P requirement, crop N requirement, or twice the N requirement (Table 1). The Kansas Dept. of Agriculture Nutrient Utilization Plan Form was used to calculate animal waste application rates. Expected corn yield was 200 bu/a. The allowable P application rates for the P-based treatments were 105 lb P_2O_5/a since soil test P levels were less than 150 ppm Mehlich-3 P. The N recommendation model uses yield goal less credits for residual soil N and previous manure applications to estimate N requirements. For the N-based swine treatment, the residual soil N levels after harvest in 2001, 2002, and 2004 were great enough to eliminate the need for additional N the following year. So no swine effluent was applied to the 1xN treatment in 2002, 2003, or 2005 or to the 2xN requirement treatment since it is based on 1x treatment (Table 1). The same situation occurred for the N based treatments using cattle manure in 2003. Nutrient values used to calculate initial applications of animal wastes were 17.5 lb available N and 25.6 lb available P_2O_5 per ton of cattle manure and 6.1 lb available N and 1.4 lb available P_2O_5 per 1000 gallon of swine effluent (actual analysis of animal wastes as applied varied somewhat from the estimated values, Table 2). Subsequent applications were based on previous analyses. Other nutrient treatments were three rates of N fertilizer (60, 120, and 180 lb N/a) along with an untreated control. The N fertilizer treatments also received a uniform application of 50 lb/a of P_2O_5. The experimental design was a randomized complete block with four replications. Plot size was 12 rows wide by 45 ft long.

The study was established in border basins to facilitate effluent application and flood irrigation. The swine effluent was flood-applied as part of a pre-plant irrigation each year. Plots not receiving swine effluent were also irrigated at the same time to balance water additions. The cattle manure was hand-broadcast and incorporated. The N fertilizer (granular NH_4NO_3) was applied with a 10 ft fertilizer applicator (Rogers Mfg.). The entire study area was uniformly irrigated during the growing season with flood irrigation in 1999-2000 and sprinkler irrigation in 2001-2005. The soil is a Ulysses silt loam. Corn was planted at about 33,000 seeds/a in late April or early May each year. Grain yields are not reported for 1999 because of severe hail damage. Hail also damaged the 2002 and 2005 crop. The center four rows of each plot were machine harvested after physiological maturity with yields adjusted to 15.5% moisture. Nitrate concentration in the soil solution at the 5 ft depth was determined periodically through the growing season in 2003 and 2004. The 5-ft depth is below the effective rooting depth of corn, so any nitrate movement past this depth is assumed non-recoverable by the corn plant. Suction-cup lysimeters (placed at 5-ft depth) are used to collect the soil water samples. The first samples are collected shortly after corn planting and then every 1-2 week intervals during the growing season as long as sufficient water is present at the 5-ft depth to allow collection. The samples are kept refrigerated after collection until delivered to the KSU Soil Testing laboratory for nitrate-N analysis.

RESULTS

Corn yields were increased by all animal waste and N fertilizer applications in 2005, as has been the case for all years except in 2002 where yields were greatly reduced by hail damage (Table 3). The type of animal waste affected yields in 4 of the 6 years with higher yields from cattle manure than from swine effluent. Averaged across the 6 yr, corn yields were 13 bu/a greater following application of cattle manure than swine effluent on an N application basis. Over application (2xN) of cattle manure has had no negative impact on grain yield in any year. However, over-application of swine effluent reduced yields in 2004 because of considerably greater salt content (2-3 times greater electrical conductivity than any previous year) causing germination damage and poor stands. No adverse residual effect from the over-application was observed in 2005.

The concentrations of NO_3-N in the soil solution at the 5-ft depth for eight sampling periods in 2003 are shown in Table 4. The NO_3-N concentrations were stable between time periods but quite variable among replications. All animal waste and N fertilizer treatments increased solution NO_3-N concentration compared with the untreated control. Application of animal wastes on a N requirement basis resulted in similar NO_3-N concentrations as fertilizer N applied at 180 lb/a (approximate recommended rate). Although for both cattle and swine wastes, no fresh applications were made in 2003 for the N based treatments because of sufficient residual soil N (for swine effluent, there was also no fresh application made in 2002). The 2x N application caused NO_3-N concentrations to more than double for both swine and cattle wastes. Application of swine effluent based on P requirement produced similar NO_3-N concentrations as the 2x N rate because of the relatively low P content in the effluent.

Compared with the 2001 values (data not shown), some treatments showed considerably higher NO_3-N concentrations in 2003. The three treatments (cattle manure applied at 2x N basis and swine effluent applied at 2x N basis or P basis) that had soil solution concentrations >100 mg kg^{-1} of NO_3-N in 2001 showed increases in NO_3-N concentrations in 2003 indicating continual accumulation of NO_3-N at the 5-ft depth. It would be expected that over-application of cattle manure (2x N basis) could result in increased soil solution NO_3-N concentrations. Similarly, since the swine effluent used in this study was relatively low in P, the application rates necessary to meet P requirements over-supplies N as shown by the elevated soil solution NO_3-N concentrations. However, for the 2xN swine effluent treatment there was no effluent applied in 2002 or 2003. With no additional effluent applied since the 2001 water samples were collected, the higher concentration of NO_3-N at the 5-ft depth in 2003 indicates movement of NO_3-N from the upper profile rather than from fresh applications.

Table 5 shows the NO_3-N concentrations in the soil solution at the 5-ft depth for eight sampling periods in 2004. Soil solution NO_3-N concentrations were similar for the untreated control and the low rate of N fertilizer, but increased by all other treatments. In general, soil solution NO_3-N concentrations were greater in 2004 than 2003. It would be expected that the soil solution NO_3-N concentrations for the N based swine effluent treatments would be greater because of the higher N content of the effluent in 2004 (with application rates based on average N content causing greater N loading than targeted). However, soil solution NO_3-N concentrations were also greater following applications of cattle waste based on N requirement and the higher rates of N fertilizer.

ACKNOWLEDGEMENT:

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Table 1. Application rates of animal wastes, Tribune, KS, 1999 to 2005.

Application basis *	Cattle manure						
	ton/a						
	1999	2000	2001	2002	2003	2004	2005
P req.	15.0	4.1	6.6	5.8	8.8	4.9	3.3
N req.	15.0	6.6	11.3	11.7	0	9.8	6.8
2XN req.	30.0	13.2	22.6	22.7	0	19.7	13.5
	Swine effluent						
	1000 gal/a						
	1999	2000	2001	2002	2003	2004	2005
P req.	28.0	75.0	61.9	63.4	66.9	74.1	73.3
N req.	28.0	9.4	37.8	0	0	40.8	0
2XN req.	56.0	18.8	75.5	0	0	81.7	0

* The animal waste applications are based on the estimated requirement of N and P for a 200 bu/a corn crop.

Table 2. Analysis of animal waste as applied, Tribune, KS, 1999 to 2005.

Nutrient content	Cattle manure						
	lb/ton						
	1999	2000	2001	2002	2003	2004	2005
Total N	27.2	36.0	33.9	25.0	28.2	29.7	31.6
Total P_2O_5	29.9	19.6	28.6	19.9	14.6	18.1	26.7
	Swine effluent						
	lb/1000 gal						
	1999	2000	2001	2002	2003	2004	2005
Total N	8.65	7.33	7.83	11.62	7.58	21.42	13.19
Total P_2O_5	1.55	2.09	2.51	1.60	0.99	2.10	1.88

Table 3. Effect of animal waste and N fertilizer on irrigated corn, Tribune, KS, 2000-2005.

Nutrient source	Rate basis[†]	Grain yield 2000	2001	2002	2003	2004	2005	Mean
		- - - - - - - - - -	- - - -	- - - -	bu/acre	- - - -	- - - -	- - - - - - - - - -
Cattle manure	P	197	192	91	174	241	143	173
	N	195	182	90	175	243	147	172
	2 X N	195	185	92	181	244	155	175
Swine e effluent	P	189	162	74	168	173	135	150
	N	194	178	72	167	206	136	159
	2 X N	181	174	71	171	129	147	145
N fertilizer	60 N	178	149	82	161	170	96	139
	120 N	186	173	76	170	236	139	163
	180 N	184	172	78	175	235	153	166
Control	0	158	113	87	97	94	46	99
$LSD_{0.05}$		22	20	17	22	36	16	12
ANOVA								
Treatment		0.034	0.001	0.072	0.001	0.001	0.001	0.001
Selected contrasts								
Control vs. treatment		0.001	0.001	0.310	0.001	0.001	0.001	0.001
Manure vs. fertilizer		0.089	0.006	0.498	0.470	0.377	0.001	0.049
Cattle vs. swine		0.220	0.009	0.001	0.218	0.001	0.045	0.001
Cattle 1x vs. 2x		0.900	0.831	0.831	0.608	0.973	0.298	0.597
Swine 1x vs. 2x		0.237	0.633	0.875	0.730	0.001	0.159	0.031
N rate linear		0.591	0.024	0.639	0.203	0.001	0.001	0.001
N rate quadratic		0.602	0.161	0.614	0.806	0.032	0.038	0.051

[†] Rate of animal waste applications based on amount needed to meet estimated crop P requirement, N requirement, or twice the N requirement.

No yields reported for 1999 because of severe hail damage. Hail reduced corn yields in 2002 and 2005.

Table 4. Nitrate concentration in soil solution at the 5-ft soil depth in 2003 following application of animal wastes and N fertilizer.

Nutrient source	Application Basis*	Time of Sampling								
		May 21	May 29	June 10	June 18	June 23	July 2	July 9	July 16	Mean
		Soil solution NO_3-N, ppm								
Cattle manure	P	45	31	46	38	41	43	45	44	42
	N	75	69	68	62	64	52	61	49	63
	2 X N	322	375	375	348	375	310	371	378	357
Swine effluent	P	264	280	281	280	283	278	296	299	283
	N	106	112	122	103	99	89	94	100	103
	2 X N	272	306	264	288	299	281	290	291	286
N fertilizer	60 N	23	20	22	19	21	18	22	22	21
	120 N	48	41	40	23	31	35	36	24	35
	180 N	102	98	105	84	86	64	71	73	85
Control	0	8	5	7	3	3	4	4	4	5
ANOVA (P>F)										
Treatment		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
Selected contrasts										
Control vs. treatment		0.028	0.034	0.019	0.020	0.012	0.014	0.006	0.005	
Animal waste vs. fert.		0.003	0.003	0.001	0.001	0.001	0.001	0.001	0.001	
Cattle vs. swine		0.139	0.145	0.188	0.090	0.109	0.038	0.070	0.047	
Cattle 1x vs. 2x		0.003	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
Swine 1x vs. 2x		0.038	0.032	0.070	0.018	0.008	0.006	0.004	0.004	
N rate linear		0.306	0.371	0.278	0.380	0.367	0.488	0.432	0.406	
N rate quadratic		0.833	0.805	0.719	0.653	0.709	0.907	0.849	0.647	

* The animal waste applications are based on the estimated requirement of N and P for a 200 bu/a corn crop.

Table 5. Nitrate concentration in soil solution at the 5-ft soil depth in 2004 following application of animal wastes and N fertilizer.

Nutrient source	Application Basis*	May 26	June 4	June 8	June 15	June 23	June 27	July 7	July 14	Mean
		Soil solution NO_3-N, ppm								
Cattle manure	P	108	109	111	102	111	99	105	111	107
	N	321	335	344	358	306	282	293	294	317
	2 X N	322	418	421	300	454	402	424	405	393
Swine effluent	P	355	366	357	505	476	446	546	531	448
	N	145	127	128	219	146	141	169	170	156
	2 X N	203	303	327	325	247	395	540	307	331
N fertilizer	60 N	14	4	5	7	4	4	4	3	6
	120 N	116	119	109	129	111	120	139	135	122
	180 N	170	183	180	177	201	211	218	234	197
Control	0	8	5	4	4	2	2	1	1	3
ANOVA (P>F)										
Treatment		0.005	0.002	0.003	0.008	0.001	0.001	0.002	0.001	
Selected contrasts										
Control vs. treatment		0.006	0.005	0.007	0.009	0.007	0.003	0.024	0.001	
Animal waste vs. fert.		0.005	0.002	0.002	0.004	0.003	0.001	0.001	0.001	
Cattle vs. swine		0.795	0.753	0.772	0.241	0.993	0.285	0.063	0.258	
Cattle 1x vs. 2x		0.995	0.409	0.465	0.642	0.185	0.248	0.294	0.249	
Swine 1x vs. 2x		0.663	0.248	0.213	0.547	0.535	0.039	0.015	0.217	
N rate linear		0.064	0.060	0.078	0.122	0.059	0.036	0.069	0.013	
N rate quadratic		0.728	0.748	0.834	0.686	0.921	0.883	0.779	0.822	

* The animal waste applications are based on the estimated requirement of N and P for a 200 bu/a corn crop.

A REVIEW OF MECHANIZED IRRIGATION PERFORMANCE FOR AGRICULTURAL WASTEWATER REUSE PROJECTS

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Summary:

This paper will focus on a discussion of considerations and then some wastewater reuse projects which have failed, required significant changes to be successful or have succeeded. An analysis will be presented of what leads to success and to failure of mechanized irrigation wastewater reuse projects both in the short and long run. From the analysis a list of parameters will be discussed which are considered critical to a project's performance. Only agricultural projects will be included in the discussion but many of the same drivers apply to industrial and municipal wastewater reuse projects.

Introduction:

Formerly on 'traditional' Midwest farms from the homestead days through the 1960's there typically were a variety of livestock maintained – some for support of the farm family and some for market. In most cases what livestock waste accumulated was handled primarily 'dry' or as a very thick slurry. At different times of year the waste was applied to the fields with little to no regard for impact to ground or surface water or matching nutrient loading from the waste to nutrient use by the crop. Numbers of animals per farm were relatively small and land fairly abundant. With the introduction of the Clean Water Act in the early 1970's and other legislative action, combined with dramatic changes in the number of head of livestock per farm have lead us to a very different situation. Today more and more the waste water producer does not own the land or sufficient land and must depend on working with neighboring farms to environmentally properly 'dispose' of their wastewater stream

Land application of wastewater with mechanical move irrigation equipment – both center pivot and linear has been successfully used for many years. Since the early 1980's the equipment and techniques for irrigating with fresh water have changed dramatically and many of these changes have been incorporated into mechanized equipment used for land application (Gilley, 1983). While these changes have brought significant improvements, also in today's world we must take into account other issues and particularly public perception of land application systems. Mechanical move irrigation equipment has been used for land application of waste water for reuse from municipal, industrial and agricultural sources. Mechanized irrigation, due to its characteristics, is considered to have advantages with regards to applying waste water for reuse, particularly from a lagoon with large amounts of water to handle. Some of these characteristics include limited labor input required, application uniformity, ease in handling large volumes of effluent and particularly the ability to apply to actively growing crops with minimal negative impact to the crop. For our discussion we will focus on center pivots. Pivots can also apply during periods of adverse climatic conditions which may prevent or prove challenging to conventional waste handling techniques requiring tractors and other equipment to move through the field.. Some concerns have been expressed include “Land application of wastes may be imposing in some locations, potentially dangerous conditions relative to environmental quality”. (Hegde 1997). Many projects choices are dictated by more than just the equipment to be used. Also critically important is the project meets public scrutiny. Some land application projects are very successful for many years and others are abandoned or shut down after a relatively short time (Valmont Industries, 1988).

Discussion:

In many cases the livestock operation producing the meat or milk has very little interest in crop production. So they are looking for somewhere to go with their waste. So what could be better than having a source of water and plant nutrients right next to your corn fields? Many livestock operations today produce large volumes of nitrogen and water. For example a 2,000 head dairy using flushing may produce in excess of 1000 acre inches of ‘water’ and 250,000 pounds of nitrogen. Just considering the nitrogen, this has a potential value of $ 45,000 if it can be used to replace the purchase of commercial nitrogen fertilizers. And on the flip side what could be better than having somewhere to go with all of the waste you are producing – potentially saving you significant capital investment and operating cost each year. .

So as a farmer near a facility what could possibly go wrong with agreeing to take waste water from a dairy, hog or beef operation or as a waste producer in sending it to an irrigator?

The answer is just about anything or everything!

Let us consider some specific potential issues.

Permitting –

This in itself may be a challenge. Both partners must agree on nutrient management plan and crops need to match nutrient loading for the land area. The farmer may be pushed to change his cropping plan by adding winter forage which may work well as long as the livestock operation is willing to buy but if not creates marketing challenges for the farmer.

Design –

To get everyone to agree on the same design is commonly a major issue -

Waste producer wants:

- Fast delivery of large volumes
- May need to eliminate large volumes early in the season and/ or late
- May have chunks and trash

Irrigator wants:

- Even volume over season
- Really only wants effluent when crop needs it
- Wants sprinkler package with good uniformity

Construction –

Construction cycle may interfere with crop production while installing pipelines and mechanical move irrigation equipment.

Operation –

Waste producer wants:

- Delivery effluent when they want
- May deliver more ‘objects’ than anticipated

Irrigator wants:

- Take effluent when they want
- No need to clean nozzles

The only thing they both agree on is they do not want any problems with neighbors and minimal labor required.

Let’s now focus on some specific projects and their performance. A review of the original choices considered, concerns, project developed, challenges and benefits will be considered.

1) Project for farrowing operation which was hydraulically challenged.
    a. Choices considered were direct injection or center pivots
        i. Area needed for land application - 125 acres
    b. Concerns with using center pivot
        i. Maintenance
    c. Project developed with center pivots in 2001
        i. Project expanded in 2003 with center pivots
        ii. Project expanded in 2004 with center pivots
        iii. Hog operation paid to install the pump, pipe and center pivot.
    d. Hog operation pays operating costs for the pumping
    e. Major challenge
        i. Crop management
        ii. Potential for getting pivots stuck

    f. Major benefit
        i. Crop production
        ii. Ability to apply during growing season

Due to previous problems with being able to get into the fields to apply with a direct injection, center pivots were considered the preferred solution. A farmer was identified early on and the design was developed to meet the hog and farm operations. Getting stuck was a problem and early pivots commonly were not operated in complete circles due to wet spots. Have added flotation options to specific drive units which as minimized the problem. Livestock producer continued to identify possible farms for expansion and did a good job of explaining the benefits.

Hog operation – happy   Irrigator – mostly happy

2) Project for integrated hog production which was nutrient limited.
    a. Choices considered were direct injection or center pivots
        i. Area needed for land application - 195 acres
    b. Concerns with using center pivot
        i. Odor
        ii. Maintenance
    c. Project developed with direct injection during 2000
    d. Major challenge
        i. Inability to apply during growing season
        ii. Inability to apply early in the season when the fields were wet

The hog operation was convinced center pivots would have the potential for too many odor issues. They did not want to consider some of the advanced design sprinkler packages available. Their vision was limited to impact sprinklers on top of the pipe. In addition little effort was put into identifying a crop producer who might be interested in participating with a center pivot.

Hog operation – ???   Land owners - ???

3) Project for large dairy.
    a. Choices considered were direct injection or center pivots
        i. Area needed for land application - 325 acres
    b. Concerns with using center pivot
        i. Handling of sand (bedding in the barns)
        ii. Neighbors wanted drops on pivot due to perception of odor
    c. Project developed with center pivots during 2004 using existing pivots near the barns. The dairy installed the pump station and piping to the pivots at their expense.

    d. Operating cost for pumping is paid by the dairy.
    e. Major challenge
        i. Civil engineering design team (no agricultural experience)
        ii. Plugging sprinkler packages
        iii. Delivery of effluent early in the spring

The dairy operation was convinced center pivots would have the potential to make things easy and keep their costs low. They (dairy operators) did not complete the installation to the original design to remove sand and solids so many problems with sprinkler nozzles plugging plus wanted to pump when the farmer was trying to plant. Farmer wanted to maintain good uniformity as was on loamy sand soils but due to narrow spacing of drops and small nozzle sizes has plugging problems. The last time the participants met was not a happy experience! Additional designs are being considered to resolve the issues.

Dairy – not happy   Irrigator – not happy

4) Project for large beef feedlot which was hydraulically challenged.
    a. Choices considered were traveling guns or center pivots
        i. Area needed for land application - 260 acres
    b. Concerns with using center pivot
        i. Capital investment
        ii. Too much water at certain times
    c. Project developed with center pivots during 2002 by piping to existing pivot irrigators at feedlots cost.
    d. Feedlot pays pumping costs.
    e. Major challenge
        i. No even flow of effluent – problems shifting between wastewater and freshwater
        ii. Too much water early in the season and after storm events

This situation uses the lagoons to control runoff from the pens. The irrigator did not understand the effluent would primarily only be available after storm events and over winter. The nutrient management plan made it appear there was equal distribution over the season. Then even if there was water to be pumped as long as the lagoons were not near capacity, the feedlot does not want to spend the money for energy to pump and hope evaporation will take care of their problem. The farmer becomes the last resort and does not have any dependable source of water.

Feedlot – happy   Irrigator – not happy

Conclusions:

Land application using mechanical move irrigation equipment has proven very beneficial to many reuse projects and can be cost effective over the life of the project. One of the keys to successful projects is an integrated approach to the design combining hardware, agronomic principles, management and neighbors together with the wastewater producer.

An analysis of the projects above would indicate the key parameters to be:

- Land application system should fit with the existing management and/or treatment processes.
- Sufficient land must be available for the expected nutrient and hydraulic load with some allowance for the future.
- Early identification of a potential farmer
- Design must be sensitive to the local concerns about odor, impact on visual landscape and other possible concerns.
- Projects must be reviewed periodically to ensure operation is meeting the design basis and the participants' needs.
- Continuing education must be kept up for consulting engineering firm's personnel so they understand the equipment, the concepts and agronomics of a land application water reuse system.

Key design considerations for the center pivots would be:

- Ability to apply very small depths to help manage lagoons
    - High speed pivot operation
- Control and remote monitoring
    - Packages such as Field Sentry, Pivot Alert, Tracker and others
    - Control panels with sensor packages such as wind, rain and others
- Close attention to sprinkler packages
    - Space as wide as possible to use larger nozzles
    - Use of regulators or flow control nozzles
        - Determine impact if no regulators used
        - Review options available from sprinkler manufacturers
- Use of flotation technology
    - Three wheel drives
    - Tracks on drive units

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Personal communication with a number of waste water projects.

EFFECT OF CROP RESIDUE ON SPRINKLER IRRIGATION MANAGEMENT

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INTRODUCTION

Sprinkler irrigation can involve frequent wetting of the soil surface. Once to twice per week wetting is common. The largest amount of soil water evaporation occurs when the soil surface is wet. At this time soil water evaporation rates are controlled by radiant energy. The more frequently the surface is wet, the more time that the evaporation rates are in the “energy” limited phase. Crop residues have the capacity to reduce light reaching the soil surface and reduce the soil water evaporation during the “energy” limited phase of evaporation. As the soil surface dries, the evaporation rate is controlled by soil water movement to the surface. However, with high frequency of water application from sprinkler irrigation the soil may remain in the “energy” limited phase a large percentage of time. This produces the opportunity for crop residues to impact soil evaporation rates.

EVAPORATION-TRANSPIRATION PARTITION

Water applied by irrigation is consumed by two processes: soil water evaporation and plant transpiration. Transpiration, the process of water evaporating near the leaf and stem surfaces, is a necessary function for plant life. Transpiration rates are related atmospheric conditions and by the crop’s growth stage. Daily weather demands cause fluctuations in transpiration as a result. Transpiration provides powerful transformation of this energy into forces for water flow through plants. It also provides evaporative cooling to the plant. Transpiration relates directly to grain yield. As a crop grows, it requires more water on a daily basis until it reaches a plateau at maturity. Soil water begins to limit transpiration when the soil dries below a threshold which is generally half way between field capacity and wilting point. Irrigation management usually calls for scheduling to avoid water stress. Ideally, limited irrigation management reduces plant water stress in critical growth periods such as reproductive and grain fill and allows more stress during less critical growth period such as vegetative growth.

Evaporation from the soil surface has a limited effect on transpiration in the influence of humidity in the crop canopy. However, the mechanisms controlling evaporation from soil are generally independent of transpiration. The combined processes of evaporation from soil (E) and transpiration (T) are measured together as evapotranspiration (ET) for convenience. Independent measurements of E and T are difficult but independent measurements are becoming more important for better water management.

Field research in sprinkler irrigated corn has shown that as much as 30% of total evapotranspiration is consumed as evaporation from the soil surface (Klocke et. al., 1985). These results were from bare surface conditions for sandy soils. For a corn crop with total ET of 30 inches, 9 inches would involve soil evaporation and 21 inches to transpiration. This indicates a window of opportunity if the unproductive soil evaporation component of ET can be reduced without reducing productive transpiration.

EVAPORATION FROM BARE SOIL

Evaporation from bare soil surface after irrigation or rainfall is controlled by the atmospheric conditions and the shading of a crop canopy if applicable. Water near the soil surface readily evaporates and does so at a rate that is limited by the energy available at the surface. If water is readily available near the surface, bare soils can evaporate 0.4 in. during one energy-limited drying cycle (Klocke, 1983). The time it takes to complete an energy limited cycle depends on the energy in the environment. Bare soil with no crop canopy on a sunny hot day with wind receives much more energy than a mulched soil under a crop canopy on a cloudy cool day with no wind.

After the energy limited evaporation has been completed, evaporation is controlled by how fast water and vapor can move to the surface. Rate of evaporation diminishes with time as the drying front moves deeper into the soil. The soil insulates itself from drying because it takes longer for water or vapor to move through the soil to the surface.

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EVAPORATION AND CROP RESIDUES

For more than 65 years, crop residues in dryland cropping systems have been credited for suppressing evaporation from soil surfaces. (Russel, 1939). Stubble mulch tillage and Ecofallow systems built on this early work with a progression of innovations in tillage and planting equipment and weed management systems to allow for crop residues to be left on the ground surface. These crop residue management practices along with crop rotations have increased grain production in the dry Central Plains. Water savings from soil evaporation suppression has been an essential element. In dryland management, accumulation of 2-4 inches of water during the over-winter/fallow period has been possible. The presence of standing wheat stubble has captured the precipitation, kept it where it has fallen, stored it, and reduced the evaporation.

Crop residues in dryland culture have reduced energy limited evaporation after rainfall events as long as the soil surface is wet. Crop residues tend to extend the energy limited evaporation phase with time when compared with bare soils. The evaporation rate is less under the crop residue. Given enough time between rainfall events, in dryland culture, accumulated evaporation under crop residue could catch up with evaporation for bare soil. This could take a time framework of weeks. The contribution of crop residues for soil water suppression is dependent on the frequency of wetting.

GARDEN CITY, KS STUDIES

Field Study

A field study was conducted in Garden City, Kansas during 2003-2005 to test the effectiveness of corn stover and wheat stubble for evaporation suppression in soybean and corn grown in 30-inch rows. Two twelve inch diameter PVC cylinders that held 6-inch deep soil cores were placed between adjacent soybean or corn rows. These “mini-lysimeters”, which were constructed from 21-inch PVC cylinders were pressed into undisturbed soil. The soil was bare or covered with no-till corn stover or standing wheat stubble to test the maximum effectiveness of various residues for evaporation suppression. Crop and mini-lysimeter treatments were replicated four times. Mini-lysimeters were irrigated once or twice weekly when rainfall did not satisfy crop needs. The mini-lysimeters were also watered to match rainfall events during 2004 since rains occurred during measurement periods that year. The mini-lysimeters were weighed daily. Weight differences were the evaporation amounts. Plant populations were reduced to match irrigation management in the once per week frequency treatment.

The results should be considered as preliminary. The statistical comparisons have not been completed. Only some of the large differences should be noted within each year. Year-to-year differences will be suggested, but should be considered speculative.

Soil water evaporation measurements began and ended within somewhat different time frameworks for the study years (table 1). Yearly variations in results due to duration of observations are reflected in the total evaporation, evaporation savings from bare soil, and the evaporation as a fraction of evapotranspiration. The latter factor is due to the growth stage during which the measurements were taken. During 2003 only the more frequent irrigation treatment for soybean was conducted. During observation period in 2003, only 8 irrigation events were measured. During 2004 ample rainfall added to 3 and 7 measured irrigation events for the two soybean treatments and 4 and 9 measured irrigation events for the two corn treatments. For 2005, only irrigation events were measured during the observation period.

Table 1. Soil Water Evaporation Summary—2003-2005.

Surface[1]	Total E (in.)	Daily Rate (in./day)	E Savings[2] (in.)	E/ET[3]	Watering Events[4]
2003 Soybean	July 18 to September 6 (51 days)				
Bare 1	3.1	0.06		25	8
Corn 1	1.8	0.03	1.3	14	8
Wheat 1	1.5	0.03	1.6	12	8
2004 Soybean	June 9 to September 20 (104 days)				
Bare 1	6.5	0.06		33	12
Bare 2	8.0	0.08		32	19
Corn 1	3.8	0.04	2.7	19	12
Corn 2	3.7	0.03	4.2	15	19
Wheat 1	3.4	0.03	3.1	17	12
Wheat 2	4.1	0.04	3.8	17	19
2004 Corn	June 2 to September 20 (111 days)				
Bare 1	5.8	0.05		32	14
Bare 2	6.6	0.06		35	22
Corn 1	3.1	0.03	2.7	17	14
Corn 2	3.8	0.03	2.8	19	22
Wheat 1	2.7	0.02	3.1	15	14
Wheat 2	3.8	0.03	2.9	19	22
2005 Corn	June 21 to August 11, 2005 (52 days)				
Bare 1	3.6	0.07		29	5
Bare 2	3.5	0.07		23	9
Corn 1	1.9	0.04	1.7	16	5
Corn 2	2.0	0.04	1.5	13	9
Wheat 1	2.4	0.05	1.1	20	5
Wheat 2	2.2	0.04	1.3	15	9

[1] Numbers indicate weekly watering frequency (1 = Once, 2 = Twice)
[2] Evaporation savings as the difference from bare soil evaporation
[3] Evaporation as a percent of calculated ET from water balance
[4] Includes rain events in 2004

Comparison of 2004 and 2005 is risky. One year was wet (2004), one year was dry in July (2005). One year had hail (2005) and the other did not (2004). One year has a longer record of observed days of data (2004).

The differences in soil water evaporation from covered and bare soil surfaces are consistent despite the variable years (table 1). The crop residues covered the entire surface and reduced evaporation nearly in half during the observation periods. Differences in evaporation between irrigation treatments with crop residues were not evident. If both irrigation treatments were predominately in energy limited evaporation, evaporation would be similar under the crop residue.

Control Study

A second set of replicated mini-lysimeters was established in a controlled outdoor, non-cropped setting. Irrigated clipped grass surrounded the control area. Measurements were taken between September 6 and October 7, 2005. The mini-lysimeters were buried in the ground but flush with the surface. The mini-lysimeters' position was rotated daily to avoid location bias in results. The 12 experimental treatments included:

> surface cover (bare soil, 25%, 50%, 75%, or 100% corn stover, or wheat stubble) X irrigation frequency (once per week or twice per week).

Partial cover corn stover treatments were established by evaluating the residue application with line-transect methods using mesh grids over the mini-lysimeters. The 100% corn stover and wheat stubble treatment lysimeters were similar to the field plot study treatments. The partial cover treatments were intended to simulate tillage practices equivalent to one pass chisel, one pass tandem disc, and two pass tandem disc for 75%, 50%, and 25% corn stover cover, respectively.

Figure 1 shows the resulting mass of residue cover on the mini-lysimeters for the control study. Percent cover and total cover mass did not always correlate well because the leaf and stem densities were not necessarily consistent among treatments. For example, average residue mass for the 50% corn stover actually exceeded the mass for the 75% corn stover treatment

Figure 2 combines the results of the cumulative soil water evaporation during September 6 to October 7. The patterns of evaporation results from bare soil, and the partially covered soil with corn stover are very similar. Statistical analysis will assist in interpretation of these data. Only the 100% corn stover and wheat stubble treatments appear to behave differently. The mass of these residue covers from Figure 1 was quite different. The reduced cover and mass of the partially covered treatments apparently allowed more radiant energy to reach the soil surface and increased evaporation.

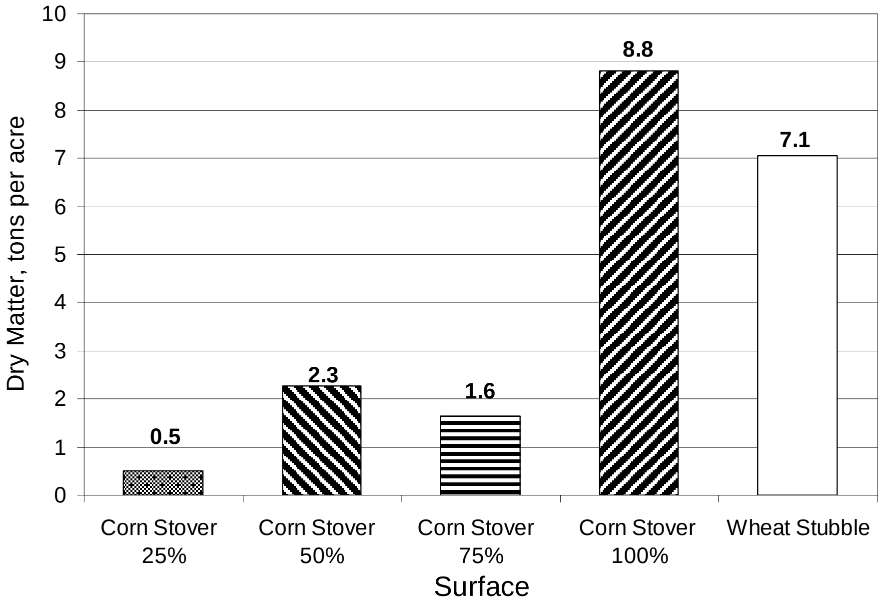

Fig. 1 Crop residue mass on mini-lysimeter surface for partial to full cover treatments.

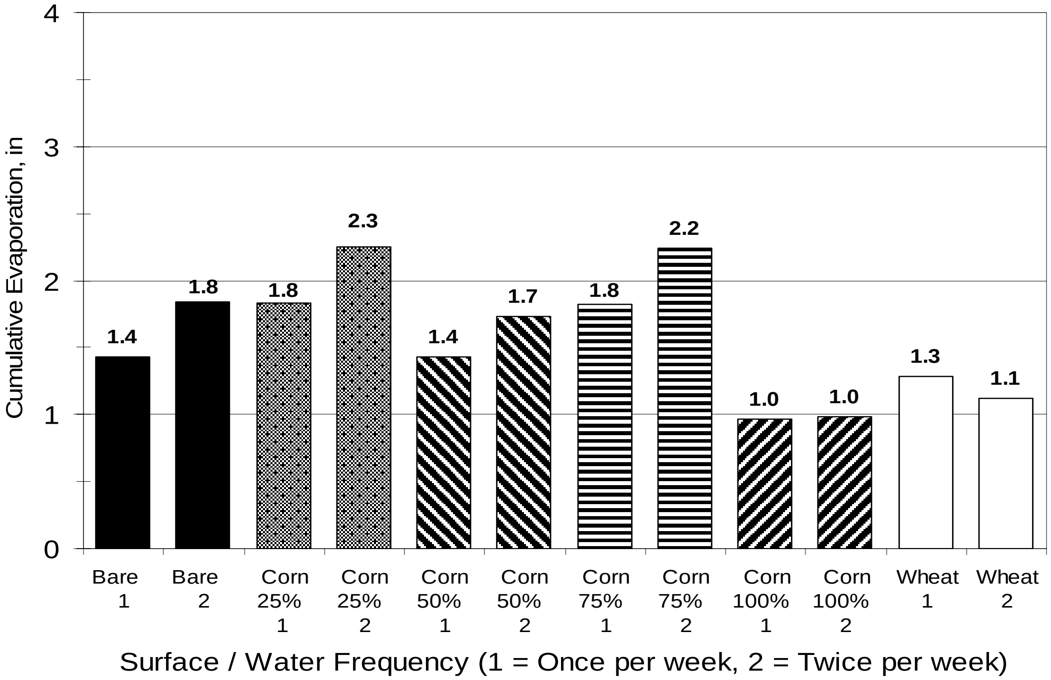

Fig. 2 Total soil water evaporation from September 6 to October 7, 2005 for bare, partially covered, and fully covered treatments.

SUMMARY

No matter how efficient sprinkler irrigation applications become, the soil is left wet and subject to evaporation. Frequent irrigations and shading by the crop leave the soil surface in the state of energy limited evaporation for a large part of the growing season. This research demonstrated that evaporation from the soil surface is a substantial portion of total consumptive use (ET). We measured up to 30% of ET was E during the irrigation season for corn and soybean on silt loam soils. We also demonstrated under a variety of conditions that crop residues can reduce the evaporation from soil in half even beneath an irrigated crop canopy. This puts us closer to our goal to understand how reduce the energy reaching the evaporating surface.

