PROCEEDINGS OF THE
2009 CENTRAL PLAINS IRRIGATION CONFERENCE

TABLE OF CONTENTS

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

MONSANTO TECHNOLOGY PIPELINE FOR CENTRAL PLAINS CONFERENCE

R. M. Lawson
Corn Yield and Stress Lead
Monsanto Corporation
St. Louis, Missouri
Voice:314-694-1000
Email:mark.lawson@monsanto.com

While corn is widely grown in the United States, from the central Corn Belt to the Western Great Plains, its yield potential is directly related to the amount of available water. From 1984 to 1992, according to the USDA, 67 percent of major crop losses were due to drought. Roughly 85 percent of corn grown in the U.S. suffers from varying degrees of drought during the growing season. About 6,800 gallons of water are required to grow a day's food for a family of four.

Water availability is already a major issue in several parts of the world and becoming a growing problem in others. Now, more than ever before, it is critical that farmers have a tool to combat the impact of water shortage on their crops.

In 2003, Monsanto successfully completed its first tests that demonstrated that some of the genes in its discovery program could enhance the drought tolerance of corn hybrids. These observations of enhanced yield and plant health were confirmed with greater precision in 2004 thru 2007.

During 2008 field trials in the Western Great Plains, drought-tolerant corn showed a six to 10 percent yield enhancement – a gain of 7-10 bushels on an average of 70-130 bushels per acre. In December 2008, the company made the first regulatory submission to the Food and Drug Administration for drought-tolerant corn – the first-ever biotech crop with that trait. Further submissions to the USDA and to other importing countries will be made in the coming months.

The crop is now in Phase 4 of the R&D pipeline, the last phase before commercialization. This phase includes development and testing of the best trait and germplasm combinations for commercial launch.

In general, the drought-tolerance gene works by mitigating the impact of low soil-moisture content on the plant's physiology. In response to inadequate water, corn plants typically begin to shut down their metabolism, slowing photosynthesis and growth-rate. The gene we have submitted for regulatory approval enables the corn plant to maintain metabolism for a longer period of time during drought stress. Ongoing testing has shown that the crop experiences no negative impact in conditions of adequate moisture.

Beyond the Great Plains, Monsanto's drought-tolerant technology is expected to also help improve on-farm productivity in other parts of the world – like Africa – where rainfall is insufficient or irregular. Monsanto's drought-tolerant technology shows promise to give corn crops worldwide a better opportunity to achieve their yield potential.

In addition to drought tolerance, Monsanto also has other corn technologies in its pipeline. SmartStax contains multiple modes of action, for insect-resistance management against above and below ground insects, and offers the company's most comprehensive weed-control system. The company expects a 2010 commercial launch for SmartStax pending regulatory approval.

These technologies as well as others in our pipeline or already on the market reflect Monsanto's commitment to help farmers boost on-farm productivity through established and new advancements in plant breeding and biotechnology. The company's investment in breeding and biotechnology research is key to meeting these commitments with more than $2.6 million per day spent on leading agricultural research.

In June 2008, Monsanto announced an ambitious plan to double yields in its three core crops – corn, cotton and soybeans – by 2030 compared to a base year of 2000 – as part of a three-point pledge called the Sustainable Yield Initiative. The company also committed to conserving more of the world's precious natural resources by reducing by a third, the aggregate amount of key inputs such as water, land and energy, required to produce each unit. Monsanto plans to do this by providing choices for modern agricultural technology to its stakeholders and has also committed to helping resource-poor farm families.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N. Thompson, Colby, Kansas

THE ROLE OF WIND ENERGY IN AGRICULTURE
A COOPERATIVE'S POINT OF VIEW

Robert J. Johnson, P.E.
Executive Manager, Engineering and Energy Services
Sunflower Electric Power Corporation
Hays, Kansas
Voice: 785-623-3319 Fax: 785-623-3385
Email:bjohnson@sunflower.net

UNDERSTANDING ELECTRIC COOPERATIVES

- We are not-for-profit entities
- Electric rates are based on cost of service, not on a return on investment
- Member consumers are the cooperative's owners
- Consumers elect a governing board of directors from their members
- The mission is long-term low-cost reliable service

SUNFLOWER (AND MID-KANSAS ELECTRIC COMPANY, LLC) MEMBERS SERVE RURAL WESTERN KANSAS

- Generation and Transmission:
    - Sunflower Electric Power Corporation
    - Mid-Kansas Electric Company, LLC

- Distribution (G&T owners):
    - Lane-Scott Electric Cooperative, Inc., Dighton
    - Pioneer Electric Cooperative, Inc., Ulysses
    - Prairie Land Electric Cooperative, Inc., Norton
    - Western Cooperative Electric Association, Inc., WaKeeney
    - Wheatland Electric Cooperative, Inc., Scott City
    - Victory Electric Cooperative Association, Inc., Dodge City

ELECTRIC DEMAND IS STEADILY RISING

- 2% TO 3% per year for the past 15 to 20 years
- Recently load growth for irrigation has far exceeded the average
- Growth from other agriculture based industries such as ethanol plants

SERVING LOAD REQUIRES DIVERSE CAPACITY RESOURCES

- Seasonal variations in load change the energy supply and cost
- Base-load, coal and hydro
- Intermediate-load, natural gas
- Peaking-load, natural gas and diesel

SUNFLOWER GENERATION PORTFOLIO

- Holcomb Station, 360 MW, Coal
- Garden City Station, 225 MW, Natural Gas
- Smoky Hills 1 Wind Farm, 50 MW, Wind

MID-KANSAS GENERATION PORTFOLIO

- Great Bend Station, 98 MW, Natural Gas
- Fort Dodge Station, 145 MW, Natural Gas
- Jeffrey Energy Center, 177 MW PPA, Natural Gas
- Clifton Station, 73 MW, Natural Gas
- Cimarron River Station, 76 MW, Natural Gas
- Smoky Hills 2 Wind Farm, 24 MW, Wind
- Gray County Wind Farm, 50 MW, Wind

WIND ENERGY IS NEGATIVE LOAD TO A UTILITY

- Intermittent capability to generate energy
- Does not provide Capacity or base load energy
- Compares favorably with intermediate and peaking variable costs
- Increases system volatility and costs

CUSTOMER-OWNED GRID-CONNECTED RENEWABLE GENERATION

- Current:
  - Parallel Generation, a buy/sell arrangement
- Proposed:
  - Net Metering

FOUR COMPONENTS TO A TYPICAL RETAIL ENERGY CHARGE

- Distribution Costs: 2 to 6 cents/kWh
- Transmission Costs: .5 to 1.5 cents/kWh
- Generation Fixed Costs: 2.5 to 3.5 cents/kWh
- Generation Variable Costs: 1.5 to 8 cents per kWh (avoided cost)

KANSAS' EXISTING PARALLEL GENERATION STATUTE

- A buy/sell arrangement that allows for "behind the meter" connection of renewable generation by a customer-generator
- No changes to existing retail rate schedule are required
- Compensation for energy sold back to utility is 150% of avoided cost
- Avoided cost is energy component of generation only
- 25 kW limit for residential
- 200 kW limit for commercial
- Must be appropriately sized for customers load
- Not more than 10 irrigation pumps per customer under this statute
- Must meet all utility safety and reliability standards
- Retail wheeling is not allowed
- Most value is to offset existing load
- Standard procedures in place to accommodate the PGS statute
- Provisions for some latitude in generator sizing
- Renewable generators can be very expensive and payback can be long or non-existent

PROPOSED NET METERING

- Net metering is a concept where a customer can use the utility system as a "bank" or "battery" to store and withdraw energy (at no cost to the customer)
- Often described as a system where the meter can run backwards when customer generates more energy than needed
- The problem is that the product taken out costs the utility much more than the benefit of the product put in
- Net metering is not currently available in Kansas but is currently being discussed
- Coops opposition to net metering is an issue of fairness
    - Why should the utility be forced to pay retail cost (transmission, generation capacity and energy) to receive only wholesale energy?
    - Why should some customers be advantaged at the cost of other customers on the system?
- Would probably not advantage a commercial customer with a demand/energy rate structure
- Could benefit cost recovery for residential customer-generators

FINAL COMMENTS

- Sunflower and Mid-Kansas:
    - Actively support customer-owned renewable generation
    - Are pursuing a 25x25 renewable energy goal
- However, intermittent renewable energy does not, and cannot, cure the shortage of economical base-load generation

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

THE TEXAS HIGH PLAINS EVAPOTRANSPIRATION (TXHPET) NETWORK

T. H. Marek
Senior Research Engineer
Texas AgriLife Research
Amarillo, Texas and
Superintendent, North Plains
Research Field
Etter, Texas
Voice: 806-677-5600
Fax: 806-677-5644
Email:t-marek@tamu.edu

D. O. Porter
Associate Professor and
Extension Agricultural Engineer
Texas AgriLife Research and
Texas AgriLife Extension Service
Lubbock, Texas
Voice:806-746-4022
Fax: 806-746-4057
Email:d-porter@tamu.edu

SUMMARY

Development, adoption and use of an evapotranspiration (ET) network system designed for irrigation scheduling entail the integration of several factors that include a simplified data acquisition approach, user understanding, multiple dissemination venues, user clientele education, resource support plus operational commitment by network personnel to maintain accurate meteorological and ET data. The Texas High Plains Evapotranspiration (TXHPET) network was developed with these factors in mind and continues to gain adoption by irrigated users to date. The TXHPET system, its development, use, output and operations are discussed.

INTRODUCTION

As irrigation continues to be the majority user of water (60%) in Texas (Texas Water Facts, 2008) and other states, increases in other water use sectors are typically dependent on transfers from the agricultural sector. Thus, agriculture is likely to continue to have to produce more with less water and depend more on conservation measures, technological advances and irrigation scheduling to optimize irrigation management. Conservation districts and other water governing agencies are increasingly embracing network based evapotranspiration (ET) requirements as the maximum allowable pumping for crops. Appropriate (high quality and location-specific) meteorological data are necessary for application of widely accepted standard ET models and calculations.

Numerous meteorological networks have been developed and are in existence today in the U.S. Most of these systems have differing primary objectives and targeted users. The purpose and scope of these networks vary in size and intent along with differing interrogation intervals. Some are large-scale climate based and can be used for varying purposes. Others are specific in nature and the data are controlled and restricted to the designated application or agency. Agriculturally based ET networks generally have the defined purpose of estimating crop ET within a particular region. Networks such as “school net” sites are basically teaching tools for students and for illustration of the variability of localized rainfall events and typically are not suitable for agricultural applications because of city and urban (siting) based parameter influences. Agricultural meteorological stations need to be representative of the environment they are located in with sensors conforming to standardized accuracy and placement (ASABE, 2004; Walter, et al., 2005). Data interrogation, processing, and transfers (uploads) must be consistent and timely for producer adoption and use. Sensor maintenance should be a priority issue of the network and adhered to for accurate, continuous quality assured and quality controlled data streams. Most importantly, ET computations should be scientifically based and documented adequately for comparison with the latest standardized ET equations.

METEOROLOGICAL STATIONS

Placement of ET weather stations should be a key component in the establishment of a successful and useful network station grid. Stations should be located in areas where irrigated agriculture is practiced. Additional considerations for placement involve known or anticipated topographical differences such as elevation. Station placement should be adequately “free” from biasing influences such paved roads, tree rows, valleys, large depression areas, potential water holding areas such as playas, lakes, large water holes, unpaved roads with dust potential, feedyard or other confined animal feeding operations, grain elevators, or other influences that may alter representative agriculturally based acquisition of meteorological parameters.

The number of stations within an ET network is not as important as their representation. The TXHPET network currently has 18 stations over an area representing more than 1.5 million irrigated acres. In the TXHPET network, representation in the Texas High Plains intensively irrigated areas typically ranges from to 900 to 1500 square miles per station. This figure can vary depending on the surrounding topography and prevailing upwind influences. Redundancy or overlap of weather stations is a good design consideration as data from adjacent units can be more easily estimated with redundant units. In many cases, redundancy cannot be determined until adequate data are acquired to indicate that it exists.

NETWORK DEVELOPMENT

Development of a regionally based ET network should involve a multi-disciplinary scientific based team as well as industry and commodity representatives. Additionally, large operation, progressive growers and crop consultants should be invited to provide valuable input in to the design and format of the output materials. Others that may be included are area agricultural agency representatives and governing water agency personnel. Early input is necessary as the crop consultants and large producers are the ones who will most likely use the outputs and they sometimes will have strong opinions as to how they want the data formatted for integration into their operations. Most producers and even many consultants do not want to spend time calculating values from equations each day. Most want a single value of daily ET to use in a straightforward, easy to understand irrigation scheduling checkbook type method or equivalent irrigation scheduling program. These desires have been learned by the development team of the Texas High Plains ET (TXHPET) network in the early 1990's. In addition, the following should be strongly considered:

1) Data must be accurate and scientifically based and supported.
2) Data must be timely (daily or more frequent depending on application goal).
3) Data must maintain integrity (through scheduled maintenance and timely repairs as needed).
4) Data must be comparative, calibrated and verified.
5) Data must be sustainable (with adequate resource support and allocation).
6) Data should conform to agriculturally based and scientific standards.

Initially, the TXHPET development team brought a group of producers to listen to their needs and they decided jointly that they wanted a single "fax sheet" of the ET data delivered on a daily basis whereby they could read a single crop value of ET for yesterday's conditions. After the initial design draft, the consultant and producer members rearranged much of the sheet to their liking to fit their needs. This involvement by the users virtually ensured that the data output format was what they wanted and not just what the science based members dictated. The single page fax file format is still in use today and contains data for cereal grain crop daily, 3-day, and 7-day ET's plus growing degree day heat units and average growth stage for short and long season crops with four dates of planting. Figure 1 illustrates the information in the TXHPET fax file format. Another file that is created daily and that has hourly formatted information for researchers and other related agricultural industry users is designated as an hourly file. A copy of this file in illustrated in Figure 2.

Date	ETo in.	Temperatures (F) ---Air-- Max	Min	Soil Min 2in.	6in.	Prec. in.	Growing Degrees Days (F) Crn	Srg	Pnt	Cot	Soy	Wht
07/16/08	.22	89	63	71	75	0.00	25	26	0	16	29	0
07/17/08	.27	91	62	70	74	0.00	24	27	0	17	28	0
07/18/08	.25	90	66	73	76	0.01	26	28	0	18	30	0

10-day avg min soil temp 68 72 Wind 6.3 mph from 226 deg.

CORN Seed Date	Acc GDD	Short Season Var. Water Use Growth Stage	Day	3day	7day	Seas. in.	Long Season Var. Water Use Growth Stage	Day	3day	7day	Seas. in.
			-----in/d-----					-----in/d-----			
04/01	1860	Milk	.32	.32	.29	22.8	Blister	.32	.32	.29	22.5
04/15	1761	Milk	.32	.32	.29	20.4	Silk,	.32	.32	.29	20.2
05/01	1550	Blister	.32	.32	.29	16.1	14-leaf	.31	.31	.28	15.9
05/15	1379	Silk,	.32	.32	.29	12.7	14-leaf	.31	.31	.28	12.6

SORGHUM Seed Date	Acc GDD	Short Season Var. Water Use Growth Stage	Day	3day	7day	Seas. in.	Long Season Var. Water Use Growth Stage	Day	3day	7day	Seas. in.
			-----in/d----					-----in/d----			
05/01	1693	Flag	.23	.23	.21	13.8	Flag	.23	.23	.21	12.7
05/15	1521	Flag	.23	.23	.21	11.2	Flag	.23	.21	.18	10.3
06/01	1206	GPD	.20	.20	.18	7.7	5-leaf	.17	.17	.16	7.2
06/15	853	5-leaf	.17	.17	.16	4.2	4-leaf	.15	.15	.13	4.1

COTTON Seed Date	Acc GDD	North Plains Area Water Use Growth Stage	Day	3day	7day	Seas. in.	South Plains Area Water Use Growth Stage	Day	3day	7day	Seas. in.
			-----in/d----					-----in/d----			
05/01	894	1st Sqr	.24	.24	.22	10.4	1st Sqr	.24	.24	.22	10.0
05/15	868	1st Sqr	.24	.24	.22	9.6	1st Sqr	.24	.24	.22	9.3
06/01	727	1st Sqr	.24	.24	.22	6.6	1st Sqr	.24	.24	.18	6.3
06/15	513	Emerged	.12	.12	.11	3.5	Emerged	.12	.12	.11	3.5

SOYBEANS Seed Date	Acc GDD	Late Group 4-Var. Water Use Growth Stage	Day	3day	7day	Seas. in.
			-----in/d----			
05/15	1629	R_3	.26	.26	.23	12.8
06/01	1271	V-6	.20	.20	.18	8.3
06/15	917	V-4	.17	.17	.15	4.8
07/01	489	Emerged	.14	.14	.12	2.0

Fescue/Bluegrass lawn water use 0.24 inch
Bermuda grass lawn water use 0.18 inch
Buffalo grass lawn water use 0.12 inch