We suggest the potential for a 2.5 to 3 inches water savings due to the wheat straw and no-till corn stover from early June to the end of the growing season. Dryland research suggests that stubble is worth at least 2 inches of water savings in the non growing season. In water short areas or areas where water allocations are below full irrigation, 5 inches of water translates into possibly 20 and 60 bushels per acre of soybean and corn, respectively.

ACKNOWLEDGEMENTS

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EFFECT OF TILLAGE AND IRRIGATION CAPACITY ON CORN PRODUCTION

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ABSTRACT

Corn production was compared in 2004 and 2005 for three plant populations (25,400, 28,600 or 32,000 plants /acre) under conventional, strip and no tillage systems for irrigation capacities limited to 1 inch every 4, 6 or 8 days. Corn yield increased approximately 10% from the lowest to highest irrigation capacity in these two years of relatively normal precipitation and crop evapotranspiration. Strip tillage and no tillage had 5% and 3% higher grain yields than conventional tillage, respectively. Results suggest that strip tillage obtains the residue benefits of no tillage in reducing evaporation losses without the yield penalty sometimes occurring with high residue. The small increases in total seasonal water use (< 1.5 inch) for strip tillage and no-tillage compared to conventional tillage can probably be explained by the higher grain yields for these tillage systems.

INTRODUCTION

Declining water supplies and reduced well capacities are forcing irrigators to look for ways to conserve and get the best utilization from their water. Residue management techniques such as no tillage or conservation tillage have been proven to be very effective tools for dryland water conservation in the Great Plains. However, adoption of these techniques is lagging for continuous irrigated corn. There are many reasons given for this lack of adoption, but some of the major reasons expressed are difficulty handling the increased level of residue from irrigated production, cooler and wetter seedbeds in the early spring which may lead to poor or slower development of the crop, and ultimately a corn grain yield penalty as compared to conventional tillage systems. Under very high production systems, even a reduction of a few percentage points in corn yield can have a significant economic impact. Strip tillage might be a good compromise between conventional tillage and no tillage, possibly achieving most of the benefits in water conservation and soil quality management of no tillage, while providing a method of handling the increased residue and increased early growth similar to conventional tillage. Strip tillage can retain surface residues and thus suppress soil evaporation and also provide subsurface tillage to help alleviate effects of restrictive soil layers on root growth and function. A study was initiated in 2004 to examine the effect of three tillage systems for corn production under three different irrigation capacities. Plant population was an additional factor examined because corn grain yield increases in recent years have been closely related to increased plant populations.

GENERAL STUDY PROCEDURES

The study was conducted under a center pivot sprinkler at the KSU Northwest Research-Extension Center at Colby, Kansas during the years 2004 and 2005. Corn was also grown on the field site in 2003 to establish residue levels for the three tillage treatments. The deep Keith silt loam soil can supply about 17.5 inches of available soil water for an 8-foot soil profile. The climate can be described as semi-arid with a summer precipitation pattern with an annual rainfall of approximately 19 inches. Average precipitation is approximately 12 inches during the 120-day corn growing season.

A corn hybrid of approximately 110 day relative maturity (Dekalb DCK60-19 and DCK60-18 in 2004 and 2005 respectively) was planted in circular rows on May 8, 2004 and April 27, 2005. Three seeding rates (26,000, 30,000 and 34,000 seeds/acre) were superimposed onto each tillage treatment in a complete randomized block design.

Irrigation was scheduled with a weather-based water budget, but was limited to the 3 treatment capacities of 1 inch every 4, 6, or 8 days. This translates into typical seasonal irrigation amounts of 16-20, 12-15, 8-10 inches, respectively. Each of the irrigation capacities (whole plot) were replicated three times in pie-shaped sectors (25 degree) of the center pivot sprinkler (Figure 1). Plot length varied from to 90 to 175 ft, depending on the radius of the subplot from the center pivot point. Irrigation application rates (i.e. inches/hour) at the outside edge of this research center pivot were similar to application rates near the end of full size systems. A small amount of preseason irrigation was conducted to bring the soil water profile (8 ft) to approximately 50% of field capacity in the fall and as necessary in the spring to bring the soil water profile to approximately 75% in the top 3 ft prior to planting. It should be recognized that preseason irrigation is not a recommended practice for fully irrigated corn production, but did allow the three irrigation capacities to start the season with somewhat similar amounts of water in the profile.

The three tillage treatments (Conventional tillage, Strip Tillage and No Tillage) were replicated in a Latin-Square type arrangement in 60 ft widths at three different radii (Centered at 240, 300 and 360 ft.) from the center pivot point (Figure 1). The various operations and their time period for the three tillage treatments are summarized in Table 1. Planting was in the same row location each year for the Conventional Tillage treatment to the extent that good farming practices allowed. The Strip Tillage and No-Tillage treatments were planted between corn rows from the previous year.

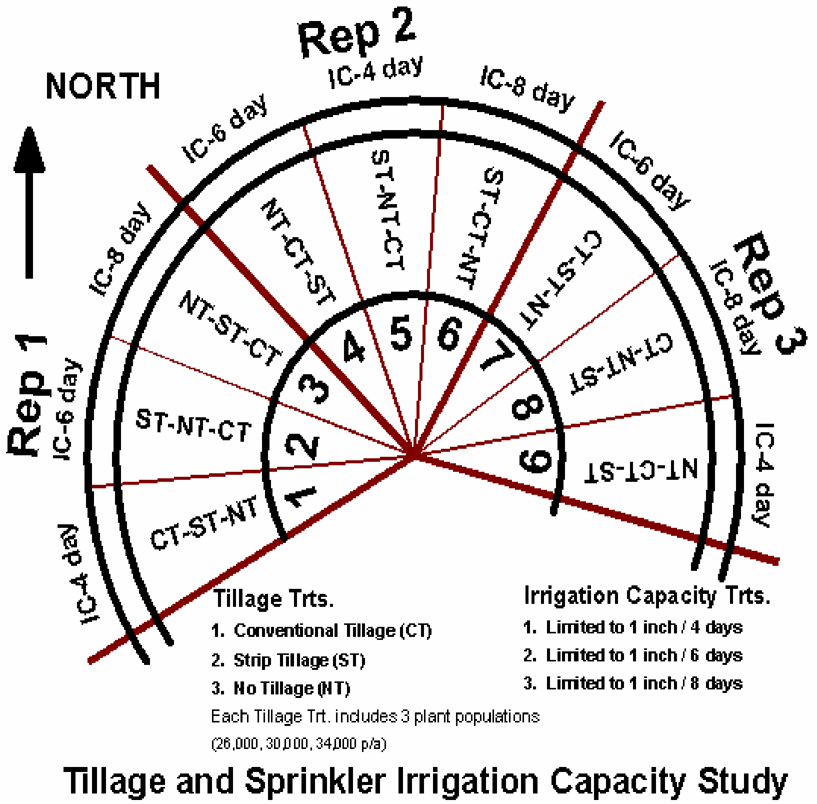

Figure 1. Physical arrangement of the irrigation capacity and tillage treatments.

Fertilizer N for all 3 treatments was applied at a rate of 200 lb/acre in split applications with approximately 85 lb/ac applied in the fall or spring application, approximately 30 lb/acre in the starter application at planting and approximately 85 lb/acre in a fertigation event near corn lay-by. Phosphorus was applied with the starter fertilizer at planting at the rate of 45 lb/acre P2O5. Urea-Ammonium-Nitrate (UAN 32-0-0) and Ammonium Superphosphate (10-34-0) were utilized as the fertilizer sources in the study. Fertilizer was incorporated in the fall concurrently with the Conventional Tillage operation and applied with a mole knife during the Strip Tillage treatment. Conversely, N application was broadcast with the No Tillage treatment prior to planting.

A post-plant, pre-emergent herbicide program of Bicep II Magnum and Roundup Ultra was applied. Roundup was also applied post-emergence prior to lay-by for all treatments, but was particularly beneficial for the strip and no tillage treatments. Insecticides were applied as required during the growing season.

Weekly to bi-weekly soil water measurements were made in 1-ft increments to 8-ft. depth with a neutron probe. All measured data was taken near the center of each plot. These data were utilized to examine treatment differences in soil water conditions both spatially (e.g. vertical differences) and temporally (e.g. differences caused by timing of irrigation in relation to evaporative conditions as affected by residue and crop growth stage).

Table 1. Tillage treatments, herbicide and nutrient application by period.

Period	Conventional tillage	Strip Tillage	No Tillage
Fall 2003	1) One-pass chisel/disk plow at 8-10 inches with broadcast N, November 13, 2003.	1) Strip Till + Fertilizer (N) at 8-10 inch depth, November 13, 2003.	
Spring 2004	2) Plant + Banded starter N & P, May 8, 2004. 3) Pre-emergent herbicide application, May 9, 2004.	2) Plant + Banded starter N & P, May 8, 2004 3) Pre-emergent herbicide application, May 9, 2004.	1) Broadcast N + Plant + Banded starter N & P, May 8, 2004 2) Pre-emergent herbicide application, May 9, 2004.
Summer 2004	4) Roundup herbicide application near lay-by, June 9, 2004 5) Fertigate (N), June 10, 2004	4) Roundup herbicide application near lay-by, June 9, 2004 5) Fertigate (N), June10, 2004	3) Roundup herbicide application near lay-by, June 9, 2004 4) Fertigate (N), June 10, 2004
Fall 2004	1) One-pass chisel/disk plow at 8-10 inches with broadcast N, November 05, 2004.	*Too wet, no tillage operations*	
Spring 2005	2) Plant + Banded starter N & P, April 27, 2005. 3) Pre-emergent herbicide application, May 8, 2005.	1) Strip Till + Fertilizer (N) at 8-10 inch depth, March 15, 2005. 2) Plant + Banded starter N & P, April 27, 2005 3) Pre-emergent herbicide application, May 8, 2005.	1) Broadcast N + Plant + Banded starter N & P, April 27, 2005 2) Pre-emergent herbicide application, May 8, 2005.
Summer 2005	4) Roundup herbicide application near lay-by, June 9, 2004 5) Fertigate (N), June 17, 2005	4) Roundup herbicide application near lay-by, June 9, 2004 5) Fertigate (N), June 17, 2005	3) Roundup herbicide application near lay-by, June 9, 2004 4) Fertigate (N), June 17, 2005

Similarly, corn yield was measured in each of the 81 subplots at the end of the season. In addition, yield components (above ground biomass, plants/acre ears/plant, kernels/ear and kernel weight) were determined to help explain the treatment differences. Water use and water use efficiency were calculated for each subplot using the soil water data, precipitation, applied irrigation and crop yield.

RESULTS AND DISCUSSION

Weather Conditions

Summer seasonal precipitation was approximately 2 inches below normal in 2004 and near normal in 2005 at 9.99 and 11.95 inches, respectively for the 120 day period from May 15 through September 11 (long term average, 11.98 inches). In 2004, the last month of the season was very dry but the remainder of the season had reasonably timely rainfall and about normal crop evapotranspiration (Figure 2). In 2005, precipitation was above normal until about the middle of July and then there was a period with very little precipitation until the middle of August. This dry period in 2005 also coincided with a week of higher temperatures and high crop evapotranspiration near the reproductive period of the corn (July 17-25). Seasonal evapotranspiration for both years was very near the long term average of 23.09 inches.

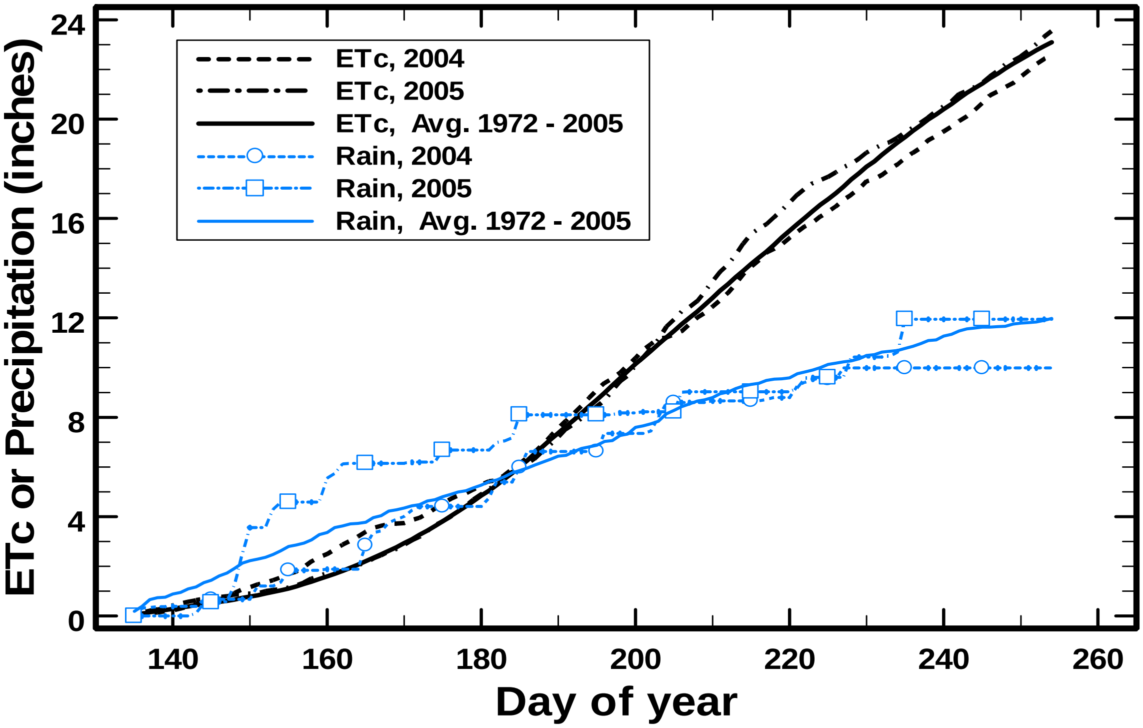

Figure 2. Corn evapotranspiration and summer seasonal rainfall for the 120 day period, May 15 through September 11, KSU Northwest Research-Extension Center, Colby Kansas.

Irrigation requirements were lower in 2004 with the 1 inch/4 day treatment receiving 12 inches, the 1 inch/ 6 day treatment receiving 11 inches and the 1 inch/8 day treatment receiving 9 inches (Figure 3). The irrigation amounts in 2005 were 15, 13, and 10 inches for the three respective treatments (Figure 4).

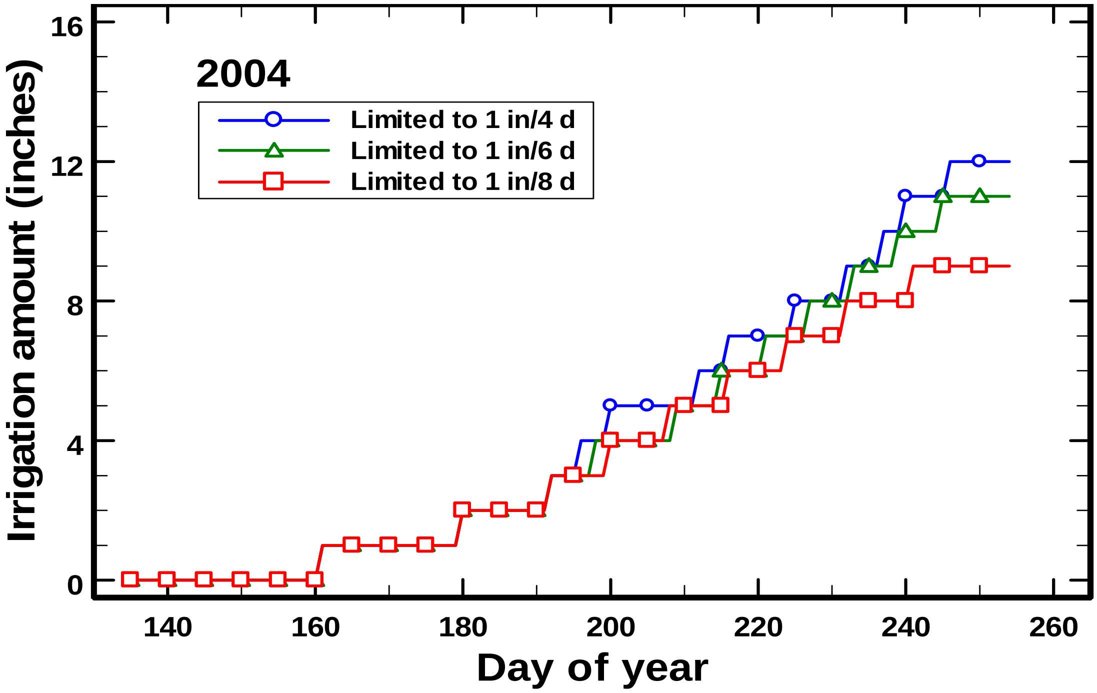

Figure 3. Seasonal irrigation for the 120 day period, May 15 through September 11, 2004 for the three irrigation treatments in an irrigation capacity and tillage study, KSU Northwest Research-Extension Center, Colby Kansas.

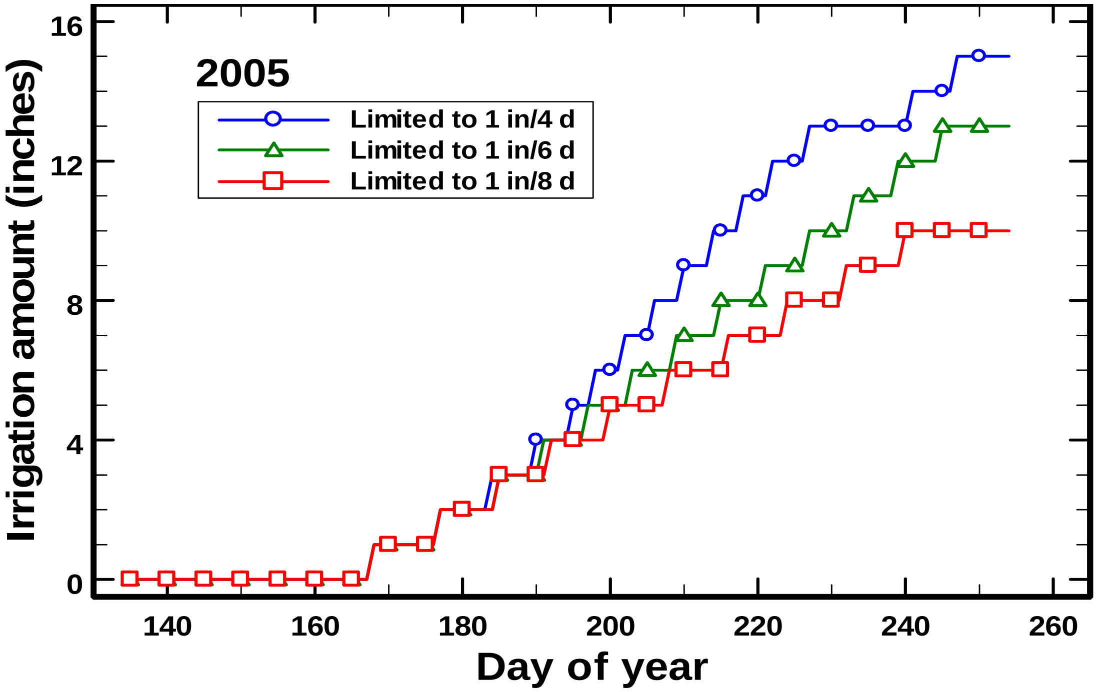

Figure 4. Seasonal irrigation for the 120 day period, May 15 through September 11, 2005 for the three irrigation treatments in an irrigation capacity and tillage study, KSU Northwest Research-Extension Center, Colby Kansas.

Crop Yield and Selected Yield Components

Corn yield was relatively high for both years ranging from 198 to 262 bu/acre Table 2 and Table 3, Figure 5). Higher irrigation capacity generally increased grain yield, particularly in 2005. Strip tillage and no tillage had higher grain yields at the lowest irrigation capacity in 2004 and at all irrigation capacities in 2005. Strip tillage tended to have the highest grain yields for all tillage systems and the effect of tillage treatment was greatest at the lowest irrigation capacity. These results suggest that strip tillage obtains the residue benefits of no tillage in reducing evaporation losses without the yield penalty sometimes associated with the higher residue levels in irrigated no tillage management.

Table 2. Selected corn yield component and total seasonal water use data for 2004 from an irrigation capacity and tillage study, KSU Northwest Research-Extension Center, Colby, Kansas.

Irrigation Capacity	Tillage System	Target Plant Population (1000 p/a)	Grain Yield bu/acre	Plant Population (p/a)	Kernels /Ear	Kernel Weight g/100	Water Use (inches)
1 in/4 days ***(12 inches)***	Conventional	26	229	27878	550	37.1	23.0
		30	235	29330	557	36.2	22.6
		34	234	32234	529	34.6	22.0
	Strip Tillage	26	245	27588	537	38.9	23.5
		30	232	30492	519	37.0	24.4
		34	237	33106	514	35.5	24.3
	No Tillage	26	218	25846	548	37.7	22.0
		30	226	29330	539	36.8	23.6
		34	251	33686	553	33.8	23.2
1 in/6 days ***(11 inches)***	Conventional	26	226	25265	557	39.0	23.0
		30	222	29621	522	34.9	23.6
		34	243	32525	522	36.0	23.9
	Strip Tillage	26	235	27298	558	36.9	23.3
		30	224	28750	556	35.0	24.4
		34	237	33396	487	35.6	24.4
	No Tillage	26	225	26426	537	37.8	24.5
		30	222	29040	556	34.6	25.0
		34	229	32234	545	32.8	23.4
1 in/8 days ***(9 inches)***	Conventional	26	198	24684	509	37.5	22.1
		30	211	29330	531	34.5	22.4
		34	216	31654	494	34.9	22.0
	Strip Tillage	26	227	25846	644	34.2	23.8
		30	229	29911	518	35.6	21.8
		34	234	32815	507	35.1	23.2
	No Tillage	26	220	27007	541	36.6	22.5
		30	225	29621	528	34.5	23.2
		34	220	32815	506	32.2	22.6

Table 3. Selected corn yield component and total seasonal water use data for 2005 from an irrigation capacity and tillage study, KSU Northwest Research-Extension Center, Colby, Kansas.

Irrigation Capacity	Tillage System	Target Plant Population (1000 p/a)	Grain Yield bu/acre	Plant Population (p/a)	Kernels /Ear	Kernel Weight g/100	Water Use (inches)
1 in/4 days	Conventional	26	218	23813	644	37.9	28.3
(15 inches)		30	238	27588	594	37.3	28.6
		34	260	30202	579	37.1	27.3
	Strip Tillage	26	238	24394	620	39.6	28.3
		30	251	27878	590	38.3	26.6
		34	253	31073	567	36.8	29.1
	No Tillage	26	228	24974	628	38.3	28.1
		30	254	26717	660	37.4	27.7
		34	262	31363	606	35.8	28.5
1 in/6 days	Conventional	26	203	24684	546	37.7	26.4
(13 inches)		30	221	27588	544	37.5	25.8
		34	208	31073	472	36.2	25.3
	Strip Tillage	26	226	24394	604	38.9	26.7
		30	207	28169	487	38.4	27.1
		34	248	31944	560	36.0	26.2
	No Tillage	26	205	24684	565	38.2	26.7
		30	224	29040	547	36.6	27.2
		34	234	31654	512	37.1	25.7
1 in/8 days	Conventional	26	187	24394	523	37.5	22.8
(10 inches)		30	218	27298	536	37.5	22.5
		34	208	31654	452	37.3	24.8
	Strip Tillage	26	212	23813	648	34.9	23.8
		30	216	27588	579	35.8	24.1
		34	240	31363	537	36.1	24.5
	No Tillage	26	208	24103	608	37.4	24.6
		30	211	27588	537	36.2	22.9
		34	216	31073	502	36.4	24.7

Higher plant population had a significant effect in increasing corn grain yields (Tables 2 and 3, Figure 6) on the average about 14 to 20 bu/a for the lowest and highest irrigation capacities, respectively. Higher plant population gives greater profitability in good production years. Assuming a seed cost of $1.49/1,000 seeds and corn harvest price of $2.57/bushel, this 14 to 20 bu/acre yield advantage would increase net returns approximately $25 to $40/acre for the increase in plant population of 6,600 seeds/acre. Increasing the plant population by 6600 plants/a on the average reduced kernels/ear by 50 and reduced kernel weight by 2.1 g/100 kernels (Tables 2 and 3). However, this was compensated by the increase in population increasing the overall number of kernels/acre by 13% (data not shown).

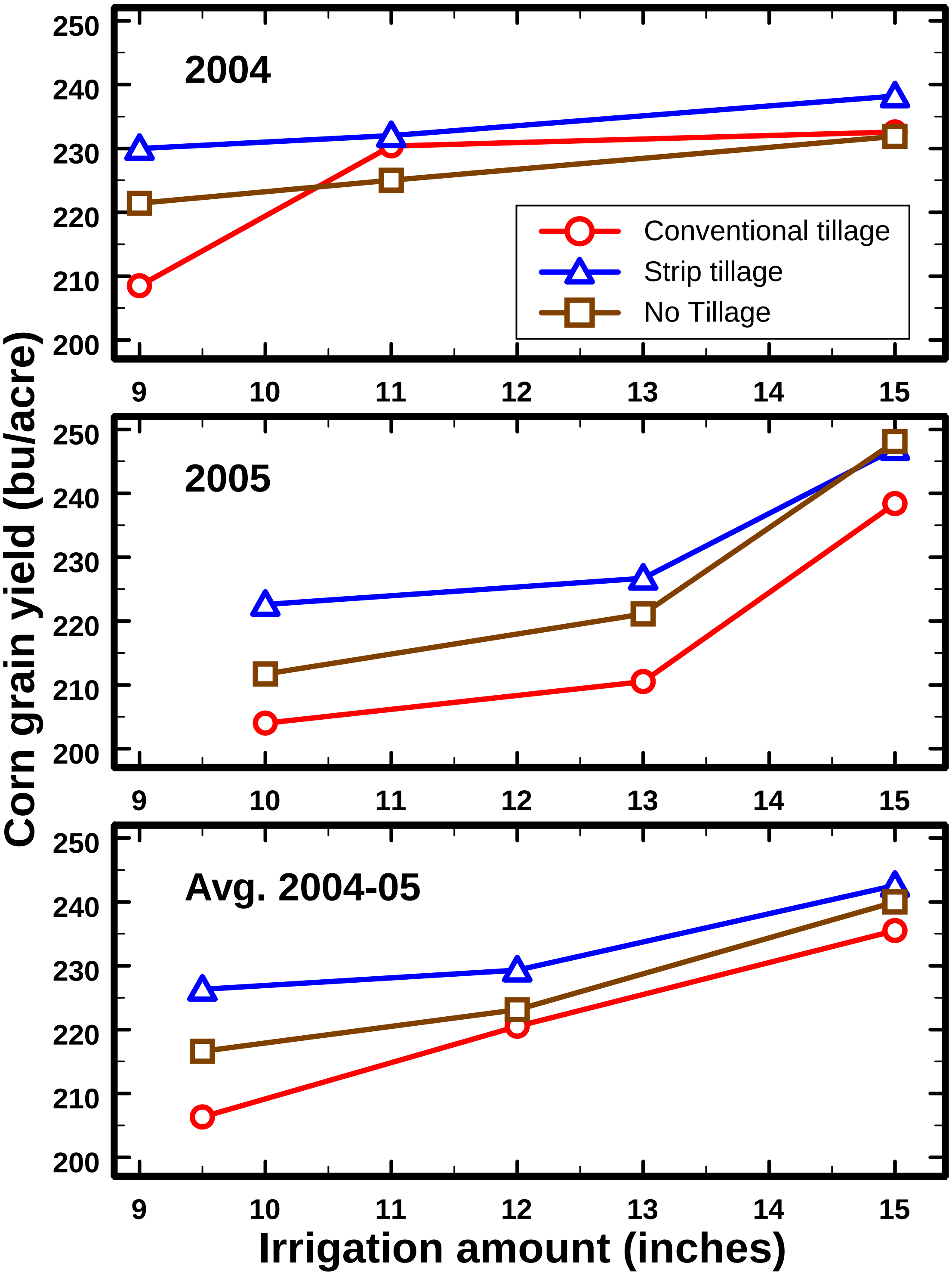

Figure 5. Corn grain yield as affected by irrigation capacity and tillage, 2004-2005, KSU Northwest Research-Extension Center, Colby Kansas.

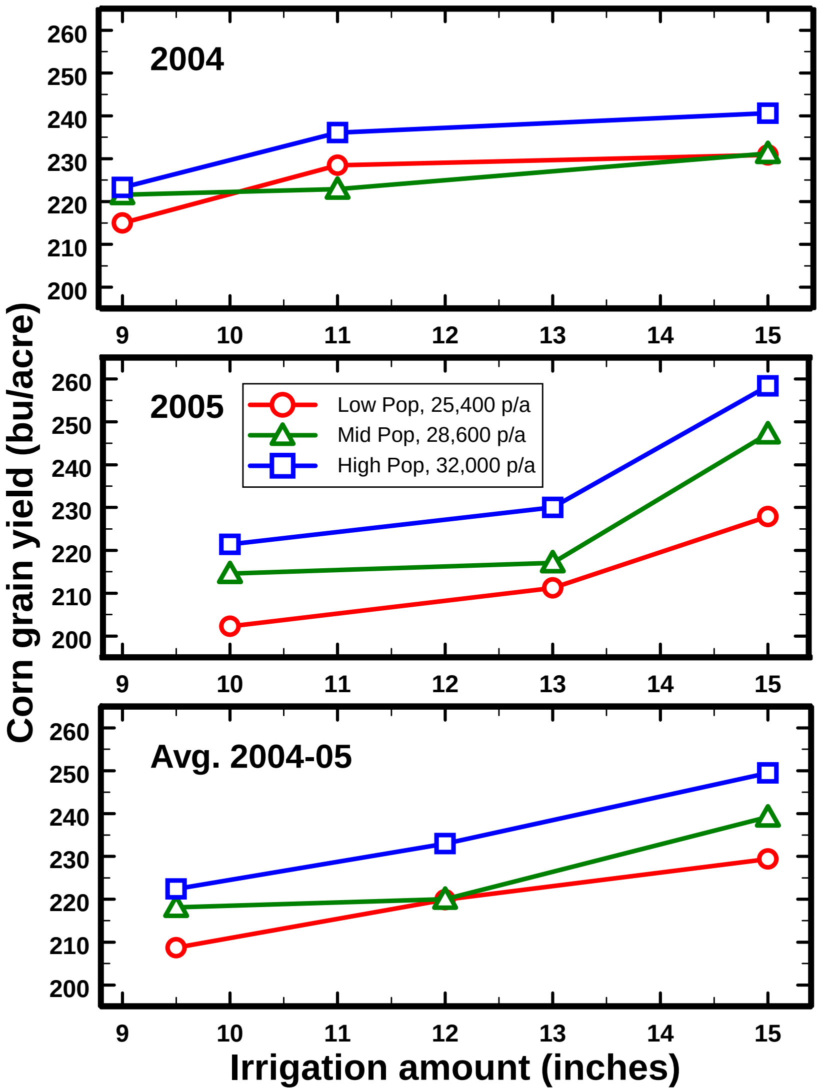

Figure 6. Corn grain yield as affected by irrigation capacity and plant population, 2004-2005, KSU Northwest Research-Extension Center, Colby Kansas.

The number of kernels/ear was lower in 2004 and relatively consistent between tillage systems and irrigation capacities compared to 2005 (Table 2 and 3, Figure 7). The potential number of kernels/ear is set at about the ninth leaf stage (approximately 2.5 to 3.5 ft tall) and the actual number of kernels/ear is finalized by approximately 2 weeks after pollination. Greater early season precipitation in 2005 (Figure 2) than 2004 may have established a higher potential for kernels/acre and then later in the 2005 season greater irrigation capacity or better residue management may have allowed for more kernels to escape abortion. The time the actual kernels/acre was being set in 2005 was a period of high evapotranspiration (Figure 2) and also coincided with multiple irrigation events for the 1inch /4 days irrigation capacity.

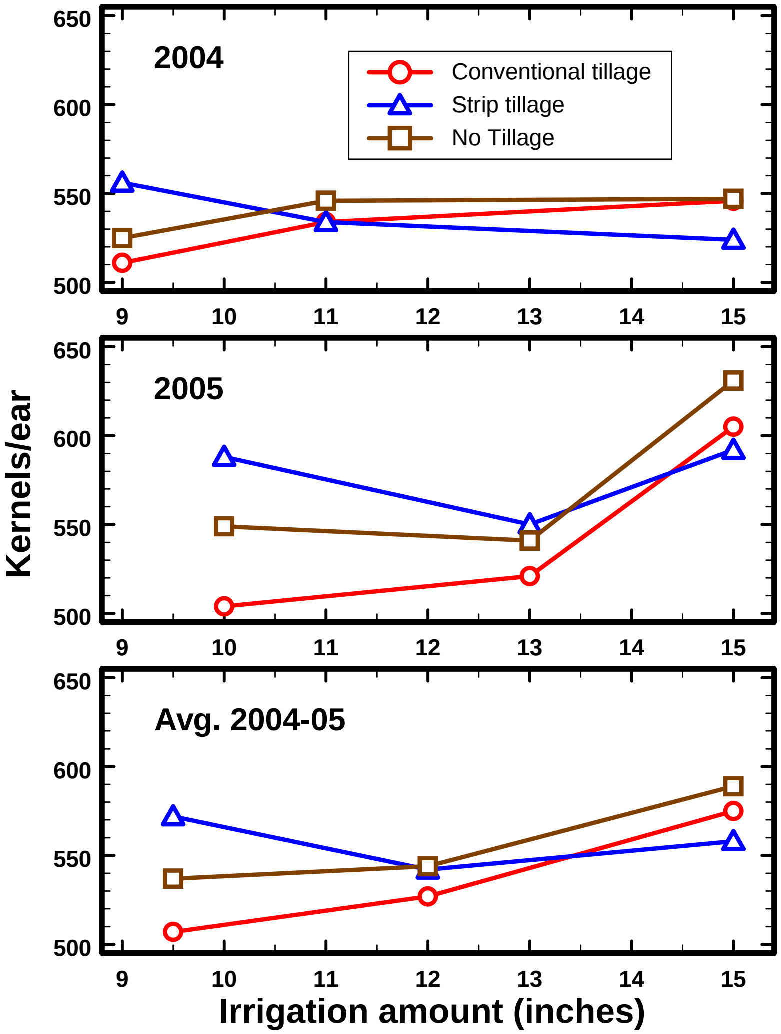

Figure 7. Kernels/ear as affected by irrigation capacity and plant population, 2004-2005, KSU Northwest Research-Extension Center, Colby Kansas.

Final kernel weight is affected by plant growing conditions during the grain filling stage (last 60 days prior to physiological maturity) and by plant population and kernels/ear. Deficit irrigation capacities often will begin to mine soil water reserves during the latter portion of the cropping season, so it is not surprising that kernel weight was increased with increased irrigation capacity (Tables 2 and 3, Figure 8). Tillage system also affected kernel weight, but it is thought by the authors that the effect was caused by different factors at the different irrigation capacities. At the lowest irrigation capacity, final kernel weight was highest for conventional tillage because of the lower number of kernels/ear. However, this higher kernel weight did not compensate for the decreased kernels/ear, and thus, grain yields were lower for conventional tillage. Strip tillage generally had higher kernel weights at higher irrigation capacity than the conventional and no tillage treatments for some unknown reason.