Figure 1. Fax output format from the TXHPET network illustrating daily crop ET values for multiple crops and planting dates.

```
     Station:ETTER, TX  Long 102 deg 0 min  Lat 36 deg 0 min
     Date:07/18/08  Year/DOY:2008200 Elev: 1103 m   Bar. Corr: 12.5
     Sunrise 545  Sunset 2003   Daylight time = 14 hours  18 minutes

Time    Rs    Ts2   Ts6   Tair  TDew   RH  AVP   VPD  WSpd Wdir SDd  PREC   BP   EToG  EtoA
CST   W/m^2    C     C     C     C      %  kPa   kPa   m/s  deg deg   mm   kPa    mm    mm
 100    0.0  25.0  26.6  23.2  16.3   65  1.85  1.00  2.2  202  15  0.00 -99.9  0.04  0.07
 200    0.0  24.6  26.3  22.0  16.7   72  1.90  0.74  1.3  213  26  0.00 -99.9  0.02  0.03
 300    0.0  24.1  26.0  20.5  17.0   81  1.94  0.46  0.7  311   9  0.00 -99.9  0.00  0.00
 400    0.0  23.7  25.7  20.3  17.2   83  1.97  0.41  0.9  272  31  0.00 -99.9  0.00  0.01
 500    0.0  23.3  25.3  20.4  17.2   82  1.97  0.43  1.5  208  15  0.00 -99.9  0.01  0.02
 600    3.5  23.0  25.1  20.1  17.3   84  1.98  0.37  1.4  238  26  0.00 -99.9  0.01  0.02
 700   36.8  22.8  24.8  20.3  17.4   83  1.99  0.40  1.7  214  13  0.00 -99.9  0.03  0.05
 800  103.7  22.8  24.6  21.0  17.1   78  1.95  0.54  2.5  242  16  0.00 -99.9  0.10  0.13
 900  220.4  23.1  24.4  22.1  17.2   74  1.96  0.70  2.9  258  13  0.00 -99.9  0.18  0.23
1000  443.6  24.0  24.3  24.2  17.1   65  1.95  1.07  3.5  256  13  0.00 -99.9  0.35  0.44
1100  727.5  25.9  24.4  27.2  16.6   52  1.89  1.72  2.9  250  16  0.00 -99.9  0.57  0.68
1200  883.6  28.7  24.8  29.1  16.8   48  1.92  2.12  2.8  234  21  0.00 -99.9  0.70  0.84
1300  992.2  31.0  25.5  29.9  16.9   46  1.93  2.29  3.8  202  20  0.00 -99.9  0.80  0.98
1400  996.1  33.2  26.4  31.0  16.2   41  1.84  2.64  3.9  192  20  0.00 -99.9  0.83  1.03
1500  905.7  34.5  27.4  31.3  14.5   36  1.66  2.90  3.7  207  23  0.00 -99.9  0.78  0.98
1600  760.0  35.2  28.3  31.7  14.0   34  1.61  3.08  4.2  203  19  0.00 -99.9  0.71  0.92
1700  388.6  34.8  29.0  30.9  13.4   34  1.54  2.93  3.7  213  19  0.00 -99.9  0.45  0.63
1800  147.6  33.1  29.5  27.7  15.7   49  1.80  1.94  4.4  184  27  0.00 -99.9  0.27  0.42
1900   71.8  31.2  29.5  25.2  17.3   61  1.98  1.24  4.4  175  12  0.00 -99.9  0.17  0.27
2000   14.7  29.7  29.2  24.9  16.7   61  1.91  1.24  3.4  176  11  0.00 -99.9  0.11  0.19
2100    0.0  28.5  28.8  24.0  16.7   64  1.90  1.08  3.6  188  40  0.00 -99.9  0.06  0.10
2200    0.0  27.5  28.4  22.7  17.1   71  1.95  0.80  2.8  310  21  0.00 -99.9  0.04  0.07
2300    0.0  26.7  27.9  20.6  17.4   82  1.99  0.44  3.3  295  17  0.00 -99.9  0.03  0.04
2400    0.0  25.9  27.5  19.6  17.8   90  2.04  0.23  2.8  248  18  0.25 -99.9  0.01  0.02

Sum    24.1 MJ                                                  0.25         6.28  8.16
Avg          27.6  26.7  24.6  16.6   64  1.89  1.28  2.8  226  43       -99.9
Max  1320.4  35.2  29.6  32.2  18.8   93  2.16  3.33  8.6                -99.9
Time   1158  1531  1748  1523  1216 2345  1216  1458 1724                 9999
Min          22.7  24.3  19.1  11.8   30  1.39  0.16                     -99.9
Time          655   949  2358  1450 1457  1450  2345                      9999

     Precipitation by 15 minute periods
     2345  0.25
```

Figure 2. Hourly file output format of the TXHPET network containing hourly meteorological data and ETo values plus daily values.

While these file formats are simple for the producers and other agricultural users, researchers generally desire more options and advanced type outputs. Both can be programmed into the system but the main focus should be on the producer utilization; otherwise, it becomes cumbersome and more of research effort than a user product. The research parts of the system may be "hidden" from the general user as necessary to prevent confusion.

Rainfall at the respective network sites is possibly the least relevant ET parameter of the data set although it is one of the most monitored by users. Users should use site specific field rainfall in their irrigation scheduling method. The values recorded by the TXHPET network are frequently in question from both producers and researchers alike and large differences often result from highly variable precipitation events or even from common rain gauge problems, including plugged funnels and ports.

Development with an ET network is typically not complete but rather an ongoing process. Advances in the hardware and software change over time and most of this activity should be transparent to the user. Over time new interrogation instrumentation and data modules plus computational methods have replaced the initial and earlier methods of acquisition. Much of the original instrumentation and sensors are no longer available so upgrades are seemingly always forthcoming. Additionally, researchers are progressing to evaluate ET values on smaller (shorter) time scales for new future irrigation application systems with data interrogation times becoming shorter.

DISSEMINATION

Data and Calculated Values

Originally, faxing of the "fax sheet" was the main dissemination method during the 1990's. Since then, the TXHPET network has developed a web based listserv whereby growers can subscribe and change at their will which stations and the type(s) of files they want to receive through e-mail at around 05:00 each day. Although the fax mode of dissemination has been diminished in terms of requests using the fax mode, its primary replacement has been that of email. A few years ago, the TXHPET system created an ET network parameter data base whereby internet users can query the system and receive data in formats selected from several available formats, including on-line graphics options. A snapshot of the site is included in Figure 3 and the site can be accessed at http://txhighplainset.tamu.edu/. This addition has cut down significantly on the number of data formatting and processing requests network personnel had to deal with on a timely basis. Backup electronic data sites on other servers support duplicative data sets to assure data security and reliable access. Although the TXHPET system has been considered successful, the network team continues to listen to the needs of the clientele and propose new tools for integration into the network sites, including more automation of the data into user based tools as well as and including upgrading the crop growth models for adequate representation of current and progressive production agriculture.

TXHPET Use

The TXHPET network has kept statistics of use and downloads since its inception and has in recent years averaged about 300,000 pages of disseminated information per year. This past summer season, an additional 180,000 plus pages of crop ET downloads were noted indicating that as energy based pumping costs increased in 2008, users wanted more exacting ET

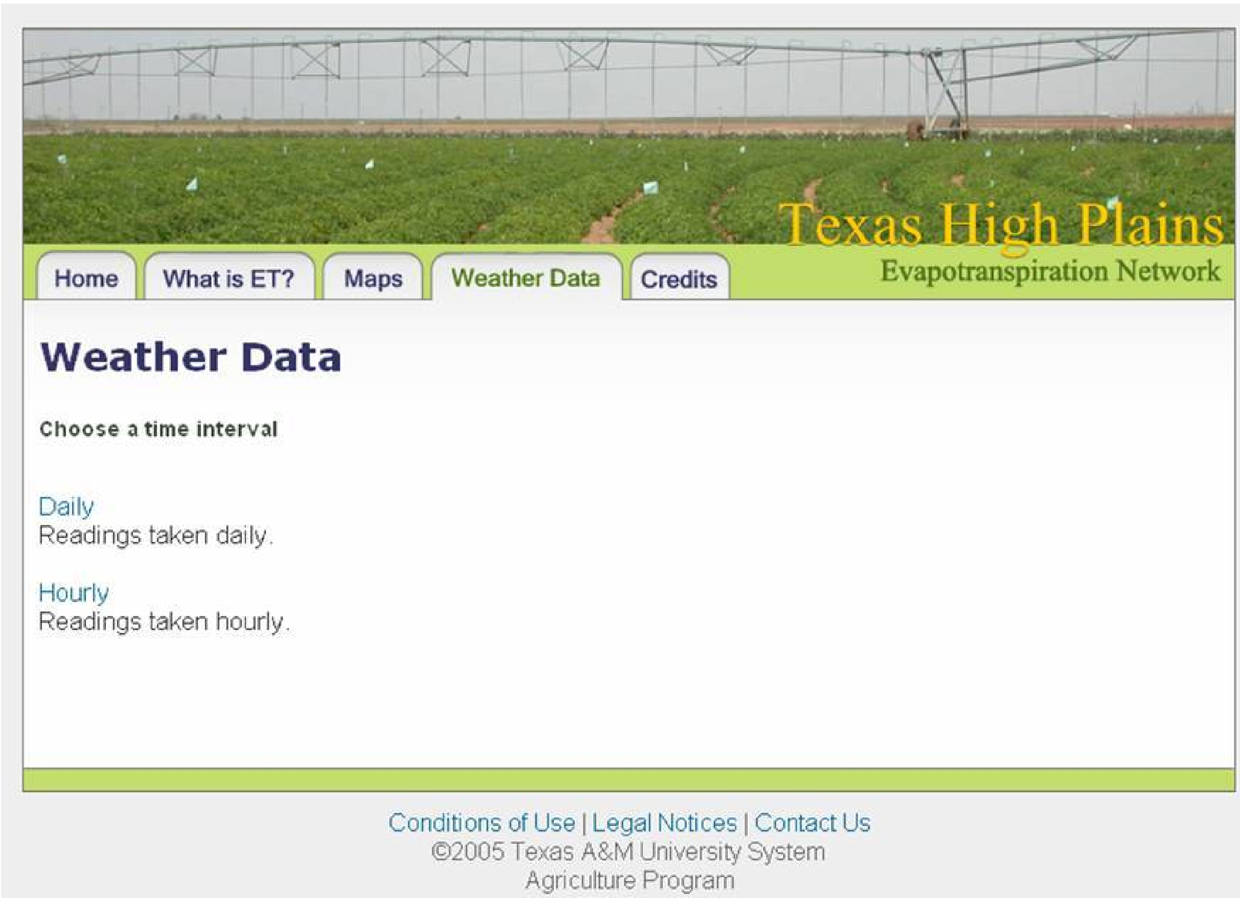


Figure 3. TXHPET network web page containing weather data selection.

data to assess and refine irrigation management practices. This also coincided with an enhanced extension education effort by the limited staff associated with the TXHPET network in the Texas High Plains. While the majority of users have been irrigated producers and crop consultants, others include farm managers, production consultants, seed production agronomists, agricultural engineers, researchers, extension specialists, water district managers and technicians, water planners and consultants, state agency regulators, design engineers and city water and parks superintendents. The highest priority network users are the producers as they are the ones who have the opportunity to conserve the greatest amount of water in the region. Also, most state water agencies appreciate the use of the network as it provides a sound basis for regional water planning efforts and documentable and consistent inputs into the groundwater availability model (GAM) used for future supply and demand planning.

FUNDING

The single most difficult challenge of operating an ET network, which has been experienced by others throughout the western U.S. is that of securing sustained funding for operations and maintenance. Development and upgrade dollars can be acquired but sustained funds for personnel are hard to secure. Operational attempts to sustain operations from sales of the data have proved unsuccessful for almost all ET based networks and only account for approximately 5% of the needed revenue annually.

CONCLUSION

A well developed and maintained ET network is essential for implementation of irrigation scheduling within an intensively irrigated region. The development of such a system should be an on-going effort whereby the interested parties, particularly the irrigated producers should provide input into future needs for integrated use of their operations. The network can also provide data for a variety of other interests that use the data for wise and efficient use of water resources.

REFERENCES

Allen, R., I. Walter, R. Elliott, T. Howell, D. Itenfisu, M. Jensen, and R. Snyder. 2005. The ASCE standardized reference evapotranspiration equation. Reston, Va.: Am Soc. Civil Engr., Environ. Water Resource. Institute.

ASABE Standards. 2004. EP505: Measurement and reporting practices for automatic agricultural weather stations. St. Joseph, Mich.: ASABE.

Porter, D.O., T.H. Marek, T.A. Howell, and L. New. 2005. The Texas High Plains Evapotranspiration Network (TXHPET) User Manual v. 1.01. Texas A&M University Agricultural Research and Extension Center Rep. 03-37. Available at: http://txhighplainset.tamu.edu/usermanual.pdf (accessed 23 January 2009).

Texas Water Facts, 2008. Texas Water Resources Institute, College Station, Texas.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N Thompson, Colby, Kansas

CLIMATE CHANGE IMPACTS ON CROP GROWTH IN THE CENTRAL HIGH PLAINS

Dr. Rob Aiken
Research Crop Scientist
K-State Northwest Research-Extension Center
105 Experiment Farm Road, Colby, Kansas
Voice: 785-462-6281 Fax: 785-462-2315
Email: raiken@ksu.edu

ABSTRACT

Historic annual increases in global carbon dioxide (CO_2) concentration are expected to continue; increased global temperatures are forecast as well. Crop productivity can benefit from increased ambient CO_2 as similar assimilation rates can be maintained with smaller canopy conductance, resulting in modestly reduced crop water requirement. Cool-season grass crops and broadleaf crops will likely gain photosynthetic efficiencies with elevated CO_2 levels. When elevated temperatures exceed optimal conditions for assimilation, stress responses can include damage to the light-harvesting complex of leaves, impaired carbon-fixing enzymes, thereby reducing components of yield including seed potential, seed set, grain fill rate, and grain fill duration. Field studies conducted under conditions of elevated CO_2indicate that benefits of elevated CO_2 are reduced by heat-induced stress responses. Crop cultural practices can be adapted to avoid stress, genetic advances may yield germplasm capable of tolerating or resisting stress factors.

INTRODUCTION

Climate change forecasts for the central High Plains, pertinent to crop growth, indicate increases in ambient carbon dioxide (CO_2) concentration, average annual temperatures, and intensity of hydrologic events (e.g. storms and drought) (IPCC, 2007). Field and controlled environment studies document substantial effects of these expected climate changes on factors affecting crop yield formation. Briefly, transpiration efficiency tends to increase with elevated ambient CO_2; elevated temperatures can impair yield formation by damaging photosynthetic capacity, reducing enzyme activity, impairing seed-set and grain-fill rates, increasing respiratory losses of assimilates, and reducing radiation capture due to accelerated crop development. Climate change forecasts indicate greater temperature increases in the High Plains relative to eastern regions. Though the High Plains may encounter greater impacts, qualitatively similar effects may be expected in the eastern Great Plains. Opportunities to mitigate these effects may require discovery and utilization of genetic resources to provide tolerant/resistant cultivars as well as revised crop cultural practices. A summary of critical processes is outlined below.

EXPECTED CLIMATE CHANGE FACTORS

Increased atmospheric CO_2 concentrations recorded at Mauna Loa are a matter of historic record (Howell, 2009). Forecasts for continued increases in ambient CO_2 depend on expected rates of fossil fuel combustion. Increased global temperatures are a more recent phenomenon (Figure 1) and are associated with greenhouse gas effects. Forecasts for continued global warming depend on the rate of greenhouse gas accumulation and modeled effects on global surface-atmosphere exchange processes. This review will focus on the expected impacts of increased atmospheric CO_2 and increased temperatures on crop productivity and yield formation, considering current knowledge of plant physiology.