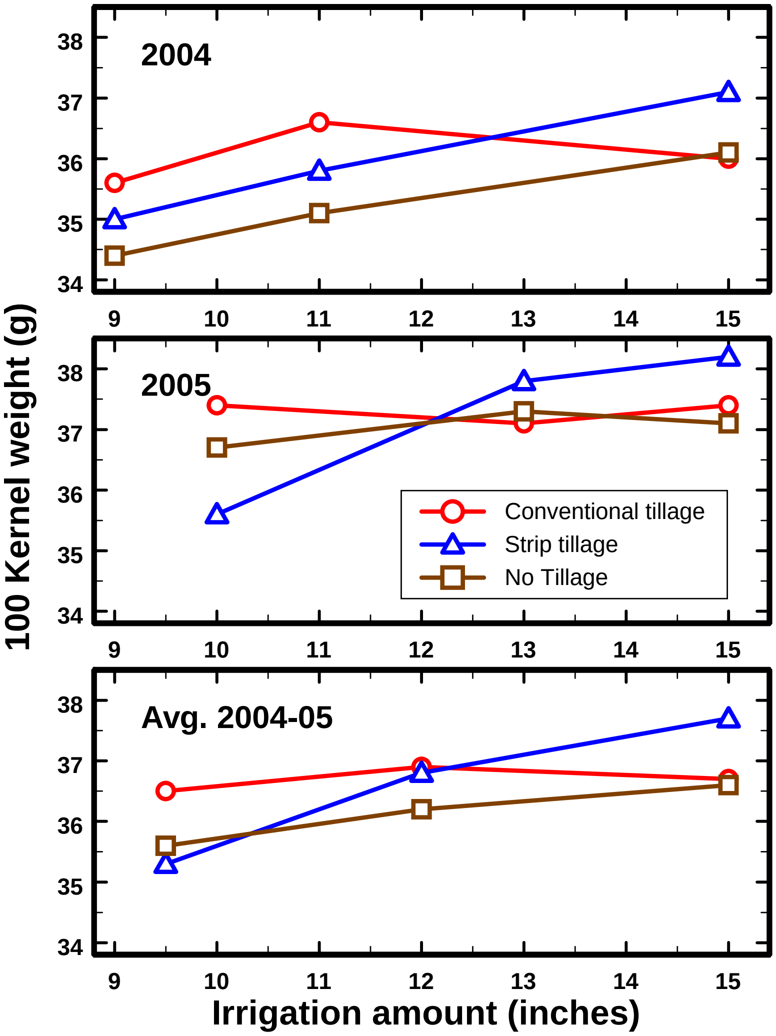

Figure 8. Kernel weight as affected by irrigation capacity and plant population, 2004-2005, KSU Northwest Research-Extension Center, Colby Kansas.

The changing patterns in grain yield, kernels/ear, and kernel weight that occurs between years and as affected by irrigation capacity and tillage system may be suggesting that additional factors besides differences in plant water status or evaporative losses is affecting the corn production. There might be differences in rooting, aerial or soil microclimate, nutrient status or uptake to name a few possible physical and biological reasons.

Total seasonal water use in this study was calculated as the sum of irrigation, precipitation and the change in available soil water over the course of the season. As a result, seasonal water use can include non-beneficial water losses such as soil evaporation, deep percolation, and runoff. Intuitively, one might anticipate that good residue management with strip tillage and no-tillage would result in lower water use than conventional tillage because of lower non-beneficial water losses. However, in this study, strip tillage and no-tillage generally had higher water use (Tables 2 and 3, Figure 9). The small increases in total seasonal water use (< 1.5 inch) for strip tillage and no-tillage compared to conventional tillage can probably be explained by the higher grain yields for these tillage systems (approximately 10 bu/a). Another possibility is that there were increased deep percolation losses in 2005 because of the higher early season precipitation.

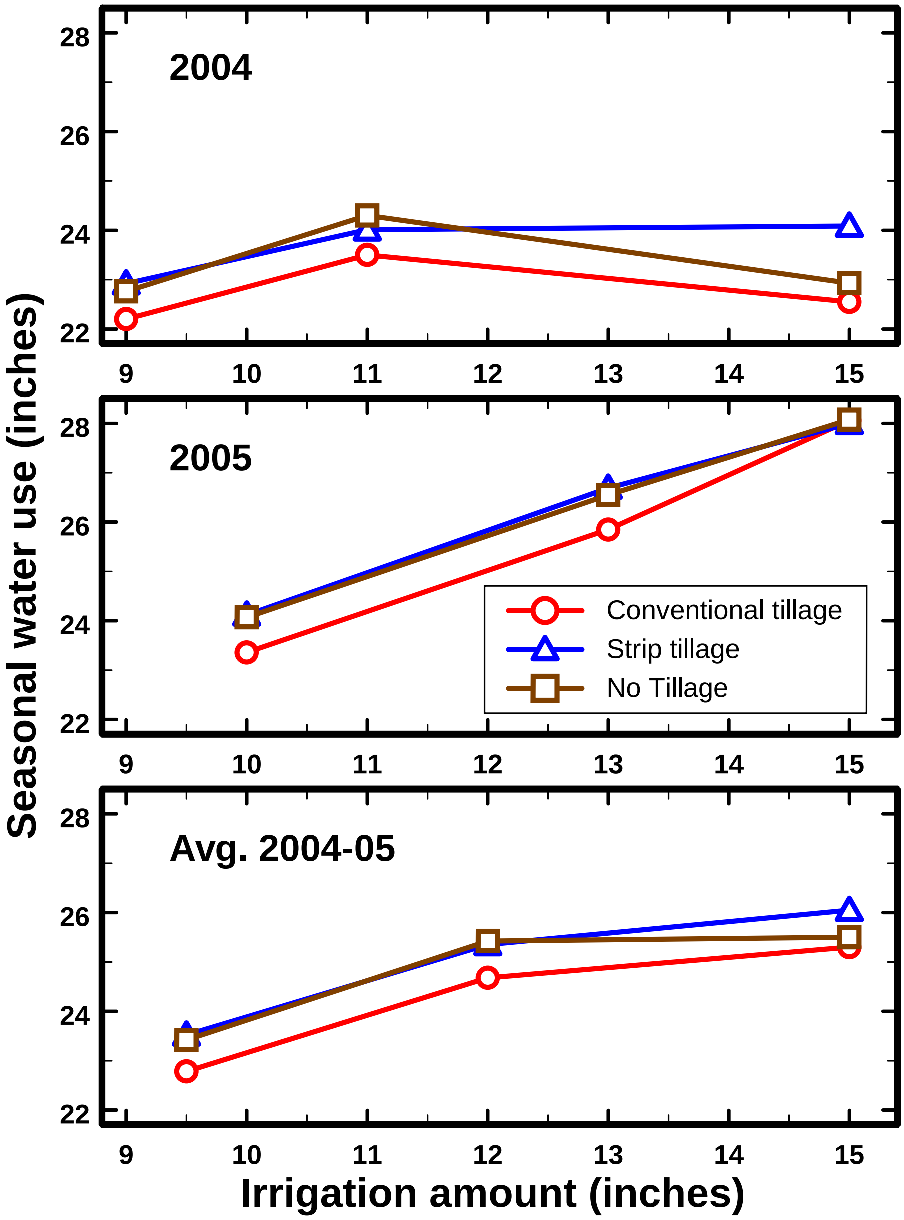

Figure 9. Total seasonal water use (sum of irrigation, precipitation, and seasonal changes in available soil water) as affected by irrigation capacity and plant population, 2004-2005, KSU Northwest Research-Extension Center, Colby Kansas.

CONCLUDING STATEMENTS

Corn grain yields were high in 2004 and 2005 with near normal precipitation and crop evapotranspiration. Strip tillage and no tillage generally performed better than conventional tillage. Increasing the plant population from 25,400 to 32,000 plants/acre was beneficial at all three irrigation capacities. The study will be continued in 2006 to determine if the production trends will remain as residue levels continue to increase.

ACKNOWLEGEMENTS

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CROP RESIDUE AND SOIL WATER

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INTRODUCTION

Final crop yield is greatly influenced by the amount of water that moves from the soil, through the plant, and out into the atmosphere (transpiration). Generally, the more water that is in the soil and available for transpiration, the greater the yield. For example, dryland wheat yield is strongly tied to the amount of soil water available at wheat planting time (Fig. 1). In this case an additional inch of water stored in the soil at wheat planting time would increase yield by 5.3 bu/a. For wheat selling at $3.21/bu, that inch of stored soil water is worth $17/a. Similar relationships can be defined for other crops. But the point is that in the Great Plains where precipitation is low and erratic, an important production factor is storing as much of the precipitation and irrigation that hits the soil surface as possible.

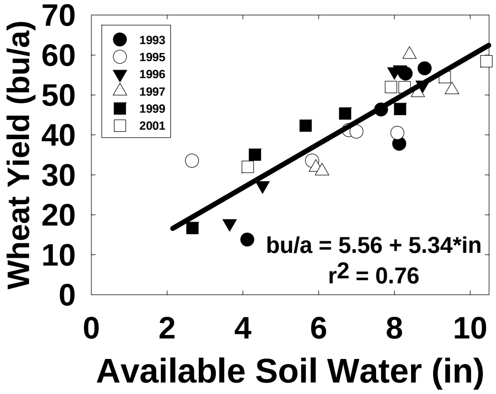

Fig. 1. Relationship between winter wheat grain yield and available soil water at wheat planting at Akron, CO.

FACTORS AFFECTING WATER STORAGE

Time of Year/Soil Water Content

The amount of precipitation that finally is stored in the soil is determined by the precipitation storage efficiency (PSE). PSE can vary with time of year and the water content of the soil surface. During the summer months air temperature is very warm, with evaporation of precipitation occurring quickly before the water can move below the soil surface. Farahani et al. (1998) showed that precipitation storage efficiency during the 2 ½ months (July 1 to Sept 15) following wheat harvest averaged 9%, and increased to 66% over the fall, winter, and spring period (Sept 16 to April 30) (Fig. 2). The higher PSE during the fall, winter, and spring is due to cooler temperatures, shorter days, and snow catch by crop residue. From May 1 to Sept 15, the second summerfallow period, precipitation storage efficiency averaged -13% as water that had been previously stored was actually lost from the soil. The soil surface is wetter during the second summerfallow period, slowing infiltration rate, and increasing the potential for water loss by evaporation.

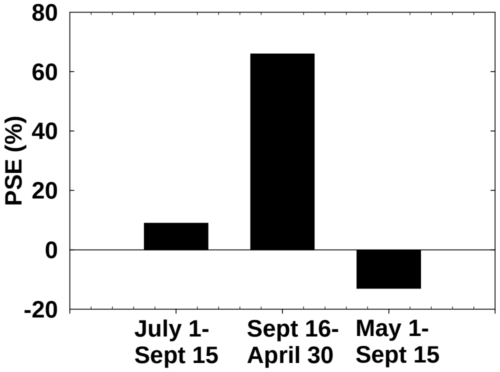

Fig. 2. Precipitation Storage Efficiency (PSE) variability with time of year. (after Farahani, 1998)

Residue Mass and Orientation

Studies conducted in Sidney, MT, Akron, CO, and North Platte, NE (Fig. 3) demonstrated the effect of increasing amount of wheat residue on the precipitation storage efficiency over the 14-month fallow period between wheat crops.

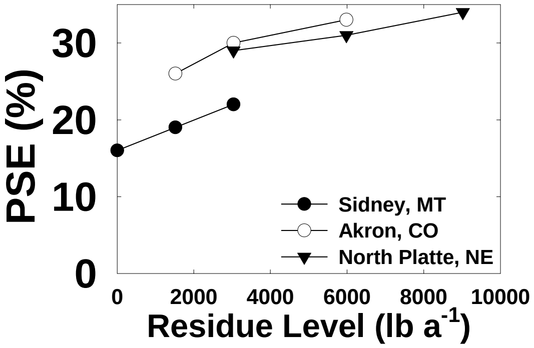

Fig. 3. Precipitation Storage Efficiency (PSE) as influenced by wheat residue on the soil surface. (after Greb et al., 1967)

As wheat residue on the soil surface increased from 0 to 9000 lb/a, precipitation storage efficiency increased from 15% to 35%. Crop residues reduce soil water evaporation by shading the soil surface and reducing convective exchange of water vapor at the soil-atmosphere interface. Additionally, reducing tillage and maintaining surface residues reduce precipitation runoff, increase infiltration, and minimize the number of times moist soil is brought to the surface, thereby increasing precipitation storage efficiency (Fig. 4).

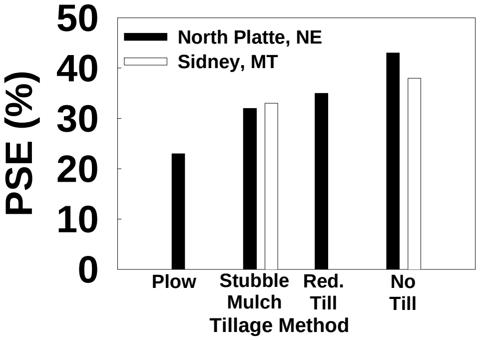

Fig. 4. Precipitation Storage Efficiency (PSE) as influenced by tillage method in the 14-month fallow period in a winter wheat-fallow production system. (after Smika and Wicks, 1968; Tanaka and Aase, 1987)

Snowfall is an important fraction of the total precipitation falling in the central Great Plains, and residue needs to be managed in order to harvest this valuable resource. Snowfall amounts range from about 16 inches per season in southwest Kansas to 42 inches per season in the Nebraska panhandle. Akron, CO averages 12 snow events per season, with three of those being blizzards. Those 12 snow storms deposit 32 inches of snow with an average water content of 12%, amounting to 3.8 inches of water. Snowfall in this area is extremely efficient at recharging the soil water profile due in large part to the fact that 73% of the water received as snow falls during non-frozen soil conditions.

Standing crop residues increase snow deposition during the overwinter period. Reduction in wind speed within the standing crop residue allows snow to drop out of the moving air stream. The greater silhouette area index (SAI) through which the wind must pass, the greater the snow deposition (SAI = height*diameter*number of stalks per unit ground area). Data from sunflower plots at Akron, CO showed a linear increase in soil water from snow as SAI increased in years with average or above average snowfall and number of blizzards. Typical values of SAI for sunflower stalks (0.03 to 0.05) result in an overwinter soil water increase of about 4 to 5 inches (Fig. 5).

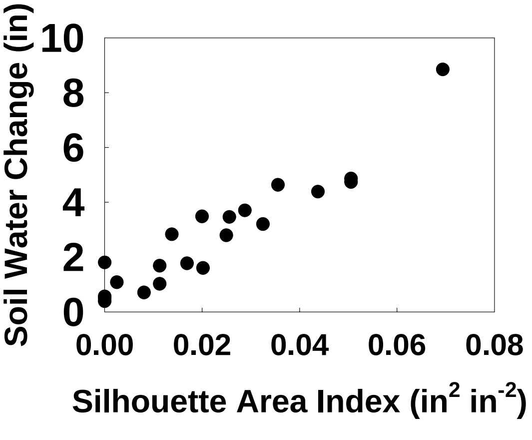

Fig. 5. Influence of sunflower silhouette area index on over-winter soil water change at Akron, CO. (after Nielsen, 1998)

Because crop residues differ in orientation and amount, causing differences in evaporation suppression and snow catch, we see differences in the amount of soil water recharge that occurs (Fig. 6). The 5-year average soil water recharge occurring over the fall, winter, and spring period in a crop rotation experiment at Akron, CO shows 4.6 inches of recharge in no-till wheat residue, and only 2.5 inches of recharge in conventionally tilled wheat residue. Corn residue is nearly as effective as no-till wheat residue in recharging soil water, while millet residue gives results similar to conventionally tilled wheat residue.

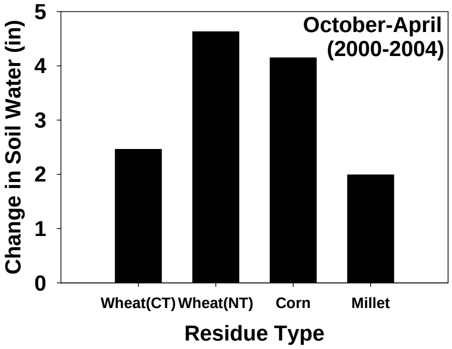

Fig. 6. Change in soil water content due to crop residue type at Akron, CO.

Good residue management through no-till or reduced-till systems will result in increased soil water availability at planting. This additional available water will increase yield in both dryland and limited irrigation systems by reducing level of water stress a plant experiences as it enters the critical reproductive growth stage.

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IRRIGATED CROP PRODUCTION ECONOMICS AND LAND LEASE ARRANGEMENTS

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INTRODUCTION

Irrigated crop producers in the U.S. Central Plains have come under pressure in recent years as groundwater levels have declined and energy prices have risen. With the limitations on the amount of water available to irrigate, and the additional cost of pumping that water, many producers are trying to determine if they should change their irrigation practices, or perhaps stop irrigating altogether. Making decisions such as these involves many variables and is therefore often complex. However, there are some economic principles that can guide producers in making complicated decisions regarding irrigated crop production decisions.

DECLINING WATER

The issues of declining water and rising energy costs undoubtedly are related in terms of decisions facing irrigators. Certainly, both irrigators with maximum irrigation capacity, and those with diminished irrigation capacity face the issue of rising energy costs. However, the impact of rising energy costs may be more acute with limited irrigation capacity as lower capacity wells require more energy to apply an inch of water than higher capacity wells. In addition, the options producers with limited irrigation capacity have in terms of cropping options may be limited as well. For example, low capacity irrigation wells may not be able to supply sufficient water during critical stages of crop production for certain crops. Consequently, high water use crop may not be an option for some producers.

To address the issue of limited well capacity, two studies were started at the K-State Southwest Research Center in Tribune, KS. The first study is a limited-irrigation study that compares four crops (corn, grain sorghum, soybean, and sunflower) at three irrigation levels (5, 10, and 15 inches). Average yields from 2001-2005 are shown in table 1. Corn, which increased in yield from 114 bu/a with 5 inches of irrigation to 173 bu/a and 191 bu/a with 10 and 15 inches of irrigation, respectively, had the highest response to water. The other three crops experienced yield increases from 21% to 28% (compared to corn at 52%) as irrigation increased from 5 to 10 inches. On a percentage basis, all crops except sunflower had similar yield increases as irrigation was increased from 10 to 15 inches. Sunflower actually had a small reduction in yield.

Table 1. Average Yield at Three Irrigation Levels in Tribune, KS (2001-05).

Crop	5 in	10 in	15 in
Corn (bu/a)	114	173	191
Grain sorghum (bu/a)	93	114	125
Soybean (bu/a)	30	39	42
Sunflower (lbs/a)	1,547	1,872	1,821

Table 2 shows the corresponding returns for each crop at each irrigation level. The values in the table represent returns to land, irrigation equipment, and management based on average production practices, costs, and prices during the study. At five inches of water, soybean had the highest average return at $35/a. Corn, grain sorghum, and sunflower followed next at $31/a, $16/a, and $-9/a, respectively. At 10 and 15 inches of irrigation, returns for corn more than double soybean, the next most profitable crop.

Table 2. Average Returns ($/a) at Three Irrigation Levels in Tribune, KS (2001-05).

Crop	5 in	10 in	15 in
Corn	31	134	151
Grain sorghum	16	31	31
Soybean	35	61	57
Sunflower	-9	0	-23

The second study initiated at the Southwest Research Center in Tribune in 2003 is a limited-irrigation crop rotation study. In this study, four rotations involving four different crops were limited to 10 inches of irrigation per rotation. The rotations include continuous corn, corn-wheat, corn-wheat-grain sorghum, and corn-wheat-grain sorghum-soybean. Since corn has a higher response to water than wheat, in all the rotations that included wheat, the wheat crop was limited to 5 inches of irrigation water, while the corn crop in that rotation received 15 inches. Continuous corn, and other crops in the rotation with corn and wheat received 10 inches of irrigation.

Average yields from the limited-irrigation rotation study are shown in table 3. Continuous corn averaged 170 bu/a, while corn (with 5 more inches of water) in the other rotations averaged between 211 and 213 bu/a. Wheat yields averaged from 32 to 34 bu/a across all rotations. These yields were lower than expected, but were largely due to late spring freezes in 2004 and 2005 and stripe rust in 2005. Yields for grain sorghum (125 to 128 bu/a) and soybean (45 bu/a) were similar to yields observed in the limited-irrigation study. Table 4 shows the average returns for each rotation. Continuous corn had the highest average return to land, irrigation equipment, and management at $111/a. The other three rotations earned returns in the range of $66 to $73/a.

Table 3. Average Yields in Limited Irrigation Rotations in Tribune, KS (2003-05).

Crop	Rotation*			
	Corn-Corn	Corn-Wheat	Corn-Wheat-Sorghum	Corn-Wheat-Sorghum-Soybean
Corn	170	213	211	213
Wheat	--	33	32	34
Grain Sorghum	--	--	125	129
Soybean	--	--	--	45

* Each rotation is limited to average total of 10 inches of irrigation. In the rotations containing wheat, the wheat crop receives 5 inches of irrigation, while the corn crop receives 15 inches, for an average of 10 inches across the rotation.

Table 4. Average Returns ($/a) in Limited Irrigation Rotations in Tribune, KS (2003-05).

Crop	Rotation*			
	Corn-Corn	Corn-Wheat	Corn-Wheat-Sorghum	Corn-Wheat-Sorghum-Soybean
Corn	118	185	204	208
Wheat	--	-23	-27	-22
Grain Sorghum	--	--	39	45
Soybean	--	--	--	88
Rotation	118	81	72	80

* Each rotation is limited to average total of 10 inches of irrigation. In the rotations containing wheat, the wheat crop receives 5 inches of irrigation, while the corn crop receives 15 inches, for an average of 10 inches across the rotation.

When water levels decline and energy prices increase, one of the first questions many producers ask is whether they should continue growing irrigated corn.

According to the two studies from Tribune, the answer to that question appears to be “Yes”. This is still the case with assumed irrigation pumping costs being 72% higher in 2005 than 2004. However, every producer needs to run his own numbers as everyone’s situation may be different. For example, because of differences in well depths, or inefficient pumping or delivery systems, one producer’s pumping cost per acre-inch may be significantly higher than another’s. Likewise, one producer’s yield response to irrigation may vary from his neighbor’s. Therefore, it is critically important that producers understand the relationship between irrigation water and yield and other yield increasing inputs (i.e. fertilizer). Only then can accurate economic comparisons of crops be conducted.

ENERGY COSTS

Arguably the biggest concern of crop producers in the Central Plains region is the issue of high energy prices. This issue, of course, affects all crop growers, but impacts irrigators to a greater extent. Consequently, all irrigators are asking questions that perhaps only producers with limited irrigation well capacities were asking in the past. In addition to considering other crop options, producers are also considering planting high input crops, but cutting back on inputs such as seed, fertilizer, and irrigation water. Historically, such practices have not always maximized profits. Following is a discussion of the economic principles governing optimal use of fertilizer and irrigation water.

The economic principle guiding the use of yield increasing inputs such as fertilizer and irrigation water is the marginal cost equal marginal revenue (MC = MR) principle. In other words profit will be maximized at the point where the cost of an additional unit of an input (MC) equals the revenue associated from the use of the additional unit of that input (MR). In crop production, this principle would dictate that fertilizer and irrigation water should continue to be added as long as the benefit (yield increase * crop price) is greater than the cost of adding another pound of fertilizer or acre-inch of irrigation water.

The greatest difficulty in determining the input level where MR just covers MC is knowing the relationship between crop yield and that input. These yield response functions to fertilizer and irrigation water are necessary to calculate the economic optimum amount of those inputs to apply. Fortunately, research has been conducted in Kansas to develop yield response functions for the major crops in Kansas. This research has been used to generate adjustments to the KSU nitrogen recommendations to reflect current high nitrogen (N) prices (Kastens, et al). It has also been incorporated into a spreadsheet that is designed to help producers determine which crop is most profitable for their operation. In addition, *KSU-Crop Budgets 2006.xls* will help producers determine the economic optimum amount of nitrogen fertilizer and irrigation water to apply given their yield goals, expected fertilizer and irrigation costs, and forecasted crop prices. The *KSU-Crop Budgets 2006.xls* spreadsheet and paper describing how the

KSU nitrogen fertilizer recommendations were modified to reflect price are available on www.AgManager.info.

Table 5 shows the economic optimum N fertilizer and irrigation rates for irrigated wheat, corn, grain sorghum, soybean, and sunflower at historical nitrogen ($0.21/lb) and irrigation pumping costs ($3.10/in). Using corn as an example, a producer with a yield goal of 225 bu/a, 20 lbs of soil test N, and 2.0% organic matter would apply 278 lbs/a of N as an economic optimum. If that same producer expected 18 inches of annual rainfall, the economic optimum amount of irrigation water to apply would be 17.1 inches.

Table 5. Economic Optimum Nitrogen Fertilizer and Irrigation Rates Based on Historical Energy Prices.

	Wheat	Corn	Sorghum	Soybean	Sunflower
Yield Goal	75	225	125	65	2,800
Soil Test N, lbs/a	20	20	20	20	20
Organic matter, %	2.0	2.0	2.0	2.0	2.0
N price, $/lb	0.21	0.21	0.21	0.21	0.21
Irrigation pumping cost, $/in	3.10	3.10	3.10	3.10	3.10
Econ. optimum N, lb/a	112	278	114	0	125
Econ. optimum irrigation, inches	12.6	17.1	12.8	16.6	15.0
Yield at econ. optimum	71.1	221.0	119.5	58.5	2,706

Table 6 shows the economic optimum N fertilizer and irrigation rates for the same crops in table 5, but with an N price of $0.40/lb and irrigation pumping costs of $6.50/in. When N and irrigation costs increase, the optimal rates of each decrease significantly. Economic optimum N rates drop from 278 lbs/a to 225 lbs/a as price increases from $0.21/lb to $0.40/lb. Likewise, economic optimum irrigation rates drop from 17.1 inches to 14.2 inches as pumping costs increase from $3.10/in to $6.50/in.

Clearly, the historically high energy prices have an impact on crop production decisions. Both optimal fertilizer N and irrigation rates decline as energy prices rise above historical averages. However, the magnitude of the decline will depend on each producer’s situation, so it is again important that every producer run his own numbers to determine the economic optimum N and irrigation rates for a given farm.

Table 6. Economic Optimum Nitrogen Fertilizer and Irrigation Rates Based on Current Energy Prices.

	Wheat	Corn	Sorghum	Soybean	Sunflower
Yield Goal	75	225	125	65	2,800
Soil Test N, lbs/a	20	20	20	20	20
Organic matter, %	2.0	2.0	2.0	2.0	2.0
N price, $/lb	0.40	0.40	0.40	0.40	0.40
Irrigation pumping cost, $/in	6.50	6.50	6.50	6.50	6.50
Econ. optimum N, lb/a	67	225	67	0	83
Econ. optimum irrigation, inches	7.6	14.2	8.3	15.2	10.6
Yield at econ. optimum	59	209	103	59	2,420

LAND LEASE ARRANGEMENTS

Current energy prices also have the possibility of impacting crop land lease arrangements. How much a crop lease agreement will be affected will depend on the type of agreement, the terms of the agreement, and the magnitude of the cost increase. While crop share leases are most common in Kansas, other types of rental arrangements have been increasing in use in recent years. The most popular type of these leases include cash rental arrangements, and “net share” leases, which are basically crop share arrangements in which the tenant provides all crop inputs, but would receive a higher percentage of the crop than they would in a typical crop share arrangement.

Equitable crop share arrangements should follow five principles: 1) Yield increasing inputs (i.e. fertilizer and irrigation water) should be shared, 2) lease terms should be reviewed and technology changes, 3) crop returns should be shared in the same percentage as resources contributed, 4) tenants should be compensated for any unused long-term investments at lease termination, and 5) effective tenant-landlord communications. In terms of managing rising input costs, principles 1 and 3 are particularly relevant. If a crop share lease is equitable (i.e. returns are shared in the same proportion as resources contributed), then sharing the yield increasing input guarantees that it will be applied at the economic optimum. In addition, sharing the yield increasing input guarantees that the lease will remain equitable regardless of the price of that input.

An example is provided in table 7. In this table, the base crop share lease is for 125 acres of center-pivot-irrigated corn, in which the tenant owns the irrigation motor and pivot, and the landlord owns the well, pump and gearhead. In this example, crop inputs that are shared include fertilizer, herbicides, insecticides, and irrigation pumping costs. When N fertilizer and irrigation pumping costs are at levels typical during the last 5 to 10 years, the equitable landlord/tenant crop share split is 23.8%/76.2%. If N fertilizer and irrigation costs increase to current levels ($0.40/lb and $6.50/in, respectively), the equitable crop share split does not change.

In another scenario, identical to the base scenario except that irrigation pumping costs are not shared, the landlord/tenant crop share split would be 20.1%/79.9%. At current prices, the equitable crop share split would be 17.1%/82.9%. This clearly demonstrates that if yield increasing input costs increase significantly, and they are not shared equitably, the lease may become inequitable if crop returns are not adjusted accordingly. Precisely how a crop share lease should or should not be adjusted will of course depend on the specifics of each lease.

Table 7. Effect of High Energy Prices on Equitable Crop Share Percentages.

Lease Scenario	Equitable Share % (L/T)
Base crop share	23.8/76.2
Crop share with high energy costs	23.8/76.2
Crop share not sharing irrigation costs	20.1/79.9
Crop share not sharing irrigation with high energy costs	17.1/82.9

Cash rents would also be affected if input costs increased. A equitable cash rent equivalent to base crop share arrangement described above would be $67.14/a. At current costs the equitable cash rent would fall to $29.15/a. The decline in cash rent is the result of a reduction in profitability from the higher energy costs. This suggests that tenants who are cash renting may need to renegotiate the lease with their landlord. Of course, approaching the landlord to help “share the pain” will have to be weighed against the prospect of potentially losing the land. Also, if tenants are looking for a long-term agreement, then long-term input prices should be used to determine an equitable cash rent.

SUMMARY

Diminishing groundwater levels and rising energy costs have had a negative impact on irrigated crop production. Producers have many decisions to make regarding crop selection and crop input use. Research has been conducted to evaluate crop response to irrigation levels and alternative limited-irrigation rotations. Results indicate that corn has a higher response to irrigation to produce

higher yields and therefore higher returns in most situations. Higher energy costs may impact optimal application rates for nitrogen fertilizer and irrigation. Depending on the crop, yield goal, and soil test nitrogen, economic optimum fertilizer rates may decline by 10 to 30%. When irrigation pumping costs are considered simultaneously, economic optimum fertilizer and irrigation rates may fall even more. Crop share lease arrangement that share fertilizer and irrigation pumping costs will not be impacted by the higher energy costs. Crop share leases that do not share fertilizer and irrigation pumping costs may need to be evaluated to determine whether any changes need to be made to the lease. Likewise, cash rents may need to be evaluated to determine whether any adjustments need to be made. With any of these issues, producers need to evaluate their situations individually, as what may be optimal for one situation may not be optimal for another.

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PUMPING PLANT EFFICIENCY,
FUEL OPTIONS AND COSTS

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Energy costs have a major impact on production costs in agriculture. Irrigated agricultural has additional energy sensitivity due to the cost of pumping irrigation water. As pumping energy costs increase, irrigators have been exploring energy options. While changing energy sources can sometimes be economical option, it can require large up-front investment costs with little guarantee that the alternative energy source will remain cost competitive. Before changing energy sources, irrigators should evaluate the performance of their current pumping plants, as wear and changes in pumping conditions over time can cause substantial loss in pumping plant efficiency. This results in the increased use of fuel for the same or less amount of water pumped.

The irrigation fuel or energy bill is composed of two parts. The first is related to pumping plant performance and the second is related to crop irrigation management.

Total fuel bill = Pumping cost/Unit Volume of Water x Volume Applied

The pumping cost per unit volume of water depends on well efficiency, pumping plant efficiency and fuel cost. The major influences on the total volume applied are related to management issues, such as irrigation schedule for the crop selected and the irrigation system efficiency. Reducing the total volume applied reduces the fuel bill proportionately, so if the amount of water applied is minimized with good irrigation scheduling and high application efficiency, the fuel bill will be minimized based on pumping volume. Good irrigation management practices and high system efficiency are the subject of other presentations. The focus of this discussion will be on the pumping cost per unit volume of water.

Pumping Cost Per Water Volume

The major factors that influence the pumping cost per volume are: pumping plant efficiency and TDH (total dynamic head), which is the total hydraulic resistance against which the pump must operate. Well efficiency is also a factor, but it is largely determined by design and construction factors that were used during the drilling and development processes. Many wells would produce a greater flow with less drawdown if the screen, gravel pack and development procedure had been better designed, but little can be done to improve the efficiency of a poorly constructed well. Many wells would also benefit from treatments to remove incrustations on well screens or treatments to control biological growths that can also clog well screens. If the water's entry into the well through the screen is restricted, more drawdown is needed to produce a given flow.

Performance evaluations indicate that many irrigation pumping plants use more fuel than necessary as compared to a properly sized, adjusted and maintained pumping plant. For example, a 1990 study in Kansas (Table 1 and Table 2), found pumping plants performance ratings ranging from 15 to 120 percent of the Nebraska performance Criteria (NPC). Irrigation pumping energy requirements can be estimated using the NPC shown in Table 3. The NPC is a guideline for a performance of a properly designed and maintained pumping plant. Some pumping plants will exceed this criteria, but most will not.

In that study, the average pumping plant used about 30 percent more fuel than necessary. Obviously, some are much worse and others actually exceeded the NPC. Causes of excessive fuel use include:

1. Poor pump selection. Pumps are designed for a particular discharge, head and speed. If used outside a fairly narrow range in head, discharge and speed, the efficiency is apt to suffer. Some pumps were poor choices for the original condition, but changing conditions such as lower water levels or changes in pressure also cause pumps to operate inefficiently.
2. Pumps out of adjustment. Pumps need adjustment from time to time to compensate for wear.
3. Worn-out pumps. Pumps also wear out with time and must be replaced.
4. Improperly sized engines or motors. Power plants must be matched to the pump for efficient operation. Engine or motor loads and speed are both important to obtain high efficiency.
5. Engines in need of maintenance and/or repair.
6. Improperly matched gear heads. Gear head pump drives must fit the load and speed requirements of the pump and engine.

Pumping plant performance evaluations can be obtained by hiring a consulting firm or contractor to take the measurements, but many farmers are reluctant to spend money to find out if something is wrong. Energy costs, however, can represent a significant portion of the production cost for a crop. The following procedure can help an irrigator analyze irrigation fuel or energy bills to see if they are reasonable for the pumping conditions and price of fuel.

If this estimate indicates low pumping plant efficiency, then hiring a firm to repair or replace the pumping plant may be justified. The irrigator needs to know 1) acres irrigated, 2) discharge rate, 3) total dynamic head, 4) total application depth, 5) total fuel bill, and 6) fuel prince/unit in order to make such an estimate.

The following procedure is outlined in the K-State Research and Extension Bulletin L-885, “Evaluating Pumping Plant Efficiency Using On-farm Fuel Bills”. The procedure is also available as a computer software program, FuelCost, available via the web at www.ozent/ksu.edu/mil. The procedure uses the NPC as the basis for the fuel use estimate.

Step 1: Determine Water Horsepower
Water horsepower (WHP) is the amount of work done on the water and is calculated by
WHP = TDH (GPM)/3960
where:
GPM - discharge rate in gallons per minute
TDH = total dynamic head (in feet) = Pumping Lift (ft) + Pressure (psi) x 2.31
TDH is usually estimated by adding total pumping lift and pressure at the pump. Since pressure is usually measured in PSI, convert PSI to feet by multiplying PSI x 2.31 (see conversions in Table 4).

Step 2: Calculate hours of pumping
H_R = D (Ac) / (GPM/450)
where:
H_R = Hours of pumping
D = Depth of applied irrigation water (inches)
Ac = Acres irrigated
GPM = discharge rate in gallons/minutes
450 = a conversion constant (see Table 4)

Step 3: Estimate hourly NPC fuel use
FU = WHP/NPC
where:
FU = Hourly fuel use using the Nebraska criteria
WHP = Water Horsepower from Step 1
NPC = Nebraska Performance Criteria (Table 3)

Step 4: Estimate seasonal NPC fuel cost
SFC = FU x H_R x Cost
Where:
SFC = Seasonal Fuel Cost if the pumping plant was operating at NPC
H_R = Hours of operation from Step 2
Cost = $/Fuel Unit

Step 5: Determine excess fuel cost

EFC = AFC - SFC
where:
EFC = Excess Fuel Cost (in dollars)
AFC = Actual Fuel Cost (in dollars)
SFC = Estimated Seasonal Fuel Cost using NPC (in dollars)

Step 6: Calculate annualized repair cost

ARP = INVEST X CRF
where:
ARP = Annualized Repair Cost
INVEST = Investment required to repair or upgrade pumping plant
CRF = Capital Recovery Factor (Table 5)

The excess fuel cost may be thought of as the annual payment to cover the cost of a pumping plant upgrade or repair. Repair costs can be annualized by using capital recovery factors (CRF). If the annualized repair cost for the interest rate and return period selected is less than the excess fuel cost, the investment in repair is merited.

This procedure is an indicator of your total pumping plant performance. It does not indicate the source of the excessive fuel use, but pumping plant tests in Kansas have generally shown that poor performance is generally due to the pump. The low efficiency may be due to excessive pump clearance, worn impellers, or changes in pumping conditions since the pump was installed.

Figure 1 provides an example farm problem. The example farm results in an annualized repair cost of $3811 and an excess fuel bill of $4014. Since $3811 is less than $4014, the investment in repair of the pumping plant would be merited. The excess fuel use could be divided by the CRF (example $4014/.3811 = $10,533) to indicate the amount you could afford to spend in upgrading the pumping plant.