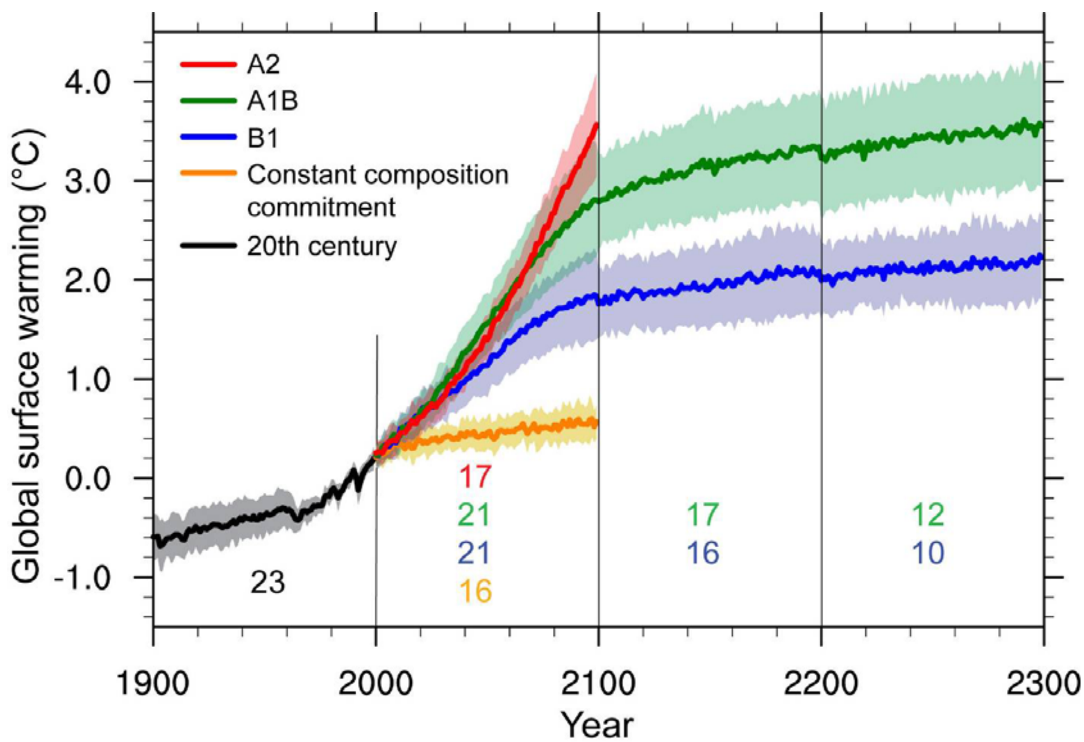


Figure 1. Global surface temperature forecast from climate change model experiments from 16 groups (11 countries) and 23 models collected at PCMDI (over 31 terabytes of model data). Committed warming averages 0.1°C per decade for the first two decades of the 21st century; across all scenarios, the average warming is 0.2°C per decade for that time period (recent observed trend 0.2°C per decade). Source: IPCC (2007) Ch. 10, Fig. 10.4, TS-32; after Feddema (2008).

CROP YIELD FORMATION

Crop yield (Y_T) can be related to water use (ET), considering the transpiration (T) component of ET, biomass productivity relative to T (TE, transpiration efficiency) and the grain fraction of biomass (HI, harvest index; Passioura 1977).

$$Y_T = TE \bullet \frac{T}{ET} \bullet ET \bullet HI \qquad [1]$$

Each component of this relationship can be altered by genetic, environmental and/or crop management effects. Tanner and Sinclair (1983) provided evidence that transpiration efficiency approaches a constant value, $\mathbf{k_d}$, when adjusted for daily vapor pressure deficit (VPD) effects. This intrinsic transpiration efficiency is greater for crops, such as corn, which utilize C4 physiology (CO_2 fixation results in oxaloacetic acid, a four-carbon compound, $\mathbf{k_d}$ = 0.118 mbar), relative to that of crops, such as soybean, with C3 physiology (CO_2 fixation results in phosphoglyceric acid, a three-carbon compound, $\mathbf{k_d}$ = 0.041 mbar).

An analogous relationship (Earl and Davis, 2003) can be developed between yield (Y_R) and biomass productivity relative to photosynthetic electron supply (RUE, radiation use efficiency), considering the fraction of absorbed radiation used to drive assimilatory processes (Φ_{PSII}, quantum yield of photosystem II), intercepted photosynthetically active radiation (IPAR), photosynthetically active radiation (PAR) and HI.

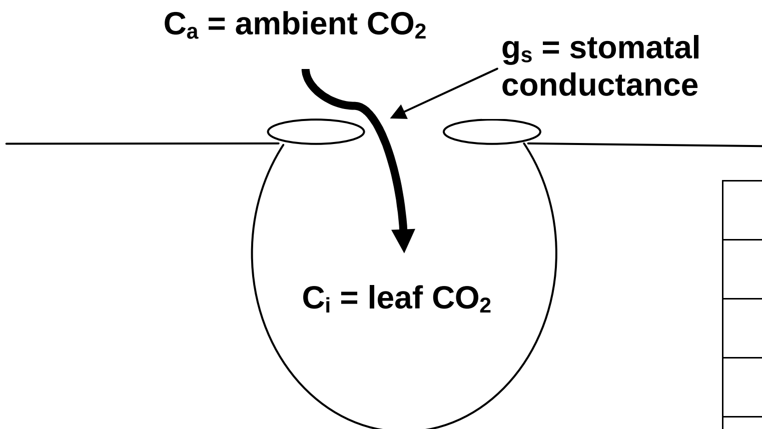
$$Y_R = RUE \bullet \Phi_{PSII} \bullet \frac{IPAR}{PAR} \bullet PAR \bullet HI \qquad [2]$$

Krall and Edwards (1991) demonstrated a direct linear relationship between gross photosynthesis and absorbed photosynthetically active radiation, when corrected for quantum yield of photosystem II. Kiniry et al. (1998) reported a linear relationship between RUE and VPD, analogous to that observed for TE. Equations [1] and [2] indicate that crop yield can be related to either the transpiration component of water use or the interception component of solar radiation, considering conversion efficiencies to biomass and yield formation factors. Rochette et al. (1996) demonstrated a linear relationship between the ET and net photosynthesis flux for well-watered corn after canopy closure when ET was adjusted for VPD effects. This supports interpretation of equations [1] and [2] as analogous. Together, these equations provide a framework for evaluating expected climate change effects on crop productivity and grain yield.

CROP RESPONSES TO EXPECTED CLIMATE CHANGE FACTORS

Ambient CO_2

Crop productivity, with respect to water use, is expected to increase as ambient CO_2 increases. Elevated CO_2 increased productivity of plants with C3 physiology—with increased yield as well (Tubiello et al., 2007). As an example, Figure 2 shows effects of ambient CO_2 concentration (320, approximate 1965 condition and 390 ppm, approximate current condition, volume basis) on water vapor efflux and CO_2 influx across a leaf stoma. Calculations of leaf conductance assume identical assimilation rates (50 µmol m^{-2} s^{-1}) and a constant ratio of CO_2 within the sub-stomatal cavity (Ci) to ambient (Ca): 0.5. In this example, stomatal conductance would be 16% smaller under current conditions of elevated ambient CO_2, relative to that around 1965. Associated with less stomatal conductance is reduced transpiration and a warmer canopy temperature. These results are expected for plants with both C3 and C4 physiology, though a greater relative increase in CO_2 fixation is expected for plants with C3 physiology due to inefficiencies associated with the carboxylating enzyme, Rubisco.



$$\boxed{A = g_s(C_a - C_i)}$$

	1965	2005
C_a	320	390
C_i	160	195
g_s	0.31	0.26
A	50	50

Figure 2. Schematic depicts CO_2 diffusion through stomatal aperture of a leaf, into the sub-stomatal cavity. Carbon fixation (**A**, assimilation) can be calculated as the product of stomatal conductance (**g_s**) and the gradient between ambient (**C_a**) and sub-stomatal (**C_i**) CO_2 concentrations. In this hypothetical example, the increase in atmospheric CO_2 concentrations, from 1965 to 2005, results in identical assimilation rates, with a smaller g_s. Smaller g_s tends to reduce evaporative loss of water, though canopy temperatures tend to increase.

The photosynthetic efficacy of Rubisco, e.g. in fixing CO_2 into six-carbon sugars, is limited by the relative concentrations of CO_2 and O_2 at the reaction site (Ainsworth and Rogers, 2007). Typically, plants with C4 physiology sequester Rubisco in bundle sheath cells, where O_2 concentrations are small, hence the superior productivity of plants with C4 physiology. Rubisco occurs in mesophyll cells of C3 plants, exposed to near-ambient O_2 concentrations, resulting in approximately one third of enzyme activity diverted from CO_2 fixation. Because of this difference, the increased assimilation response of plants with C3 physiology, to increased CO_2 concentration can generally be attributed to increased Rubisco efficacy in mesophyll cells, though plant acclimation to elevated CO_2 can introduce further complexities.

The relative impacts of elevated CO_2 on photosynthesis, growth and yield formation of plants with C3 and C4 physiology is somewhat controversial. Long et al. (2006) reported that Free-Air CO_2 Enrichment (FACE) technologies indicate ~ 50% less yield benefits from elevated CO_2 than earlier studies of crop responses to elevated CO_2, based on enclosure techniques. The FACE studies indicate plants with C4 physiology have little increase in assimilation with CO_2 enrichment (Rubisco tends to be CO_2-saturated at current ambient CO_2 levels) but stomatal conductance is reduced for these plants, thereby reducing water consumption. Wall et al. (2001) reported, for well-watered sorghum, that under FACE, stomatal conductance decreased 37% and assimilation increased 9%, and leaf water potential increased (reduced leaf water deficit) by 3%; however, no change in final shoot biomass was detected. Long et al. (2006) found increased productivity for plants with C3 physiology with CO_2 enrichment, but the yield increase was less than that projected from earlier enclosure studies. These studies show that, though assimilation capacity increased by 36%, the increase in canopy assimilation was 20%; biomass increase was 17% and yield increase was 13%. The limited yield response, relative to increased productivity potential, could result from plant acclimation to elevated CO_2 conditions. The FACE studies indicate that opportunities to realize the potential benefits of elevated CO_2 for C3 crops will require further development.

Table 1. Percentage increases in yield, biomass, and photosynthesis of crops grown at elevated CO_2 (550 ppm, volume basis) relative to ambient CO_2 in enclosure studies summarized by Cure and Acock (1986). Percentage increases for FACE studies were generated by meta-analysis of Long et al. (2006). Taken from Long et al. (2006).

Source	**Wheat**	**Soybean**	**C4 Crops**
		Yield	
Cure and Acock (1986)	19	22	27
FACE studies	13	14	0*
		Biomass	
Cure and Acock (1986)	24	30	8
FACE studies	10	25	0*
		Photosynthesis	
Cure and Acock (1986)	21	32	4
FACE studies	13	19	6

*Data from only one year in Leakey et al. (2006).

Evidence is emerging that plants adjust, or acclimate to elevated CO_2 conditions. Watling et al. (2000) reported changes in the carbon-fixing potential for sorghum grown at elevated CO_2, relative to the current condition. These changes included increased leakage of CO_2 from bundle sheath cells to mesophyll, requiring further metabolic processing, decreased activity of PEP carboxylase (the initial C4 CO_2-fixing enzyme), resulting in reduced carboxylation efficiency and assimilation potential. Comparative analysis of gene expression in soybean (Ainsworth et al., 2006) under current and elevated CO_2 indicated that respiratory breakdown of starch, promoting cell expansion and leaf growth, was accelerated with elevated CO_2. Controlled environment and FACE studies confirm that increased ambient CO_2 can increase biomass productivity for C3 crops, reduced crop water use, and elevated canopy temperatures for C3 and C4 crops. Realizing potential benefits of elevated CO_2 conditions will require discovery and utilization of adaptive traits as well as adaptive crop management.

Increased atmospheric CO_2 can alter crop-pest interactions. Zavala et al. (2008) found that soybean could be more susceptible to coleopteran herbivores (e.g. invasive Japanese beetle and variant of western corn rootworm) under elevated CO_2 due to down-regulation of genes coding for production of cysteine proteinase inhibitors; these inhibitors are deterrents to coleopteran herbivores. Other unexpected consequences could involve enhanced growth of plant pests, with C3 physiology, and reduced herbicide efficacy—further aggravating climate change impacts.

Temperature

Heat stress on crops can impair assimilation by damaging light-harvesting apparatus and by reducing carbon-fixing enzyme capacity. Yield formation processes, including seed set and grain fill rate, can be impaired at elevated temperatures. The duration of growing season—and subsequent radiation capture—can be reduced by increased temperatures, as indicated by the growing degree day concept. Muchow et al. (1990) found greatest grain yield potential of corn occurred in a cool, temperate environment, due to increased growth duration and increased radiation capture; under warmer sub-tropical conditions growth duration, light absorption, and grain yields were reduced. Factors affecting intensity of heat stress and crop responses to heat stress are briefly discussed.

Canopy temperatures are generally linked to ambient temperatures, but can increase with radiative loading and decrease with evaporative cooling. Canopy productivity can be damaged when temperatures exceed critical levels. Optimum temperatures for photosynthesis (light harvesting) and carbon-fixing enzymes are approximately 30 to 38 ^{o}C (86 – 100 ^{o}F) for corn (Oberhuber et al., 1993; Crafts-Brandner and Salvucci, 2002); 25 to 30 ^{o}C (77 – 86 ^{o}F) for winter wheat (Yamasaki et al., 2002) and 32 ^{o}C (90 ^{o}F) for soybean (Vu et al., 1997). Net photosynthesis in corn was inhibited at leaf temperatures exceeding 38 ^{o}C (100 ^{o}F), though severity of inhibition decreased with acclimation (plant adjustment to greater temperature, Crafts-Brandner and Salvucci, 2002; Krall and Edwards, 1991).

The temperature acclimation process is thought to involve a protein known as Rubisco activase, which maintains the Rubisco enzyme in an active state when under heat stress. Rubisco activation in corn decreased for leaf temperatures greater than 32.5 ^{o}C (90 ^{o}F), with near-complete inactivation at 45 ^{o}C (113 ^{o}F, Crafts-Brandner and Salvucci, 2002). Acclimation of photosynthesis to temperature for winter wheat, in the range of 15 to 35 ^{o}C (59 – 95 ^{o}F), involved the light-harvesting apparatus (Yamasaki et al., 2002). Thermotolerance of C3 crops was increased by growth under elevated CO_2 conditions, but decreased for C4 crops (Wang et al., 2008). Ristic et al. (2008) reported a rapid, low-cost technique to detect heat tolerance of light-harvesting apparatus, indicated by chlorophyll content, in wheat, corn, and possibly other crops. Elevated temperatures can impair light-harvesting apparatus and inactivate critical carbon-fixing enzymes, thereby reducing assimilation rates and ultimate yield potential. The specific mechanisms affected by heat stress remain a subject of active investigation (Sage et al., 2008).

Seed number and seed weight are commonly critical components of grain yield formation. Heat stress can impair both aspects of yield potential. Potential seed number, commonly determined during ear, panicle, head, or pod formation, is influenced by assimilate supply at the end of juvenile development, which can be reduced by heat stress. Pollen viability and the pollination process can be impaired by heat stress, reducing seed set and yield potential (Lillemo et al., 2005; Schoper et al., 1986; Keigley and Mullen, 1986; Grote et al, 1994). Grain fill rate can be related to canopy productivity—particularly productivity of leaves in the upper canopy—during this developmental stage (Borras and Otegui, 2001). Thus effects of heat stress on radiation capture and carbon fixation (see above) may reduce the grain-fill/seed weight component of yield potential. Direct effects of heat stress on pollen viability, pollination and seed set can reduce seed number; indirect effects of heat stress on canopy productivity can reduce seed weight during grain fill. Muchow and Sinclair (1991) simulated effects of increased temperatures on corn yield; they reported a 10% yield decrease with 4 ^{o}C (7 ^{o}F) average temperature increase, despite an assumed 33% increase in normalized transpiration efficiency. These effects are expected for plants with either C3 or C4 physiology.

Adaptive traits to increase transpiration efficiency could aggravate heat stress effects. Increasing canopy resistance under conditions of large evaporative demand can increase transpiration efficiency. Hall and Hoffman (1976) reported decreased leaf conductance of sunflower and pinto bean with increased VPD, independent of leaf water potential. Teare et al. (1973) compared canopy behavior of sorghum and soybean following a stress period. Canopy resistance of sorghum canopy was nearly three times that of soybean; relative air temperature above the sorghum canopy was 3 ^{o}C greater than that above soybean, despite a larger root system and more water in the soil profile for the sorghum crop. Sloane et al. (1990) reported a slow-wilting soybean cultivar; this cultivar was later found to reduce water use, under conditions of large evaporative demand, by limiting maximum transpiration rates (Sinclair et al., 2008). Controlled environment studies demonstrated that leaf xylem conductivity limited water supply to evaporative surfaces, reducing transpiration rates when VPD exceeded 1.9 kPa. A simulation study (Sinclair et al., 2005) indicated that, under favorable conditions, grain sorghum yields were reduced for cultivars with the canopy trait of limited maximum transpiration but yields increased by 9-13% when yield potential was less than 450 kg ha^{-1} (72 bu a^{-1}). The limited transpiration trait is expected to improve yield potential under water deficit conditions. However, this trait could increase likelihood of heat stress, as elevated VPD tends to correspond with radiative loading—particularly for irrigated crops in semi-arid regions.

Other consequences of elevated temperatures in crop production systems can include greater respiratory losses of photosynthate and shifts in crop-pest interactions. Warm night temperatures can result in increased loss of assimilates due to greater respiration rates, which can increase with temperature. Tropically adapted sorghum lines maintain productivity by restricting respiratory losses, while temperate-adapted sorghum lines fail to accumulate significant biomass under conditions of warm nights, due to accelerated respiratory losses (Kofoid, pers. comm.). Other production factors which could be affected by warmer global temperatures include increased survival of insect and disease pests (due to warmer winter conditions), increased productivity of weeds, and corresponding reduced efficacy of pesticides.

YIELD FORMATION FACTORS AFFECTED BY EXPECTED CLIMATE CHANGE

Productivity for crops with C3 physiology is expected to benefit from increased atmospheric CO_2; the corresponding yield formation factors would be TE for [1] and Φ_{PSII} for [2]. Secondary effects would include accelerated canopy formation, increasing the transpiration fraction of ET [1] and the intercepted fraction of PAR [2]. Though HI may have reached an upper limit by extensive breeding, for some crops, HI might be expected to increase, for other crops, to the extent that potential seed number, seed-set, and grain fill rate can be increased.

In contrast, warmer ambient temperatures and stress-augmented increases in canopy temperatures would likely reduce crop productivity and components of yield for crops with C3 or C4 physiology. Increased VPD would effectively reduce the TE factor of [1] while reduced efficacy of light-harvesting apparatus and carbon-fixation could combine to reduce the Φ_{PSII} factor of [2]. Reduced canopy formation would tend to decrease the transpiration fraction of ET [1] and the interception fraction of PAR [2]; similarly, decreased harvest index could result from reduced potential seed number, seed-set, and grain fill rate.

Benefits of increased CO_2 could readily be offset by increased heat stress. Field studies comparing crop growth at ambient and elevated CO_2 levels indicate gains from elevated CO_2 levels were less than anticipated; the reduced level of benefits were attributed to stress responses to factors including elevated canopy temperature. Realizing full benefits of increased atmospheric CO_2 would require avoidance or tolerance of stress associated with rising global temperatures. Hubbert et al. (2007) found that photosynthesis in rice can be affected by breeding strategy; photosynthetic capacity and stability under heat stress could be a useful target when yield is limited by biomass accumulation rather than harvest index.

REFERENCES

Ainsworth, E.A., A. Rogers, L.O. Vodkin, A. Walter and U. Schurr. 2006. The effects of elevated CO_2 concentration on soybean gene expression. An analysis of growing and mature leaves. Plant Physiol. 142:135-147.

Ainsworth, E.A. and A. Rogers. 2007. The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. Plant, Cell and Env. 30:258-270.

Borras, L. and M. E. Otegui. 2001. Maize kernel weight response to post-flowering source-sink ratio. Crop Sci. 49:1816-1822.

Crafts-Brandner, S.J. and M.E. Salvucci. 2002. Sensitivity of photosynthesis in a C4 plant, maize, to heat stress. Plant Physiol. 129:1773-1780.

Cure, J.D. and B. Acock. 1986. Crop responses to carbon dioxide doubling—a literature survey. Agric. For. Meteorol. 38:127-145.

Earl, H.J., and R.F. Davis. 2003. Effect of drought stress on leaf and whole canopy radiation use efficiency and yield of maize. Agron. J. 95:688-696.

Feddema, J. 2008. Testimony before Kansas House Energy & Utilities Committee. February 6, 2008. www.climateandenergy.org/_FileLibrary/FileImage/FeddemaKUandIPCC.pdf.

Grote, E.M., G. Ejeta and D. Rhodes. 1994. Inheritance of glycinebetaine deficiency in sorghum. Crop Sci. 34:1217-1220.

Hall, A.E. and G.J. Hoffman. 1976. Leaf conductance response to humidity and water transport in plants. Agron. J. 68:876-881.

Howell, T.A. 2009. Global climatic change effects on irrigation requirements for the central Great Plains. Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009.

Hubbart, S., S. Peng, P. Horton, Y. Chen and E.H. Murchie. 2007. Trends in leaf photosynthesis in historical rice varieties developed in the Philippines since 1966. J. Exp. Bot. doi:10.1093/jxb/erm192.

Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Keigley, P.J. and R.E. Mullen. 1986. Changes in soybean seed quality from high temperature during seed fill and maturation. Crop Sci. 26:1212-1216.

Kiniry, J.R., J.A. Landivar, M. Witt, T.J. Gerik, J. Cavero and L.J. Wade. 1998. Radiation-use efficiency response to vapor pressure deficit for maize and sorghum. Field Crops Research 56:265-270.

Krall, J.P. and G.E. Edwards. 1991. Environmental effects on the relationship between the quantum yields of carbon assimilation and in vivo PSII electron transport in maize. Aust. J. Plant Physiol. 18:267-278.

Leakey, A.D.B., M. Uribelarrea, E.A. Ainsworth, S.L. Naidu, A. Rogers, D.R. Ort and S.P. Long. 2006. Photosynthesis, productivity and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought Plant Physiol. 140:779-790.

Lillemo, M., M. van Ginkel, R.M. Trethowan, E. Hernandez and J. Crossa. 2008. Differential adaptation of CIMMYT bread wheat to global high temperature environments. Crop Sci. 45:2443-2453.

Long, L.P., E.A. Ainsworth, A.D.B. Leakey, J. Nosberger and D.R. Ort. 2006. Food for thought: lower than expected crop yield stimulation with rising CO_2 concentrations. Science. 312:1918-1921.

Muchow, R.C., T.R. Sinclair and J.M. Bennett. 1990. Temperature and solar radiation effects on potential maize yield across locations. Agron. J. 82:338-343.

Muchow, R.C. and T.R. Sinclair. 1991. Water deficit effects on maize yields modeled under current and “greenhouse” climates. Agron. J. 83:1052-1059.

Oberhuber, W. and G.E. Edwards. 1993. Temperature dependence of the linkage of quantum yield of photosystem II to CO_2 fixation in C4 and C3 plants. Plant Physiol. 101:507-512.

Passioura, J.B. 1977. Grain yield, harvest index, and water use of wheat. J. Aust. Inst. Agric. Sci. 43, 117–120.

Ristic. Z. U. Bukovnik, P.V. Vara Prasad and M. West. 2008. A model for prediction of heat stability of photosynthetic membranes. Crop Sci. 48:1513-1522.

Rochette, P., R.L. Desjardins, E. Pattey and R. Lessard. 1996. Instantaneous measurement of radiation and water use efficiencies of a maize crop. Agron. J. 88:627-635.

Sage, R.F., D.A. Way and D.S. Kubien. 2008. Rubisco, Rubisco activase and global climate change. J. Exp. Bot. 59:1581-1595.

Schoper, J.B., R.J. Lambert and B.L. Vasilas. 1986. Maize pollen viability and ear receptivity under water and high temperature stress. Crop Sci. 26:1029-1033.

Sinclair, T.R., M.A. Zwieniecki and N.M. Holbrook. 2008. Low leaf hydraulic conductance associated with drought tolerance in soybean. Phys. Plant. 132:446-451.

Sinclair, T.R., G.L. Hammer and E.J. van Oosterom. 2005. Potential yield and water-use efficiency benefits in sorghum from limited maximum transpiration rate. Functional Plant Biology 32(10)945-952.

Sloane R.J., R.P. Patterson and T.E. Carter, Jr. (1990) Field drought tolerance of a soybean plant introduction. Crop Sci 30:118–123.

Tanner, C.B. and T.R. Sinclair. 1983. Efficient water use I crop production: Research or re-search? P. 1-27. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in crop production. ASA, Madison, WI.

Teare, I.D. E.T. Kanemasu, W.L. Powers and H.S. Jacobs. 1973. Water use efficiency and its relation to crop canopy area, stomatal regulation and root distribution. Agron. J. 65:207-211.

Tubiello, F.N., J.F. Soussana, and S.M. Howden. 2007. Crop and pasture response to climate change. PNAS 104:19686-19690.

Vu, J.C.V., L.H. Allen, Jr., K.J. Boote and G. Bowes. 1997. Effects of elevated CO_2 and temperature on photosynthesis and Rubisco in rice and soybean. Plant, Cell and Environment 20:68-76.

Wall, G.W., T.J. Brooks, N.R. Adams, A.B. Cousins, B.A. Kimball, P.J. Pinter Jr, R.L. LaMorte, J. Triggs, M.J. Ottman, S.W. Leavitt, A.D. Matthias, D.G. Williams and A.N. Webber. 2001. Elevated atmospheric CO_2 improved sorghum plant water status by ameliorating the adverse effects of drought. New Phytologist 152:231-248.

Wang, D., S.A. Heckathorn, D. Barua, P. Joshi, E.W. Hamilton and J.J. LaCroix. 2008. Effects of elevated CO_2 on the tolerance of photosynthesis to acute heat stress in C3, Cr, and CAM species. Am. J. Bot. 95(2):165-176.

Watling, J.R., M.C. Press and W.P. Quick. 2000. Elevated CO_2 induces biochemical and ultrastructural changes in leaves of the C4 cereal sorghum. Plant Physiol. 2000:1143-1152.

Yamasaki, T., T. Yamakawa, Y. Yamane, H. Koike, K. Satoh and S. Katoh. 2002. Temperature acclimation of photosynthesis and related changes in photosystem II electron transport in winter wheat. Plant Physiol. 128:1087-1097.

Zavela, J.A., C.L. Casteel. E.H. DeLucia and M.R. Berenbaum. 2008. Anthropogenic increase in carbon dioxide compromises plant defense against invasive insects. PNAS 105(13):5129-5133.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

GLOBAL CLIMATIC CHANGE EFFECTS ON IRRIGATION REQUIREMENTS FOR THE CENTRAL GREAT PLAINS

T.A. Howell, Ph.D., P.E.
Research Leader (Supervisory Agricultural Engineer)
USDA-Agricultural Research Service
P.O. Drawer 10
Bushland, Texas 79012-0010
Voice: 806-356-5746 Fax: 806-356-5750
Email: terry.howell@ars.usda.gov

INTRODUCTION

Change is inevitable, but variability is certain in weather, especially in the Great Plains. The Great Plains is considered the U.S. bread basket and certainly is critically important to national and even world agricultural productivity. The Great Plains agricultural crop productivity is dependent upon water, both from precipitation and groundwater. Groundwater from the vast Ogallala Aquifer in the Central Plains is predicted to continue to decline as long as irrigation remains viable considering escalating energy costs and farm production costs (seed, fertilizer, equipment, etc.). Water right transfers from agriculture to urban and industrial requirements will further exacerbate this inevitable resource strain. Labor or farm skills for the rapidly escalating advances in agricultural technology may become a limiting factor in the future, too. Weather directly affects the water requirements of crops and thus their irrigation requirement.

Climate change is controversial, as to warming or cooling and especially the cause, but the world data on increased atmospheric carbon dioxide (CO_2) and green house gases (GHGs) is incontrovertible. The impact of rising CO_2 is generally considered 'positive' in terms of photosynthesis and its effects on plant control of transpiration through stomatal regulation. GHGs likely impact only atmospheric solar transmittance both for short-wave (mainly by water vapor and ozone) and long-wave radiation (mainly by carbon dioxide, nitrous oxide, and methane). Many believe that GHGs contribute to the earth temperature rise from the so called 'green house effect,' but many leading scientists also believe that any warming cycle is potentially derived from plasma bursts or "sun spot activity' on the sun and part of longer-term historical weather trends (many centuries).

CLIMATE FORECASTS

Climate or weather is a stochastic process that has a predictable component and a random component. The normal random part of climate and weather makes the discernment of any ‘change’ in climate difficult. El Niño-Southern Oscillation phenomena have been demonstrated to influences weather in many parts of the world. The El Niño-Southern Oscillation (ENSO) is characterized by its extremes -- El Niño is the warming cycle of the eastern tropical Pacific Ocean and La Niña is the cooling cycle. Figure 1 illustrates the most recent sea surface temperature (SST) anomalies in the tropical Ocean (Australian continent is visible in the lower left and the Mexico and Central America locations are in the upper right). The National Center for Environmental Prediction (NCEP) of the NOAA/National Weather Service predicts (Jan. 15, 2009 predictions) due to the La Niña conditions of SST that developed in December 2008 that the Central Plains air temperature in May-June-July 2009 will be above ‘normal’ in most of the Southern Great Plains and Southwestern U.S. (Fig. 2) and that the rainfall will be near normal (50:50 chance of being ‘normal’ (Fig. 3). This is useful information for 2009 crop management strategic planning (crop species selection, crop hybrid selection, irrigation planning, and even commodity hedging for crop sales or the futures market). They illustrate near-term weather predictions useful in irrigation management. These NOAA predictions are updated monthly, so anyone can keep current on the near-term weather predictions. The NCEP has shorter-term and longer-term predictions on their web site located at [http://www.cpc.ncep.noaa.gov/products/predictions//multi_season/13_seasonal_outlooks/color/churchill.php]. Figures 2 and 3 are U.S. examples showing interesting forecasts for the Central Great Plains for the 2009 summer.

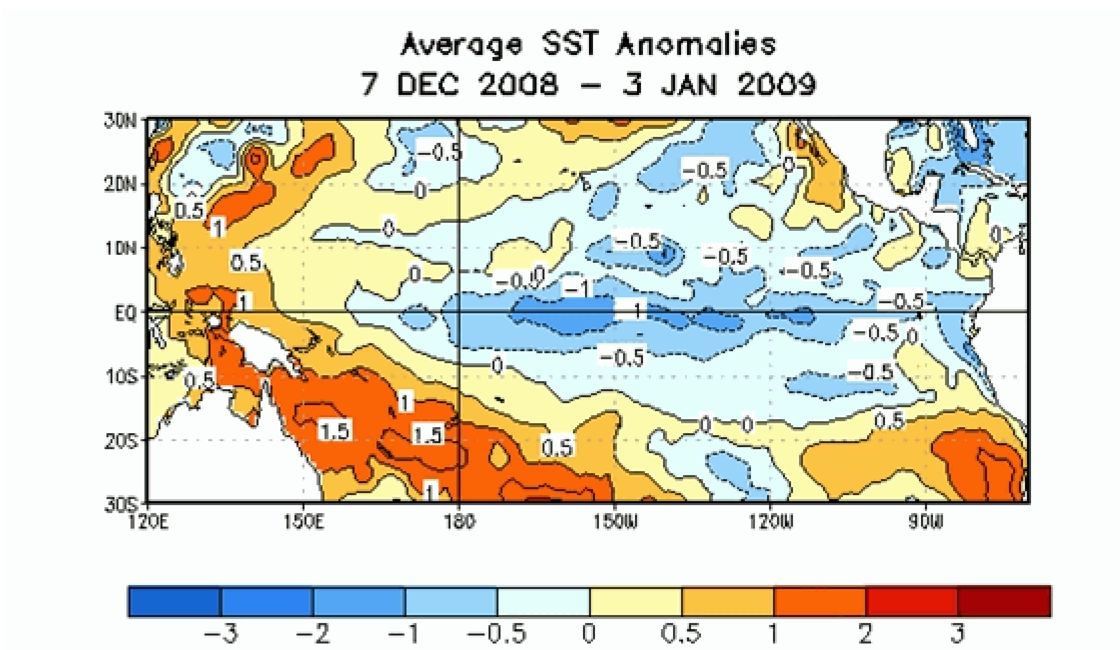


Figure 1. Average sea surface temperature (SST) anomalies (°C) for the four-week period 7 Dec. 2008 to 3 Jan. 2009. Anomalies are computed with respect to the 1971-2000 base period weekly means (Xue et al., 2003). From http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.html (viewed on 22 Jan. 2009).

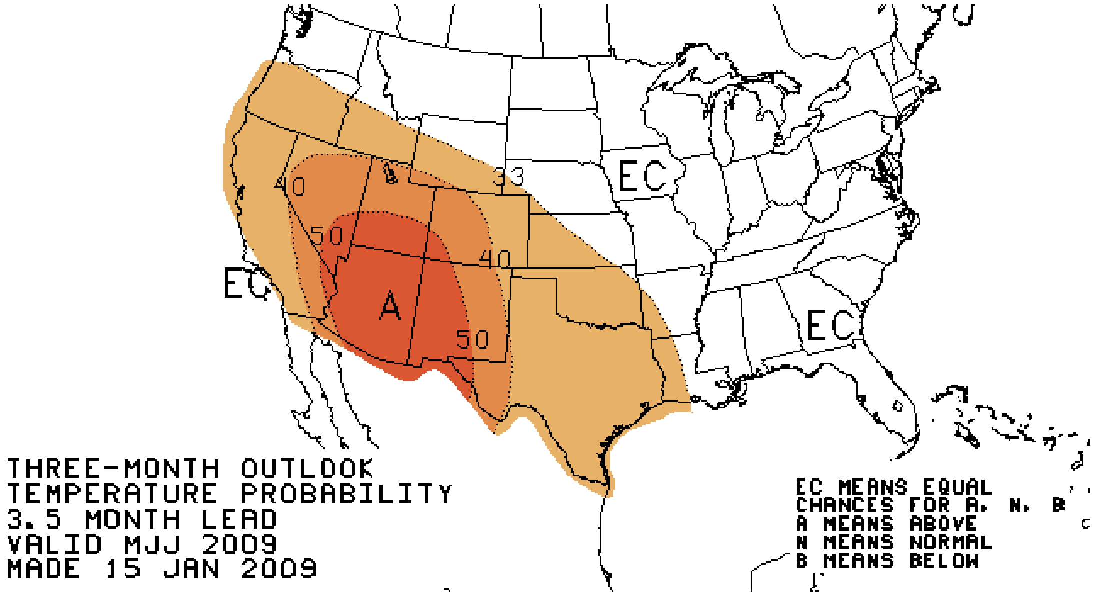


Figure 2. NOAA National Center for Environmental Predictions for May-June-July 2009 temperature from January 15, 2009 predictions using the ENSO SST using procedures from Saha et al. (2006).