Figure 1: Example Farm Problem

Acreage:	130 acres
Pumping Life:	330 feet
System Pressure:	22 psi
System Discharge Rate:	600 gpm
Total Irrigation Application:	16.5 inches per acre
Fuel Type: Natural Gas	Price $9.00 per MCF
Total Fuel Bill:	$16500

Step 1: Determine Water Horsepower

WHP = TDH x (GPM)/3960
= (300 + 22 x 2.31) x (600)/3960
= 53.2 WHP

Step 2: Calculate Hours of Pumping

HR = D(Ac)/GPM/450
= (16.5) (130)/(600/450)
= 1609 hrs.

Step 3: Estimate Hourly NPC Fuel Use

FU = WHP/NPC
= 53/61.7
= 0.86 MCF/Hr

Step 4: Estimate Seasonal NPC Fuel Cost

SFC = FU x Hr x Cost
= 0.86 x 1609 x 9
= 12486

Step 5: Determine Excess Fuel Cost

EFC = AFC-SFC
= 16500 - 12486
= 4014

Step 6: Calculate Annualized Repair Cost

Estimate of pump repair: $10,000
Desired CRF using 3 years and 7% interest
from Table 3: CRF = 0.3811
ARC = INVEST x CRF
= 10,000 (0.3811)
= $3811

The water horsepower equation, shown in Step 1, establishes that the power needed to lift water is proportional to the amount and the total head requirement. Reducing either will reduce water horsepower requirement and therefore reduce fuel use. However, each pumping plant, if properly designed, will operate most efficiently at a given head-discharge relationship. Once installed, changes in head on discharge requirements could result in a loss of pumping efficiency. K-State Research and Extension Bulletin L-886, “Reading Pump and Engine Performance Curves”, is available in hard copy at your county Extension office or via the web at www.oznet.ksu.edu/mil, will provide additional information on this subject.

Irrigation Energy Source Options

Natural gas has been the dominate energy source for irrigation in Kansas as historically it was readily available and relatively inexpensive in much of the major irrigated areas. This unfortunately may no longer be true and irrigators have been examining other energy source options, which are primarily diesel, propane, and electricity.

The Nebraska Performance Criteria can also be used to compare these major energy sources, assuming the pumping plants are performing at 100 percent NPC. K-State Research and Extension Bulletin MF-2360 discusses this procedure, but energy cost comparisons can also be made using FuelCost, or FuelCost on-line at www.ozent.ksu.edu/mil. Cost equivalent fuel multipliers can be developed using NPC values as shown in Table 6. Cost comparisons of for some fuel prices are shown in Table 7. For example, the equivalent fuel cost of electricity, given $8/MCF natural gas is $0.11/KW (8 x 0.0143). These comparisons are based on the unit energy content of the energy sources and do not include other costs associated with the convenience of operation, maintenance, or additional costs such as minimum service charges or peak electric demand charges.

Summary

Irrigation pumping costs increase in proportion to energy prices but some of the pumping cost may be due to poor pumping plant performance. An estimation of the pumping plant performance may be possible using on-farm records, which could help an irrigator to decide on the best course of action for future irrigated crops. Bulletins and computer software on pumping plant energy are available through K-State Research and Extension.

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Table 1. Summary of Well and Pumping Plant Performance Testing Data from the Dakota Aquifers Program, (MacFalane, P.A., et.al., 1990)

Area	Static Level Ft.	Dynamic Level Ft.	Well Yield Gpm	NPC Rating %
Southwest	240 (70-330)	277 (160-430)	774 (170-1230)	85 (40-120)
West Central	109 (30-330)	142 (40-280)	668 (400-1050)	81 (30-115)
North Central	49 (25-100)	98 (40-155)	432 (275-860)	61 (15-110)

Table 2. Summary of Pumping Plant Performance Evaluation by Energy Source from the Dakota Aquifer Program (MacFarlane, P.A., et.al., 1990)

			Quartile average			
		Ave	1st	2nd	3rd	4th
Energy	No.	%	%	%	%	%
Natural Gas	32	85.5	112.1	96.1	80.3	53.4
Electric	18	77.4	107.3	87.0	69.9	45.4
Diesel	17	69.9	97.8	81.2	66.4	34.2
Propane	4	47.3	—	—	—	—

71 total - Weighted average 77.3%

Table 3. Nebraska Performance Criteria for Pumping Plants

Energy Source	**WHP-HRS per Unit or Fuel**
Diesel	12.50 per gallon
Propane	6.89 per gallon
Natural Gas	61.7 per MCF
Electricity	0.885 per KWH (kilowatt-hour)

Table 4. Useful Irrigation Conversions

1 psi (pounds per square inch) = 2.31 feet of head

1 acre-inch/hour = 450 gallons/minute

Table 5. Selected Capital Recovery Factors (CRF)

Length of Load or Length of Useful Life Years	**Annual Interest Rate (%)**				
	5	**7**	**10**	**12**	**15**
2	.5378	.5531	.5712	.5917	.6151
3	.3672	.3811	.4021	.4163	.4380
4	.2820	.2820	.3155	.3292	.3503
5	.2310	.2310	.2638	.2774	.2983
7	.1728	.1728	.2054	.2191	.2404
10	.1295	.1295	.1627	.1770	.1993
15	.0963	.0963	.1315	.14	.1710

Table 6: Cost Equivalent Fuel Multiplier Table

Electricity	1	0.0143	0.071	0.128
Natural Gas (925 btu/cf)	69.72	1	4.94	8.96
Diesel	14.12	0.203	1	1.81
Propane	7.79	0.112	0.551	1

Table 7: Typical Cost Comparison

Electricity ($/KW)	0.08	0.11	0.14	0.23
Natural Gas ($/mcf)	5.58	8.00	9.88	16.13
Diesel ($/gal)	1.13	1.62	2.00	3.26
Propane ($/gal)	0.62	0.90	1.10	1.80

CROP SELECTIONS AND WATER ALLOCATIONS FOR LIMITED IRRIGATION

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INTRODUCTION

Irrigators are facing challenges with declining well yields or reduced allocations from water districts. To make reductions in water use, irrigators are considering shifts in cropping patterns that earn better net economic returns. A cropping season planning tool, the Crop Water Allocator (CWA), available at www.oznet.ksu.edu/mil , has been developed to find optimum net returns from combinations of crops, irrigation amounts, and land allocations (crop rotations) that program users choose to examine. Because personal computers can bring solutions to complex questions, this program can be used by individual irrigators at their workplace. The model uses yield-irrigation relationships for 11-21 in. of rainfall in western Kansas. The user can customize the program with crop localized crop production costs or rely on default values from typical western Kansas farming operations. Irrigators are able to plan for the optimum economic use of their limited water supply by testing their options with CWA.

Groundwater declines and dwindling surface water deliveries are normal rather than infrequent. Record energy costs are driving irrigators to fewer applications or crops that require less water. Irrigators have adjusted by turning to more efficient irrigation application techniques and water-conserving cropping practices. All of these measures have given incremental improvement to the use and effectiveness of water at the farm level.

Irrigators choose crops on the basis of production capabilities, economic returns, crop adaptability to the area, government programs, crop water use, and their preferences. When full crop evapotranspiration demand cannot be met, yield-irrigation relationships and production costs become even more important inputs for management decisions. Under full irrigation, crop selection is driven by the prevailing economics and production patterns of the region. Crops that respond well to water, return profitably in the marketplace and/or receive favorable government subsidies are usually selected. These crops can still under perform in limited irrigation systems, but management decisions arise as water is limited: should fully watered cops continue to be used; should other crops be considered; what proportions of land should be devoted to each crop; and finally, how much water should be apportioned to each crop? The final outcome of these questions is returning the optimal net gain for the available inputs.

Determining the relative importance of the factors that influence the outcome of limited-irrigation management decisions can become complex. Commodity prices and government programs can fluctuate and change advantages for one crop relative to another. Water availability, determined by governmental policy or by irrigation system capacity, may also change with time. Precipitation probabilities influence the level of risk the producer is willing to assume. Production costs give competitive advantage or disadvantage to the crops under consideration.

With computationally powerful personal computers becoming common on the desks of irrigators during the last 5 years, mathematical models for decision tools can be given to managers at their work place. The objective of this project has been to create a decision tool with user interaction to examine crop mixes and limited water allocations within land allocation constraints to find optimum net economic returns from these combinations. This decision aid is for intended producers with limited water supplies to allocate their seasonal water resource among a mix of crops. But, it may be used by others interested in decisions concerning allocating limited water to crops. Decisions are intended as a planning tool for crop selection and season allocations of land and water to crop rotations.

BACKGROUND

Net economic return is calculated for all combinations of crops selected and the water allocated. Subsequent model executions of land-split (crop rotation) scenarios can lead to more comparisons. The land split options are: 50-50; 25-75; 33-33-33; 25-25-50; 25-25-25-25. Irrigation system parameters, production costs, commodity prices, yield maximums, annual rainfall, and water allocation were also held constant for each model execution, but can be changed by the user in subsequent executions. The number of crops eligible for consideration in the crop rotation could be equal to, or greater than, the number of land splits under consideration. Optimum outcomes may recommend fewer crops than selected land splits. Fallow is considered as a crop (cropping system selection) because a valid option is to idle part of a field or farm.

The model examines each possible combination of crops selected for every possible combination of water allocation by 10% increments of the gross allocation. The model has an option for larger water iteration increments to save computing time. For all iterations, net return to land, management, and irrigation equipment is calculated:

Net return = (commodity price X yield) – (irrigation cost + production cost)

where:

commodity prices were determined from user inputs, crop yields were calculated from yield-irrigation relationships derived from a simulation model based on field research, irrigation costs were calculated from lift, water flow, water pressure, fuel cost, pumping hours, repair, maintenance, and labor for irrigation, and production costs were calculated from user inputs or default values derived from Kansas State University projected crop budgets.

All of the resulting calculations of net return are sorted from maximum to minimum and several of the top scenarios are summarized and presented to the user.

One of the features of CWA is that the user can choose among five land splits or fixed configurations of dividing the land resource (50-50; 25-75; 33-33-33; 25-25-50; 25-25-25-25). These splits reflect the most probable crop-rotation patterns in western Kansas. The user can examine the results of each one of the land splits in sequential executions of the model, but the algorithm treats land split as a constant during an individual scenario. Producers divide their fields into discrete parcels, and rotate their crops in this same pattern, which led to this simplifying assumption and to the possibility of an iterative solution of the model.

The grain yield-irrigation relationship forms the basis for calculating the gross income from the crop Irrigation translates into grain yield, which combines with price to determine income. Grain yields for corn, grain sorghum, sunflower, and winter wheat were estimated by using the “KS Water Budget v. T1” software. Software development and use are described in Stone et al. (1995), Khan (1996), and Khan et al. (1996). Yield for each crop was estimated from relationships with irrigation amount for annual rainfall and silt loam soils with loess origins derived from research in the High Plains of western Kansas and eastern Colorado. The resulting yield-irrigation relationship for corn (fig. 1) shows a convergence to a maximum yield of 220 bu/ac from the various combinations of rainfall and irrigation. A diminishing-return relationship of yield with irrigation applied was typical for all crops. Each broken line represents normal annual rainfall for an area.

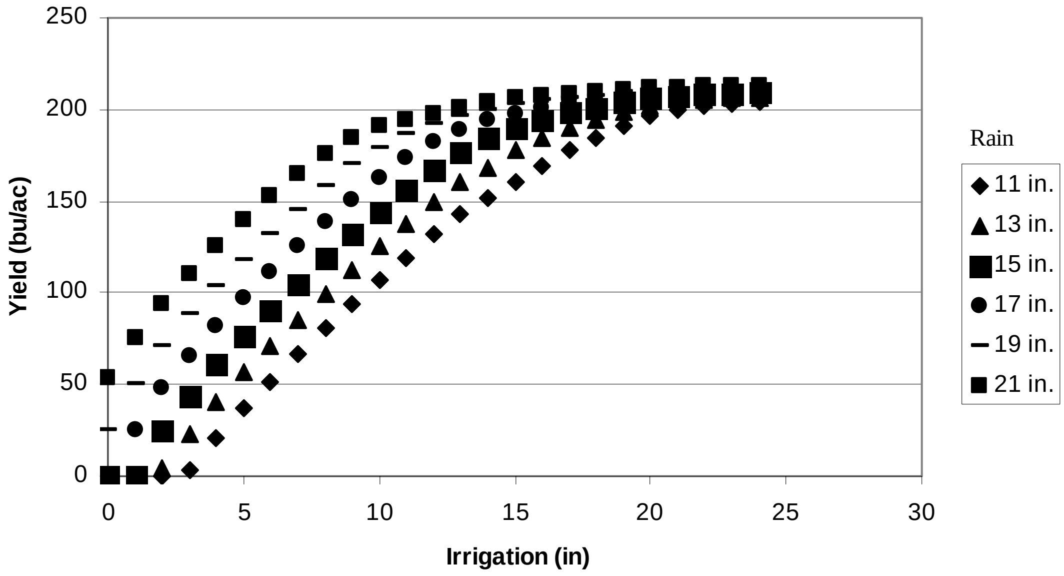

Figure 1. Yield-irrigation relationship for corn with annual rainfall from 11-21 in.

The crop production budgets are the foundation for default production costs used in CWA. Program users can input their own costs or bring up default costs to make comparisons. For western Kansas, cost-return budgets for center-pivot irrigation of crops (Dumler and Thompson, 2004) provided the basis for default production-cost values for CWA. Results can be sensitive to production costs, which require realistic production inputs.

The program was designed with user-friendly, customized interface screens with discrete input information cells or keyed actions. The input cells have drop-down choices, where appropriate, and direct links to help information. A help library is also available that serves a technical guide for the program. Information inputs are categorized into general, irrigation, and crop production, according to the input screens receiving the data. Each crop has a separate production-cost screen. User inputs including water supply, irrigation costs, crop production costs, commodity prices, and maximum crop yields can be tailored to user circumstances. These inputs directly influence the selection of the optimum crop rotation, water allocation among those crops, and ultimate net return of the cropping system. The Crop Water Allocator can be found at: www.oznet.ksu.edu\mil

ACKNOWLEDGEMENTS

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IRRIGATION OF OILSEED CROPS

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ABSTRACT

Development, water use and yield formation of oilseed crops are inter-related. Greatest yields are expected with a well-established canopy, a plant population sufficient to support a large number of seeds set per acre and favorable weather conditions for an extended seed fill period. Oilseed water requirements closely follow canopy formation and evaporative conditions. Supplemental irrigation scheduled by the water balance method results in higher yields than with irrigation scheduled by growth stage. A straight-line relationship between yield and water use indicates the yield threshold (maximum water use with no expected yield) and yield response to increased water use. When precipitation, available soil water and limited irrigation fail to meet crop water requirements, yield reductions depend on the degree of plant water stress at critical stages of growth. Full-season soybean with full irrigation offers greatest productivity potential. A smaller yield threshold and extensive rooting system for sunflower provides advantages for limited irrigation or double-crop conditions. Winter canola can provide good productivity during fall and spring growing seasons when heat stress can be minimized.

INTRODUCTION

Oilseed crops (i.e. soybean, sunflower, canola) provide management options for irrigators seeking to reduce irrigation requirements, diversification and/or to reduce input costs. In 2003, soybeans were planted on 25% of irrigated cropland in Nebraska and on 12% of irrigated acres in Kansas (NASS). Sunflower is emerging as an irrigated crop in W. Kansas with a substantial increase in double-cropped sunflowers reported in 2005. Canola, irrigated in the San Luis Valley of Colorado, is an emerging feedstock for biodiesel production.

Irrigated soybean yields range from 55 to over 70 bu/A in variety trials conducted throughout the central Great Plains (2003 – 2005); greatest yields occurred in north-central Kansas and the east-central Platte valley of Nebraska. Varieties with top yields exceeded trial averages by 10%. Irrigated sunflower yields ranged from 2200 to 2900 lb/A in similar trials located in the central High Plains with greatest yields in NW Kansas. Top-yielding hybrids exceeded trial averages by

20% or more. Irrigated winter canola yields of 2600 lb/A have been recently reported for w. Nebraska.

Several irrigation guidelines are available for oilseed crops (Baltensperger et al., 2004; Bauder, 2006; Kranz et al., 2005; Rife and Salgado, 1999; Rogers, 1997; Rogers et al., 2005). This report is intended to integrate these guidelines with recent and regional field studies. Emphasis is given to crop development, water use and yield responses for irrigated oilseed crops.

DEVELOPMENT, WATER USE, YIELD FORMATION

Oilseed development, water use and yield formation are inter-related. Water, nutrients, sunshine and soil conditions must be sufficient, with minimal stress from pests and heat for crop growth to meet potential productivity. Water requirements and yield formation factors frequently correspond with development stages. Crop-specific considerations will follow a general discussion of oilseed development, water use and components of yield.

Development

Uniform seedling emergence is favored by soil-seed contact in a firm moist seedbed at a sufficient soil temperature. Expansive growth of seedling leaves require assimilates, derived from photosynthesis and nutrient uptake, as well as sufficient plant-available water for turgor-driven growth. Development of new leaves corresponds with plant temperature as well as time. Thus, leaf appearance is related to degree-days (^{o}F-d). For example, new leaves of a standard sunflower hybrid appear in 67 ^{o}F-d intervals. Leaf appearance and growth comprise the major processes of canopy formation.

Rapid canopy closure is desirable, because the crop canopy shades the soil and reduces evaporative water losses. Leaf expansion is typically exponential during early to mid-vegetative growth when supported by sufficient water, nutrients and non-stress conditions. Crop water requirements increase with canopy formation (Figure 1) because transpiration increases in proportion to leaf area. Light penetration into lower layers of the crop canopy is desirable. Photosynthesis can be limited by the amount of light reaching shaded leaves. Canopy formation nears completion with flowering for some determinant crop types such as sunflower. However, canopy formation continues with flowering for indeterminant crops such as canola and most soybean varieties of maturity group IV and earlier.

Reproductive development marks the end of the juvenile phase and begins with differentiation of floral buds. Potential seed number (a yield formation factor) can be set at this point, for determinant crops. Development and growth of floral organs proceeds systematically through stages including pollen shed, seed set and seed fill. Again, sufficiency of water, nutrients and light will support these yield formation processes. The onset of reproductive development frequently varies with thermal time, but may be affected by day-length as well. Reproductive stages of soybean, sunflower and canola are presented in Tables 1, 2 and 3.

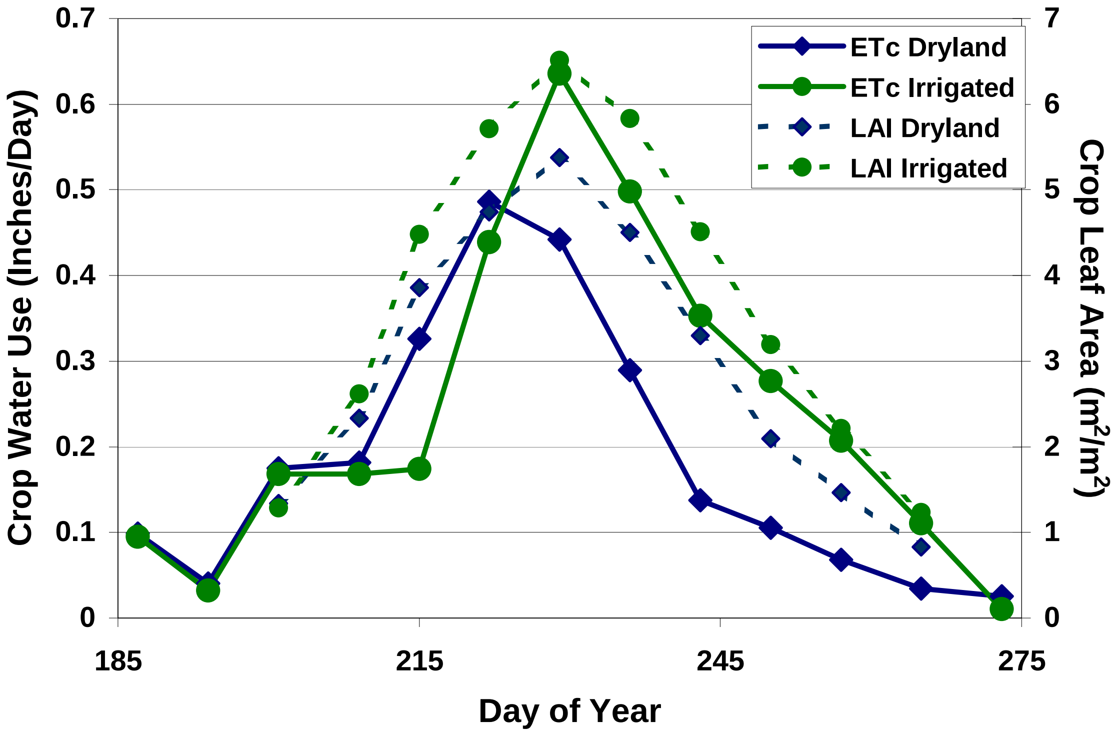

Figure 1. Sunflower water use and canopy formation (leaf area) for dryland and irrigated crop (adapted from Aiken and Stockton, 2003).

Table 1. Description of soybean reproductive stages (from Ritchie et al., 1994).

Stage	Title	Description
R1	Beginning flowering	Open flower at any node on main stem. Indeterminate plants start at bottom and flower upward. Determinate plants start at top four nodes and flower downward.
R2	Full bloom	Open flowers on one of the two uppermost nodes on main stem.
R3	Beginning pod	Pod 3/16 inch long at one of the four uppermost nodes on main stem.
R4	Full pod	Pod 3/4 inch long at one of the four uppermost nodes on main stem.
R5	Beginning seed	Seed 1/8 inch long in one of the four uppermost nodes on main stem.
R6	Full seed	Pod containing a green seed that fills pod cavity on one of the four uppermost nodes.
R7	Begin maturity	One normal pod on main stem has reached mature pod color.
R8	Full maturity	95% of pods have reached mature pod color. Approximate 5 to 10 days ahead of harvest.

Table 2. Description of sunflower reproductive stages (from Schneiter and Miller, 1981.)

Stage	Description
R-1	The terminal bud forms a miniature floral head rather than a cluster of leaves. When viewed from directly above, the immature bracts form a many-pointed starlike appearance.
R-2	The immature bud elongates 1/4 to 3/4 inch above the nearest leaf attached to the stem. Disregard leaves attached directly to the back of the bud.
R-3	The immature bud elongates more than 3/4 inch above the nearest leaf.
R-4	The inflorescence begins to open. When viewed from directly above immature ray flowers are visible.
R-5	This stage is the beginning of flowering. The stage can be divided into substages dependent upon the percent of the head area (disk flowers) that has completed or is in flowering. [i.e., R-5.3 (30%), R-5.8 (80%), etc.]
R-6	Flowering is complete and the ray flowers are wilting.
R-7	The back of the head has started to turn a pale yellow color.
R-8	The back of the head is yellow but the bracts remain green.
R-9	The bracts become yellow and brown. This stage is regarded as physiological maturity.

Table 3. BBCH decimal description of canola growth stages (from Canola Council of Canada www.canola-council.org).

Stage	Description
0	Germination: sprouting development
1	Leaf development
3	Stem elongation
5	Inflorescence (flower cluster) emergence
6	Flowering
7	Development of seed
8	Ripening

Stand establishment, canopy formation and reproductive development are significant components of the yield formation process. The crops' capacity to fill seed and achieve yield potential can depend on the active leaf area and number of seeds set per acre. Greatest yields are expected with well-established canopy, a plant population sufficient to support a large number of seeds set per acre and favorable weather conditions for an extended seed fill period.

Water use

Oilseed water requirements closely follow canopy formation and evaporative conditions. When scheduling irrigation relative to evaporative conditions, crop coefficients can be used to calculate daily crop water use (e.g., KanSched, Rogers et al., 2002). Typical crop coefficients, daily water use and development stages for soybean and sunflower are presented in Figure 2. Lower seasonal water requirements for canola can be expected for the spring growing season, which is shorter and with less evaporative demand than the summer growing season of soybean and sunflower. When soil water reserves are insufficient, actual crop water use is less than evaporative demand (Figure 3) and yield reductions are likely.

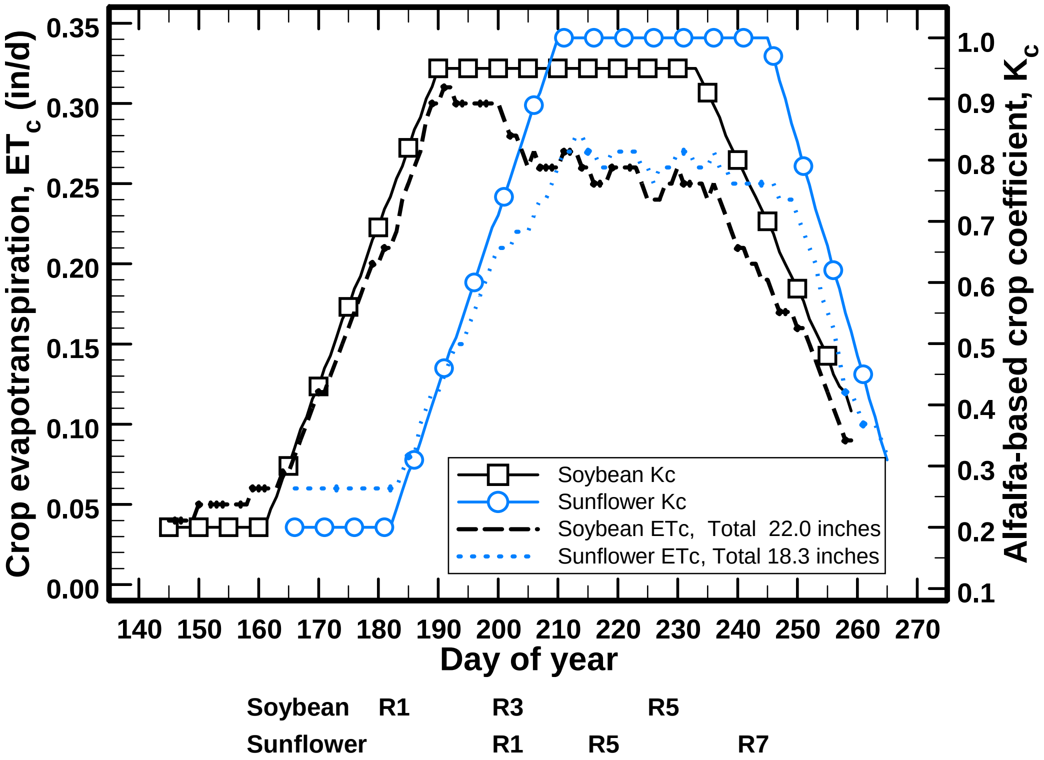

Figure 2. Crop coefficient (Kc) and daily crop evapotranspiration (ETc) for soybean and sunflower, calculated from 34 years (1972-2005) of weather recorded at Colby, KS. Reproductive development stages for soybean and sunflower are noted below the graph for reference.

Irrigation is generally required to meet crop water requirements in the central Great Plains. Two methods of scheduling irrigation are by water budget or by growth stage. Water budgets seek to maintain available soil water above a minimum value (e.g., 65% of available water holding capacity). Growth stage irrigation seeks to provide sufficient water to meet crop water requirements during specific critical stages. Studies in west-central Nebraska (Klocke et al., 1989; Elmore et al., 1988) and north-central Kansas (Gordon, 1996) indicate greater soybean yields with water budgets than with growth stage irrigation scheduling. Similar studies are in progress for sunflower.

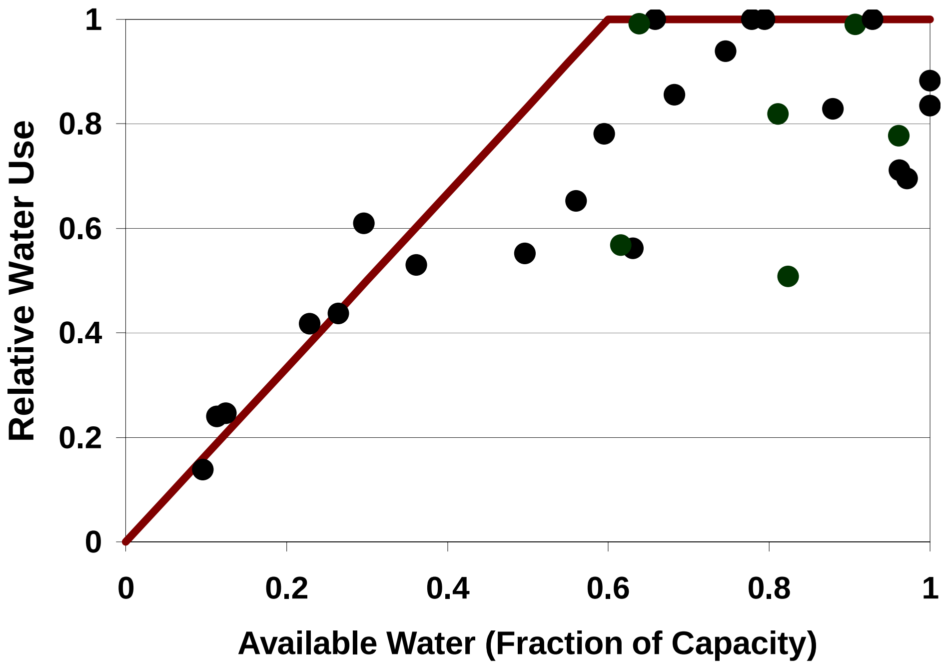

Figure 3. Water uptake by sunflower roots (relative to maximum observed uptake) is reduced when the available soil water in the wettest soil layer is less than 60% of available water capacity. The line approximates an envelope containing observations of water uptake in relation to available soil water. Water uptake from all soil layers is equivalent to crop evapotranspiration (Aiken and Stockton, 2003).

For limited irrigation systems, water available to the oilseed crop is likely to be insufficient during canopy formation and/or reproductive development stages. For example, Figure 4 shows that sunflower canopy formation at flowering (R5) can be limited by available soil water during earlier reproductive growth (R3). Limited irrigation, while not providing full water requirement of the crop, can improve seed yield. For example, a one-inch irrigation applied to soybean in SE Kansas at R4 (full pod), R5 (beginning seed) or R6 (full seed) increased seed yield by 241 lb/A. The R4 application increased the number of seeds per plant while the R5 and R6 applications increased seed weight (Sweeney et al., 2003).

Yield responses

When supply of water limits crop water use, seed yields are frequently limited as well. A straight line can represent the relationship between seed yield and seasonal crop water use (Figure 5). For example, soybean yield at Colby, KS increased 3.7 bu/A with each additional inch of water use (precipitation, irrigation plus change in stored soil water). The yield threshold (the amount of water use at which the first increment of yield is expected) occurred with 7.3 inches of crop water use. Similar results were reported for west-central Nebraska (Klocke et al., 1989; Payero et al., 2005). For sunflower, the yield threshold was 4.2 inches and the yield response was 166 pounds per inch of crop water use (Figure 6).

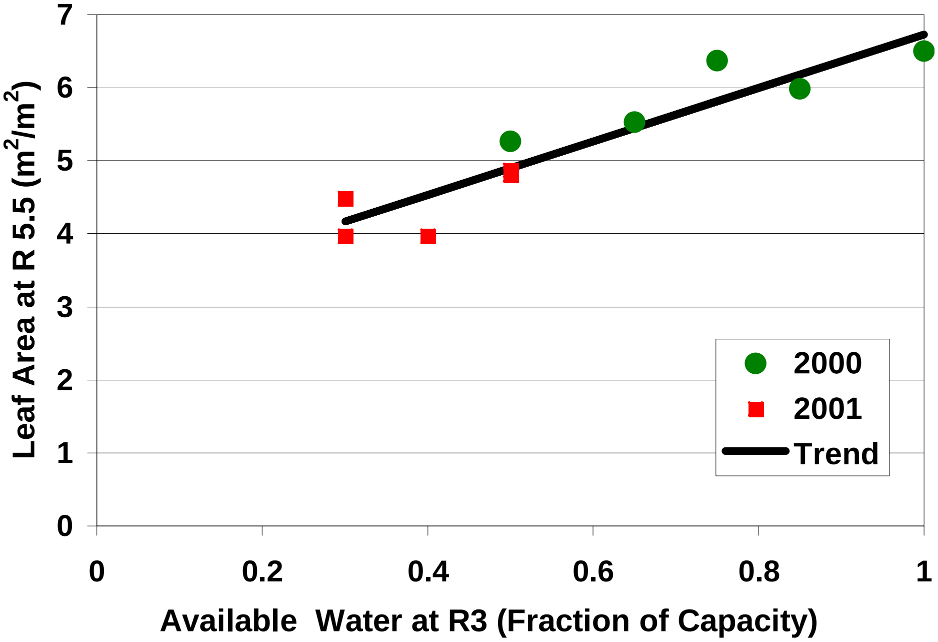

Figure 4. Sunflower leaf area at flowering (R5) in relation to available soil water at mid-bud (R3) growth stage (Aiken and Stockton, 2003).

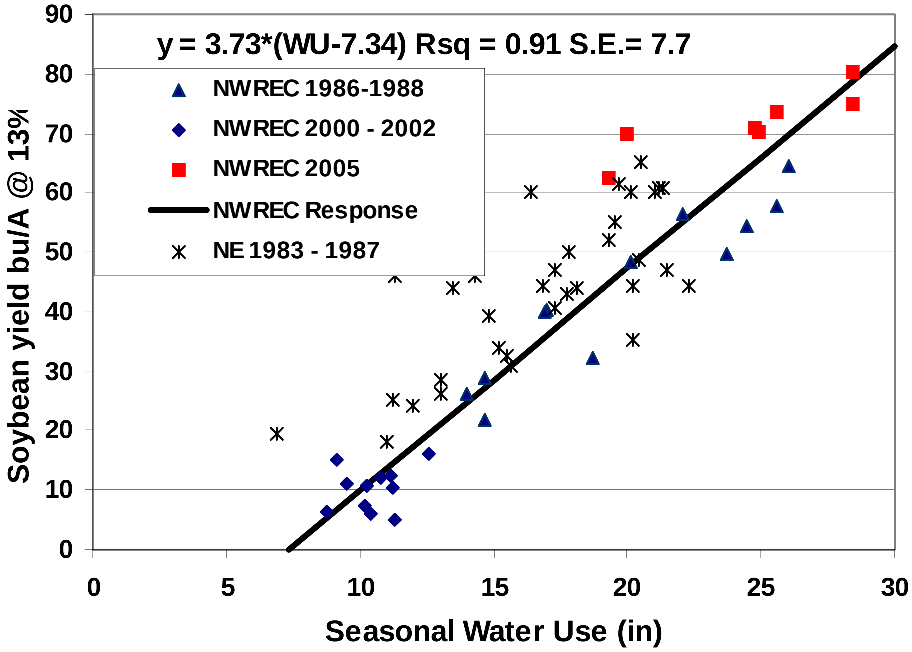

Figure 5. Soybean yield response to seasonal water use at Colby, KS and central Nebraska sites (adapted from Aiken and Gordon, 2003; Lamm, 1989).

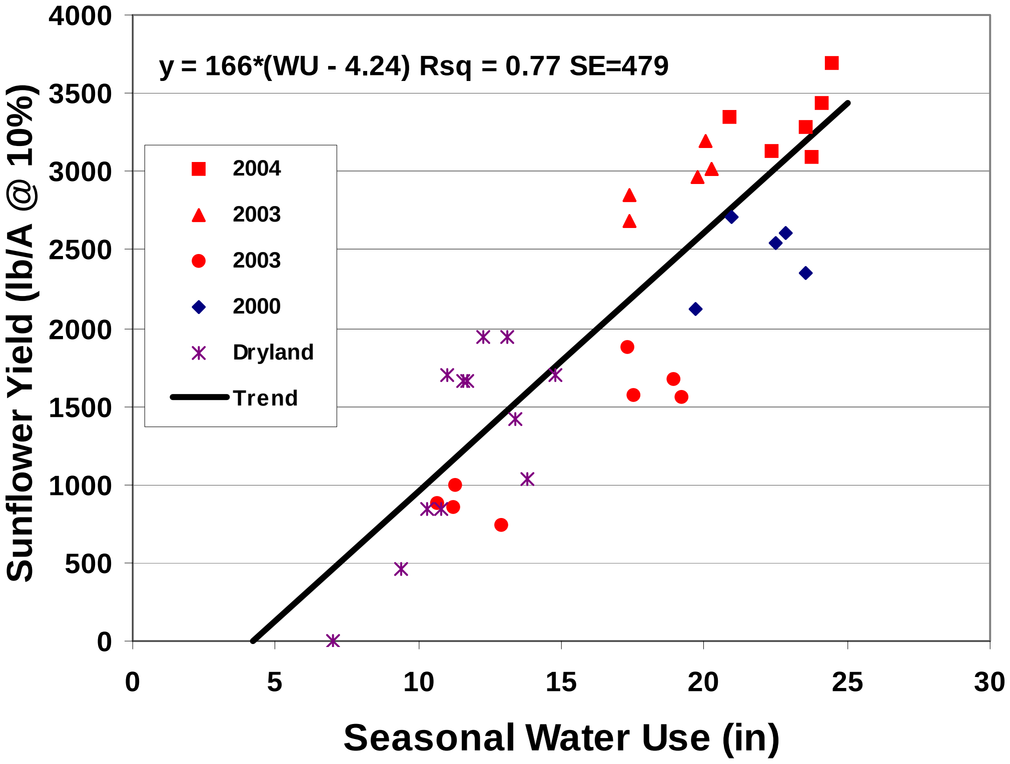

Figure 6. Sunflower yield response to seasonal water use at Colby, KS (adapted from Aiken and Stockton, 2003; Lamm, pers. comm).