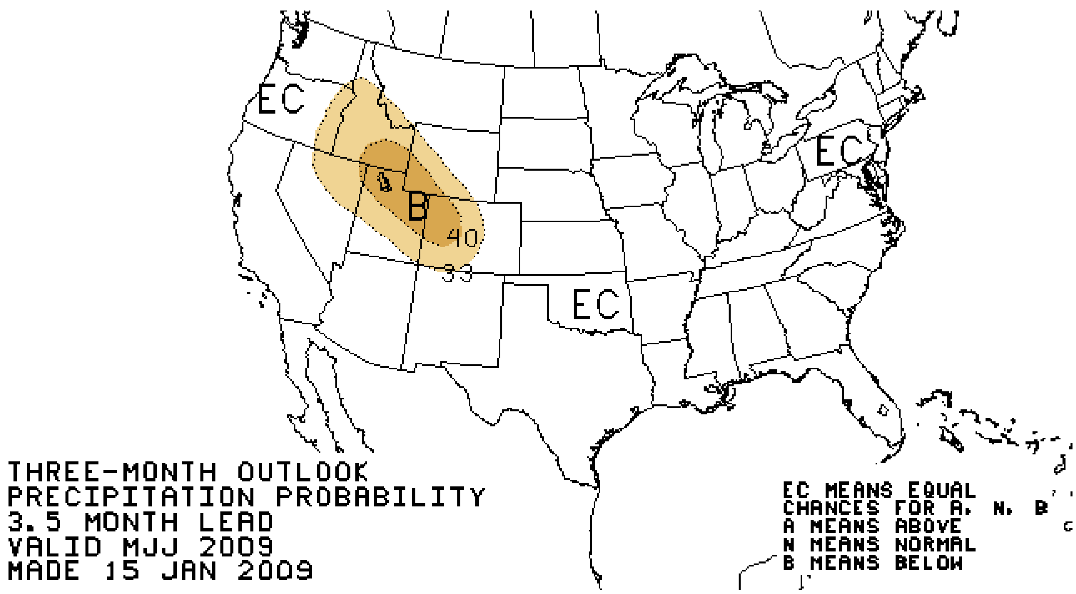


Figure 3. NOAA National Center for Environmental Predictions for May-June-July 2009 precipitation from January 15, 2009 predictions based on the ENSO SST using procedures from Saha et al. (2006).

CLIMATE CHANGE AND VARIABILITY

Increasing concentrations of GHGs in the earth's boundary layer make the earth's atmosphere opaque to long-wave radiation preventing long-wave radiation from escaping through the atmosphere. The trapped long-wave radiation in the earth's atmosphere is believed to alter the earth's radiation energy balance and thereby increasing the surface temperature. GHGs include carbon dioxide, water vapor, methane, nitrous oxide, chlorofluorocarbons, and other gases. Carbon dioxide (CO_2) concentration in the atmosphere has increased since the industrial revolution from the burning of carbon-based fuels (wood, coal, petroleum, etc.). Neftel et al. (1985) estimated that the preindustrial global atmospheric CO_2 concentration was in the range of 265-290 ppm (volume based) based on ice core samples from the Siple Station (West Antarctica). The longest CO_2 records are from the Mauna Loa Observatory, Hawaii (Fig. 4) from NOAA and the Scripps Institution of Oceanography, University of California, San Diego. Carbon dioxide concentrations have increased from 315 ppm in 1958 to 385 ppm in 2008. This increase in atmospheric CO_2 is generally attributed to deforestation and the burning of fossil fuels such as fuel oil, natural gas, and coal. The atmospheric CO_2 concentrations are expected to double from the preindustrial concentrations at some point in the 21st century (Ramírez and Finnerty, 1996). The annual mean CO_2 concentration growth rate has approximately doubled from 1 ppm yr^{-1} in the 1950s to about 2 ppm yr^{-1} since 2000.

Water vapor is also a GHG that is highly variable both spatially and temporally. Atmospheric water vapor is the result of evaporation from lakes, rivers, and oceans and evapotranspiration (ET) from land surfaces. 'Green house' warming should result in an increase in evaporation and ET because of increased surface temperature. However, the increased atmospheric water vapor will likely increase cloudiness. Exact prediction of cloudiness at a specific location is imprecise due to local elevation, position (latitude and longitude), and global winds. Increased clouds in some areas may increase the likelihood of convective and/or influence orographic precipitation. The clouds also reflect direct solar irradiance and scatter short-wave irradiance (diffuse solar radiation) reaching the earth's surface. Most expect at many global locations that net radiation, one of the most important surface energy balance parameters determining crop water use rates, will possibly be reduced with a feed-back effect to reduce 'green house' warming.

Ramírez and Finnerty (1996) reviewed the large uncertainties in the global 'green house' warming hypothesis. To summarize their review, they cited research results based on data from remote sensing during the 1979 to 1988 years that showed no obvious trend in atmospheric temperature over the 10-yr period; some statistical evidence that supported a 0.4°C decrease in temperature

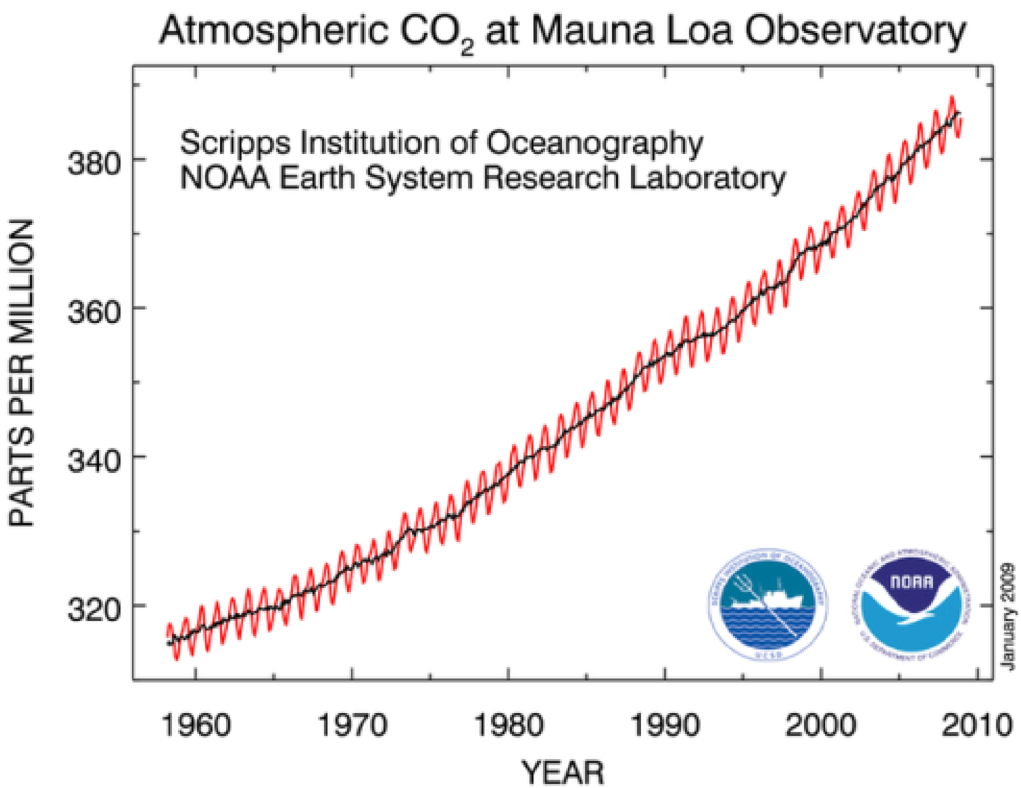


Figure 4. Volumetric CO_2 records from the Mauna Loa Observatory, HI from NOAA and the Scripps Institution of Oceanography, University of California, San Diego. The red (or gray in B&W) lines are the monthly mean data and the black (or darker in B&W) line is the annualized data. [Source: Dr. Pieter Tans, NOAA/ESRL (http://www.esrl.noaa.gov/gmd/ccgg/trends/), viewed Jan. 23, 2009].

for the northern hemisphere from the years 1940-1980; a global temperature rise less than 0.4°C from 1880 to 1970; and according to the statistical analysis of climate records and from an analysis of global climate records from land and the oceans around the world, a temperature increase over the past 90 years that was in the range of 0.4-0.6 °C. Singer and Avery (2007) cited studies from 450 peer-reviewed authors and co-authors that found reason to doubt the 'global warming hypothesis'. Avery (2008) indicated that these concerns did not mean that fossil fuels use and other GHG sources shouldn't be reduced (Wang, 2008), but that additional engineering solutions including greater efficiency in transportation, energy efficient buildings, and greater planning for droughts and shifting patterns in water availability should be included.

CO_2 and Plant Response to Climate Change

Rising atmospheric CO_2 has been called 'atmospheric fertilization' because greater concentrations in CO_2 will lead to greater rates in photosynthesis.

Bisgrove and Hadley (2002) provide a useful review of global warming on plant responses. Because rising CO_2 and a possible temperature increase and possible decrease in precipitation could dramatically alter future climatological records, the increased frequency of extreme weather events (droughts, floods, colder winters, extreme heat waves, etc.) is widely speculated but nearly impossible to quantify. Global climate change will impact other factors of irrigated agriculture, too, like weeds (both species and their growth rates) and diseases.

Current carbon dioxide concentrations limit plant photosynthesis based upon the following photosynthesis equation:

$$\begin{aligned}&\mathbf{6\ CO_2\ (carbon\ dioxide) + 6\ H_2O\ (water)} \longrightarrow \\ &\mathbf{(with\ energy\ from\ sunlight)} \longrightarrow \qquad \ldots[1] \\ &\mathbf{C_6H_{12}O_6\ (glucose,\ a\ carbohydrate) + 6\ O_2\ (oxygen)}\end{aligned}$$

Green house growers of horticultural crops have raised the concentration of CO_2 in the enclosed greenhouses to increase crop growth and yield for many years. Research has shown that doubling of CO_2 concentrations will lead to approximately a 40-50% increase in the growth of plants (Kimball et al., 1983; Poorter, 1993). Kimball (1983) reported that doubling CO_2 concentrations increased biomass productivity on average by 33% in vegetal species studied with a decrease in evapotranspiration. Poorter's (1993) review reported that herbaceous crop plants produced more biomass than herbaceous wild species (58% vs. 35%), and potentially fast growing wild species had greater biomass than slow growing species (54% vs. 23%). In addition, he found that leguminous species capable of symbiosis with nitrogen fixing organisms had larger responses to CO_2 compared with other species. Poorter (1993) also indicated that there was a tendency for herbaceous dicotyledons (broadleaved plants) to show a larger response than monocotyledons like grasses. Plants, however, adapt to elevated CO_2 concentrations, and the long-term exposure to elevated CO_2 is much less than short-term elevated CO_2 exposure. In addition, it has been reported that some species in an elevated CO_2 environment have a lower stomata density. Nonetheless, the effect of increased CO_2 remains a significant factor in increasing photosynthesis and increasing water use efficiency.

Carbon dioxide concentration is a main mechanism that plants use to regulate the respiration rate and the rate of absorption of CO_2 for photosynthesis by changing the stomatal resistance. An increase in atmospheric CO_2 will increases the leaf's internal CO_2 absorption rate mainly for C3 species. The plant will respond by increasing its stomatal resistance (a partial closing of the stomate pore), which reduces the CO_2 absorption rate to maintain a desired internal substomatal CO_2 concentration. Kimball and Idso (1983) reported stomata responded to increased CO_2 by regulating photosynthesis in more than 50 species. Transpiration is reduced by this increased stomatal resistance and leaf temperature is increased (Morison, 1987). An increase in stomatal resistance will reduce the plant transpiration rate, thereby increasing the plant water use efficiency (assimilation per unit transpiration). Most agricultural plants are categorized by their photosynthetic mechanisms that control the chemical processes in their glucose manufacture from CO_2 and H_2O (water) [eqn. 1] as C3 and C4 species because of their photosynthetic pathways [for a more thorough review of the impacts of elevated CO_2 and temperature on photosynthesis see Sage (2002) and Ainsworth and Rogers (2007)]. Other plants are called CAM that stands for Crassulacean Acid Metabolism after the plant family in which it was first found (*Crassulaceae*) and because the CO_2 is stored in the form of an acid before use in photosynthesis. CAM species are mainly succulents such as cactuses and agaves. Common C3 species include wheat, cotton, soybean, and most legumes like alfalfa while common C4 crop species include sorghum, corn, and sugarcane. Some grass species are either C3 or C4 types. C3 plants fix atmospheric CO_2 directly onto 5 carbon sugar RuBP (ribulose bisphosphate) and thus into glucose. C4 plants first fix atmospheric CO_2 into 4-carbon acids in the mesophyll of the leaf and decarboxylate the 4-carbon acids in the bundle sheath cells where the CO_2 is then fixed by RuBP carboxylase (all of this takes place during the day). CAM plants first fix atmospheric CO_2 into malic acid and other 4C-acids at night. During the day, malic acid is decarboxylated and the CO_2 released is then fixed by rubisco (all of this takes place in the same cell). Generally, the C4 photosynthetic pathway is considered more water efficient than C3 species. However, C3 species typically are more sensitive to elevated CO_2 (Rosenberg et al., 1988). The carbon-fixing efficacy of Rubisco depends on the ratio of CO_2:O_2. For C3 plants, this is closely coupled to ambient conditions, and efficacy is approximately 2/3 while for C4 plants, the CO_2:O_2 ratio is much greater and carboxylation efficacy is nearly 100% (Ainsworth and Rogers, 2007). Therefore, increased CO_2 in air should directly increase assimilation for plants with C3 physiology. For C4 plants, the elevated CO_2 effects are indirect due to increased stomatal resistance and reduced transpiration.

EFFECTS OF CLIMATE ON IRRIGATION REQUIREMENT

Two main modes have been used to estimate long-term climate change on crop water requirements and irrigation requirement. The earlier and simpler ones used were sensitivity analyses of regular ET equations and/or crop simulation models to estimated climate scenarios based on projections of weather scenarios (Rosenberg, 1981). Several examples are illustrated: Warrick (1984) used 1930s weather data with a statistical yield model that showed a 50% wheat yield decline in the Great Plains; Terjung et al. (1984) used a yield model with four climate scenarios for air temperature, solar irradiance, and precipitation to find that ET and total applied irrigation were sensitive to the climatic scenarios and locations used; Liverman et al. (1986) reported lower dryland yields under cloudy, hot, and dry climates; and Rosenzweig (1985) suggested that in the Southern Great Plains spring wheat varieties might be required to replace winter wheat cultivars due to colder winter temperatures with a doubling of CO_2.

Most recent efforts have used general circulation models (GCMs) from various global climate research efforts (Rosenzweig, 1990). Many GCM models have been developed (see Hansen et al., 1983; Smith and Tripak, 1989; and Manabe and Wetherald, 1987 for explanations and examples). The Intergovernmental Panel on Climate Change (IPCC; see http://www.ipcc.ch/) that was established in 1988 has attempted to serve as the 'clearing house' and 'repository' to provide reports at regular intervals that can become standard works of reference to be widely used by policymakers, experts and students. Houghton et al. (2001) is an example. The 4th Climate Change 2007 Synthesis Report was just released in 2008 (see the IPCC web site above).

Most recent attempts to investigate climate change on irrigation have used GCMs as a climate basis (Allen et al., 1991; Ramírez and Finnerty, 1996; Peterson and Keller, 1990; Rosenzweig, 1990; Smith et al., 2005; Rosenberg et al., 1999; Brumbelow and Georgakakos, 2001; Thompson et al., 2005; and Reilly et al., 2003). Many GCMs were simulations under 2 X CO_2 concentrations that result in global temperature increases of 2-5°C, with regional temperature changes from -3°C to +10°C. Precipitation fluctuates in the range of -20% to +20% from current regional averages (Peterson and Keller, 1990). GCMs generally are limited in resolution to a 0.5° x 0.5° grid. The 'predicted' weather represents that whole grid. They simplify the spatial and temporal scales of global fluid dynamics as well as the complex physics that drive the exchanges of water, heat, and energy between the earth's atmosphere, oceans, and continental land masses on those grids; however, in most cases GCMs still require near 'super' computers to make all the complex computations necessary. Hence, they are typically operated at major universities and/or governmental agencies. GCMs' spatial scales are considered too large to accurately capture smaller scale terrain and other heterogeneities on the local and regional climate scale. Different GCMs use different modeling strategies and often produce different model climates. Therefore, there is a rather large uncertainty associated with the predicted potential climate changes. Two widely used GCMs are the BMRC (Australian Bureau of Meteorology Research Center) (McAveney et al., 1991) and the UIUC (University of Illinois at Urbana Champaign (Schlesinger, 1997). Table 1 illustrates the GCM simulation climate scenarios used by Smith et al. (2005) in their series of papers by the two above GCMs. The BMRC model temperatures changes were slightly larger than the 'global' scenarios while the precipitation was reduced over the U.S. For the UIUC model without sulfates, the temperatures matched the 'global' scenarios well, but the precipitation was increased considerably compared with the BMRC model. For the UIUC + Sulfates model runs, the simulated temperatures were lower than the BMRC scenarios and the precipitation increased as a mean over the conterminous U.S. Figure 5 shows the predicted annual mean temperatures for the conterminous U.S. from Smith et al. (2005). The Australian model (BMRC) predicts a slightly warmer Central Great Plains for the +1°C GMT scenario and a smaller temperature change for the western parts of the Central Great Plains, except the eastern portions and the southern parts (Texas, Oklahoma). It predicts a significantly drier trend (Fig. 6) for the Central Great Plains region for both scenarios. The Univ. of Illinois model without sulfates (UIUC) predicted a warmer Central Great Plains for both scenarios and an increased precipitation in the Central Great Plains. When sulfates were included in the UIUC model, it predicted a more modest temperature change with only a small precipitation increase for the +2.5°C scenario.

Table 1. Annual mean change in temperature and precipitation over the conterminous United States by the GCM climate change scenarios (scaled to the 1960 to 1989 historical climate data). Source: Smith et al. (2005).

GCM	GMT[1]	Temp. Change (°C)	Precip Change (mm)
BMRC	1.0	1.5	-39
	2.5	3.6	-98
UIUC	1.0	0.9	98
	2.5	2.3	245
UIUC + Sulfates	1.0	0.4	132
	2.5	1.6	287

[1] GMT is global mean temperature

Climate change (changes in temperature and/or precipitation regimes) would likely lead growers to change crops, cultivars, and management practices, including irrigation, to mitigate any adverse effects or to take advantage of more favorable conditions. Peterson and Keller (1990) suggested that higher temperatures and reduced precipitation could increase crop water demand in some areas and prompt the development of irrigation in regions previously devoted to dryland or rainfed cropping. They reported that the percentage of cropland irrigated in the western U.S. increased when global mean temperature (GMT) exceeded 3°C and a decline in production resulted from inadequate water for irrigation. Tung and Douglas (1998) found in a study of crop response to GCM projected climate change with double atmospheric CO_2 concentrations that the higher ET effects outweighed the effects of CO_2 fertilization in some areas of the U.S., and they suggested that irrigation could mitigate effects of climate change.

In another simulation study of CO_2 induced climatic changes, Allen et al. (1991) reported higher ET demand and irrigation water requirement for alfalfa, but decreases for winter wheat and corn, although the GFDL (Geophysical Fluid Dynamics Laboratory) model had increased corn irrigation requirement (Fig. 7b), in the Great Plains due to higher temperatures and changes in precipitation patterns (Fig. 7). Allen et al. (1991) used CGMs from Princeton Univ. (GDFL, Geophysical Fluid Dynamics Laboratory) and the GISS (Goddard Institute for Space Studies) (Hansen et al., 1984).

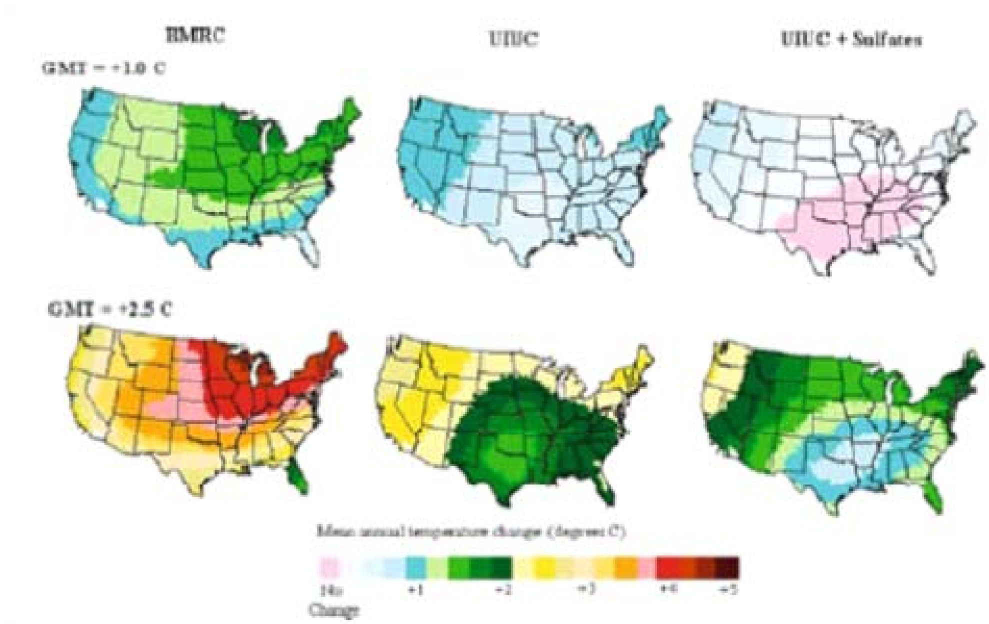


Figure 5. Annual mean temperature change from baseline for three GCMs for two global mean temperature scenarios. Source: Smith et al. (2005). Note: 5°C change = 9°F change.

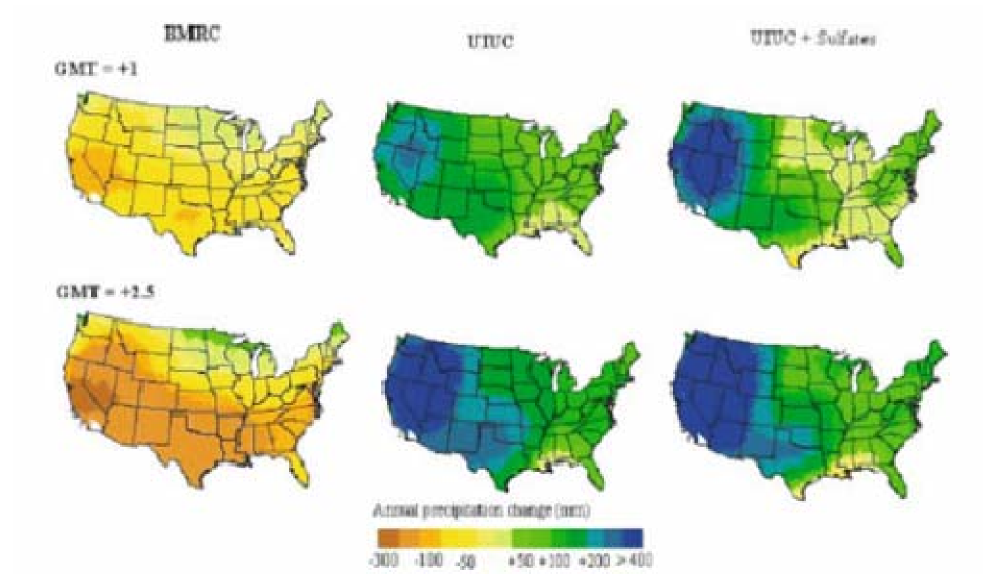


Figure 6. Annual precipitation change from baseline for three GCMs for two global mean temperature scenarios. Source: Smith et al. (2005). Note: 200 mm change = 7.88 in. change.

Brumbelow and Georgakakos (2001) used GCMs from the Canadian Centre for Climate Modeling and Analysis Global Coupled Model 1 (CGCM1) and some from the UK Meteorological Office Hadley Climate Model version 2 (HadCM2) together with crop simulation models and USDA soils data (STATSGO) (NRCS, 1994) to estimate climate change impacts on crop productivity and irrigation in the conterminous U.S. They are one of the few simulation studies that validated model outputs with U.S. county yield data for a 19-yr calibration period. Table 2 summarizes their mean irrigation requirement changes in four Great Plains regions and for three crops. Figure 8 illustrates their predicted change in corn yield and irrigation requirement for the conterminous U.S. The predicted mean change in irrigation requirement in most of the Central Great Plains had a 'neutral' change (-10 to 10 mm). The western portions of the Central Great Plains had a more pronounced decrease in irrigation requirements from -40 to -11 mm. Predicted irrigated corn yields decreased 600 to 1,200 kg ha^{-1} (~10 to 20 bu ac^{-1}).

Table 2. Regional mean changes in irrigation requirement in mm and % change (in parenthesis) for three crops in the Great Plains. Source: adapted from Brumbelow and Georgakakos (2001).

Region	Soybean	Winter Wheat	Corn
Northwestern GP	na[1]	-25.9 (-39%)	-15.1 (-75%)
Northeastern GP	2.5 (31%)	-16.0 (-49%)	-0.8 (-100%)[2]
Southwestern GP	30.6 (86%)	28.1 (22%)	-15.7 (50%)
Southeastern GP	23.9 (156%)	16.1 (56%)	-4.0 (43%)

[1]'na' region was not simulated.
[2]Percent appears large due to the small value of the 'baseline' irrigation requirement (< 10 mm).

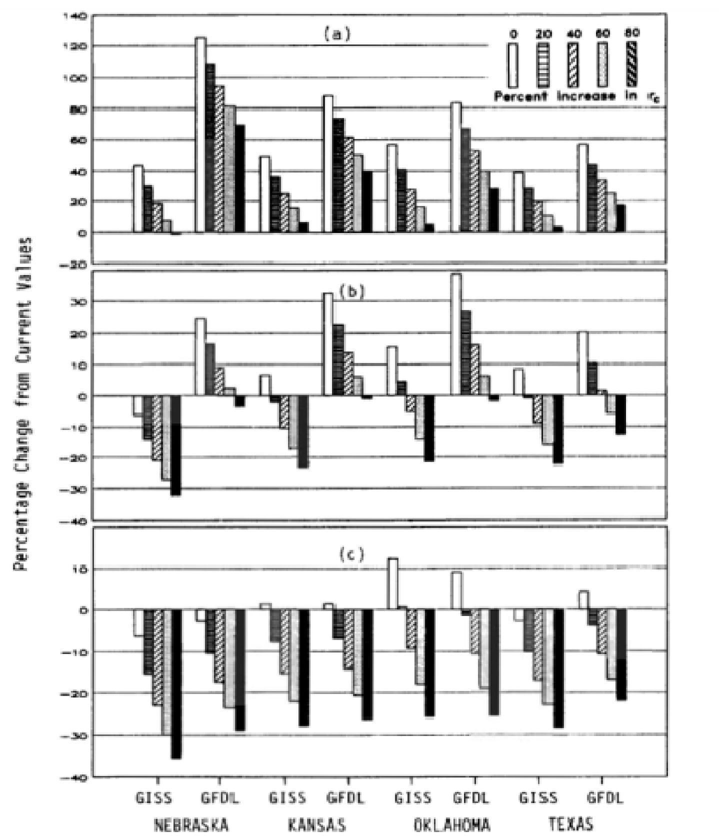


Figure 7. Projected percent change in seasonal irrigation requirement from 'baseline' (current values) for four Great Plains states for five levels of simulated increase in bulk stomatal resistance from increased CO_2 for (a) alfalfa [top]; (b) corn [center]; and (c) winter wheat [bottom]. Source: Allen et al. (1991).

Strzepek et al. (1999) modeled water supply and demand for irrigation in the U.S. Corn Belt with climate change using a suite of GCM-derived scenarios of climate change. They found that producers

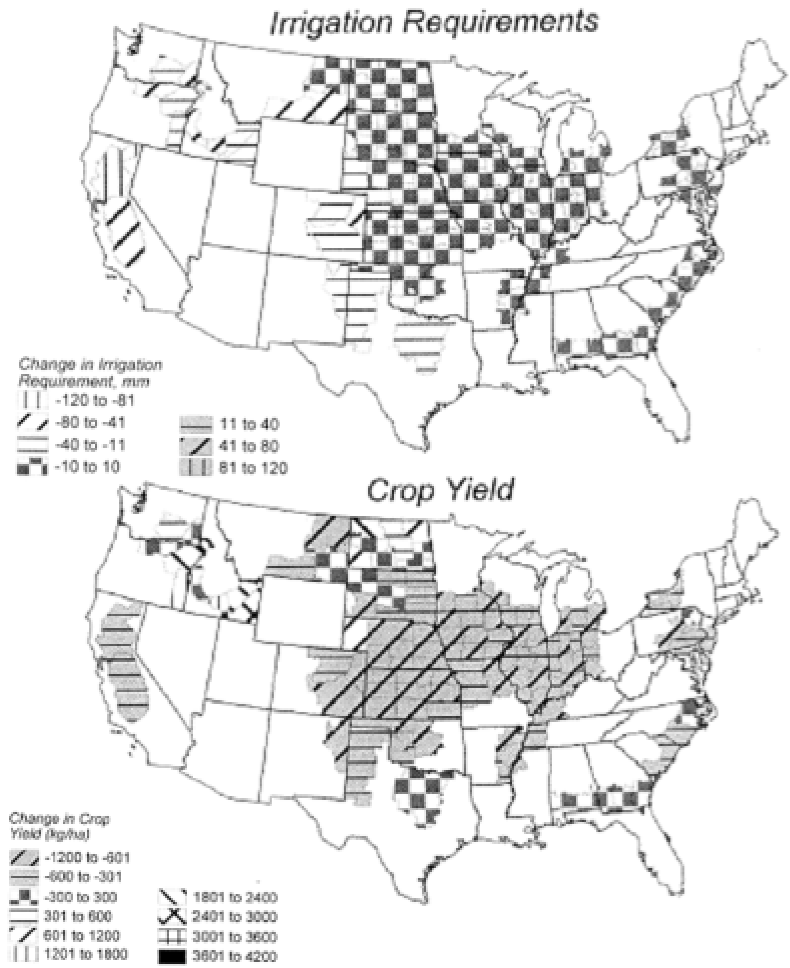


Figure 8. Changes in mean corn irrigation requirements (top) and crop yield (bottom). Source: adapted from Brumbelow and Georgakakos (2001).

would benefit from utilizing irrigation, but they also indicated a concern in the spring for excessive soil water perhaps requiring more subsurface drainage. In the near term, they suggested that the relative abundance of water for U.S. agriculture can be maintained. They suggested that progressively greater changes in agricultural production and practices from climate change impacts were expected by 2050 and beyond in agreement with Reilly et al. (2001).

SUMMARY

Accurately predicting global climatic change impacts on the Great Plains remains largely uncertain. Nevertheless, future environments in the Central Great Plains will have elevated CO_2 and GHGs in the atmosphere that will impact the surface energy balance, photosynthesis, water use efficiency, cloudiness, and precipitation, and likely extreme weather phenomena. These all have some degree of uncertainty and probably more variability than past climatic patterns. Most reports indicate few impacts immediately; however, in the out-years (~>2050) we should begin seeing significant shifts in weather in the Great Plains. Some will be ‘positive’ (growers need to be prepared to utilize) while others might be more ‘adverse’ (growers will need to make strategic decisions to minimize impacts). Undoubtedly, some changes in Great Plains agriculture will be necessitated, e.g., crop hybrid changes, crop species adjustments, crop management, etc., and irrigation will continue to be a significant factor, especially in the Central Great Plains, for mitigating global climate change impacts and providing national food security.

REFERENCES

Ainsworth, E.A., and A. Rogers. 2007. The response of photosynthesis and stomatal conductance to rising [CO_2]: Mechanisms and environmental interactions. Plant, Cell and Environ. 30(3):258-270.

Allen, R.G., F.N. Gichuki, and C. Rosenzweig. 1991. CO_2-induced climatic changes and irrigation-water requirements. J. Water Res. Planning Mgmt. 117(2):157-178.

Avery, D.T. 2008. Global warming every 1,500 years: Implications for an engineering vision. Leadership and Mgmt.in Engrg. 8(3):153-159.

Bisgrove, R., and P. Hadley. 2002. Gardening in the global greenhouse: The impacts of climate change on gardens in the UK. Technical Report. UKCIP (UK Climate Impacts Program), Oxford. 134 p. [http://www.rhs.org.uk/news/climate_change/climate_technical.pdf]

Brumbelow, K., and A. Georgakakos. 2001. An assessment of irrigation needs and crop yield for the United States under potential climate changes. J. Geophys. Res. 106(D21):27,383-27,405.

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis. 1983. Efficient three-dimensional global models for climate studies: Models I and 11. Monthly Weather Rev. 3:609-22.

Hansen, J.E., D. Rind, G. Russell, P. Stone, I.Fung, R. Ruedy, and J. Lerner. 1984. Climate sensitivity: Analysis of feedback mechanisms. pp. 130-163. In: *Climate Processes and Climate Sensitivity*, Am. Geophysical Union Mono. 29, Maurice Ewing Vol. 5, J.E. Hansen and T. Takahashi (eds.), Am. Geophysical Union, Washington, DC.