Under limited irrigation, water can be allocated to minimize the impact of water deficits on yield formation. For example, soybean yield can be most sensitive to water deficits during flowering and full pod reproductive stages (Table 4). The yield response to limited irrigation can be greatest if water is applied to alleviate deficits during stages which are most critical for yield formation. Critical stages, with maximum crop water use rates, are R3 to R6 for soybean and R1 to R7 for sunflower. Water stress during these critical stages is expected to reduce yield potential. However, Table 4 and Figure 4 indicate that sunflower is also susceptible to soil water deficits during vegetative growth. Additionally, a recent study at Akron, CO showed that delaying limited irrigation until the R4 stage increased oil content of sunflower, though yields were less than that of full irrigation. Irrigators with limited capacity will benefit from good judgement and additional water use and growth stage information.

Double cropping

Soybean or sunflower can be double-cropped after wheat harvest where growing season temperatures and the length of growing season are sufficient. Yield potential will be reduced due to the reduced growing period and effects of the yield threshold. The smaller yield threshold of sunflower may indicate a comparative advantage for double-cropping. Cooler weather can extend the duration of grain fill period but may alter the composition of fatty acids in oil (cooler temperatures can slow the conversion of linoleic fatty acids to oleic forms in oilseeds).

Table 4. Susceptibility of soybean and sunflower to soil water deficits (Adapted from Lamm and Stone, 2005).

	Soybean		Sunflower	
Growth Stage	Time period (days)	Susceptibilty Factor	Time period (days)	Susceptibilty Factor
Vegetative	38	6.9	53	43.0
Flowering	33	45.9	17	33.0
Seed Formation	44	47.2	23	23.0
Ripening	-	-	7	1.0

CROP-SPECIFIC CONSIDERATIONS

Soybean

A full-season, well-watered soybean crop offers relatively greatest productivity potential for non-calcareous soils with acid to neutral pH. The nitrogen-fixing crop can require minimal N fertilizer, provided soil is properly inoculated. Iron chlorosis can limit productivity on calcareous soils with pH exceeding 7.5 (Penas and Wiese, 1990); foliar diseases can also limit productivity. “Early determinate varieties are recommended for production systems involving narrow rows, high seeding rates, early plantings, good fertility, and a yield potential in excess of 50 bushels per acre” (Schapaugh, 1997). Photoperiod effects on flower initiation highlight the importance of selecting varieties from maturity groups appropriate for planting period and desired days to maturity.

Sunflower

Sunflower is commonly planted in early June, in the central Great Plains, to avoid stem weevil and sunflower moth pests. The deep-rooted crop can extract more soil water than other crops. Combined with the smaller yield threshold, sunflower can give relatively greater yields when water supplies are limited. The heat-tolerant crop also tolerates calcareous soil and high pH conditions. Decreasing daylength (when less than 15 h) near the R1 stage can reduce the duration of reproductive stages, due to photoperiod effects, when grown at latitudes less than 40^o.

Canola

Winter canola is established in early fall and harvested mid-summer, similar to winter wheat. The yield advantage of winter varieties over spring varieties is similar to that of winter wheat, approximately 30%. The small-seeded cool-season crop may be difficult to establish, as well as sensitive to heat stress during yield formation stages.

Physiological perspectives

Oilseed crops tend to produce less yield than feed grain crops (i.e., corn and grain sorghum). Less productivity results from differences in photosynthesis and in seed composition. The C3 physiology of oilseed crops is inherently less effective than the C4 physiology of feed grain crops. The C3 carbon-fixing enzyme Rubisco, is approximately 2/3 effective when exposed to atmospheric oxygen concentrations. Plants with C4 physiology also use Rubisco, but it functions in bundle sheath cells where oxygen concentrations are very small, and the enzyme functions at near complete effectiveness, resulting in increased crop productivity.

The second difference between oilseed and feed grain crops involves oil and protein content. The amount of starch which can be produced from a unit of carbohydrate (sugars produced from photosynthesis) is 0.88. The remaining fraction, 0.12, is consumed in the conversion process. More carbohydrate is used up in the formation of oil (0.67) and protein (0.65). As a consequence, the fraction of carbohydrate converted to oil is 0.33; to protein is 0.35. Smaller seed yields of oilseed crops is a consequence of greater oil and protein (in the case of soybean) content, for which a greater fraction of the photosynthetically-fixed carbohydrates are consumed.

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CROP WATER USE
IN LIMITED-IRRIGATION ENVIRONMENTS

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INTRODUCTION

The goal in High Plains agriculture is to use water most effectively in production systems to generate crop yield. To achieve this goal, we must use effective means to capture and store precipitation in the soil profile during noncrop periods, to capture and efficiently use precipitation received during the growing season, and to apply irrigation water in amounts and at times that are most efficient. The selection of appropriate crops – ones that match the expected water supply conditions of the production system – is also a requirement. This paper discusses options and practices that can lead to more effective use of water. These discussion points have application to both dryland and irrigated production systems.

YIELD vs. WATER RELATIONSHIPS

Crop yield vs. water relationships provide information that can be used in making decisions on the appropriateness of crops in production systems, through a consideration of the expected water supply conditions. Figure 1 illustrates the general relationships between seed yield and water amount (ET or water use). ET refers to evapotranspiration while water use refers to ET plus losses by runoff and internal drainage from the soil profile. Seed yield vs. ET is a linear relationship, although variability can and does exist. Seed yield vs. water use (ET + Runoff + Drainage) is typically a curvilinear relationship, with losses from runoff and drainage increasing with increasing water supply in the system. The seed yield vs. ET relationship is more transferable among geographic locations than is the seed yield vs. water use relationship that is more influenced by soil and landform characteristics that influence runoff and drainage.

Table 1 lists values of “Threshold ET”, “Maximum ET for a typical full-season variety”, “Slope of seed yield vs. ET”, and “Slope of long-term seed yield vs. ET” for five crops from research in western Kansas (Khan, 1996; Khan et al., 1996). “Threshold ET” is the ET necessary to move into the seed producing segment of the yield vs. ET relationship: at the “Threshold ET” value and below, seed yield is zero. “Maximum ET” is seasonal ET measured from emergence to physiological

The “Threshold ET” value is of critical importance in assessing if seed yield will likely be obtained in drier crop environments. Within the four summer row crops of Table 1, “Threshold ET” is 5.4 inches for sunflower, 6.9 inches for sorghum, 7.8 inches for soybean, and 10.9 inches for corn. If water supply available for crops is limited, the “Threshold ET” values illustrate why sunflower or sorghum would be preferred over corn. Also, the water stress sensitivity of growth stages of various cops is important in assessing their suitability for drier environments. The “Slope of yield vs. ET” is important in assessing the response of crops to irrigation that is converted into ET. Within the four summer row crops of Table 1, yield response per inch of ET is 218 lb/acre/inch for sunflower, 276 lb/acre/inch for soybean, 683 lb/acre/inch for sorghum, and 946 lb/acre/inch for corn. These values illustrate the greater yield responsiveness of corn to irrigation.

The relationships of Table 1 were developed from multiple data sources (treatments, years, and locations) and represent conditions consistent with full-season cropping in the central High Plains. The values of Table 1 can be altered by specific conditions of crops and growing seasons. Growing season ET of a specific year will be greater, or less, than the “Maximum ET” values of Table 1 if the year has greater, or less, potential ET than the average year. With water-stress conditions, if water application is beneficially timed, yield can be obtained even when actual ET is less than “Threshold ET.” And, if water application is poorly timed and water-stress conditions exist, yield may not be obtained even though actual ET is greater than “Threshold ET.” With water-stress conditions, if water application is beneficially timed, the yield benefit will be greater than the “Slope of yield vs. ET” of Table 1. And, if water application is poorly timed and water-stress conditions exist, the yield benefit will be less than the “Slope of yield vs. ET” of Table 1.

YIELD RESPONSE TO WATER STRESS

Yield sensitivity to water deficit during various growth periods (e.g., vegetative, flowering, grain formation, and ripening) varies among crops. In general, grain crops are more sensitive to water deficit during flowering and early seed formation than during vegetative and ripening (Doorenbos and Kassam, 1979). Soybean is an exception, being more sensitive to water stress during bean formation than during flowering or vegetative. If growth is under water-stress conditions, rain or irrigation at the most water-sensitive growth period will provide more yield increase per unit of water than if water is applied during other growth periods. Table 2 gives the relative yield response (decrease) per unit of ET deficit (water deficit) during growth periods of five crops. The values should be compared within a crop to get the relative weighting of water stress sensitivity of various growth periods for the individual crop. That is, within corn, an inch of ET deficit during flowering decreases grain yield 3.8 times as much as an inch of ET deficit during the vegetative stage (0.53/0.14 = 3.8). Within grain sorghum, an inch of ET deficit during flowering decreases grain yield 2.0 times as much as an inch of ET deficit during the vegetative stage (0.42/0.21 = 2.0). Along with sensitivity to water stress in corn being greatest during flowering, daily ET is greatest during flowering through the milky-fluid growth stage. These two factors working together produce the critical need for water in corn during flowering.

Table 2. Relative yield response per unit of ET (within a crop) to water deficit during selected growth periods.

	Growth period			
Crop	Vegetative	Flowering	Yield formation	Ripening
Corn	0.14	0.53	0.19	0.14
Grain sorghum	0.21	0.42	0.21	0.16
Sunflower	0.25	0.42	0.27	0.06
Winter wheat	0.19	0.51	0.25	0.05
Soybean	0.10	0.40	0.50	-----

The relative weighting of water stress sensitivity within a crop is illustrated in Table 2. Relative weightings of water sensitivity give insight into the growth periods of most critical water need for those five crops. Rainfall during the most sensitive growth periods will give the greatest yield benefit. Also, limited irrigation should be timed to avoid water stress at the most sensitive growth stages. That timing strategy will give the greatest yield benefit from a limited water resource. The timing of limited irrigation to give maximum seed yield benefit is given in Table 3.

Table 3. Timing of limited irrigation for maximum seed yield benefit.

Crop	Initiation of limited irrigation….	To avoid (lessen) water stress particularly during
Corn	Near (prior) or at tasseling	Silking
Grain sorghum	Head extension	Flowering
Sunflower	Head development	Disk flowering
Winter wheat	Head extension	Flowering
Soybean	Mid to late pod set	Early to mid bean fill

Of the five crops of Tables 1, 2, and 3, corn and soybean are the two most affected by water-critical growth periods. Corn yield is most negatively impacted by water stress from near-tasseling through silking, typically mid through late July. Soybean yield is most negatively impacted by water stress during bean fill, typically mid August to mid September. Therefore, if in a limited-irrigation production system and the water supply can not be depended on to avoid (or lessen) water stress in the critical times for corn and soybean, these two crops become much less attractive as crop choices. The suitability of crops for rainfed-only production systems in drier environments is influenced by "Threshold ET" (Table 1) and water stress sensitivity (Table 2). Crops with greater "Threshold ET", and with greater water stress sensitivity, are less appropriate for rainfed-only systems than crops with lower "Threshold ET" and lower water stress sensitivity. The suitability of crops for limited-irrigation production systems in drier environments is influenced by "Threshold ET", water stress sensitivity, crop response to added water ("Slope of yield vs. ET"), and dependability of the irrigation water supply.

PREPLANT IRRIGATION

Preplant irrigation is often an inefficient use of water in production systems where in-season irrigations are applied. In Texas, Musick et al. (1971) found that preplant irrigation did not increase grain sorghum yields appreciably when all treatments received the same two or three in-season irrigations. With irrigated corn in west-central Kansas, Stone et al. (1987) found no significant grain yield increase from preplant irrigation when there were multiple in-season irrigations. After an analysis of available soil water (ASW) data from corn fields receiving in-season irrigation in northwest Kansas, Rogers and Lamm (1994) stated "preseason irrigation of corn should not be a recommended practice for the region."

As producers attempt to stretch limited water supplies and the times of application to maintain systems that use limited-capacity wells, questions arise on the advisability of using preplant irrigation. In a review of preplant irrigation in the High Plains, Musick and Lamm (1990) concluded that "benefits of preplant irrigation are likely to be greatest when the soil profile is dry before planting" and "benefits are likely to be low when soil profiles are moderately wet at time of irrigation." The retention and storage of preplant irrigation in our deep silt loam soils are heavily dependent on water content of the soil profile during and after irrigation. As soil water content increases, water losses from evaporation, profile drainage, and surface runoff increase. A need exists for guidelines and illustrations of preplant irrigation efficiencies that will aid producers as they consider the practice to stretch limited well capacities and water supplies. From work in irrigated areas of the Canadian prairies, Hobbs and Krogman (1971) concluded that preseason irrigation was advisable (relatively efficient) when soil water was below 50% of maximum ASW. Dormant-season irrigation research in west-central Kansas found that water loss from the soil profile occurs at increasing levels as water content of the soil profile rises above 60% of maximum ASW (Stone et al., 1987). Rogers and Lamm (1994) stated that additional irrigation above the amount required to bring the profile to 50% of maximum ASW has a high probability of being lost or wasted.

To illustrate water loss from preplant irrigation in spring, we used the KS Water Budget software (Khan et al., 1996) to project soil water levels and corn grain yields (Table 4). Projections were for conventionally-tilled corn (as opposed to no-till) with annual precipitation of 17.5 inches. As a point of reference, Goodland, KS has long-term annual precipitation of 17.7 inches. We assumed four levels of ASW in the 6-foot soil profile on 15 March (column 1, Table 4): 10, 30, 50, and 70% of maximum ASW, which are 1.4, 4.2, 7.1, and 9.9 inches of water in the profile, respectively. We then projected ASW on 15 May and corn grain yield for the four initial levels of ASW with no irrigation, and 17.5 inches of precipitation (column 2, Table 4). Column 3 shows results where 1.0 inch of water was added to profile water on 15 April, and then no later irrigations. In each of columns 4, 5, and 6, an additional 1.0 inch of water was added to profile ASW on the indicated date. We did not estimate irrigation application efficiencies, but were estimating the retention efficiency of water added to stored soil water on the expressed dates. Where ASW was at 10% of maximum on 15 March, about 0.9 inches of each 1.0 inch added to storage in April was in storage on 15 May, and yield increase was 15 to 17 bu/acre per 1.0 inch of water added to storage in April. Where ASW was at 30% of maximum on 15 March, there was again about 0.9 inches of each 1.0 inch added to storage in April in storage on 15 May. Yield increase was 12 to 17 bu/acre per 1.0 inch of water added to storage in April, with the yield increase decreasing with increasing irrigation amount. Where ASW was at 50% of maximum on 15 March, the first 2 inches showed an increase in storage on 15 May of 0.9 inches per 1.0 inch added to storage. The fourth 1.0 inch of added water showed a gain on 15 May of only 0.6 inch. Grain yield showed a similar trend, with the first 2 inches showing yield increase of 13 and 11 bu/acre. The fourth 1.0 inch added to storage showed a yield increase of 5 bu/acre. Where ASW was at 70% of maximum on 15 March, water gains and yield benefits resulting from water additions were dropping rapidly. The third 1.0 inch addition to storage showed an improvement of only 0.4 inch of water and 2 bu/acre of yield. The fourth 1.0 inch addition showed improvements of only 0.2 inch of water and 1 bu/acre of yield.

The projections in Table 4 illustrate the precipitous decrease in benefits from spring preplant irrigation as ASW increases above about 60% of maximum. Rainfall conditions for a given year would influence the projected values and efficiencies of Table 4. Also, these projections do not consider the application efficiencies of preplant irrigation. The use of spring preplant irrigation on the deep silt loam soils does appear to be a relatively efficient use of water if the ASW level plus added water does not exceed 60% of maximum ASW, and if the water can be added to the soil profile with acceptable water application efficiencies.

Table 4. Illustration matrix for preplant irrigation[1]

Soil water on 15 March[2]	Net irrigation during spring (inches)[3]				
	0.0	1.0	2.0	3.0	4.0
10% 1.4 in.	2.7 in.[4] 0 bu/ac[5]	3.6 in. 13 bu/ac	4.5 in. 30 bu/ac	5.4 in. 46 bu/ac	6.3 in. 61 bu/ac
30% 4.2 in.	5.1 in. 40 bu/ac	6.1 in. 57 bu/ac	7.0 in. 73 bu/ac	7.9 in. 87 bu/ac	8.8 in. 99 bu/ac
50% 7.1 in.	7.7 in. 83 bu/ac	8.6 in. 96 bu/ac	9.5 in. 107 bu/ac	10.3 in. 115 bu/ac	10.9 in. 120 bu/ac
70% 9.9 in.	10.0 in. 112 bu/ac	10.7 in. 118 bu/ac	11.2 in. 122 bu/ac	11.6 in. 124 bu/ac	11.8 in. 125 bu/ac

[1] Annual precipitation of 17.5 inches. Conventionally-tilled corn. Four levels of available soil water (ASW) are assumed for 15 March.

[2] Available soil water as percentage of maximum, and in inches, for the 6-ft profile on 15 March.

[3] If applied, 1st 1.0 in. of irrigation on 15 April, 2nd 1.0 in. on 8 April, 3rd 1.0 in. on 1 April, and 4th 1.0 in. on 25 March.

[4] Inches of available soil water in the 6-ft profile on 15 May.

[5] Corn grain yield in bushels per acre.

PRECIPITATION STORAGE DURING NONCROP TIMES

The improved ability of no-till systems, compared with conventional, stubble-mulch (sweep) tillage, to capture and retain precipitation during fallow and to have more water stored in the soil profile for the next crop has been quantified in a number of dryland studies in the High Plains (Table 5). Key factors that lead to improved capture and storage of precipitation in noncrop periods are reduced levels of tillage, increased amounts of residue, and keeping the residue as upright as possible. Water loss from evaporation resulting from a single tillage event can be about 1/2 inch (Good and Smika, 1978). The water loss amount is influenced by depth of tillage, extent of disturbance, crop residue remaining on the surface after tillage, soil water amount at the time of tillage, and weather conditions after tillage. The gain in stored soil water during fallow is increased by increasing the amount of residue (mulch) (Greb et al., 1967). Storage of precipitation during fallow is also increased by having the residue in an upright position (Smika, 1983). During winter, standing residue can trap blowing snow and keep this water source on the field. Standing residue also benefits precipitation storage by decreasing evaporation losses, as compared with flat residue. Of the atmospheric conditions of air temperature, vapor pressure deficit, solar radiation, and wind speed, “Soil water losses were best correlated with wind movement” (Smika, 1983). Standing residue decreases wind speed at the soil surface, thereby reducing the evaporation of water. The decreasing of wind speeds at the soil surface by standing residue is also why standing residue is so effective at reducing soil erosion by wind.

Table 5. Additional water gain during fallow with no-till compared with conventional-till of various rotations and locations in the High Plains.

		Additional stored water in soil profile with no-till compared with conventional-till at planting of:[+]				
Years	Location	Wheat in WW	Wheat in WF	Wheat in WSF	Sorghum in WSF	Reference
		inches				
1963-66	North Platte, NE		3.4	1.5		Smika & Wicks, 1968
1975-87	Akron, CO		1.7			Smika, 1990
1993-01	Akron, CO		2.8			Nielsen et al., 2002
1987-90	Garden City, KS	0.7	1.5	1.5	1.6	Norwood, 1992
1984-93	Bushland, TX	1.1	0.6		0.9	Jones & Popham, 1997

[+] WW = continuous wheat, WF = wheat-fallow, and WS = wheat-sorghum-fallow.

The principles of less tillage, more residue, and upright residue can lead to additional water stored in the soil profile as with the systems of Table 5. Variability exists in precipitation storage data from field studies, however, 1.5 to 2 inches of additional water stored at planting as a result of no-till techniques compared with conventional till is a reasonable expectation in typical cropping systems of the central High Plains. It is reasonable to project that reduced tillage-increased residue principles will result in more stored water at planting in limited irrigation systems, as is the case in dryland cropping systems.

EFFICIENCY OF WATER SUPPLY USE DURING GROWING SEASONS

The relation between growing season water supply (ASW at emergence and in-season precipitation), and grain yield of sorghum and wheat is presented in Fig. 2 and 3, respectively. The data sets are from 30 years of research near Tribune, KS. Data are from dryland cropping systems, and some from preplant irrigation: with no data having in-season irrigations. Grain yields increased at mean rates of 6.7 bu/acre (sorghum) and 3.78 bu/acre (wheat) per inch of water supply. These values are less than the long-term slopes of 9.2 bu/acre (sorghum) and 4.5 bu/acre (wheat) of yield increase per inch of ET from Table 2. Water supply has lower slope than ET because some of the water supply would be lost as runoff and evaporation from precipitation events, and some would remain in the soil profile as water stored at crop maturity.

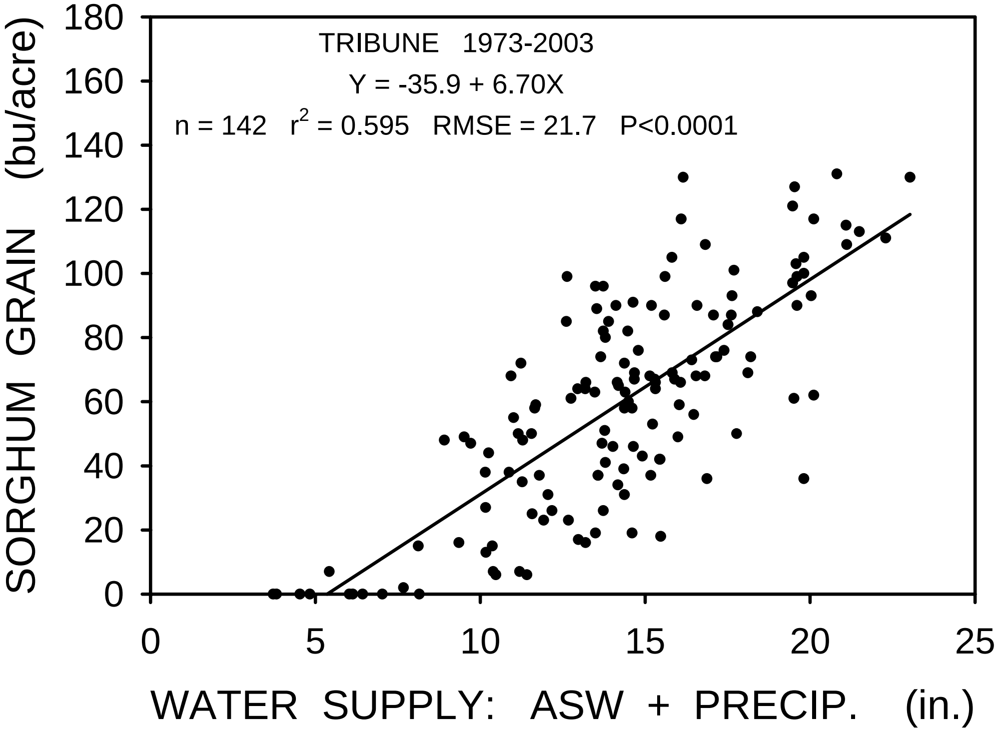

Fig. 2. Grain sorghum yield associated with water supply (available soil water plus within-season precipitation).

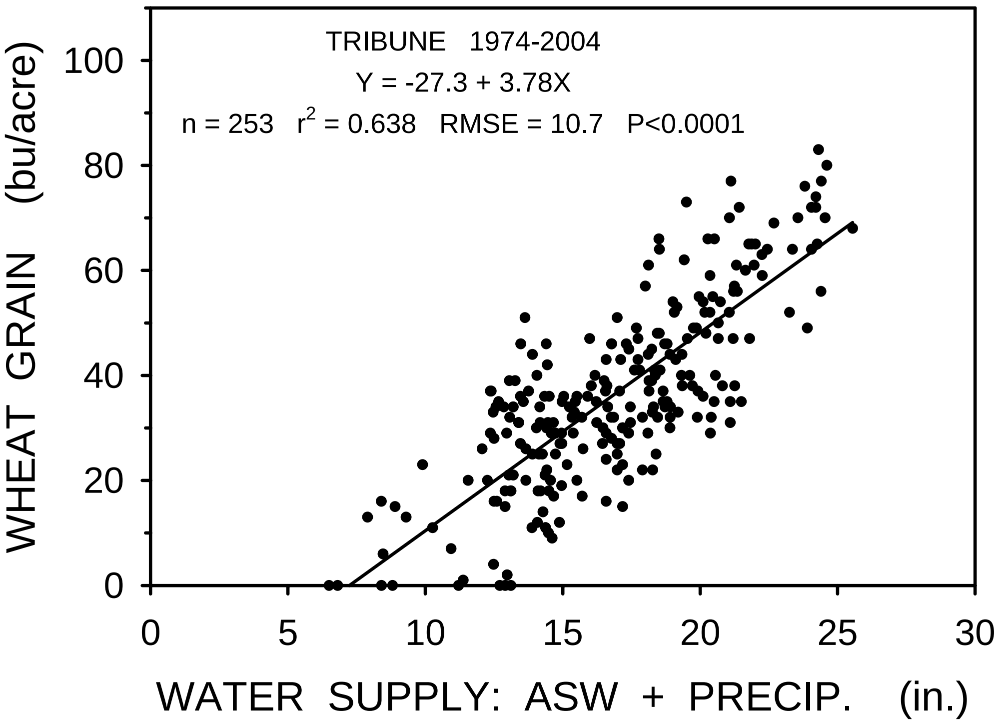

Fig. 3. Winter wheat yield associated with water supply (available soil water plus within-season precipitation).

We then separated out the data of Fig. 2 and 3 that was from conventional (sweep) tillage and no tillage dryland systems. The sorghum conventional till data are in Section A of Fig. 4 and the no-till data in Section B. With conventional till, the sorghum yield vs. water supply slope was 5.22 bu/acre/inch and with no till the slope was 7.45 bu/acre/inch. The wheat conventional till data are in Section A of Fig. 5 and the no-till data in Section B. With winter wheat, the grain yield vs. water supply slope was 3.24 bu/acre/inch with conventional (sweep) till and 5.20 bu/acre/inch with no till. The data of Fig. 4 and 5 indicate that residue and no till management provide for greater water use efficiency during the growing season compared with the conventional till systems. This improvement is from decreased evaporation and maintaining of infiltration capacities with residue.

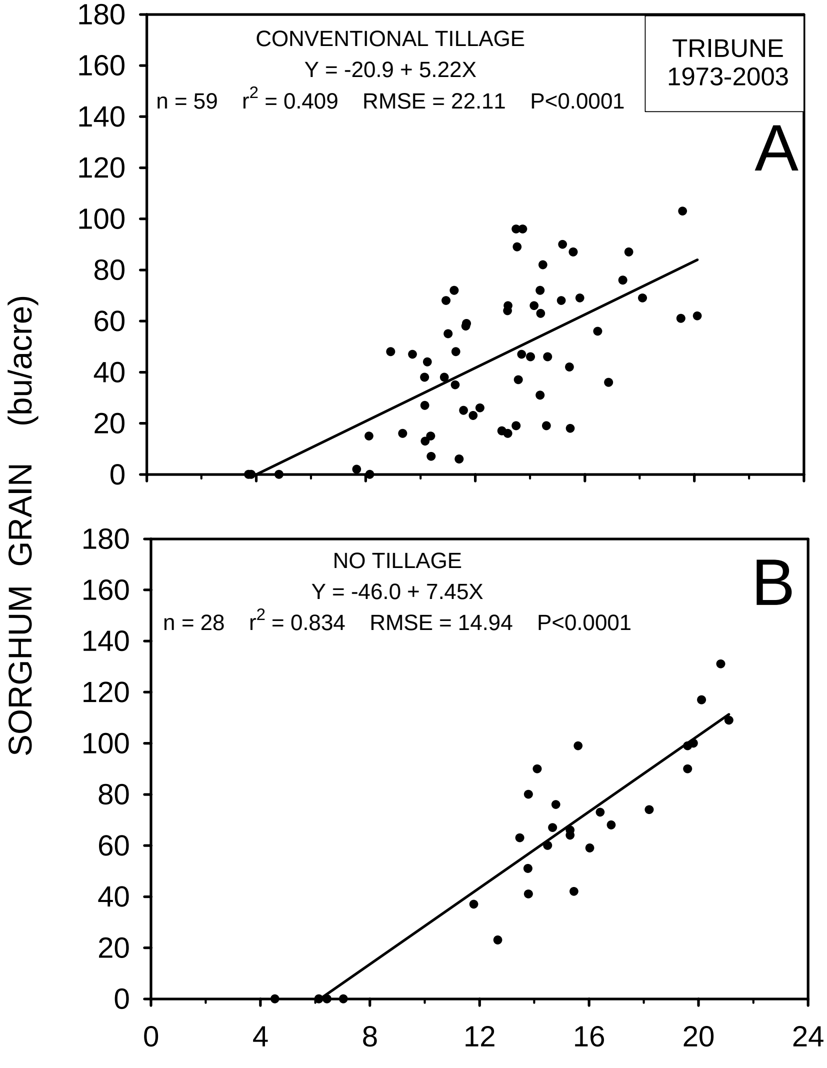

Fig. 4. Grain sorghum yield associated with water supply (available soil water plus within-season precipitation) for the dryland conventional tillage (section A) and dryland no tillage (section B) treatment groups.

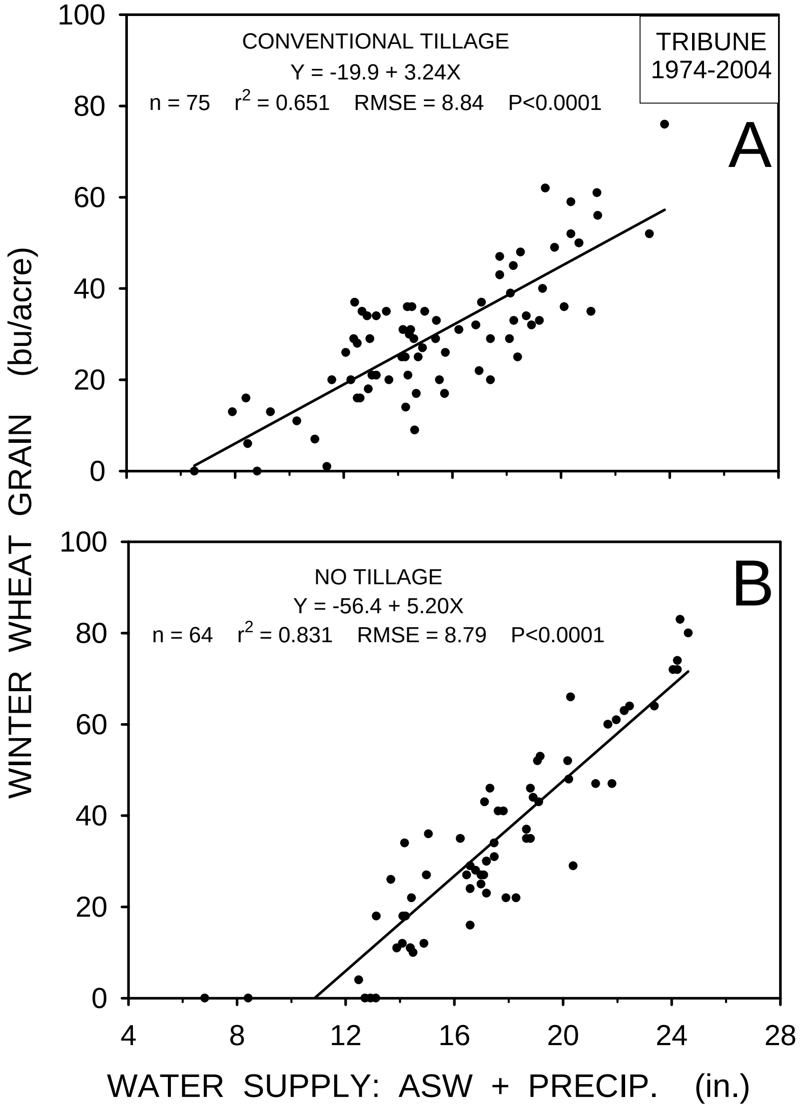

Fig. 5. Winter wheat yield associated with water supply (available soil water plus within-season precipitation) for the dryland conventional tillage (section A) and dryland no tillage (section B) treatment groups.

The improved yield response to water supply in no till compared with conventional till was in both sorghum (Fig. 4) and wheat (Fig. 5). It is reasonable to project the tillage-residue influence to limited irrigation environments, with the thought that increased residue would provide for more efficient use of in-season water supplies, as we have demonstrated with dryland cropping systems.

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WHERE DID ALL THE IRRIGATORS GO?
TRENDS IN IRRIGATION AND DEMOGRAPHICS IN KANSAS

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Abstract

The 2000 United States Census indicated that Kansas had grown by 8.51 percent in population since 1990, compared to the national average growth rate of 13.15 percent. Only nine (9) of 105 counties in Kansas experienced growth equal to or greater than the national average growth rate. From 2000-2004 only 8 counties grew at or above the national average growth rate. In 1990, Kansans were 1.00 percent of the U.S. population, in 2004 only 0.94% of the population. The 2004 population estimates had 56 of 105 counties in Kansas declining in population since 2000. Of the 54 counties overlying the High Plains aquifer, only three (3) counties had equal or greater growth than the national average. In addition the census also indicated a cultural transition as many counties experienced domestic out-migration and foreign immigration.

Agricultural Census data document a 5.26 percent decrease in the total market value of agricultural products from 1997 to 2002, while the total number of farms increased 4.58 percent in Kansas during the same period. The number of Irrigated farms decreased by 3.58 percent with total irrigated acres declining by only 1.07 percent to 2.678 million acres over the same five year period. Total acreage in crop production declined 1.59 percent, while the market value of crops sold decreasing 24.9% from $3.22 billion in 1997 to $2.42 billion in 2002.

Since 1990, irrigation technology has dramatically changed to more efficient low pressure pivot and SDI (subsurface drip irrigation) systems. With more efficient water use, irrigators have been able to grow significantly more corn and other water intensive crops. Given the 3.5 percent decrease in the number of irrigated farms since 1997, the resulting 1.08 percent decline in irrigated acres indicates increased acreage efficiency by remaining irrigators.

This presentation intends to demonstrate spatial and temporal trends in irrigation and demographics for Kansas, with focus on the 54 counties overlying the High Plains Aquifer.

Population Change in Kansas Contrasted with the US

In the 20th century, the population of Kansas increased from 1.5 to about 2.7 million people, growing approximately 8 percent per decade. In the latest decade (1990 to 2000), the US Census indicated Kansas growth at 8.51 percent, compared to the national average of 13.15 percent. Historically, when comparing two decennial census, Kansas has experienced 5-10 percent less growth than the nation. During the last decade, 9 of 105 Kansas counties (indicated with blue outline) experienced growth equal to or greater than the national average growth rate as illustrated in the Population Ratio 1990:2000 map.

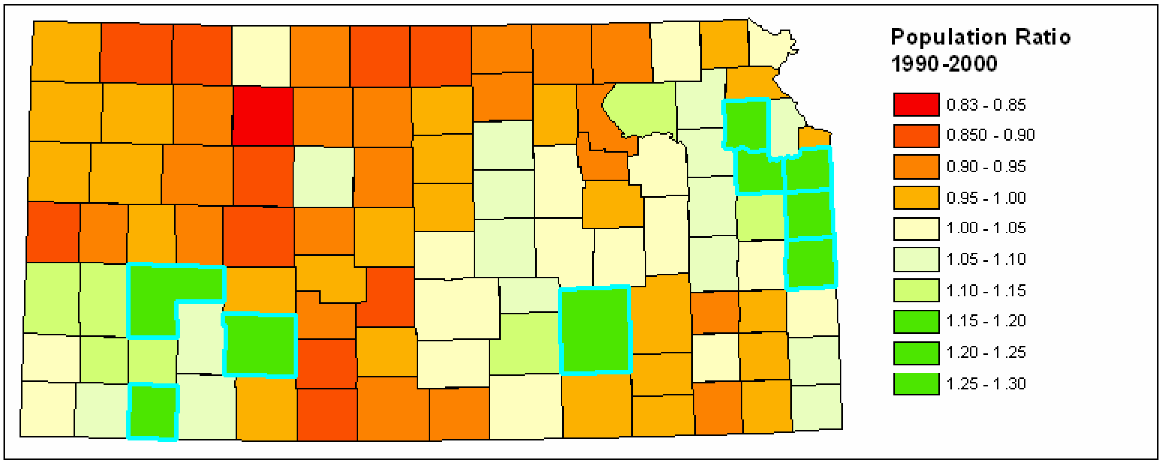


Figure 1. Kansas Population Ratio 1990-2000

Comparing the latest population estimate (2004) with 2000, only 8 counties grew at or above the national average growth rate. In 1990, Kansans totaled 1.00 percent of the U.S. population, in 2004 only 0.94% of the population. The 2004 population estimates had 56 of 105 counties in Kansas declining in population since 2000. Of the 54 counties overlying the High Plains aquifer, only three (3) counties had equal or greater growth than the national average. In the last century (1900-2000) census data indicate that county population peaked in 1939 on average across the state as illustrated in Figure 2 and Table 1.