Houghton, J.T., Y. Ding, Y., D.J. Griggs, and M. Noguer, M. (eds.). 2001. *Climate Change 2001: The Scientific Basis*. Cambridge Univ. Press, Cambridge, U.K.

Liverman, D.M., W.H. Terjung, J.T. Hayes, and L.0. Mearns. 1986. Climatic change and grain corn yields in the North American Great Plains. Climatic Change 9:327-47.

Kimball, B.A. 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. Argon. J. 75: 779-788

Kimball, B.A., and S.B Idso. 1983. Increasing atmospheric CO_2: Effects on crop yield, water use, and climate. Agric. Water Mgmt. 7(1):55-72.

Kimball, B.A., Jr., J.R. Mauney, G. Guinn, F.S. Nakayama, P.J. Pinter, K.L. Clawson, R.J. Reginato, and S.B. Idso. 1983. Effects of increasing atmospheric CO_2 on the yield and water use of crops. Responses of Vegetation to Carbon Dioxide No. 021, U.S. Dept. of Energy Series, Agricultural Research Service, U.S. Dept. of Agric., Washington, DC.

Manabe, S., and R. Wetherald. 1987. Large-scale changes of soil wetness induced by an increase in atmospheric carbon dioxide. J. Atmos. Sci. 44:1211-36.

McAveney, B.J., R. Colman, J.F. Fraser, and R.R. Dhani. 1991. The response of the BMRC AGCM to a doubling of CO_2, Bureau of Meteorology Research Centre (BMRC) Technical Memorandum No. 3. Melbourne, Australia.

Morison, J.I.L. 1987. Intercellular CO_2 concentration and stomatal response to CO_2. pp. 242-243. In: *Stomatal Function*, Stanford Univ. Press, Stanford, CA.

National Resources Conservation Service (NRCS). 1994. State soil geographic (STATSGO) database: Data use information. U.S. Dept. of Agric., Misc. Publ. 1492, Washington, D. C. [see http://soils.usda.gov/survey/geography/statsgo/].

Neftel, A., E. Moor, H. Oeschger, and B. Stauffer. 1985. Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries. Nature 315:45-47.

Peterson, D.F., and A.A. Keller. 1990. Effects of climate change on U.S. irrigation. J. Irrig. Drain. Engrg. 116(2):194-210.

Poorter, H. 1993. Interspecific variation in the growth response of plants to an elevated ambient CO_2 concentration. In: *CO_2 and Biosphere*, J. Rozema, H. Lambers, and S.C. H, van de Geijn (eds.), Cambridge, ML 77- 97. Kluwer Academic Publ.

Reilly, J., F. Tubiello, B. McCarl, D. Abler, R. Darwin, F. Fuglie, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, L. Mearns, D. Ojima, E. Paul, K. Paustian, S. Riha, N. Rosenberg, and C. Rosenzweig. 2003. U.S. agriculture and change: New results. Climate Change 57:43-69.

Reilly, J., F. Tubiello, B. McCarl., and J. Melillo. 2001. Climate change and agriculture in the United States. In: *National Assessment Synthesis Team, Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, Cambridge Univ. Press, Cambridge. 618 p.

Rosenberg, N.J. 1981. The increasing CO_2 concentration in the atmosphere and its implication on agricultural productivity. I: Effects on photosynthesis, transpiration and water use efficiency. Climatic Change 3(3):265-279.

Rosenberg, N.J., D.J. Estein, D. Wang, L. Vail, R. Srinivasan, and J.G. Arnold. 1999. Possible impacts of global warming on the hydrology of the Ogallala Aquifer region. Climate Change 42:677-692.

Rosenberg, N.J., B. Kimball, P. Martin, and C. Cooper. 1988. Climate change,CO_2 enrichment and evapotranspiration. pp. 131-147. In: *Climate and Water: Climate Change, Climatic Variability, and the Planning*

and Management of U.S. Water Resources, P. E. Waggoner (ed.), John Wiley and Sons, New York, N.Y.
Rosenzweig, C. 1990. Crop response to climate changes in the Southern Great Plains: A simulation study. Prof. Geog. 42:20-37.
Rosenzweig, C. 1985. Potential CO_2-induced climate effects on North American wheat producing regions. Climatic Change 7:367-89.
Sage, R.F. 2002. Variation in the k_{cat} of Rubisco in C_3 and C_4 plants and some implications for photosynthetic performance at high and low temperature. J. Exp. Bot. 53(369):609-620.
Saha, S., S. Nadiga, C. Thiaw, J. Wang, W. Wang, Q. Zhang, H. M. van den Dool, H.-L. Pan, S. Moorthi, D. Behringer, D. Stokes, M. Pena, S. Lord, G. White, W. Ebisuzaki, P. Peng, P. Xie. 2006. The NCEP climate forecast system. J. Climate 19(15):3483-3517.
Schlesinger, M.E. 1997. Geographical scenarios of greenhouse-gas and anthropogenic –sulfateaerosol induced climate changes, Report for Energy Modeling Forum (EMF-14). Univ. of Illinois, Urbana-Champagne, USA. 85 p.
Singer, S., and D.T. Avery. 2007. *Unstoppable global warming: Every 1,500 years*. Rowman & Littlefield, Lanham, MD.
Smith, J., and D. A. Tirpak. 1989. Study methods. In The Potential Effects of Global Climate Change on the United States, ed. J. Smith and D. A. Tirpak, chapter 111. Washington, DC: U.S. Environmental Protection Agency.
Smith, S.J., A.M. Thompson, N.J. Rosenberg, R.C. Izaurralde, R.A. Brown, and T.M.L. Wigley. 2005. Climate change impacts for the conterminous USA: Part 1. Scenarios and context. Climate Change 69:7-25.
Strzepek, K. M., Major, D. C., Rosenzweig, C., Iglesias, A., Yates, D. Y., Holt, A., and Hillel, D. 1999. New methods for modeling water availability for agriculture under climate change: The U.S. Cornbelt. J. Am. Water Resour. Assoc. 35(6):1639-1655.
Terjung, W.H., D.M. Liverman, and J.T. Hayes. 1984. Climatic change and water requirements for grain corn in the North American Great Plains. Climatic Change 6:193-220.
Thompson, A.M., N.J. Rosenberg, R.C. Izaurralde, and R.A. Brown. 2005. Climate change impacts for the conterminous USA: Part 5. Irrigated agriculture and national grain production. Climate Change 69:89-105.
Tung, C.P.A.H., and A. Douglas. 1998. Climate change, irrigation and crop response. J. Am. Water Resour. Assoc. 34(5):1071-1085.
Wang, X. 2008. GHG mitigation policies and land use interactions. Leadership and Mgmt. in Engrg. 8(3):148-152.
Warrick, R.A. 1984. The possible impacts on wheat production of a recurrence of the 1930s drought in the U.S. Great Plains. Climatic Change 6:5-26.
Xue, Y., T.M. Smith, and R.W. Reynolds. 2003. Interdecadal changes of 30-yr SST normals during 1871-2000. J. Climate 16(10):1601-1612.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

CORN IRRIGATION MACROMANAGEMENT AT THE SEASONAL BOUNDARIES – INITIATING AND TERMINATING THE IRRIGATION SEASON

Freddie R. Lamm
Research Irrigation Engineer
Email: flamm@ksu.edu

Abdrabbo A. Abou Kheira
Research Irrigation Engineer
Email: abdo@ksu.edu

KSU Northwest Research-Extension Center
105 Experiment Farm Road, Colby, Kansas
Voice: 785-462-6281 Fax: 785-462-2315

ABSTRACT

Decisions about when to initiate and terminate the irrigation season are important irrigation macromanagement decisions that can potentially save water and increase net income when made correctly, but can have negative economic consequences when made incorrectly. A combination of nine years of pre-anthesis water stress studies and sixteen years of post-anthesis water stress studies for corn was conducted at the Kansas State University Northwest Research-Extension Center in Colby, Kansas on a productive, deep, silt loam soil. Overall, the pre-anthesis water stress studies suggest that corn grown on this soil type has great ability to handle early-season water stress, provided the water stress can be relieved during later stages. A critical factor in maximizing corn grain yields as affected by pre-anthesis water stress is maximizing the kernels/area. Maintaining a water deficit ratio (well-watered calculated corn water use / sum of irrigation and precipitation) greater than 0.7 to 0.8 or limiting available soil water depletion in the top 4 ft of soil profile to approximately 30% maximized the kernels/area. Overall, the post-anthesis water stress studies suggest that corn yield is nearly linearly related to the amount of crop water use during the post-anthesis period and that total crop water use amounts may average nearly 17 inches. Producers should plan for crop water use during the last 30 and 15 day periods that may average nearly 5 and 2 inches, respectively, to avoid yield reductions. Management allowable depletion during the post-anthesis period should be limited to 45% of the available soil water for an 8-ft profile on the deep silt loam soils of this climatic region.

INTRODUCTION

Definition of Macromanagement and Scope of the Problem

Corn (Zea mays L.) is the primary irrigated crop in the U.S. Great Plains. There are a number of efficient methods to schedule irrigation for corn on a real-time, daily, or short-term basis throughout the season. These scheduling methods essentially achieve water conservation by delaying any unnecessary irrigation event with the prospect that the irrigation season might end before the next irrigation event is required. There are larger irrigation management decisions [i.e., irrigation macromanagement (Lamm et al., 1996)] that can be considered separately from the step-by-step, periodic scheduling procedures. Two important macromanagement decisions occur at the seasonal boundaries, the initiation and termination of the irrigation season. Irrigators sometimes make these seasonal boundary determinations based on a traditional time-of-year rather than with sound rationale or science-based procedures. However, a single, inappropriate, macromanagement decision can easily have a larger effect on total irrigation water use and/or crop production than the cumulative errors that might occur due to small, systematic errors in soil-, plant-, or climatic-based scheduling procedures. This does not discount step-by-step irrigation scheduling. To the contrary, it is an implicit assumption that improved macromanagement at the seasonal boundaries can only provide the potential for increased water conservation when used in conjunction with the step-by-step, periodic scheduling procedures.

Most of the established literature on irrigation management during the early and late corn growth stages is 35-45 years old and was written at a time when irrigated corn yields were much lower (50-100 bu/acre lower) than they are today. It is quite possible that some of the numerous yield-limiting stresses (e.g., water, insects, weeds, nutrient, and soil) that were tolerable at the lower yield level are less tolerable today. On the other side of the issue, there has been much improvement in corn hybrids during the period with incorporation of traits that allow water stress tolerance and/or water stress avoidance.

Pre-Anthesis Water Stress

The corn vegetative stage is often considered the least-sensitive stage to water stress and could provide the opportunity to limit irrigation water applications without severe yield reductions. The vegetative stage begins at crop emergence and ends after tasseling, which immediately precedes the beginning of the reproductive period when the silks start to emerge. The potential number of ears/plant is established by the fifth leaf stage in corn. The potential number of kernels/ear is established during the period from about the ninth leaf stage until about one week before silking. Stresses during the 10 to 14 days after silking will reduce the potential kernels/ear to the final or actual number of kernels/ear. Therefore, in research studies designed to examine water stresses during the first one-half of the corn crop season, both ears/plant and kernels/ear might be critical factors. Additionally, there could be permanent damaging effects from the vegetative and early-reproductive period water stress that may affect grain filling (kernel weight). Often, irrigators in the Great Plains, start their corn irrigation season after early season cultural practices are completed such as herbicide or fertilizer application or crop cultivation at the lay-by growth stage (approximately 18-24 inch corn height). Crop evapotranspiration is increasing rapidly and drier weather periods are approaching, so often there is soil water storage that can be replenished by timely irrigation then for use later in the summer. However, this does not always mean that the corn crop required the irrigation at that point-in-time.

Post-Anthesis Water Stress

In contrast, the post-anthesis grain filling stage in corn is considered to be highly sensitive to water stress with only the flowering and early reproductive period being more sensitive. Plant water stress can cause kernel abortion if it occurs early enough in the post-anthesis period but is more often associated with poor grain filling and thus reduced kernel weight. Grain kernel weight is termed as a very loosely restricted yield component (Yoshida, 1972; Shaw, 1988), meaning that it can be manipulated by a number of factors. The final value is also set quite late, essentially only a few days before physiological maturity. The rate of grain filling is linear for a relatively long period of time from around blister kernel to near physiological maturity. Yield increases of over 4 bushels/acre for each day are possible during this period. Providing good management during the period can help to provide a high grain filling rate and, in some cases, may extend the grain filling period a few days thereby increasing yields. Availability of water for crop growth and health is the largest single controllable factor during this period. However, the rate of grain filling remains remarkably linear unless severe crop stress occurs (Rhoads and Bennett, 1990). This is attributed to remobilization of photosynthate from other plant parts when conditions are unfavorable for making new photosynthate. Irrigators in the Central Great Plains sometimes terminate the corn irrigation season on a traditional date such as August 31 or Labor Day (First Monday in September) based on long term experience. However, a more scientific approach might be that season termination may be determined by comparing the anticipated soil water balance at crop maturity to the management allowable depletion (MAD) of the soil water within the root zone. Some publications say the MAD at crop maturity can be as high as 0.8 (Doorenbos and Kassam, 1979). Extension publications from the Central Great Plains often suggest limiting the MAD at season end to 0.6 in the top 4 ft of the soil profile (Rogers and Sothers, 1996). These values may need to be re-evaluated and perhaps adjusted downward (smaller MAD value). Lamm et al. (1995) found subsurface drip-irrigated corn yields in northwest Kansas began to decrease rapidly when available soil water in the top 8 ft was lower than 56-60% of field capacity for extended periods in July and August. Lamm et al. (1994) permitted small daily deficits to accumulate on surface-irrigated corn after tasseling, and subsequent analysis of those data showed declining yields when available soil water levels approached 60% of field capacity for a 5-ft soil profile at physiological maturity

General Objective

This presentation will summarize the results from several long term field studies at the KSU Northwest Research-Extension Center in Colby, Kansas on a productive, deep, silt loam soil where irrigation treatments were either initiated or terminated at various points-in- time before and after anthesis, respectively.

PROCEDURES

General Procedures

The studies were conducted at the KSU Northwest Research-Extension Center at Colby, Kansas,USA on a productive, deep, well-drained Keith silt loam soil (Aridic Argiustolls) during the sixteen-year period, 1993-2008. In general, the 1990s were a much wetter period than the 2000s. The summers of 2000 through 2003 would be considered extreme droughts. The climate for the region is semi-arid with a summer pattern of precipitation with an annual average of approximately 19 inches. The average precipitation and calculated corn evapotranspiration during the 120-day corn growing period, May 15 through September 11 is 11.8 inches and 23.1 inches, respectively. The corn anthesis period typically occurs between July 15 and 20.

The corn was planted in 2.5 ft spaced rows in late April to early May, and standard cultural practices for the region were used.

Irrigation was scheduled as needed by a climate-based water budget except as modified by study protocols that will be discussed in the sections that follow. Calculated crop evapotranspiration (ET_c) was determined with a modified Penman equation for calculating reference evapotranspiration (ET_r) multiplied by empirical crop coefficients suitable for western Kansas. Precipitation and irrigation were deposits into the crop water budget and ET_c was the withdrawal.

Soil water was measured in each plot on a weekly or biweekly basis with a neutron probe to a depth of 8 ft. in 1-ft increments. These data were used to determine crop water use and to determine critical soil water depletion levels. Water use values were calculated as the sum of the change in available soil water to the specified profile depth, plus the irrigation and precipitation during the specified period. This method of calculating crop water use would also include any deep percolation or rainfall runoff that may have occurred.

Corn yield and yield components of plants/area, ears/plant, and kernel weight were measured by hand harvesting a representative 20-ft row sample. The number of kernels/ear was calculated with algebraic closure using the remaining yield components.

Specific Procedures for Pre-Anthesis Water Stress Studies

Data from two studies where the initiation date of the irrigation season was varied were combined in the analysis. The first study consisted of five years of data (1999 through 2003) with the hybrid Pioneer 3162 (full season, 118 days to maturity). The second study during the four-year period (2004 through 2007) used two corn hybrids [Pioneer 32B33 (full season, 118 days to maturity) and Pioneer 33B50 (medium season, 112 days to maturity)]. Both studies utilized the same field site that had a subsurface drip irrigation (SDI) system installed in 1990 with 5-ft dripline spacing and an emitter spacing of 12 inches. The 2.5-ft spaced corn rows were planted parallel and centered on the driplines such that each corn row would be 15 inches from the nearest dripline. The nominal dripline flowrate was 0.25 gpm/100 ft, which is equivalent to an emitter discharge of 0.15 gal/h for the 12-inch emitter spacing. The 2004-2007 study had six main irrigation treatments and the two corn hybrid split-plot treatments replicated three times in a randomized complete block (RCB) design. The 1999-2003 study used the same experimental design without the split plot. The whole plots were 8 rows wide (20 ft) and 200 ft long.