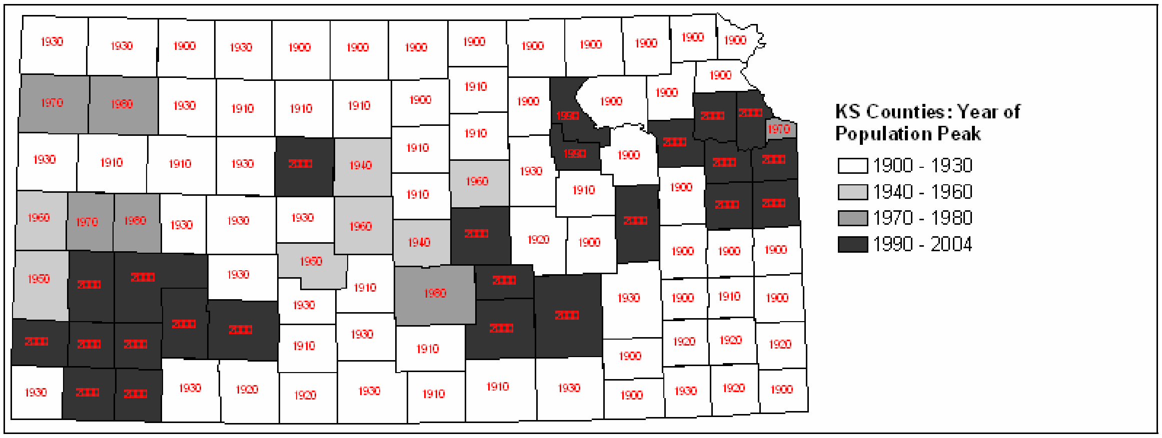
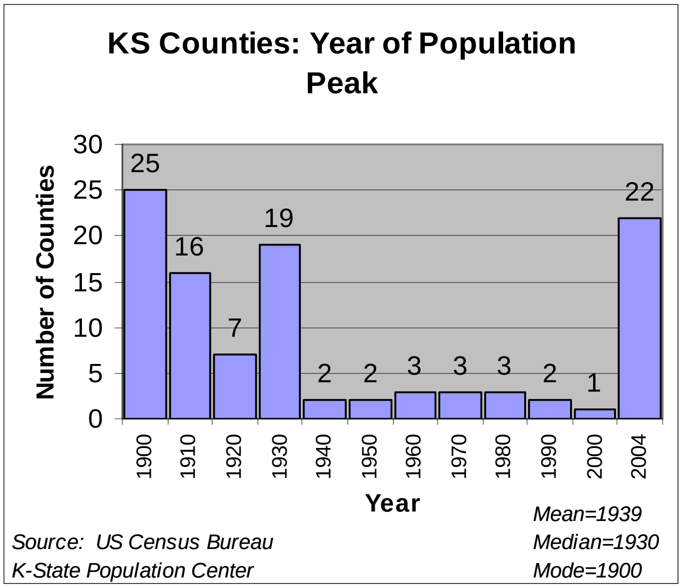


Figure 2. Kansas Counties Year of Population Peak

Figures 1 and 2 indicate growth of counties having larger communities or metropolitan areas. Both US, and Kansas population growth has been mainly concentrated in metropolitan areas throughout the last hundred years as illustrated in the following maps comparing the population distribution by county in 1900 and 2004. In Figure 3 note that in 1900 a more even statewide distribution of population existed than 2004.



Mean=1939
Median=1930
Mode=1900

Source: US Census Bureau
K-State Population Center

Table 1. Kansas Counties Year of Population Peak

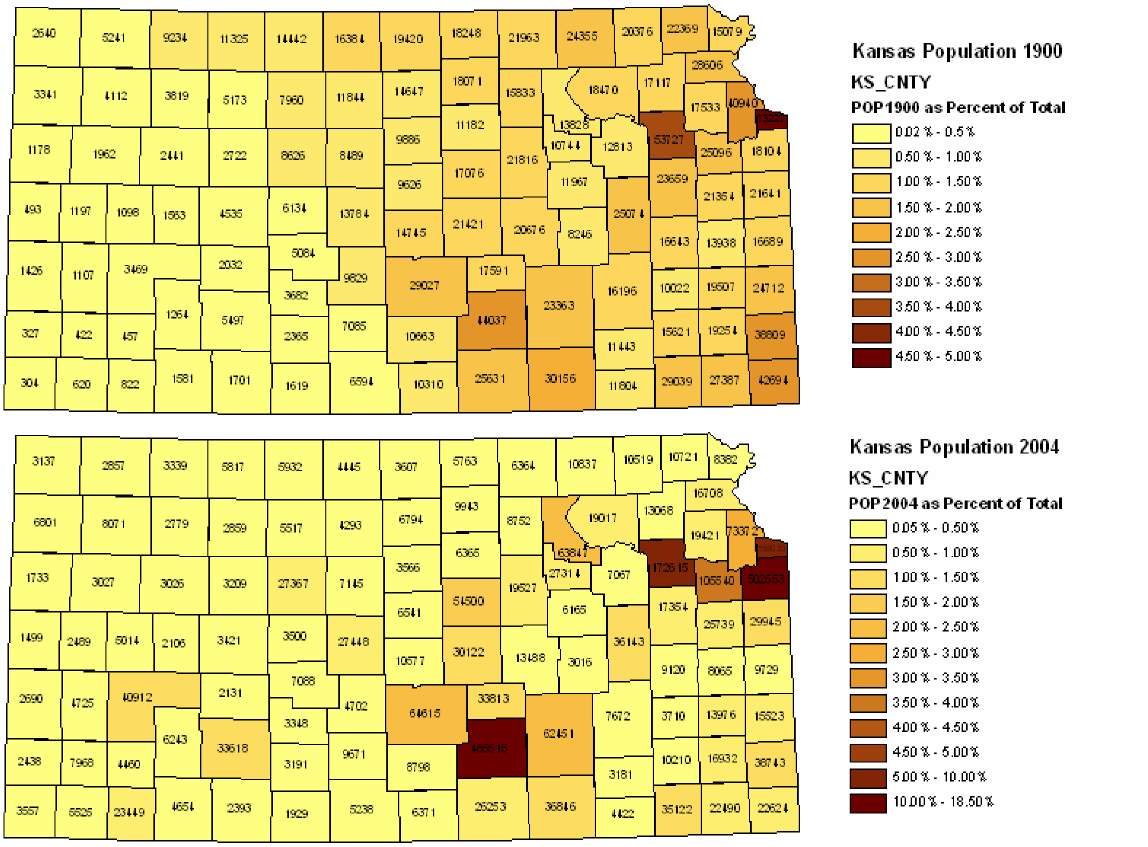


Figure 3. Kansas County Population 1900 and 2004 as a Percent of State Population

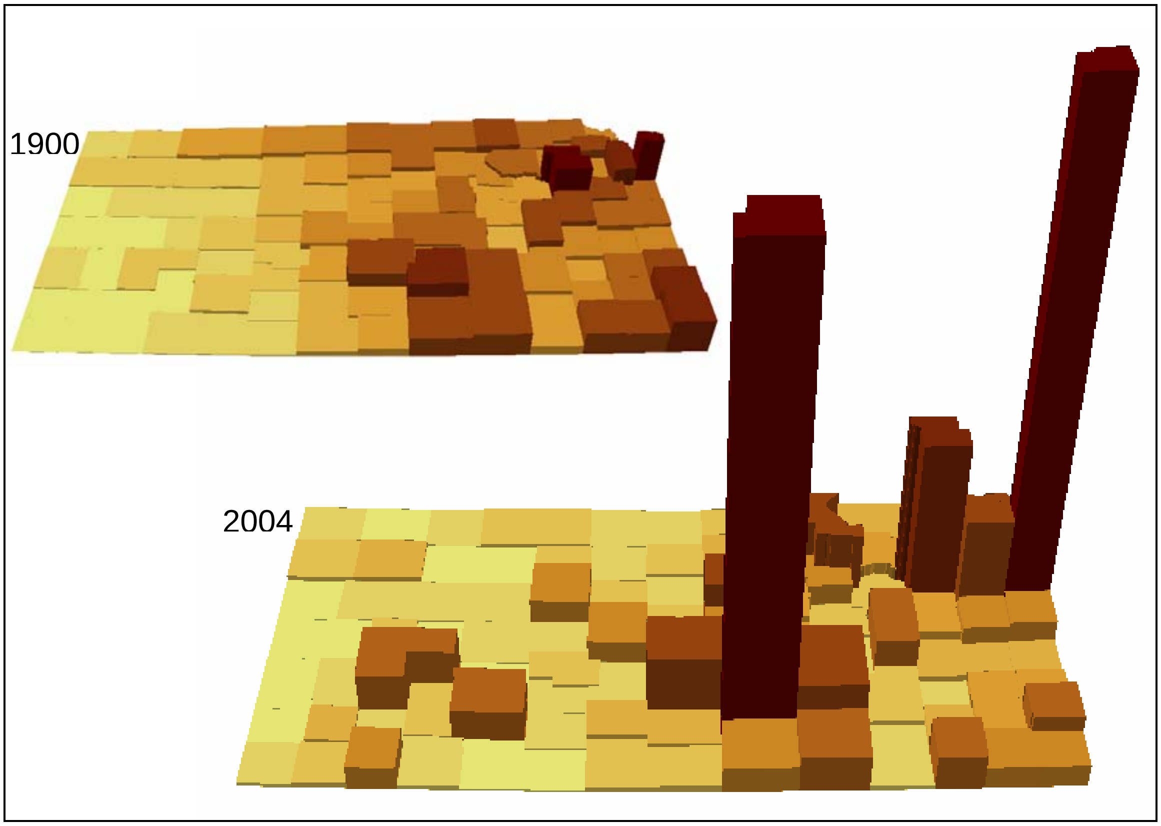


Figure 4. Kansas County Population 1900 and 2004 Extruded by Population

The three-dimensional maps of Kansas emphasize a drastic change in population distribution from 1900-2004, as well as the trend toward metropolitan growth which parallels the US. Kansas counties near the metropolitan areas of Kansas City and Wichita, and along the Interstate 70 and 35 corridors from Kansas City to Topeka and Wichita experienced the greatest growth. In contrast, there were counties in Western Kansas that lost more than 10 percent of their population between 1990 and 2000—Graham, Ness, Greeley and Comanche.

Population projections by US Census Bureau and the Kansas Water Office indicate a steady and similar trend for Kansas as seen in the past century. Between 2000 and 2030 the population of Kansas is projected to increase approximately 9 percent, again well below the projected 29 percent increase in the US. The projected growth disparity between Kansas and the US creates both economic and political challenges. More challenging however, is the compositional aspect of the population change. Of the predicted increase between 2000 and 2030, approximately 237,000 of 252,000 people, will be in the 65+ age category. As illustrated in Figure 5 for Sheridan County, which is representative of many counties in western Kansas, there is an erosion of the base population age cohort of 0-4, and drastic thinning of the 20-34 age cohorts which normally replace the base age cohort.

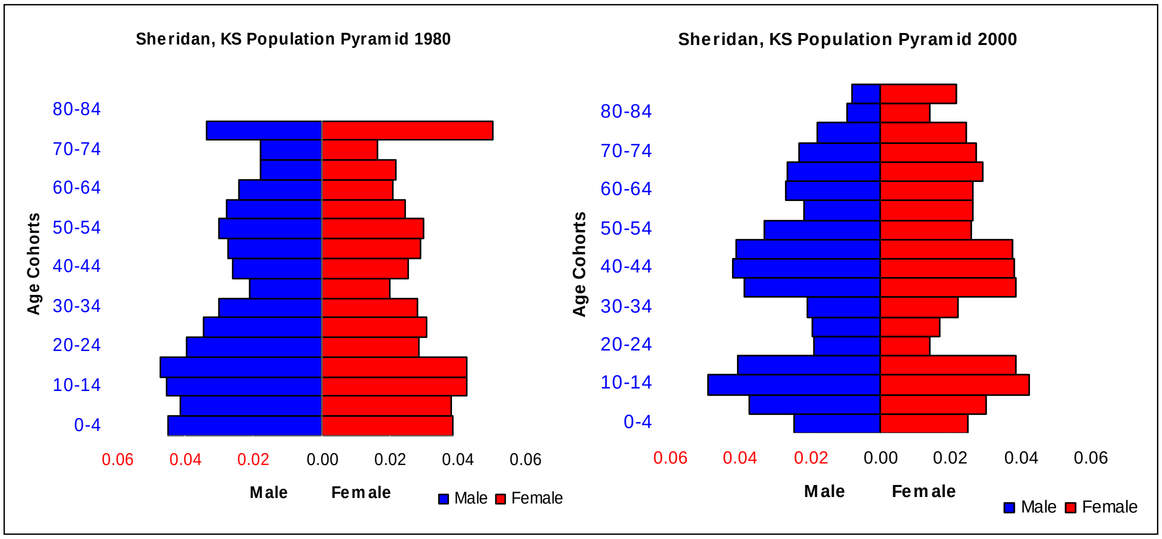


Figure 5. Sheridan County Kansas Population Pyramids for 1980 and 2000

Therefore the bulk of the predicted population increase will be the transition of the baby boomers into higher age cohorts above 60. Since Kansas does not have significant retirement migration destinations, the population will be aging in place, further perpetuating economic and social challenges for particular communities, especially those in Western Kansas.

Aging will not be the only compositional change in Kansas. Southwestern counties experienced a rapid influx of international migrants in recent history. This corresponds with the dominant economic activities in animal and meat production, a pattern that likely will not change. The spread of the Hispanic population across the rural Midwest is a relatively new phenomenon facing policy makers and community professionals. The Hispanic population in 1990 comprised 4 percent of the total population of Kansas, and in 2000 increased to 7% of the state population. In High Plains Aquifer Counties, Hispanics in 2000 accounted for 9 percent of the population and the total White percentage fell to 76%, while Kansas as a whole went from 86% to 80% in the same period.

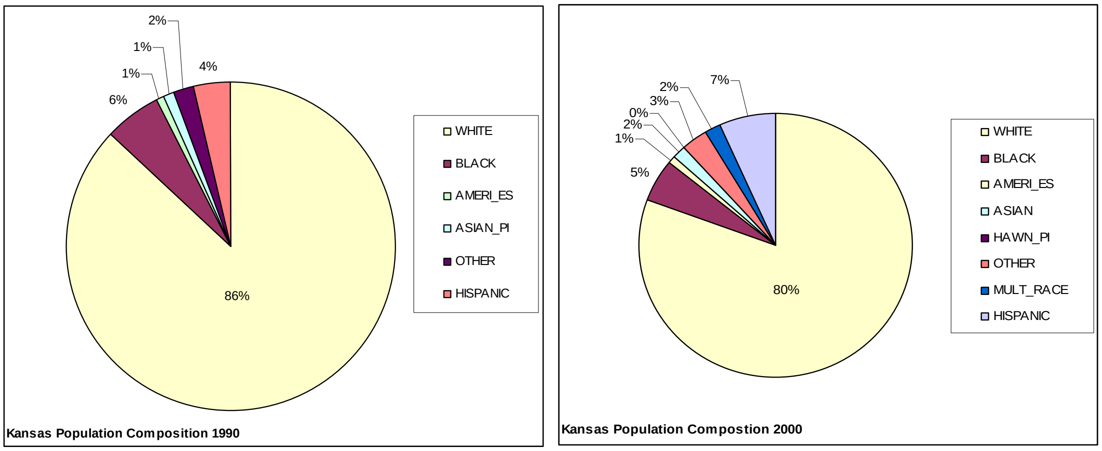


Figure 6. Kansas Population Composition 1990-2000

Agricultural Changes in Kansas

Kansas Agricultural Census data for 1997 and 2002 document a 5.26 percent decrease in the total market value of agricultural products, while the total number of farms increased 4.58 percent in Kansas during the same period. The number of Irrigated farms decreased by 3.58 percent with total irrigated acres declining by 1.07 percent to 2.678 million acres over the same five year period. Total acreage in crop production declined 1.59 percent, while the market value of crops sold decreasing 24.9% from $3.22 billion in 1997 to $2.42 billion in 2002.

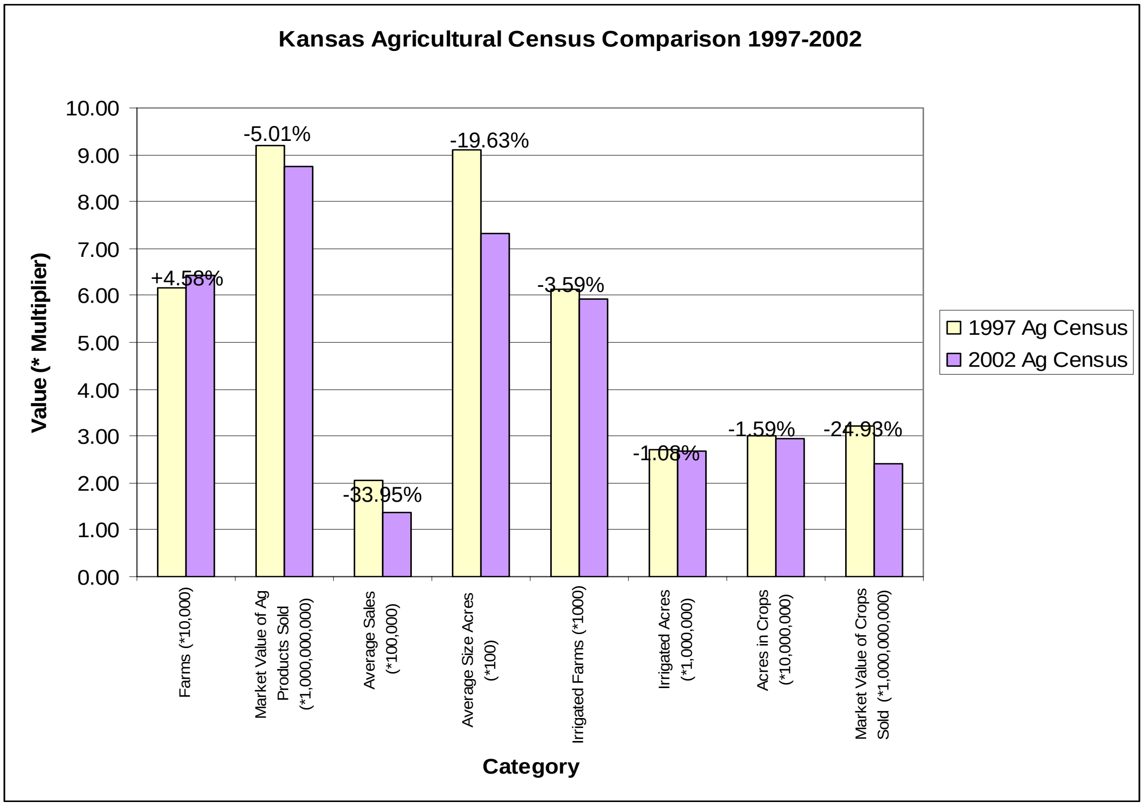


Table 2. Kansas Agricultural Census Comparison 1997-2002

Comparing the 1997 and 2002 Agricultural Census data for Kansas by county reveals that 31 of 105 counties lost total numbers of farms with six counties losing 10% or more farms. See Figure 7. The Average size of farms decreased in 54 of the 105 counties with the greatest decrease in average size per farm being 37%, and the greatest increase being 36% in Marshall County. Nine counties experienced a 10% or greater increase in average farm size. See Figure 8. Total crop acres decreased in 67 counties and increased in the remaining 38, with the greatest increase in crop acres being 16% in Barber County. See Figure 9. Average Farm Sales declined in 83 of the 105 counties. Of the 22 counties that had increased average farm sales between 1997 and 2002, Decatur and Sheridan counties experienced the largest increases at 80.6% and 95.3% respectively. On average Kansas counties Average Farm Sales were 89.95% of the 1997 values. See Figure 10.

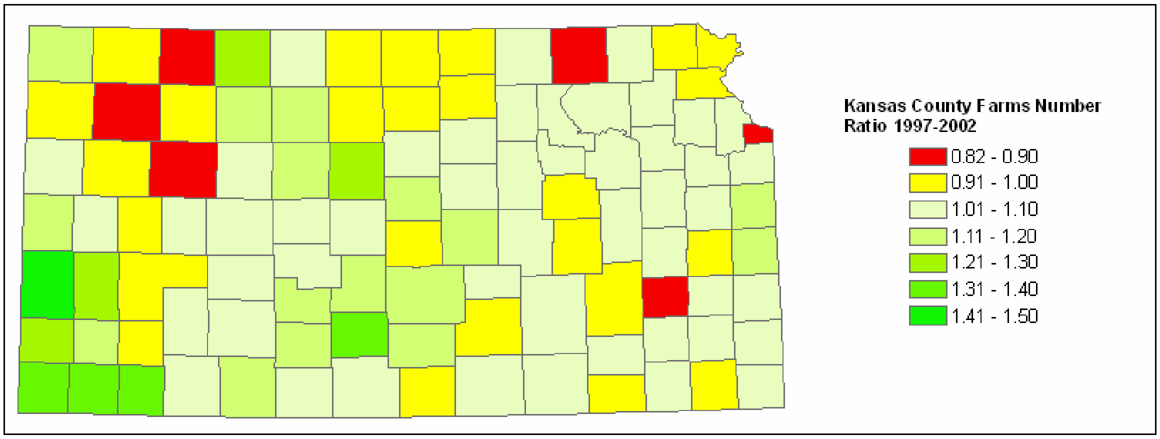


Figure 7. Kansas County Farms (Number) Ratio 1997-2002

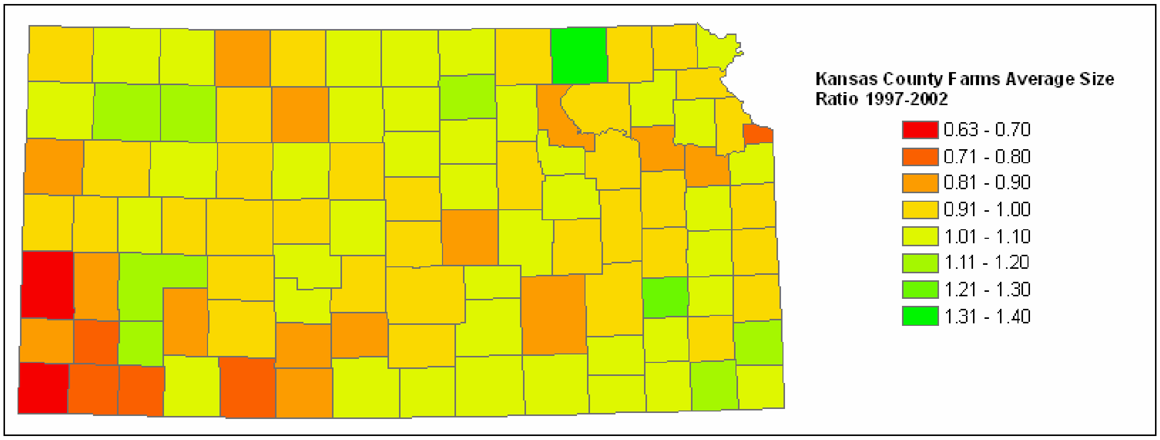


Figure 8. Kansas County Farms Average Size Ratio 1997-2002

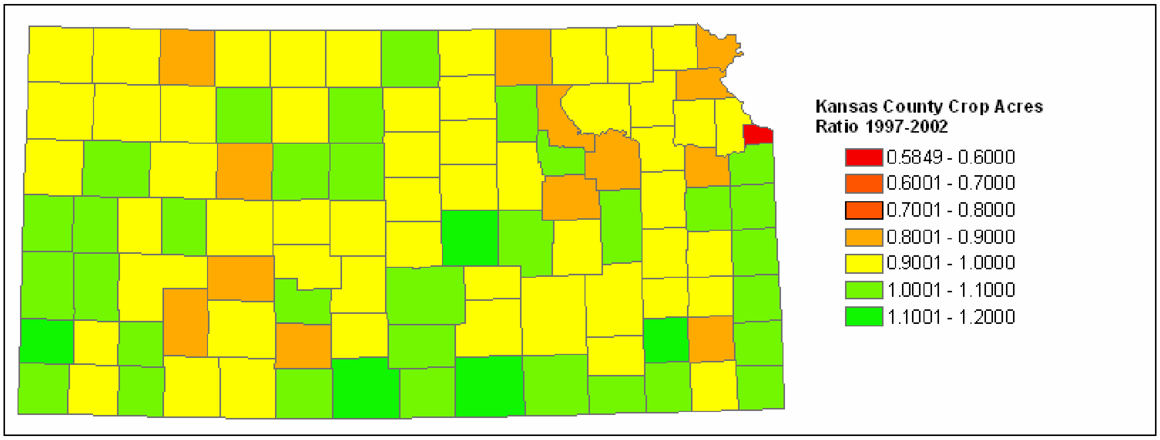


Figure 9. Kansas County Crop Acres Ratio 1997-2002

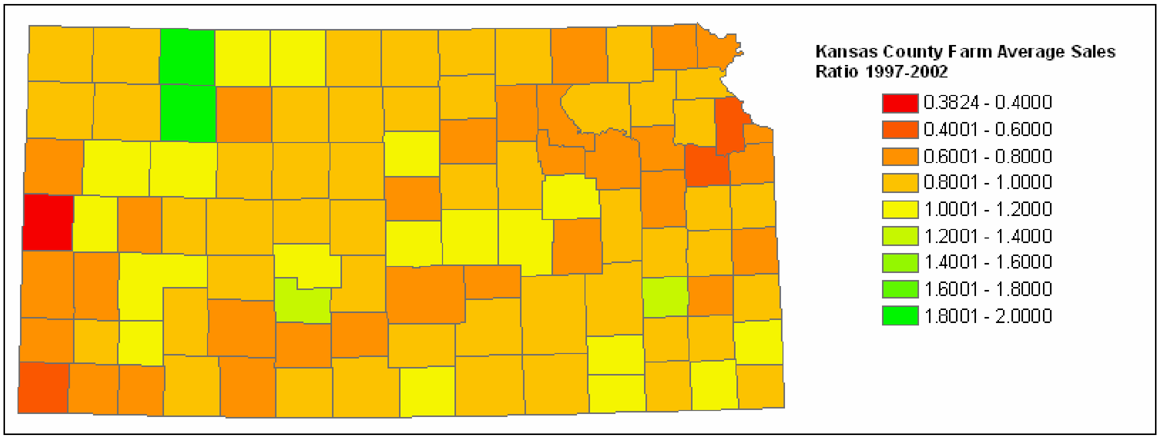


Figure 10. Kansas County Average Farm Sales Ratio 1997-2002

Since 1990, irrigation technology has dramatically changed to more efficient low pressure pivot and SDI (subsurface drip irrigation) systems. With more efficient water use, irrigators have been able to grow significantly more corn and other water intensive crops. Given the 3.5 percent decrease in the number of irrigated farms since 1997, the resulting 1.08 percent decline in irrigated acres indicates increased acreage efficiency by remaining irrigators. Figure 11 illustrates changes in irrigated acres, sprinkler and SDI acreage in Kansas (Source D.H. Rogers).

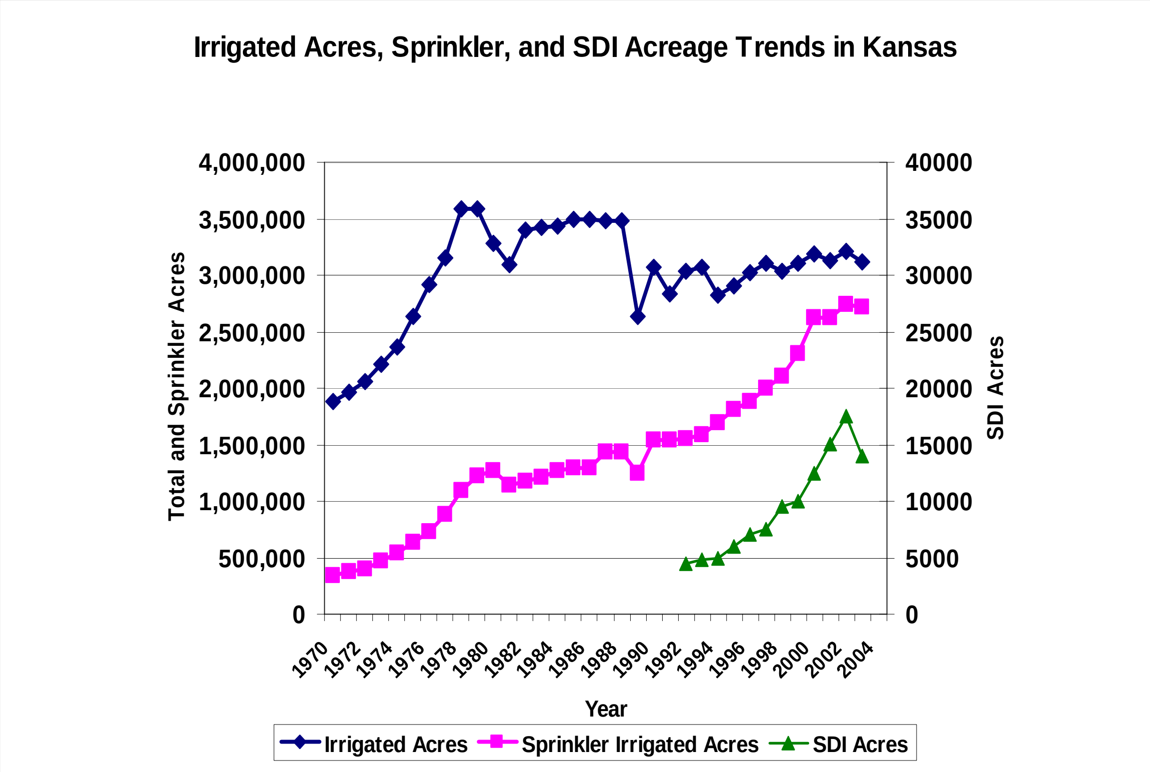


Figure 11. Kansas Irrigated Acres, Sprinkler, and SDI Acreage Trends (Source D.H. Rogers)

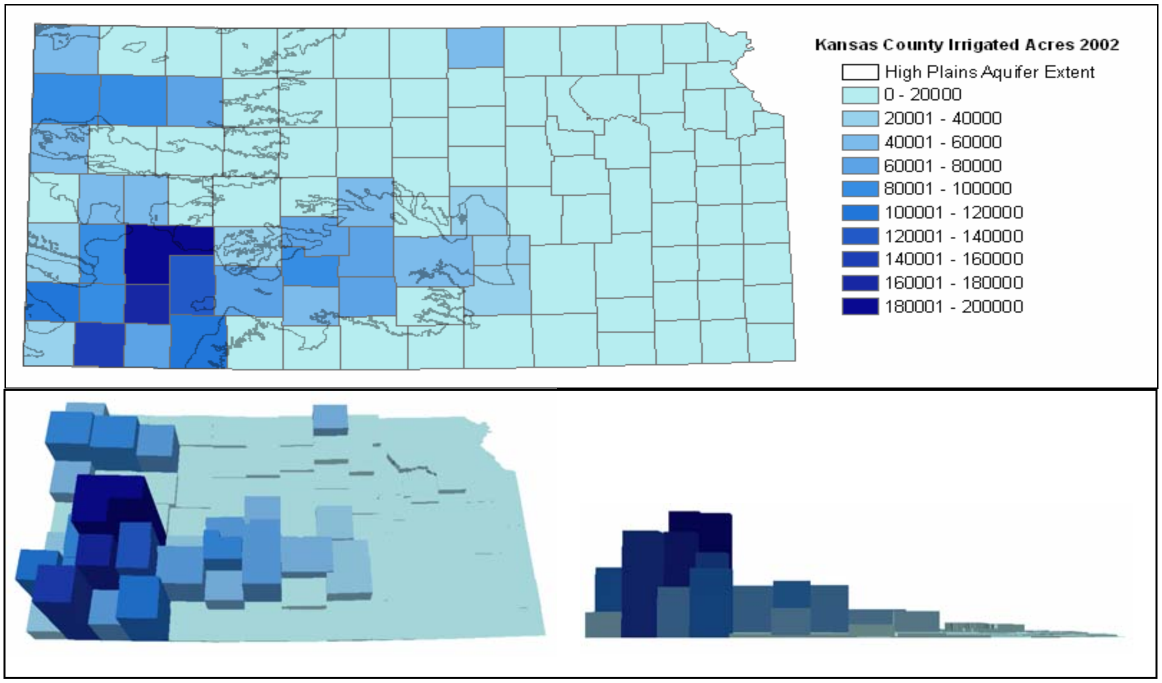


Figure 12. Kansas County Irrigated Acres 2002.

Kansas County irrigated acres in 2002 (shown above in map and 3D and section formats) indicate only one county outside the extent of the High Plains Aquifer with greater than 20,000 irrigated acres. Total irrigated acres in 2002 for the 54 counties overlying the High Plains Aquifer were 2,452,734. The Kansas Geological Survey estimated lifetime of High Plains Aquifer water resources indicates a dire situation for counties that have not grown in the past decade and a bleak outlook for parts of most counties that had experience growth since 1990.

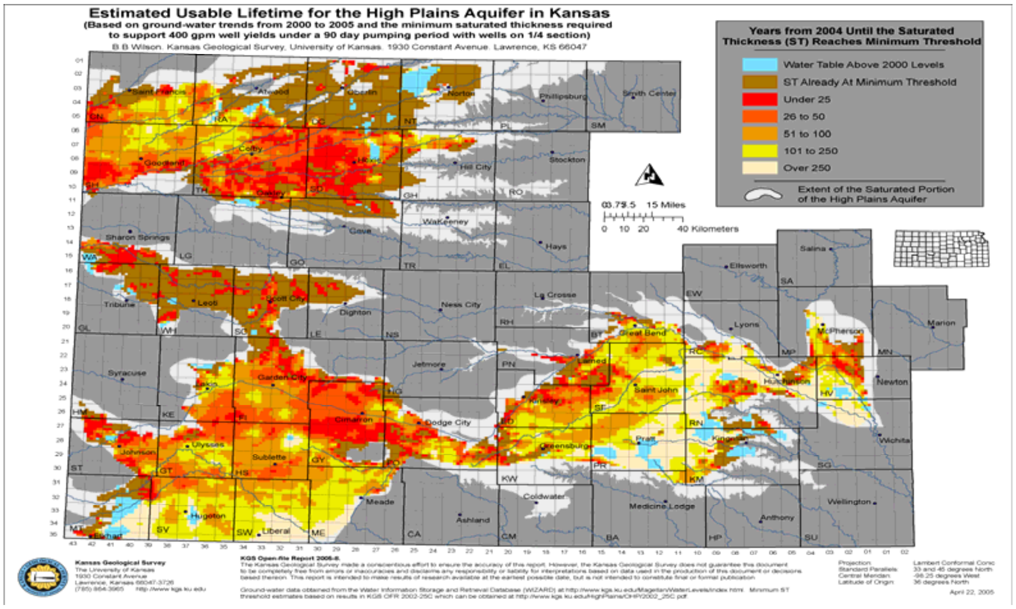


Figure 13. Estimated Useable Lifetime (Source: KGS OFR 2005-8)

Conclusions

Research questions regarding the drivers of socio-economic, agriculture and irrigation change are just beginning to be formulated and researched, however one apparent connection between population growth and irrigation has been identified in this study. When Population Ratio 1990-2000 colors are placed on 3D County Irrigated Acres, counties in the southwest corner of the state that irrigate the largest number of acres are also those that have shown growth in the last decade. Given the KGS estimated useable lifetime of the aquifer, the same southwestern counties are likely the only counties in the western half of the state with potential to grow into the future based on the continuation of existing agricultural practices and estimated useable lifetime of the aquifer. Many important questions remain, however one very large issue for southwestern counties will be the age cohort projections and potential impact on agriculture production due to workforce aging.

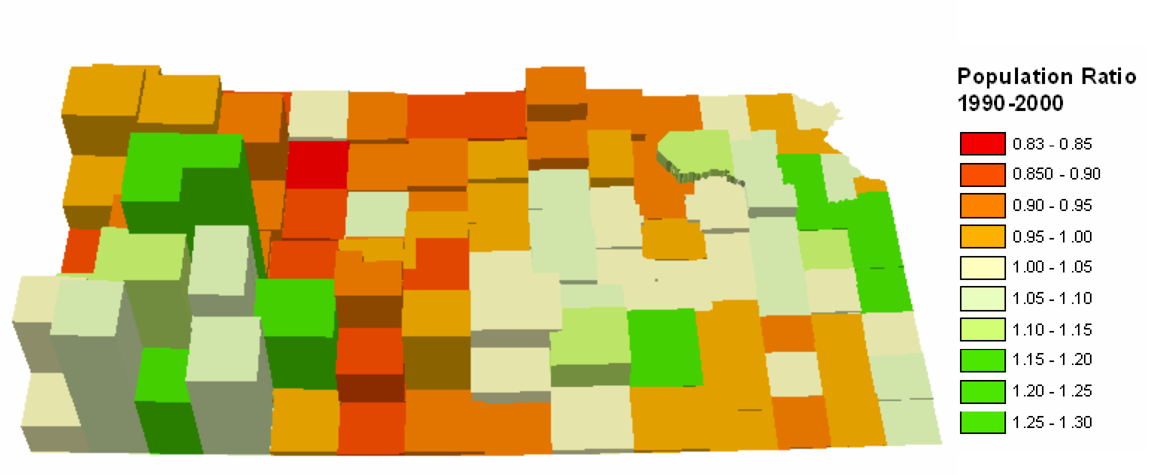


Figure 14. Kansas County Population Ration 1990-2000 and Irrigated Acres Extruded

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DRY BEAN WATER MANAGEMENT

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The past several years of sustained drought and below average snowpack and summer rains have many in agriculture searching for ways to stretch limited supplies of water. Not only has stream flow decreased, but ground water levels have declined and in many areas pumping restrictions have been imposed. At the same time, competition for water outside of agriculture further increases the demand for limited resources. The combination of drought and the increased demand for water will impose even more challenges for irrigated agriculture. It will require changing current irrigation practices and incorporation of new ideas to better utilize available water supplies as efficiently as possible. This means not only using irrigation water efficiently, but also using precipitation and stored soil water for crop production. Understanding the water needs of a crop will be a key to effective water management.

Water Use

The amount of water needed for irrigation varies by the crop being grown and the climatic conditions from year to year. Given in Table 1 are estimated water use rates for regionally grown crops.

Alfalfa	Corn	Drybean	Spring Grain	Soybean	Sunflower	Winter Grain
31-33	23-26	15-16	18-20	18-20	18-26	18-22

Table 1. Seasonal crop water use (in.) for regionally grown crops.

The depth from which corn gets most of its water is generally considered to be in the top 3 to 4 ft of the soil profile. Corn uses approximately 24 inches of water during the growing season and is often considered a crop that uses a large amount of water. Yet as we look closer, some of the crops we thought used less water, for example sunflowers and winter wheat, we find can use as much water as corn. However in the case of sunflowers and winter wheat, these crops can extract more water from the profile than some other crops without adversely impacting yield potential. Sunflowers also have the ability to effectively extract water to depths of up to eight feet. In this case sunflowers may be viewed as a “drought tolerant” crop when in fact the crop has actually extracted more water from the soil and extracted water from deeper in the soil profile. Anyone growing sunflowers knows that following this crop the soil can be left in a very dry condition the following spring.

Dry beans use approximately 16 inches of water during the growing season, which is approximately 8 inches less than what corn needs. This makes dry beans a good crop to grow if irrigation water is limited or if used as part of a crop rotation system to reduce overall irrigation needs. Dry beans are a shallow rooted crop with the majority of roots found in the top 18 in. of the soil profile. Roots can grow deeper into the soil profile to get water but this usually occurs late in the growing season as the plants begin to mature.

Water Management

The question of when is the best time to apply water to a crop often comes up when water supplies are limited. Some producers feel that stressing dry beans early in the growing season has little impact on yield and may even improve yield by forcing the roots to grow deeper into the soil profile. A similar question asked is whether stopping irrigation late in the season reduces yield?

For dry beans, early and late season water stress experiments have been conducted at the Panhandle Research and Extension Center in Scottsbluff, NE. The results of those experiments are given below.

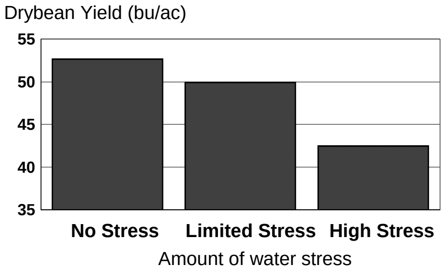

Figure 1a. Effect of early season water stress on dry bean yield using sprinkler irrigation.

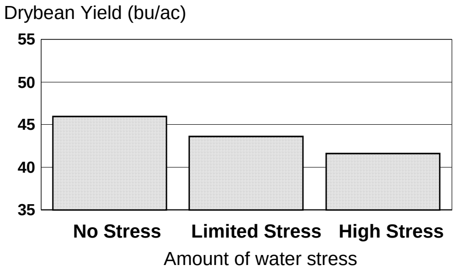

Figure 1b. Effect of early season water stress on dry bean yield using furrow irrigation.

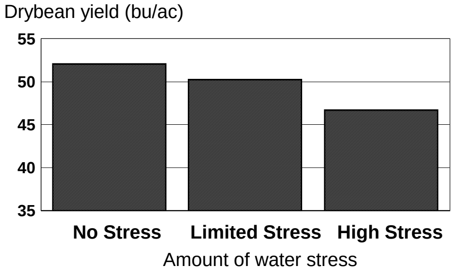

Figure 2a. Effect of late season water stress on dry bean yield using sprinkler irrigation.

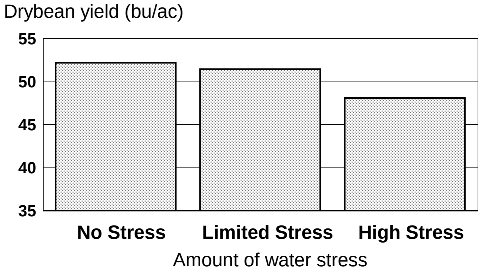

Figure 2b. Effect of late season water stress on dry bean yield using furrow irrigation

Figures 1a and 1b, show the results of dry bean yield when water is limited during early season growth for sprinkler and furrow irrigation systems, respectively. The no stress treatment had irrigation starting approximately the last week in June to the first week in July. For the limited and high stress treatments, the initial irrigation was delayed for one week and two weeks, respectively. When sprinkler irrigation was used, yield tended to decline more as water stress increased compared to the furrow irrigation system. This is especially true for the high stress treatment under sprinkler. Yield loss was greater when water was withheld for two weeks because of the inability of the sprinkler system to replace soil water and meet the future water demand of the crop. The furrow irrigation system in these experiments refilled the soil profile and thus was able to provide adequate and immediate water for future water use. Under grower conditions if stress is allowed, furrow irrigation will likely require an extended period of time to irrigate the complete field thus causing further yield reduction similar to the sprinkler trials. Because the sprinkler and furrow experiments were conducted at different locations, comparisons between the two irrigation systems should not be made.

In figures 2a and 2b, the results of shutting off water late in the season are also shown for both sprinkler and furrow irrigation systems. The no stress treatment had irrigations throughout the growing season. Starting August 10, the limited stress treatment received every other irrigation that was scheduled for the no stress treatment while the high stress treatment received no further irrigations. Similar to the early season water stress results, dry beans irrigated with a sprinkler system showed a slightly steeper decline in yield as water stressed increased. The decline in yield is again likely related to the inability of the sprinkler irrigation system to supply water in excess to the requirements of the crop. Once irrigation was reduced or stopped less water was available in the soil profile to meet crop demands. Once again, the sprinkler and furrow experiments were conducted at different locations and comparisons cannot be made between the two irrigation systems.

When comparing the early and late season experiments, there is a steeper decline in dry bean yield when water stress occurs at the beginning of the season as compared to water stress late in the season. These results are probably not uncommon and could be expected for most crops. Early in the season plant root development is limited and therefore water stress can occur rapidly. The lack of water during initial stages of plant growth likely impacts the majority of the root system. Late in the growing season, roots are more developed and reach further into the soil profile. Therefore water stress late in the season will first impact roots high in the soil profile while those deep in the profile may continue to extract some water to meet the needs of the crop. Finally, because the plant is nearing maturity, the need for water is declining on a daily basis. As a result, the root system can more easily keep up with the needs of the plant as water in the profile slowly moves to replace the water used by the crop.

These results show for western Nebraska that if water is limited and the irrigator has the ability to choose when water supplies can be used on their bean crop, the choice should be to use water early in the season to maintain plant growth and encourage root development deep into the soil profile. Reducing irrigation late in the season can result in water stress which will likely reduce yield. However, compared to water stress early in the season, late season stress can have less of an impact on total production.

CROP PRODUCTION COMPARISON UNDER VARIOUS IRRIGATION SYSTEMS[1]

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SUMMARY

Studies on crop productivity for major irrigated crops in the Great Plains were reviewed for different types of modern pressurized irrigation systems. Crops included corn, cotton, grain sorghum, winter wheat, and preliminary data on soybean and sunflower. Irrigation systems consisted of spray and LEPA devices commonly found on center pivots, and drip irrigation (usually SDI). Spray, LEPA, and SDI were compared at Halfway and Bushland, TX, and simulated LEPA and SDI were compared at Colby, KS. Nearly all studies involved varying the irrigation capacity (fixed application per unit time) or irrigation rate (percentage of soil water replenishment). Yield response in terms of irrigation method could usually be described as SDI ≥ LEPA ≥ SPRAY for low irrigation capacities (or rates), and SPRAY ≥ LEPA ≥ SDI for full (or nearly full) capacities or rates. In some cases, yield response was more consistent across irrigation rates. Although additional data are lacking that would explain these differences, it appears that LEPA, and to a greater extent SDI, result in greater partitioning of

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[1] Joint contribution from the USDA-Agricultural Research Service and Kansas Agricultural Experiment Station. Contribution No. 06-193-A from the Kansas Agricultural Experiment Station.

water to plant transpiration relative to spray for low irrigation rates. At greater irrigation rates, the yield depressions observed for SDI and/or LEPA relative to spray were less clear, although these may be the result of poor aeration and nutrient leaching by deep percolation.

INTRODUCTION

The U.S. Great Plains produces a major portion of the nation’s corn, wheat, sorghum, soybeans, sunflower, and in the southern and central portions, cotton. High yields are possible with irrigation, and roughly 8 Mha (out of 20 Mha in the U.S.) are presently irrigated in an eight state area that includes South Dakota, Nebraska, southeastern Wyoming, eastern Colorado, Kansas, the Oklahoma Panhandle, northwestern Texas, and eastern New Mexico (Howell, 2001; Lamm and Brown, 2004). The region is mostly semiarid, with extremely variable precipitation (both temporally and spatially), high evaporative demand due to high solar radiation, high vapor pressure deficit, and periods of high regional advection, especially in the southern portion (Howell et al., 1997b). The primary water resource for this eight state area is the Ogallala Aquifer, one of the largest freshwater aquifers in the world. The Ogallala has been declining in most areas because withdrawals have exceeded recharge after intensive irrigation began in the late 1930s, when internal-combustion engines and rural electrification first became widely available for pumping. However, the rate of decline has abated in some areas such as the High Plains of Texas (Musick et al., 1990) due to either reductions in irrigated area, conversion to more efficient irrigation systems, or both.

The earliest irrigation systems in the Great Plains were generally graded furrow, and these were most suitable for land with small slopes (<1%). Musick et al. (1988) mentions improvements in sprinkler systems after World War II allowed expansion of irrigation to land otherwise unsuitable for furrow systems. This was followed by center pivots in the 1960s and 1970s. Earlier center pivot sprinkler configurations were high-pressure impact, but these were replaced by low-pressure spray and low-pressure precision applicators (LEPA) since the 1980s (Lyle and Bordovsky, 1983). Spray heads are commonly positioned above the crop (variously termed overhead spray or mid-elevation spray applicator – MESA) or within the crop canopy (in-canopy spray or low-elevation spray applicator – LESA). In the mid-1980s, surface and subsurface drip irrigation (SDI) became adopted by cotton producers in the Trans Pecos region of Texas (Henggeler, 1995), and SDI has been used successfully for corn production in Kansas (Lamm et al., 1995; Lamm and Trooien, 2003).

Center pivots with modern sprinkler packages (e.g., MESA, LESA, or LEPA) can be highly efficient in terms of uniformity and application efficiency (Schneider, 2000), as can SDI (Camp, 1998), and numerous studies have documented high crop productivity using either type of system. With declining water resources and escalating energy costs, total irrigated area in the Great Plains will likely decrease; however, remaining irrigated land will likely see greater adoption of efficient irrigation technology and techniques, including deficit irrigation, irrigated-dryland rotations (Stewart et al., 1983; Unger and Wiese, 1979), and careful irrigation scheduling (Howell et al., 1998a). Studies in Texas, Kansas, and elsewhere indicate that relative performance of different irrigation systems in terms of crop productivity often changes with irrigation rate (i.e., level of deficit irrigation) and climate, among other factors, which should be considered in selecting an irrigation system.

The objectives of this paper are to review studies of crop productivity under various irrigation systems, with an emphasis on how crop productivity is affected by types of systems across a range of irrigation rates. The scope will be limited to major crops irrigated in the Great Plains, including corn, cotton, grain sorghum, winter wheat, and some preliminary data on soybean and sunflower (we plan to expand this paper to include other crops such as peanuts, fresh market vegetables, and additional data on soybean and sunflower as they become available). Data presented will be limited to pressurized irrigation systems (i.e., sprinkler, LEPA, and drip) from studies conducted at the USDA-Agricultural Research Service in Bushland, TX, the Texas Agricultural Experiment Station in Halfway, TX, and the Kansas State University Northwest Research-Extension Center in Colby, KS. Soils at these locations are generally deep, well drained, and loam to clay loam in texture. Consequently, results presented herein may not be applicable to locations having coarser or finer soils, or for shallow-rooted crops. Some additional references are given for studies conducted outside the Great Plains, and a few involve comparisons with furrow irrigation. This review is by no means comprehensive and does not contain rigorous statistical analyses, but is intended to highlight major findings that appear common to different crops at the three locations.

SOME EFFICIENCY AND ECONOMIC ASPECTS OF SPRAY, LEPA, AND SDI

Schneider (2000) reviewed published research of application efficiencies and uniformity coefficients for spray and LEPA systems. Reported application efficiencies for spray methods generally exceeded 90% and were from 95% to 98% for the LEPA methods. Reported uniformity coefficients in the direction of travel ranged from 0.75 to 0.90 for spray and from 0.75 to 0.85 for LEPA; along the mainline (perpendicular to travel) these were from 0.75 to 0.85 for spray and from 0.94 to 0.97 for LEPA. The review noted that measured application efficiencies for spray were sensitive to the device used, and because of the start and stop movement of most irrigation systems, measured uniformities of LEPA were sensitive to the length of basin checks, irrigation system span alignment, and distance from the tower where system speed was controlled. Water is usually applied to alternating interrows with LEPA; thus, the high reported LEPA uniformities along the mainline are the result of measuring water only where it is actually applied, disregarding the rows and nonirrigated interrows. The review also discussed potential water loss pathways and concluded that runoff is generally the greatest potential loss for both LEPA and spray; hence, some form of runoff control such as basin tillage (furrow dikes) or reservoir tillage is required to achieve these high efficiencies and uniformities.

Schneider and Howell (2000) measured surface runoff from a slowly permeable Pullman clay loam soil with a 0.25% slope over two seasons of irrigated grain sorghum production. Treatments consisted of the spray and LEPA methods with and without basin tillage (furrow dikes) for five levels of soil water replenishment, or irrigation rate IR (0%, 40%, 60%, 80%, and 100%). They observed no runoff for the spray method using furrow dikes for all IR, and no runoff for any sprinkler-tillage method combination for the 40% IR. Grain yields and water use efficiencies were significantly reduced with increasing runoff. For 100% IR, runoff losses averaged 12% for spray without dikes, 22% for LEPA with dikes, and 52% for LEPA without dikes. They noted that as the seasons progressed, the furrow dikes eroded, decreasing soil water storage capacity on the soil surface and increasing the potential for runoff. Howell et al. (2002) reported that furrow dikes improved corn yield for both full and limited spray irrigation compared to flat and bed tillage (no dikes), but did not observe runoff due to dike erosion. Schneider (2000) discussed other potentially large water loss pathways, including deep percolation, wind drift, and surface evaporation (Tolk et al., 1995) and emphasized that both LEPA and spray can be highly efficient, provided that these pathways are carefully evaluated in order to select the most appropriate sprinkler package.

Water loss pathways described for spray and LEPA can potentially be eliminated with SDI through proper design, maintenance, and management, which is likely to also conserve expensive fertilizer and chemicals commonly injected into irrigation water (Lamm and Trooien, 2003). We further postulate that furrow dikes may be more effective for rainfall capture for SDI than LEPA or spray because of reduced erosion (Jones and Clark, 1987). Camp (1998) reviewed published research on SDI and noted that crop yields were equal to or exceeded those of other irrigation systems, and water use was significantly less. However, adoption of SDI in the Great Plains remains low relative to center pivots primarily because of capital costs but also due to greater maintenance and management requirements, among other factors. If preplant rainfall is sparse and unreliable, crop germination can be difficult with SDI (Howell et al., 1997a; Enciso et al., 2005).

O’Brien et al. (1998) showed that SDI can be more economical than center pivots for decreased field sizes (~20 ha or less), provided system life was at least 10 years (preferably 15-20 years) for continuous corn production. SDI is particularly suited to small and oddly-shaped fields; furthermore, center pivots quickly lose their cost advantage where they cannot make a complete circle. On the other hand, Segarra et al. (1999) reported that SDI was not always competitive with LEPA for continuous cotton, despite SDI having greater lint yields. But they noted that economic outcomes were also sensitive to system life, as well as installation costs, pumping lift requirements, and hail damage to crops. Enciso et al. (2005) reported that net returns of SDI in a cotton production system were sensitive to lateral spacing (alternate interrows vs. every row), lateral installation depth, and crop germination, where lateral spacing (i.e., amount of drip tape required) was a tradeoff between capital cost and risks assumed in crop germination.

These varying results illustrate the difficulty in making general guidelines for SDI (a conclusion also reached by Camp, 1998), and suitability of SDI should, at minimum, be assessed on a crop-, site-, and producer-specific basis. The following sections review productivity for different pressurized irrigation systems according to crop, and selected publications are summarized for corn, cotton, grain sorghum, and winter wheat in Tables 1, 2, 3, and 4, respectively.

CORN, SOYBEAN, AND SUNFLOWER

Subsurface drip irrigation (SDI) research has been conducted at the Kansas State University Northwest Research-Extension Center in Colby, KS since 1989 on a deep, medium textured, well-drained Keith silt loam soil (Lamm and Trooien, 2003). Lamm (2004) compared seven years (1998-2004) of corn productivity at this location for SDI and simulated LEPA, where the effects of LEPA were mimicked by delivering precise amounts of water to furrow diked basins through pressure regulated flow dividers and flexible supply tubes. Irrigation capacity for simulated LEPA was varied by applying 25 mm (1 in) of water at 4, 6, and 8 day intervals. Irrigation was applied daily with SDI at 2.5, 3.3, 4.3, and 6.4 mm per day (0.10, 0.13, 0.17, and 0.25 in per day; see Table 5 for SI to English unit conversions). This resulted in a range of seasonal irrigations applied relative to meeting the full irrigation requirement. Grain yield vs. seasonal irrigation were grouped for years having average or greater rainfall (1998, 1999, 2004; Fig. 1a) or significant drought (2000-2003; Fig. 1b) for simulated LEPA and SDI, where yield and seasonal irrigations were averaged for each group of years. For average to wet years, grain yield with SDI was slightly greater than simulated LEPA, but *vice versa* for drought years. In average to wet years, differences in grain yields were primarily due to kernel weight, but in drought years, this was due to the number of kernels per ear (see Lamm, 2004 for actual yield component data).

Soybean and sunflower production were also compared between simulated LEPA and SDI at Colby, KS (Figs 2 and 3, respectively). Irrigation rates (IR) were varied according to 60%, 80%, and 100% of meeting the full irrigation requirement (i.e., in Fig. 2, 178, 305, and 356 mm average seasonal irrigation totals, respectively). For both crops, relative yields between simulated LEPA and SDI again varied by IR, with SDI resulting in greater production at the lower IR, but less production at the higher IR. Although only a single season is represented for each crop, it is interesting that production patterns were somewhat similar to corn in that 2005 received less rainfall than 2004. We presently do not have data

Table 1: Selected studies of crop productivity with pressurized irrigation systems for corn.

Irrigation Methods	**Additional factors**	**Location**	**Reference**
Impact sprinklers	Irrigation rate	Bushland, TX	Howell et al. (1989)
LEPA sock	Irrigation rate	Bushland, TX	Howell et al. (1995a)
MESA	Short and full season hybrids, crop ET	Bushland, TX	Howell et al. (1998b)
MESA	Irrigation rate, tillage (furrow dikes, clean raised beds, flat planting)	Bushland, TX	Howell et al. (2002)
MESA, LESA, LEPA bubble, LEPA sock	Irrigation rate	Bushland, TX	Schneider and Howell (1998)
SDI	Review article	Colby, KS	Lamm and Trooien (2003)
SDI	lateral spacing, lateral depth	Colby, KS	Lamm et al. (1997)
SDI	Irrigation rate, irrigation frequency, lateral depth	Colby, KS	Lamm et al. (1995)
Simulated LEPA, SDI	Irrigation capacity	Colby, KS	Lamm (2004)
Surface drip, SDI	Irrigation rate, irrigation frequency	Bushland, TX	Howell et al. (1997a)

Table 2: Selected studies of crop productivity with pressurized irrigation systems for cotton.

Irrigation Methods	**Additional factors**	**Location**	**Reference**
Furrow, level basin, sprinkler, surface drip, SDI	Review article, crop ET, water use efficiency, water value	AZ and CA, also references worldwide	Grismer (2002)
Furrow, solid set sprinklers, surface drip	Irrigation rate	Sanliurfa, Turkey	Cetin and Bilgel (2002)
Furrow, surface drip	Irrigation rate, irrigation frequency	Five Points, CA	Howell et al. (1987)
LEPA sock	Irrigation capacity, irrigation frequency	Halfway, TX	Bordovsky et al. (1992)
LEPA sock, SDI	Irrigation capacity, irrigation frequency (LEPA only)	Halfway, TX	Segarra et al. (1999)
LESA, LEPA sock, SDI	Irrigation capacity, preplant irrigation rate	Halfway, TX	Bordovsky and Porter (2003)
MESA	Irrigation rate, crop ET	Bushland, TX	Howell et al. (2004)
MESA, LESA, LEPA sock, SDI	Irrigation rate	Bushland, TX	Colaizzi et al. (2005)
SDI	Irrigation frequency	St. Lawrence, TX	Enciso et al. (2003)
SDI	Preplant irrigation, lateral spacing, lateral depth	St. Lawrence, TX	Enciso et al. (2005)
Surface drip	Irrigation timing by canopy temperature, irrigation rate, irrigation frequency, initialization of irrigation season, plant dates	Lubbock, TX	Wanjura et al. (2002)
Surface drip, LEPA sock	Irrigation rate, irrigation frequency	Koruklu, Turkey	Yazar et al. (2002)

Table 3: Selected studies of crop productivity with pressurized irrigation systems for grain sorghum.

Irrigation Methods	Additional factors	Location	Reference
LEPA sock	Irrigation rate, irrigation frequency	Halfway, TX	Bordovsky and Lyle (1996)
MESA, LEPA sock	Irrigation rate, tillage (furrow dikes, clean raised beds)	Bushland, TX	Schneider and Howell (2000)
MESA, LESA, LEPA bubble, LEPA sock	Irrigation rate	Bushland, TX	Schneider and Howell (1995)
MESA, LESA, LEPA sock, SDI	Irrigation rate	Bushland, TX	Colaizzi et al. (2004)

Table 4: Selected studies of crop productivity with pressurized irrigation systems for winter wheat.

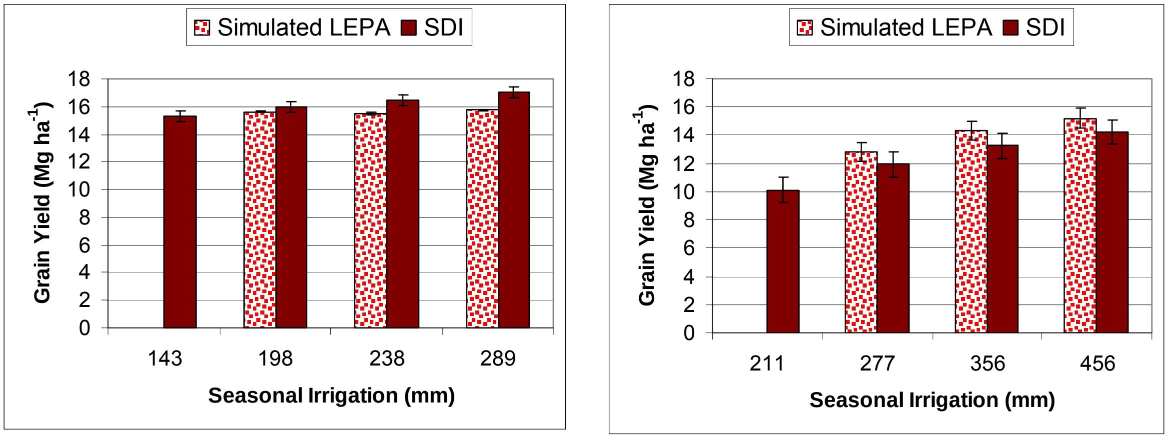
Irrigation Methods	Additional factors	Location	Reference
MESA, impact sprinklers (end of season 1 year only)	Crop ET	Bushland, TX	Howell et al. (1995b)
MESA, LEPA bubble, LEPA sock	Irrigation rate, irrigation timing, irrigation termination	Bushland, TX	Schneider and Howell (1997)
MESA, LESA, LEPA bubble, LEPA sock	Irrigation rate	Bushland, TX	Schneider and Howell (2001)

Table 5: Unit conversions. Conversions from weight (lbs) to volume (bu) based on dry and standard moisture contents for selected crops taken from Hirning et al. (1987).

	dry weight		**standard weight**		
Crop	**lb bu^{-1}**	**bu ac^{-1} per Mg ha^{-1}**	**percent moisture**	**lb bu^{-1}**	**bu ac^{-1} per Mg ha^{-1}**
corn	47.32	18.8	15.50	56.00	15.9
grain sorghum	47.00	19.0	14.00	55.00	16.2
soybean	52.20	17.1	13.00	60.00	14.8
sunflower	90.00	9.9	10.00	100.00	8.9
wheat	51.90	17.2	13.50	60.00	14.8

1 mm = 0.03937 in
1 ha = 2.47 ac
1 kg = 2.2 lb
1 kg ha^{-1} = 0.8907 lb ac^{-1}
1 Mg ha^{-1} = 890.7 lb ac^{-1}

that would explain these production differences, but tentatively offer several hypotheses. When water supply is limited, SDI likely results in greater partitioning of water to transpiration and less to soil evaporation, which would result in slightly less water stress. At greater IR, the greater concentration of SDI-delivered water and nutrients in the root zone may result in poor aeration or nutrient leaching, which may limit yields (Lamm et al., 1995; Colaizzi et al., 2004). Payero et al. (2005) investigated the deficit irrigation for soybeans using surface drip at Curtis, NE (2002), and solid set sprinklers at North Platte, NE (2003 and 2004). They used a greater range of IR than at Colby, but relative performance drip and sprinkler could not be compared because these were at different locations and different years.



a)

b)

Figure 1: Corn yield and seasonal irrigation averages for simulated LEPA and SDI for a) three average to wet years (1998, 1999, 2004); and b) four dry years (2000, 2001, 2002, 2003) at Colby, KS (Lamm, 2004).

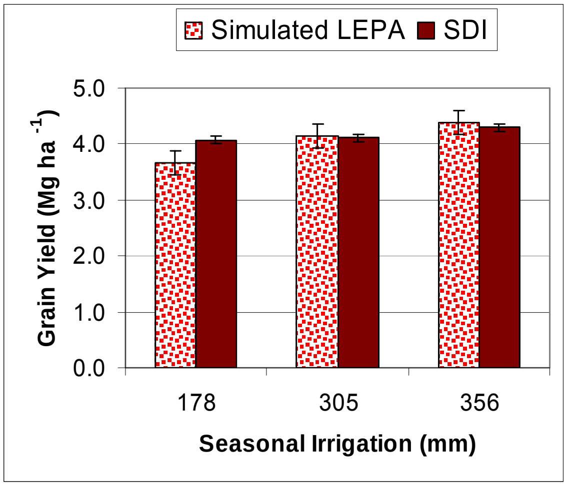


Figure 2: Soybean yield and seasonal irrigation (2005) at Colby, KS (F. R. Lamm, preliminary data).

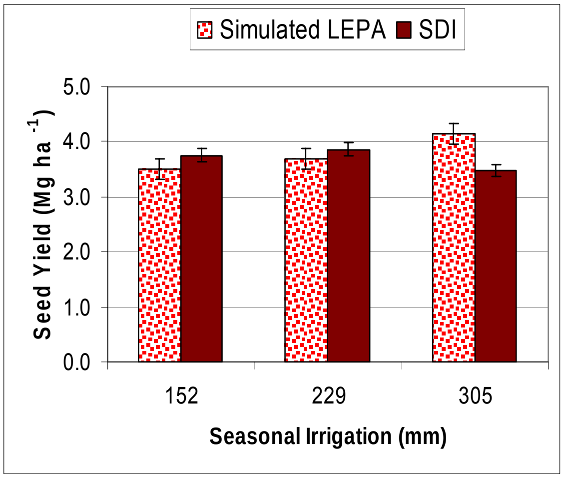


Figure 3: Sunflower yield and seasonal irrigation (2004) at Colby, KS (F. R. Lamm, preliminary data).

Corn yields for various irrigation systems across a range of IR were also investigated by the USDA-Agricultural Research Service at Bushland, TX. The Bushland location contains a slowly permeable Pullman clay loam (fine, mixed, superactive, thermic torrertic Paleustoll), with a dense B21t later 0.15- to 0.40-m below the surface, and a calcic horizon beginning about 1.2 m below the surface. Schneider and Howell (1998) compared MESA, LESA, LEPA Bubble, and LEPA sock (Fig. 4), and Howell et al. (1997) compared surface drip and SDI at daily and weekly intervals (Fig. 5). In both studies, seasonal irrigation totals were the result of variable IR (0%, 25%, 50%, 75%, and 100% in Fig. 4; 0%, 33%, 66%, and 100% in Fig. 5). The 0% IR represents actual, or in some years nearly

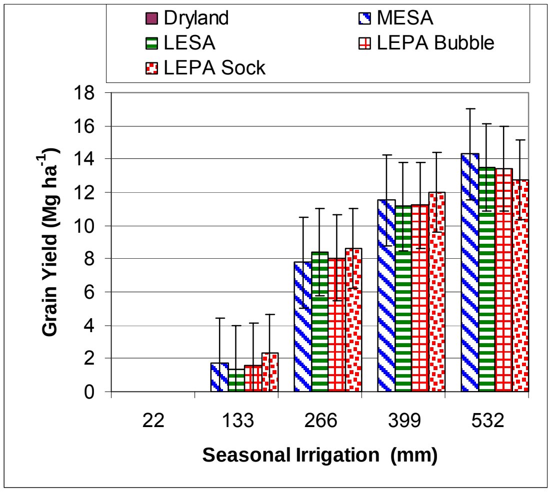


Figure 4: Corn yield and seasonal irrigation averages (1994, 1995) at Bushland, TX (Schneider and Howell, 1998).

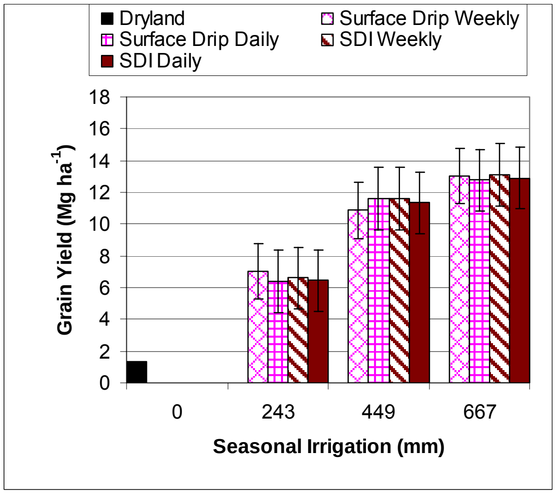


Figure 5: Corn yield and seasonal irrigation averages (1993, 1994) at Bushland, TX (Howell et al., 1997).

actual, dryland conditions, as uniform spray irrigations were sometimes given to all experimental plots to ensure adequate germination. Corn yields were much more sensitive to IR than the irrigation method. In Fig. 4, zero corn yields resulted for 0% IR (22 mm average seasonal irrigation). Slight differences in grain yields resulted between spray and LEPA configurations, with the LEPA sock having a small advantage over all other methods under deficit irrigation (< 100% IR), whereas MESA resulted in the greatest corn yields at full irrigation (532 mm). In Fig. 5, grain yield was insensitive to drip irrigation frequency (weekly or daily) and lateral installation (at or below the surface), probably because these factors were buffered by the relatively large soil water holding capacity and rooting depth. Although yield per irrigation applied appeared to be less with drip than with spray or LEPA (from a side-by-side comparison of Fig. 4 and 5), it should be noted that these represent averages of different years and were conducted on different experimental plots, and identical yield response to water should not be expected for different years or locations (Howell et al., 1995a).

WINTER WHEAT

Irrigated winter wheat production was documented in two studies with various configurations of spray and LEPA at Bushland, TX (Schneider and Howell, 1997; 2001; see also Schneider and Howell, 1999 for a summary of winter wheat, grain sorghum, and corn). Grain yields were less responsive to IR than corn as winter wheat has much greater drought tolerance. Grain yield response to irrigation method were numerical only (statistically insignificant), but these are nonetheless discussed. Grain yield trends in the first study (Fig. 6) were similar to those for corn (Fig. 4), where LEPA sock had a slight advantage at 33% IR (168 mm average), and MESA had a slight advantage at the 67% and 100% IR (289 and

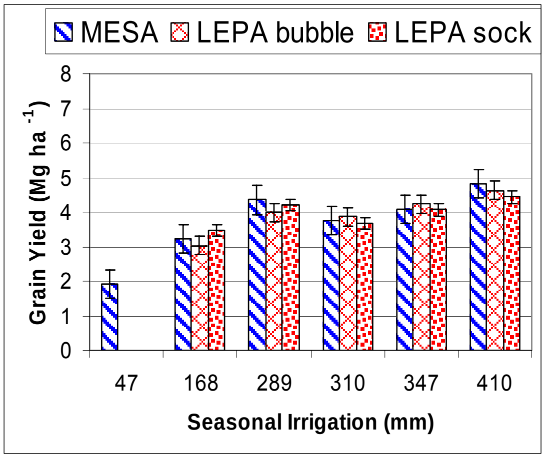


Figure 6: Winter wheat yield and seasonal irrigation averages (1994, 1995) at Bushland, TX (Schneider and Howell, 1997).

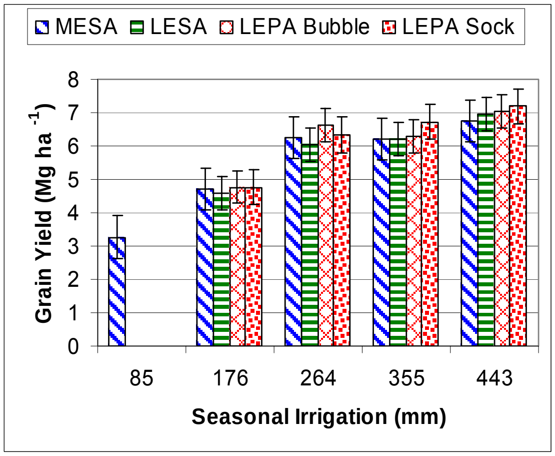


Figure 7: Winter wheat yield and seasonal irrigation averages (1998, 1999) at Bushland, TX (Schneider and Howell, 2001).

410 mm seasonal irrigation averages, respectively). The 310 and 347 mm seasonal irrigation averages also represent 100% IR, except initial irrigations were delayed until early boot (310 mm), or irrigations were terminated at early grain filling (347 mm), and the LEPA bubble had a slight advantage with these treatments. In the second study (Fig. 7), the LEPA methods resulted in equal or slightly greater wheat yield than spray (MESA or LESA); with the LEPA sock resulting in the greatest yield at 75% and 100% IR (355 mm and 443 mm, respectively). The slight yield advantages of MESA and LEPA noted in each study could not be correlated to differences in rainfall patterns (data not shown), as was the case for the simulated LEPA-SDI study for corn at Colby, KS (Fig. 1). Schneider and Howell (2001) concluded that reducing irrigation rates to 50% of the full requirement only resulted in 5- to 14% yield reductions for spray or LEPA methods, with yields exceeding 6.0 Mg ha^{-1}. Direct comparisons of wheat production between spray/LEPA and SDI have not been published to our knowledge, but winter wheat has been produced successfully with SDI on a commercial farm in Coolidge, AZ, with grain yield exceeding 6.0 Mg ha^{-1} with approximately 300 mm of water.

GRAIN SORGHUM

Grain sorghum is commonly rotated with cotton (Bordovsky and Lyle, 1996) or winter wheat (Stewart et al., 1983), and has a considerably less water requirement than corn. Bordovsky and Lyle (1996) investigated the effect of irrigation interval (3.5, 7.0, 10.5, and 14 days) on grain sorghum with LEPA equipped with double-ended drag socks and using furrow dikes. The study was conducted on an Olton loam soil (fine, mixed, thermic Aridic Paleustolls) in Halfway, TX, with 40%, 70%, 100%, and 130% IR. The 3.5-day interval resulted in greater grain sorghum yields than longer intervals for all irrigation rates (Fig. 8), but this was significant only when grain yield was averaged for all rates and years. Yields were not significantly different for 70% IR (251 mm average seasonal irrigation) and above.

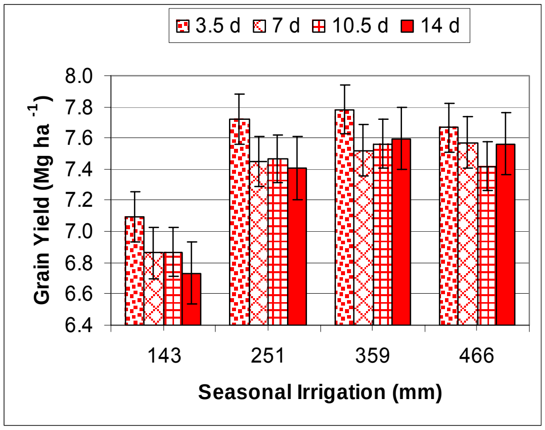


Figure 8: Grain sorghum yield and seasonal irrigation averages (1992, 1993, 1994) for LEPA at Halfway, TX (Bordovsky and Lyle, 1996).

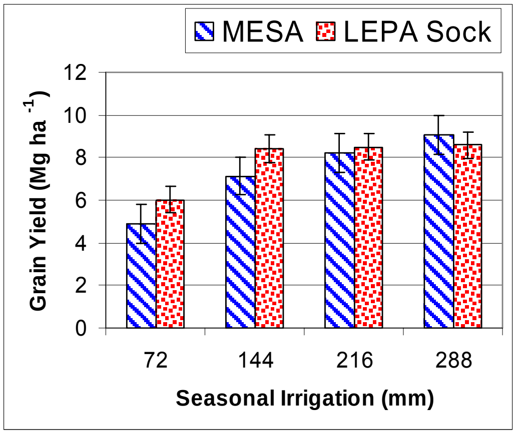


Figure 9: Grain sorghum yield and seasonal irrigation averages (1992, 1993) at Bushland, TX (Schneider and Howell, 1995).

Schneider and Howell (1995) evaluated grain sorghum response to MESA and LEPA sock for 25%, 50%, 75%, and 100% IR in Bushland, TX (Fig. 9). Average grain yields were greater with LEPA than MESA for 25% and 50% IR (72 and 144 mm in Fig. 9); however, MESA outperformed LEPA at 100% IR (288 mm in Fig. 9). The authors postulated that LEPA resulted in greater partitioning of water to transpiration at low irrigation rates. This trend was similar to that observed for soybean and sunflower in Colby, KS (Figs. 2 and 3, respectively) for simulated LEPA and SDI.

Colaizzi et al. (2004) also reported results of grain sorghum at Bushland, TX, where the study of Schneider and Howell (1995) was modified to include SDI in place of the LEPA bubbler. Grain yields with SDI were significantly greater than MESA, LESA, or LEPA at 25% and 50% IR, but this trend was reversed for 75% and 100% IR (Fig. 10; respective average seasonal irrigations of 79, 177, 275, 373, and 471 mm). In two out of three years, grain yields were significantly less with SDI and LEPA compared to MESA (data not shown). Deep percolation was evident for the fully irrigated SDI (and sometimes LEPA) plots, based on successive measurements of the volumetric soil water profile by neutron scattering. This could conceivably result in nutrient leaching and poor aeration. In a study with corn under SDI in Colby, KS (1989, 1990, 1991) Lamm et al. (1995) reported yield depressions in two out of three years (1989 and 1990) for 125% IR and attributed this to poor aeration or leaching of nutrients. Darusman et al. (1997) deduced deep percolation from tensiometer measurements for the 1990 and 1991 seasons of that study and reported greater soil water flux below the root zone for 100% and 125% IR. In Fig. 10, enhanced yields with spray at 75% and 100% IR could also be linked to greater partitioning of water to evaporation from droplets intercepted by the crop canopy. Larger humidity values within the

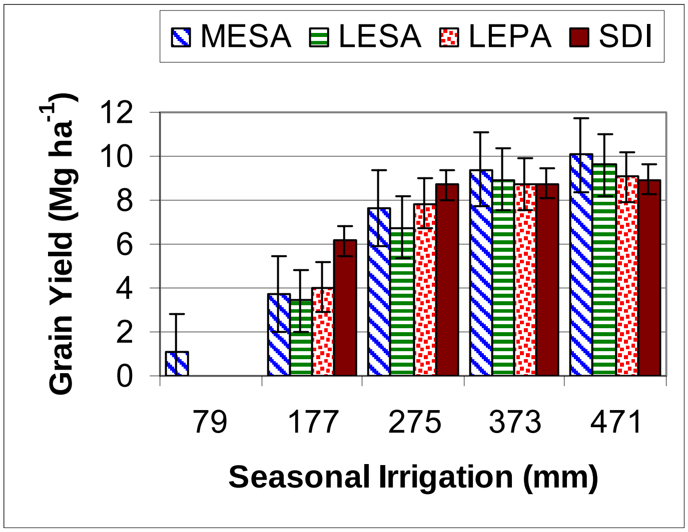


Figure 10: Grain sorghum yield and seasonal irrigation averages (2000, 2001, 2002) at Bushland, TX (Colaizzi et al., 2004).

canopy following spray irrigation would minimize stomatal closure under the heat and strong winds common in the region and enhance plant respiration while suppressing transpiration. Tolk et al. (1995) observed significant transpiration reduction of corn for several hours following daytime irrigation by overhead impact sprinklers, but very little transpiration reduction following irrigation by LEPA.

COTTON

Cotton has traditionally been produced at the southern portion of the Great Plains in an area centered at Lubbock, TX. In recent years, cotton production has expanded northward into Kansas as an alternative to corn because it has similar revenue potential for about half the water requirement (Howell et al., 2004). However, cotton production in thermally-limited climates pose some risk as both lint quantity and quality are correlated to accumulated heat units (Wanjura et al., 2002). Crop water productivity (marketable yield per unit water consumed) tends to increase with vapor pressure deficit, and irrigated cotton is particularly suited to arid and semiarid environments (Grismer, 2002; Zwart and Bastiaanssen, 2004).

Cotton may have been the first row crop to be drip-irrigated in Texas (Henggeller, 1995), and presently, it probably accounts for most of the SDI-irrigated land area in the Great Plains, simply based on casual observations and the number of published studies. Some cotton producers perceive SDI to result in enhanced seedling emergence and earlier crop maturity due to the absence of evaporative cooling associated with LEPA and to a greater extent spray irrigation. This is a critical consideration in thermally-limited climates, and may trigger greater adoption of SDI as cotton production migrates northward. There is presently, however, little direct evidence in support of this view, as next to air temperature, soil water depletion in the root zone appears most responsible for inducing earliness (Mateos et al., 1991; Orgaz et al., 1992). In fact, the reduced evaporative cooling thought to be associated with SDI could also be countered by the greater cooling effect of increased irrigation frequency (Wanjura et al., 1996). In consideration of these confounding factors, detailed studies of near-surface soil water and temperature for spray, LEPA, and SDI are currently underway at Bushland, TX. There have been many interesting observations of cotton under spray, LEPA, and SDI, and some studies conducted at Halfway and Bushland, TX are summarized next.

Segarra et al. (1999) analyzed four years of continuous cotton at Halfway, TX under LEPA and SDI (Fig. 11). Irrigation capacities were 2.5, 5.1, and 7.6 mm d^{-1}, which were typical of well capacities in the region; seasonal irrigation amounts were not given. LEPA irrigation frequencies were varied at 1, 2, and 3 days, but SDI frequency was daily. For all irrigation capacities, average lint yields were greater with SDI than LEPA, and these differences increased as irrigation capacity decreased. Average lint yields did not show a consistent response to LEPA irrigation frequency. Bordovsky and Porter (2003) investigated the influence of preplant irrigation amount and irrigation capacity for spray, LEPA, and SDI at the same location (Fig. 12). Both factors resulted in different seasonal irrigation amounts, but lint yield was consistently greatest with SDI, and LEPA was consistently greater than spray. For both irrigation capacities, full preplant irrigation resulted in greater lint yield than limited preplant irrigation (despite

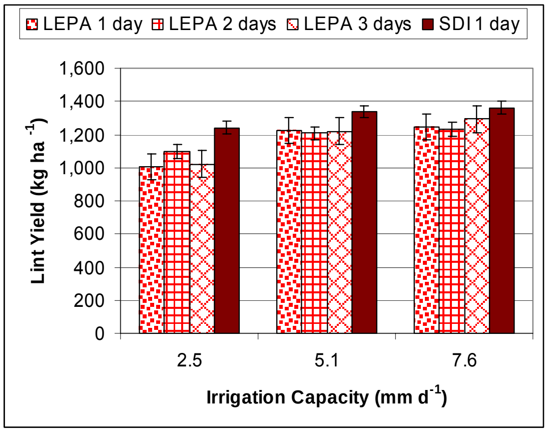


Figure 11: Cotton lint yield averages (1995, 1996, 1997, 1998) and irrigation capacities and frequencies (i.e., 1-3 days) at Halfway, TX. Seasonal irrigation amounts were not given (Segarra et al., 1999).

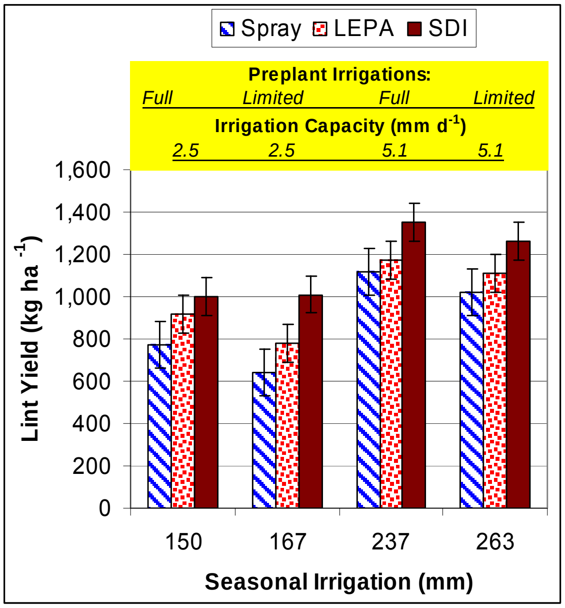
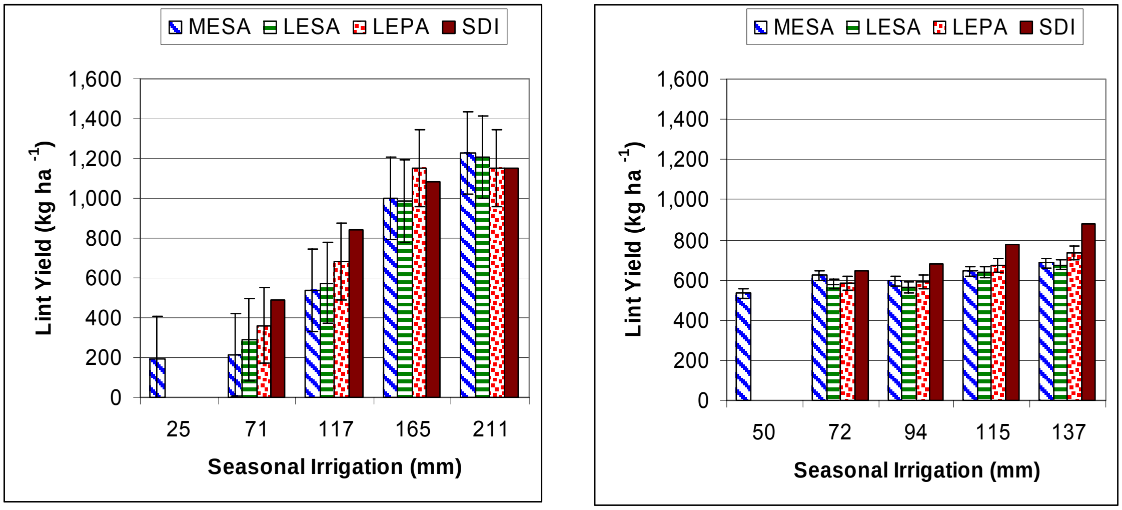


Figure 12: Cotton lint yield and seasonal irrigation averages (1999, 2000, 2001) at Halfway, TX. Additional factors were preplant irrigation amounts (full and limited) and irrigation capacities (2.5 and 5.1 mm d^{-1}) (Bordovsky and Porter, 2003).

greater seasonal irrigation being applied), implying early season water deficits likely occurred.

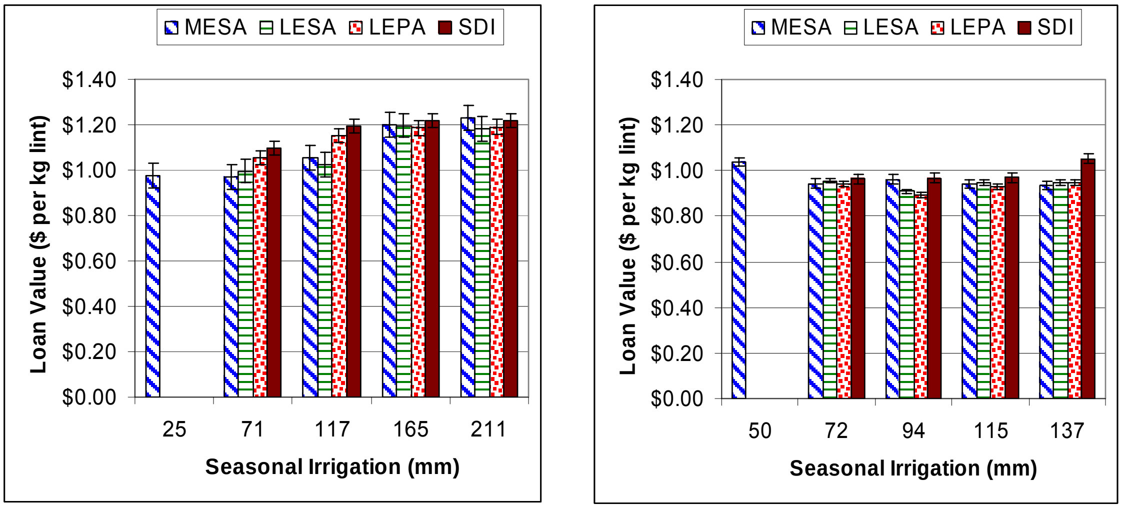
The Halfway, TX climate has sufficient heat units to produce cotton reliably; however, limited heat units in Bushland, TX make cotton production less reliable. Colaizzi et al. (2005) present the results of two contrasting cotton seasons in Bushland, where 2003 was hot and dry, whereas 2004 was relatively cool and wet. The experimental design was identical to the grain sorghum study (Colaizzi et al., 2004), where MESA, LESA, LEPA, and SDI were compared at 0%, 25%, 50%, 75%, and 100% IR. In 2003 (Fig. 13a), lint yield for SDI was significantly greater at 25% and 50% IR (71 and 117 mm seasonal irrigation, respectively) than all other methods, and LEPA was significantly greater than MESA or LESA. At 75% IR (165 mm seasonal irrigation), LEPA and SDI were greater than MESA and LESA, with lint yield under LEPA the greatest. At 100% IR (211 mm seasonal irrigation), MESA and LESA were slightly greater than LEPA and SDI, which were nearly equal. This result contradicts those of Burke (2003), who postulated that sprinklers induced pollen bursting, flower loss, and subsequent yield reductions. He reported greater lint yield under LEPA than spray, especially when irrigations occurred later in the afternoon; however, IR could not be determined from irrigation information given. Lint yield trends observed at Bushland in 2003 were very similar to those discussed previously for soybeans, sunflower, and grain sorghum. In 2004 (Fig. 13b), lint yield with SDI was significantly greater than all other methods except at 25% IR (72 mm seasonal irrigation). The patterns between wet and dry seasons were similar to those observed for corn in Colby, KS (Fig. 1; Lamm, 2004); however, lint yield was more responsive to IR in 2003 than in 2004.



a) 2003
b) 2004

Figure 13: Cotton lint yield and seasonal irrigation for a) 2003, a relatively hot and dry year; and b) 2004, a relatively cool and wet year at Bushland, TX (Colaizzi et al., 2005).

The fiber quality of lint is becoming increasingly important in the world market; for example, many textiles are adopting high-spin technologies that require longer and stronger fibers (e.g., Yu et al., 2001). Fiber quality is comprised of several parameters (length, strength, uniformity, color, micronaire, etc.). Cotton producers will receive a premium or discount relative to a base price for overall fiber quality, and the final price is termed the *loan value* (units of $ per kg lint). Loan values in 2003 (Fig. 14a) were greater for SDI at 25% and 50% IR (71 and 117 mm seasonal irrigation, respectively) than all other methods, and LEPA was greater than the spray methods. Loan values were nearly equal at 75% IR (165 mm seasonal irrigation), but MESA was significantly greater than all other methods at 100% IR (211 mm seasonal irrigation). The poor growing conditions in 2004 resulted in poorer fiber quality, as reflected by the generally lower loan values (Fig. 14b). Loan values were greatest for SDI at 100% IR (137 mm seasonal irrigation), followed by 0% IR (simulated dryland treatment with 50 mm seasonal irrigation). Overall fiber quality trends (Fig. 14) were somewhat similar to those for lint yield (Fig. 13), where fiber quality appeared responsive to IR up to 75% in 2003 but were relatively insensitive to IR in 2004. Cotton maturity did not appear responsive to irrigation method; maturity was most correlated to IR as soil water depletion progressed through increasing IR at the end of the season. However, SDI did enhance lint yield at low IR in the dry year and regardless of IR in the wet year. In many cases SDI was correlated to higher fiber quality, as reflected by slightly greater loan values relative to LEPA or spray.



a) 2003 b) 2004

Figure 14: Cotton loan value and seasonal irrigation for a) 2003, a relatively hot and dry year; and b) 2004, a relatively cool and wet year at Bushland, TX (Colaizzi et al., 2005).

CONCLUSIONS

Relative yield response between different irrigation methods usually changed with irrigation capacity (fixed application per unit time) or irrigation rate (percentage of soil water replenishment), and these were often similar for different crops and locations. Yield response in terms of irrigation method could usually be described as SDI ≥ LEPA ≥ SPRAY for low irrigation capacities (or rates), and SPRAY ≥ LEPA ≥ SDI for full (or nearly full) capacities or rates. In some cases, yield response was more consistent across irrigation rates, which may be related to rainfall patterns. For example, corn grain yield in Colby, KS was SDI ≥ LEPA when rainfall was average or above average, but LEPA ≥ SDI for below average rainfall. In Bushland, TX, cotton lint yield during a relatively cool and wet season was SDI ≥ (LEPA or SPRAY). SDI is thought to enhance cotton earliness due to reduced evaporative cooling compared to LEPA or spray. This was not observed for the two years of data at Bushland, TX; however, SDI sometimes resulted in better fiber quality.

There is a lack of existing data to conclusively explain the similar yield response trends observed for SDI, LEPA, and spray; that these occurred for different crops and locations implies that certain processes might dominate for a given irrigation method. It does appear that LEPA, and to a greater extent SDI, result in greater partitioning of water to plant transpiration relative to spray for low irrigation rates. At greater irrigation rates, the yield depressions observed for SDI and/or LEPA relative to spray were less clear, although these may be the result of poor aeration and nutrient leaching by deep percolation. The type of data required to further investigate these processes are presently very difficult to obtain. Nonetheless, some examples include near-surface soil water and temperature (which are presently being acquired at Bushland, TX), separate measurements of evaporation and transpiration, and careful studies of plant development and nutrient uptake.

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IRRIGATION MANAGEMENT WITH SALINE WATER

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INTRODUCTION

One of the most common water quality concerns for irrigated agriculture is salinity. Recommendations for effective management of irrigation water salinity depend upon local soil properties, climate, and water quality; options of crops and rotations; and irrigation and farm management capabilities.

What Is Salinity?

All major irrigation water sources contain dissolved salts. These salts include a variety of natural occurring dissolved minerals, which can vary with location, time, and water source. Many of these mineral salts are micronutrients, having beneficial effects. However, excessive total salt concentration or excessive levels of some potentially toxic elements can have detrimental effects on plant health and/or soil conditions.

The term “salinity” is used to describe the concentration of (ionic) salt species, generally including: calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), bicarbonate (HCO_3^{-}), carbonate(CO_3^{2-}), sulfate (SO_4^{2-}) and others. Salinity is expressed in terms of electrical conductivity (EC), in units of millimhos per centimeter (mmhos/cm), micromhos per centimeter (μmhos/cm), or deciSiemens per meter (dS/m). The electrical conductivity of a water sample is proportional to the concentration of the dissolved ions in the sample; hence EC is a simple indicator of total salt concentration.

Another term frequently used in describing water quality is Total Dissolved Solids (TDS), which is a measure of the mass concentration of dissolved constituents in water. TDS generally is reported in units of milligrams per liter (mg/l) or parts per million (ppm). Specific salts reported on a laboratory analysis report often are expressed in terms of mg/l or ppm; these represent mass concentration of each component in the water sample. Another term used to express mass concentration is normality; units of normality are milligram equivalents per liter (meq/l). The most common units used in expressing salinity are summarized in Table 1.

Table 1. Units commonly used to express salinity*

Mass Concentration (Total Dissolved Solids):
mg/l = milligrams per liter   ppm = parts per million   ppm ≅ mg/l

Electrical Conductivity (increases with increasing TDS):
conductivity = 1/resistance   (mho = 1/ohm)
millimhos/cm = millimhos per centimeter
μmhos/cm = micromhos per cm
dS/m = deciSiemens per meter
1 dS/M = 1 mmho/cm = 1000 μmho/cm

Salinity Conversions:
0.35 X (EC mmhos/cm) = osmotic pressure in bars
651 X (EC mmhos/cm) = TDS in mg/l*
10 X (EC mmhos/cm) = Normality in meq/l
0.065 X (EC mmhos/cm) = percent salt by weight

* Also has been related as:
TDS (mg/l) = EC (dS/m) X 640 for EC < 5 dS/m
TDS (mg/l) = EC (dS/m) X 800 for EC > 5 dS/m

Normality
meq/l = milligram equivalents per liter (*aka* milliequivalents per liter)
meq/l = mg/l ÷ equivalent weight
equivalent weight = atomic weight ÷ electrical charge

Example: To convert 227 ppm calcium concentration to meq/l:
ppm = mg/l; therefore 227 ppm = 227 mg/l
Calcium atomic weight = 40.078 g/mol
valence: +2 (charge = 2)
equivalent weight = 40.078 / 2 = 20.04
meq/l = 227 / 20.04 = 11.33
Therefore 227 mg/l = 11.33 meq/l for calcium.

** Compiled from various sources*

Why Is Salinity a Problem?

High salinity in water (or soil solution) causes a high osmotic potential. In simple terms, the salts in solution and in the soil “compete” with the plant for available water. Some salts can have a toxic effect on the plant or can “burn” plant roots and/or foliage. Excessive levels of some minerals may interfere with relative availability and plant uptake of other micronutrients. Soil pH, cation exchange capacity (CEC) and other properties also influence these interactions.

High concentration of sodium in soil can lead to the dispersion of soil aggregates, thereby damaging soil structure and interfering with soil permeability. Hence special consideration of the sodium level or "s*odicity"* in soils is warranted.

How Do You Know if You Have a Salinity Problem?

Water and soil sampling and subsequent analysis are key to determining whether salinity will present a problem for a particular field situation. If wastewater or manure is applied to a field regularly, or if the irrigation water source varies in quality, soil salinity should be monitored regularly for accumulation of salts.

Water quality and soil chemical analyses are necessary to determine which salts are present and the concentrations of these salts. Standard laboratory analyses include total salinity reported as electrical conductivity (EC) or as Total Dissolved Solids (TDS). Salinity indicates the potential risk of damage to plants. General crop tolerances to salinity of irrigation water and soil are listed in Table 2. These values should be considered only as guidelines, since crop management and site specific conditions can affect salinity tolerance.

Table 2. Tolerance* of selected crops to salinity in irrigation water and soil.

Crop	Threshold EC in irrigation water in mmhos/cm or dS/m		Threshold EC in soil (saturated soil extract) in mmhos/cm or dS/m	
	0% yield reduction	50% yield reduction	0% yield reduction	50% yield reduction
Alfalfa	1.3	5.9	2.0	8.8
Barley	5.0	12.0	8.0	18.0
Bermudagrass	4.6	9.8	6.9	14.7
Corn	1.1	3.9	1.7	5.9
Cotton	5.1	12.0	7.7	17.0
Sorghum	2.7	7.2	6.8	11.0
Soybean	3.3	5.0	5.0	7.5
Wheat	4.0	8.7	6.0	13.0

* After Rhoades, et.al. (1992); Fipps (2003) and various sources

Additional information, including concentrations of specific salt components, indicates the relative risk of sodicity and toxicity. High sodium can present a risk of toxicity to plants. It can also indicate a risk of soil aggregate dispersion, which can result in breakdown of soil structure, and hence reduce the soil's permeability. Relative risk of soil damage due to sodicity is indicated by the Sodium Adsorption Ratio (SAR), which relates the relative concentration of sodium [Na^+] compared to the combined concentrations of calcium [Ca^+] and magnesium [Mg^+]. SAR is calculated by the following equation:

$$SAR = \frac{[Na^+]}{(([Ca^+] + [Mg^+]) / 2)^{1/2}}.$$

MANAGING IRRIGATION TO MITIGATE SALINITY

Minimize Application of Salts

An obvious, if not simple, option to minimize effects of salinity is to minimize irrigation applications and the subsequent accumulation of salts in the field. This can be accomplished through converting to a rain-fed (dryland) production system; maximizing effectiveness of precipitation to reduce the amount of irrigation required; adopting highly efficient irrigation and tillage practices to reduce irrigation applications required; and/or using a higher quality irrigation water source (if available). Since some salts are added through fertilizers or as components (or contaminants) of other soil additives, soil fertility testing is warranted to refine nutrient management programs.

Crop Selection

Some crops and varieties are more tolerant of salinity than others. For instance barley, cotton, rye, and Bermudagrass are classified as salt tolerant (a relative term). Wheat, oats, sorghum, and soybean are classified as moderately salt tolerant. Corn, alfalfa, many clovers, and most vegetables are moderately sensitive to salt. Some relatively salt tolerant crops (such as barley and sugarbeet) are more salt sensitive at emergence and early growth stages than in their later growth stages. Currently crop breeding programs are addressing salt tolerance for several crops, including small grains and forages.

Some field crops are particularly susceptible to particular salts or specific elements or to foliar injury if saline water is applied through sprinkler irrigation methods. Elements of particular concern include sodium (Na), chlorine (Cl), and Boron (B). Tolerances to salinity in soil solution and irrigation water and tolerances to Na, Cl, and B are listed for various crops in references listed in the Additional Information Resources section.

Irrigation Leaching

The classical “textbook” solution to salinity management in the field is through leaching (washing) accumulated salts below the root zone. This is often accomplished by occasional excessive irrigation applications to dissolve, dilute and move the salts. The amount of excess irrigation application required (often referred to as the “leaching fraction”) depends upon the concentrations of salts within the soil and in the water applied to accomplish the leaching. A commonly used equation to estimate leaching fraction requirement (expressed as a percent of irrigation requirement) is:

$$\text{Leaching fraction} = \frac{\text{electrical conductivity of irrigation water}}{\text{permissible electrical conductivity in the soil}} \times 100\ \%$$

Where irrigation water quantity is limited, sufficient water for leaching may not be available. The combined problem of limited water volume and poor water quality can be particularly difficult to manage.

Soil additives and field drainage can be used to facilitate the leaching process. Site specific issues, including soil and water chemistry, soil characteristics and field layout, should be considered in determining the best approach to accomplish effective leaching. For instance, gypsum, sulfur, sulfuric acid, and other sulfur containing compounds, as well as calcium and calcium salts may used to increase the availability of calcium in soil solution to “displace” sodium adsorbed to soil particles and hence facilitate sodium leaching for remediation of sodic soils. In soils with insufficient internal drainage for salt leaching and removal, mechanical drainage (subsurface drain tiles, ditches, etc.) may be necessary.

Irrigation Method Selection

Where foliar damage by salts in irrigation water is a concern, irrigation methods that do not wet plant leaves can be very beneficial. Furrow irrigation, low energy precision application (LEPA) irrigation, surface drip irrigation and subsurface drip irrigation (SDI) methods can be very effective in applying irrigation without leaf wetting. Of course, more advanced irrigation technologies (such as LEPA or SDI) can offer greater achievable irrigation application efficiency and distribution uniformity.

Wetting patterns by different irrigation methods affect patterns of salt accumulation in the seedbed and in the root zone. Evaporation and root uptake of water also affect the salt accumulation patterns. Often the pattern of salt accumulation can be detected by a visible white residue along the side of a furrow, in the bottom of a dry furrow, or on the top of a row. Additional salt accumulations may be located at or near the outer/lower perimeter (outer wetting front) of the irrigated zone in the soil profile.

Seedbed and Field Management Strategies

In some operations, seed placement can be adapted to avoid planting directly into areas of highest salt accumulation. Row spacing and water movement within the soil can affect the amount of water available for seedlings as well as the amount of water required and available for the dilution of salts.

Irrigation Scheduling

Light, frequent irrigation applications can result in a small wetted zone and limited capacity for dilution or leaching of salts. When salt deposits accumulate near the soil surface (due to small irrigation amounts combined with evaporation from the soil surface), crop germination problems and seedling damage are more likely. In arid and semi-arid conditions a smaller wetted zone generally results in a smaller effective root zone; hence the crop is more vulnerable to salt damage and to drought stress injury.

Although excessive deep percolation losses of irrigation are discouraged for their obvious reduction in irrigation efficiency and for their potential to contribute to groundwater contamination, occasional large irrigation applications may be required for leaching of salts. Managing irrigation schedules (amounts and timing) to support a large root zone helps to keep salt accumulations dispersed and away from plant roots, provides for better root uptake of nutrients, and offers improved protection from short-term drought conditions.

Advantages of Organic Matter

Organic matter offers chemical and physical benefits to mitigate effects of salts. Organic matter can contribute to a higher cation exchange capacity (CEC) and therefore lower the exchangeable sodium percentage, thereby helping to mitigate negative effects of sodium. By improving and preserving soil structure and permeability, organic matter helps to support ready movement of water through the soil and maintain higher water holding capacity of the soil. Where feasible, organic mulches also can reduce evaporation from the soil surface, thereby increasing water use efficiency (and possibly lowering irrigation demand). Because some organic mulch materials can contain appreciable salts, sampling and analysis for salt content of these products are recommended.

Special Considerations: SDI maintenance

Some salts, including calcium and magnesium carbonates that contribute to water hardness, merit special consideration for subsurface drip irrigation systems. These salts can precipitate out of solution and contribute to significant clogging of drip emitters and other components (such as filters). Water quality analysis, including acid titration, is necessary to determine appropriate SDI maintenance requirements. Common maintenance practices include periodic acid injection (shock treatment to prevent and/or dissolve precipitates) and continuous acid injection (acid pH maintained to prevent chemical precipitation).

Some excellent references describing water quality considerations and maintenance recommendations for subsurface drip irrigation systems are available from Kansas State University Extension. The publication, “Filtration and

Maintenance Considerations for Subsurface Drip (SDI) Systems" is available at: http://www.oznet.ksu.edu/library/ageng2/mf2361.pdf ; and "Subsurface Drip Irrigation Systems (SDI) Water Quality Assessment Guidelines" can be accessed at: http://www.oznet.ksu.edu/library/ageng2/mf2575.pdf.

ADDITIONAL INFORMATION RESOURCES

Irrigation Salinity Management Information on the Internet

This list of references, though not exhaustive on the subject, has been assembled to aid the reader in accessing additional information on salinity management in agricultural irrigation.

- Texas Cooperative Extension and Texas Agricultural Experiment Station
  - Irrigation water quality: Critical Salt Levels for Peanuts, Cotton, Corn and Grain Sorghum
    - http://lubbock.tamu.edu/cotton/pdf/irrigwaterqual.pdf
  - Irrigation Water Quality Standards and Salinity Management Strategies
    - http://agnews.tamu.edu/drought/DRGHTPAK/SALINITY.HTM
  - Irrigation Water Quality Standards and Salinity Management
    - http://itc.tamu.edu/documents/extensionpubs/B-1667.pdf
  - What's In My Water?
    - http://itc.tamu.edu/documents/extensionpubs/E-176.pdf
  - Maintaining Subsurface Drip Irrigation Systems
    - http://itc.tamu.edu/documents/extensionpubs/L5406.pdf
- Kansas State University Research and Extension
  - Filtration and Maintenance Considerations for Subsurface Drip (SDI) Systems
    - http://www.oznet.ksu.edu/library/ageng2/mf2361.pdf
  - Subsurface Drip Irrigation Systems (SDI) Water Quality Assessment Guidelines
    - http://www.oznet.ksu.edu/library/ageng2/mf2575.pdf
- University of Nebraska Cooperative Extension
  - Irrigation Water Quality Criteria
    - http://www.ianr.unl.edu/pubs/WATER/g328.htm
- Colorado State University Cooperative Extension
  - Irrigation Water Quality Criteria
    - http://www.ext.colostate.edu/PUBS/CROPS/00506.html
- University of California Agriculture and Natural Resources
  - Irrigation Water Salinity and Crop Production
    - http://anrcatalog.ucdavis.edu/pdf/8066.pdf
- The University of Arizona Cooperative Extension
  - Saline and Sodic Soil Identification and Management for Cotton
    - http://cals.arizona.edu/crops/cotton/soilmgt/saline_sodic_soil.html
    - http://cals.arizona.edu/pubs/crops/az1199.pdf
  - Leaching for Maintenance: Determining the Leaching Requirement for Crops
    - http://ag.arizona.edu/pubs/water/az1107.pdf

USDA-ARS George E. Brown, Jr. Salinity Laboratory
    Handbook No. 60 Saline and Alkali Soils (out of print, but available online)
        http://www.ars.usda.gov/Services/docs.htm?docid=10158
USDA-NRCS National Water and Climate Center
    Salinity in Agriculture links
        http://www.wcc.nrcs.usda.gov/salinity/
Food and Agriculture Organization (FAO) of the United Nations
    The Use of Saline Waters for Crop Production - FAO Irrigation and Drainage Paper 48
        http://www.fao.org/docrep/T0667E/T0667E00.htm
    Evolution, Extent and Economic Land Classification of Salt Affected Soils
    Prognosis of Salinity and Alkalinity - FAO Soils Bulletin 31
        http://www.fao.org/docrep/x5870e/x5870e04.htm#TopOfPage
    Irrigation with Wastewater
        http://www.fao.org/docrep/T0551E/t0551e07.htm

REFERENCES

Fipps, Guy. 2003. Irrigation Water Quality Standards and Salinity Management. Fact Sheet B-1667. Texas Cooperative Extension. The Texas A&M University System, College Station, TX.

Rhoades, J.D., A. Kandiah, and A.M. Mashali. 1992. The Use of Saline Waters for Crop Production. FAO Irrigation and Drainage Paper 48. Food and Agriculture Organization of the United Nations, Rome, 1992.