The six irrigation treatments (pre-anthesis water stress studies) were imposed by delaying the first normal irrigation either 0, 1, 2, 3, 4, or 5 weeks. This typically resulted in the first irrigation for Trt 1 being between June 5 and June 15 and the first irrigation for Trt 6 being around July 10 to July 24. In some years, excessive rainfall between two adjacent treatment initiation dates would negate the need for irrigation. In that case, the later treatments would be delayed an additional week to provide an extended data set. After the treatment initiation date occurred, SDI was scheduled to provide 0.4 inches/day until such time that the climate-based water budget fully eliminated calculated soil water deficits. It should be noted that this irrigation capacity of 0.4 inches/day is much greater than the typical irrigation capacity in this region. Additionally, the procedure of eliminating the severe irrigation deficits later in the season after the plants had been stunted may lead to excessive deep percolation. The purpose of the study was not to optimize irrigation use within the study but rather to determine what capability the corn crop had to tolerate early season water stress. Thus, the procedures were tailored to alleviate soil water deficits relatively quickly after the treatment initiation date.

Analysis of variance (AOV) of the yield and yield component data was performed for the 6 treatments for the 1999-2003 data set using a one-way AOV and using a split plot two-way AOV for the 2004-2007 data set.

Specific Procedures for Post-Anthesis Water Stress Studies

Four separate studies were conducted over the years 1993 through 2008 to examine the effects of post-anthesis water stress on corn. Prior to anthesis, all treatments in each of the studies were fully irrigated according to their need.

A two-year study (1993 through 1994) consisting of six irrigation treatments with three replications in a complete randomized block design was conducted in small level basins consisting of 6 corn rows each (15 ft) approximately 90 ft long. Surface irrigation was used to provide irrigation amounts for each event that were between 2.5 to 3 inches to help achieve higher distribution uniformity than smaller applications would have provided. The six irrigation treatments were termination of the irrigation season on either August 5, 10, 15, 20, 25 or 30. The corn hybrid was Pioneer 3183 (a full season hybrid of approximately 118 day maturity). The year 1993 was an extremely poor corn production year characterized by very cool and wet conditions while 1994 was a good year for corn production.

A four-year study (1995 through 1998) consisting of nine irrigation treatments with four replications in a complete randomized block design was conducted in small level basins consisting of 8 corn rows each (20 ft) approximately 90 ft long. Surface irrigation was used in this study with event irrigation amounts of approximately 2.5 to 3 inches. The nine irrigation treatments were termination of the irrigation season at either anthesis, anthesis plus 6, 12, 18, 24, 30, 36, 42 or 48 days. The corn hybrid was Pioneer 3183 (a full season hybrid of approximately 118 day maturity). Corn yields in 1995 were somewhat depressed due to a hail storm but were good in 1996 through 1998.

Another study was conducted from 1999 through 2001 using subsurface drip irrigation to more closely control soil water levels and distribution uniformity of irrigation water. In this study, seven irrigation treatments were replicated three times in a complete randomized block with plot size of 8 corn rows (20 ft) by approximately 280 ft. In this study irrigation during the post-anthesis period was managed for two distinct periods. Four of treatments began at anthesis with one treatment receiving no irrigation after anthesis and the other three treatments only receiving irrigation if the available soil water in the top 5 foot of profile fell below approximately 68, 48 or 27% of field capacity. Three additional treatments were no irrigation after two weeks following anthesis and soil water maintenance level treatments of either 48 or 27% of field capacity beginning also at that time. After anthesis, irrigation amounts were generally not greater than 0.5 inches for each required event and were conducted as needed to return the available soil water to the required treatment level. The year 1999 had above normal precipitation but 2000 and 2001 were extreme drought years. This study utilized an subsurface drip irrigation (SDI) system installed in 1999 with 5-ft dripline spacing and an emitter spacing of 24 inches. The 2.5-ft spaced corn rows were planted parallel and centered on the driplines such that each corn row would be 15 inches from the nearest dripline. The nominal dripline flowrate was 0.25 gpm/100 ft, which is equivalent to an emitter discharge of 0.30 gal/h for the 24-inch emitter spacing. The corn hybrid was Pioneer 3162 (a full season hybrid of approximately 118 day maturity).

The final post-anthesis water stress study (2002 through 2008) was conducted on the same SDI field site as the 1999 through 2001 study but the seven irrigation treatments were the irrigation season being terminated at one week intervals beginning one week after anthesis. This typically meant that the first irrigation treatment ceased about July 20 to 27 and the last irrigation treatment ceased about August 31 to September 7. The crop was fully irrigated until the irrigation termination date occurred and irrigation event amounts were generally not greater than 0.5 inches. The seven irrigation treatments were replicated three times in a complete randomized block design. The corn hybrid was Pioneer 3162 (a full season hybrid of approximately 118 day maturity). Post anthesis water productivity was calculated as the crop yield in bu/acre divided by the post-anthesis crop water use.

RESULTS AND DISCUSSION

Results for Pre-Anthesis Water Stress Studies

Statistical and tabular data analysis for pre-anthesis water stress studies

Delaying irrigation only statistically affected the yield components in three of the nine crop years and then only for the later irrigation dates (Tables 1 and 2). Delaying irrigation until July 10, 2001, July 17, 2003 and July 27, 2005 significantly reduced the number of kernels/ear and the grain yield. These three years had an average weather-based calculated July crop ET_c rate of 0.32 inches/day. In comparison the average July crop ET_c rate value was 0.26 inches/day for the other six years. It should be noted that the years 2000 through 2003 were extreme drought years in northwest Kansas. Delaying irrigation also significantly reduced ears/plant in 2003 and 2005. In 2003, the reduction in kernels/ear and ears/plant for Trt 6 was partially compensated for by a statistically higher kernel weight. Overall, these results suggest that corn grown on this soil type has great ability to handle vegetative and early-reproductive period water stress provided the water stress can be alleviated during the later stages.

The hybrid selection affected yield in only one of the four years, 2006, with the longer season Pioneer 32B33 providing significantly greater yields for the later irrigation initiation dates (Table 2). This is probably because of earlier pollination for the Pioneer 33B50 prior to receiving irrigation. Kernels/ear was significantly less for the shorter season Pioneer 33B50 hybrid in three of four years. Hybrid selection did not affect ears/plant in any of the four years. In 2004, kernel weight was significantly higher for Pioneer 33B50 for some irrigation treatments, probably because of the smaller number of kernels/ear for this hybrid in that year.

It should be noted that the results do not mean that irrigation can be delayed in the Western Great Plains until mid to late July. These plots generally started the season with reasonably full soil profiles. Most irrigators do not have irrigation systems with adequate capacity (gpm/acre) to quickly alleviate severely depleted soil water reserves. In addition, it is difficult to infiltrate large amounts of water into the soil quickly with sprinkler and surface irrigation systems without causing runoff problems. Rather, look at these study results as describing the corn plant’s innate ability to tolerate vegetative-period water stress.

Table 1. Summary of yield component and irrigation data from an early season water stress study for corn hybrid Pioneer 3162, KSU-NWREC, Colby, Kansas, 1999-2003.

Year and Parameter		Trt 1		Trt 2		Trt 3		Trt 4		Trt 5		Trt 6	
1999	First Irrigation Date	22-Jun		29-Jun		6-Jul		13-Jul		20-Jul		27-Jul	
	Total Irrigation (in.)	11.2		11.2		11.2		10.0		10.0		7.6	
	Yield (bu/a)	253	a*	265	a	256	a	255	a	259	a	255	A
	Plant Pop. (p/a)	31073	A	32234	a	31944	a	31653	a	32234	a	32234	A
	Ears/Plant	0.99	A	0.99	a	0.97	a	1.00	a	0.99	a	1.01	A
	Kernels/Ear	575	A	570	a	555	a	572	a	543	a	555	A
	Kernel Wt. (g/100)	36.3	A	36.9	a	37.8	a	35.8	a	38.1	a	35.9	A
2000	First Irrigation Date	5-Jun		12-Jun		19-Jun		26-Jun		3-Jul		10-Jul	
	Total Irrigation (in.)	19.7		19.7		19.7		18.9		18.9		18.9	
	Yield (bu/a)	225	A	235	a	225	a	227	a	216	a	217	A
	Plant Pop. (p/a)	27878	A	28169	a	26717	a	26717	a	27007	a	27297	A
	Ears/Plant	1.02	A	1.04	a	0.99	a	1.03	a	1.02	a	1.01	A
	Kernels/Ear	544	A	553	a	568	a	544	a	548	a	529	A
	Kernel Wt. (g/100)	36.9	a	36.8	a	38.0	a	38.4	a	36.4	a	37.8	A
2001	First Irrigation Date	12-Jun		19-Jun		26-Jun		3-Jul		10-Jul		17-Jul	
	Total Irrigation (in.)	19.2		19.2		19.2		19.2		19.2		19.2	
	Yield (bu/a)	254	a	260	a	261	a	250	a	213	b	159	C
	Plant Pop. (p/a)	33977	a	34993	a	35138	a	35284	a	34413	a	33831	A
	Ears/Plant	0.96	a	0.98	a	0.99	a	0.99	a	0.97	a	0.99	A
	Kernels/Ear	581	a	584	a	582	a	541	a	476	b	347	C
	Kernel Wt. (g/100)	33.8	a	33.2	a	32.8	a	33.7	a	34.6	a	34.9	A
2002	First Irrigation Date	12-Jun		19-Jun		26-Jun		3-Jul		10-Jul		17-Jul	
	Total Irrigation (in.)	18.5		18.0		18.0		18.0		18.0		18.0	
	Yield (bu/a)	233	a	232	a	217	a	219	a	222	a	223	A
	Plant Pop. (p/a)	34558	a	34848	a	34558	a	35719	a	35719	a	34558	A
	Ears/Plant	0.98	a	0.97	a	0.98	a	0.99	a	1.00	a	0.99	A
	Kernels/Ear	454	a	443	a	407	a	435	a	391	a	422	A
	Kernel Wt. (g/100)	38.6	a	39.8	a	40.3	a	36.6	a	40.5	a	39.2	A
2003	First Irrigation Date	12-Jun		21-Jun		26-Jun		3-Jul		10-Jul		17-Jul	
	Total Irrigation (in.)	18.8		18.0		18.0		17.2		17.2		17.2	
	Yield (bu/a)	177	a	180	a	190	a	186	a	171	a	93	B
	Plant Pop. (p/a)	32815	a	33396	a	34267	a	33106	a	34558	a	32815	A
	Ears/Plant	0.96	a	0.92	b	0.96	a	1.00	a	0.97	a	0.82	C
	Kernels/Ear	588	a	567	a	576	a	569	a	486	b	262	C
	Kernel Wt. (g/100)	24.1	b	26.2	b	25.5	b	25.2	b	26.8	b	33.6	A

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

Table 2. Summary of corn yield component and irrigation data from an early season water stress study for hybrids Pioneer 33B50 and 32B33, KSU-NWREC, Colby, Kansas, 2004-2007.

Year and Parameter		**Trt 1**	**Trt 2**	**Trt 3**	**Trt 4**	**Trt 5**	**Trt 6**
2004 First Irrigation	**Hybrid**	8-Jun	28-Jun	13-Jul	20-Jul	27-Jul	3-Aug
Total Irrig. (in.)		12.8	11.6	10.8	10.8	10.8	10.8
Yield (bu/a)	33B50	220 aA*	213 aA	206 aA	233 aA	245 aA	210 aA
	32B33	226 aA	211 aA	209 aA	222 aA	229 aA	206 aA
Plant Pop. (p/a)	33B50	29040 aA	28169 aA	28169 aA	28169 aA	28750 aA	27878 aA
	32B33	28459 aA	29621 aA	29621 aA	28459 aA	29040 aA	28459 aA
Ears/Plant	33B50	0.85 aA	0.91 aA	0.89 aA	0.93 aA	0.88 aA	0.84 aA
	32B33	0.88 aA	0.80 aA	0.79 aA	0.90 aA	0.83 aA	0.83 aA
Kernels/Ear	33B50	595 aB	574 aB	589 aB	595 aA	648 aA	590 aB
	32B33	624 aA	616 aA	634 aA	600 aA	643 aA	612 aA
Kernel Wt. (g/100)	33B50	38.0 aA	36.8 aA	35.7 aA	38.2 aA	38.2 aA	38.6 aA
	32B33	36.8 aB	36.4 aA	36.2 aA	36.8 aB	37.6 aA	36.4 aB
2005 First Irrigation	**Hybrid**	21-Jun	28-Jun	6-Jul	12-Jul	19-Jul	26-Jul
Total Irrig. (in.)		13.2	13.2	13.2	13.2	13.2	13.2
Yield (bu/a)	33B50	254 aA	259 aA	256 aA	238 abA	227 bA	149 cA
	32B33	254 abcA	254 abcA	258 abA	264 aA	235 cA	162 dA
Plant Pop. (p/a)	33B50	28750 aA	28459 aA	28459 aA	28459 aA	29621 aA	28169 aA
	32B33	28459 aA	29040 aA	28459 aA	27848 aA	28750 aA	29621 aA
Ears/Plant	33B50	0.99 abA	1.00 aA	0.99 abA	0.98 abA	0.96 bcA	0.95 cA
	32B33	0.98 bA	0.97 bcA	1.01 aA	1.00 abA	0.96 bcdA	0.94 dA
Kernels/Ear	33B50	641 abA	653 aA	670 aA	604 bA	564 cA	422 dA
	32B33	638 bA	647 abA	644 abA	680 aA	654 abA	421 cA
Kernel Wt. (g/100)	33B50	35.4 aA	35.4 aA	34.5 aA	36.0 aA	35.9 aA	33.6 aA
	32B33	36.2 aA	35.4 aA	35.4 aA	35.5 aA	33.1 aA	35.1 aA
2006 First Irrigation	**Hybrid**	8-Jun	15-Jun	26-Jun	29-Jun	6-Jul	14-Jul
Total Irrig. (in.)		14.0	13.6	12.8	12.8	12.4	12.4
Yield (bu/a)	33B50	225 aA	230 aA	220 aB	220 aA	220 aB	206 aB
	32B33	229 aA	234 aA	246 aA	230 aA	241 aA	244 aA
Plant Pop. (p/a)	33B50	27588 aA	27007 aA	28169 aA	28169 aA	27588 aA	27297 aA
	32B33	28459 aA	27878 aA	28459 aA	27878 aA	28168 aA	28169 aA
Ears/Plant	33B50	0.98 aA	0.98 aA	0.99 aA	0.99 aA	0.99 aA	0.96 aA
	32B33	0.96 aA	0.98 aA	0.98 aA	0.97 aA	0.98 aA	0.97 aA
Kernels/Ear	33B50	561 aB	594 aAB	544 aB	547 aB	550 aB	519 aB
	32B33	597 aA	602 aA	618 aA	583 aA	585 aA	612 aA
Kernel Wt. (g/100)	33B50	37.8 aA	37.2 aA	36.8 aA	36.5 aA	37.4 aA	38.7 aA
	32B33	35.7 aA	36.2 aA	36.3 aA	37.1 aA	38.1 aA	37.2 aA
2007 First Irrigation	**Hybrid**	7-Jun	21-Jun	28-Jun	4-Jul	12-Jul	19-Jul
Total Irrig. (in.)		12.1	11.3	11.3	11.3	11.3	10.9
Yield (bu/a)	33B50	243 aA	252 aA	250 aA	245 aA	234 aA	213 aA
	32B33	259 aA	235 aA	252 aA	239 aA	255 aA	229 aA
Plant Pop. (p/a)	33B50	29040 aA	29621 aA	29331 aA	28459 aA	29040 aA	28169 aA
	32B33	29040 aA	28459 aA	28169 aA	27878 aA	28459 aA	28169 aA
Ears/Plant	33B50	0.98 aA	0.99 aA	1.00 aA	0.99 aA	0.99 aA	1.00 aA
	32B33	0.98 aA	0.95 aA	0.99 aA	0.99 aA	0.99 aA	0.97 aA
Kernels/Ear	33B50	668 aB	672 aB	693 aA	682 aA	645 aB	597 aB
	32B33	728 aA	724 aA	712 aA	712 aA	714 aA	674 aA
Kernel Wt. (g/100)	33B50	32.5 aA	32.5 aA	31.2 aA	32.4 aA	32.0 aA	32.2 aA
	32B33	31.6 aA	30.6 aA	32.3 aA	30.9 aA	32.3 aA	31.7 aA

* *Irrigation treatment values within the same row followed by the same lower case letters are not significantly different at P=0.05, and hybrid treatment values within the same column followed by the same upper case letters are not significantly different at P=0.05.*

Graphical data analysis for pre-anthesis water stress studies

The tabular data do not give a mechanistic explanation of the results. Attempts were made to relate yield component data to a large number of water factors in the broad categories of water use, evaporative demand, and critical profile soil water levels. Relative values of yield and yield components were determined by normalizing each data point to the corresponding value for the earliest irrigation treatment in that year. These relative values were used for comparisons between years. Final grain yield was largely determined by the number of sinks or kernels/area (plants/area x ears/plant x kernels/ear) indicating there was little or no effect on the grain-filling stage imposed by the vegetative and early-reproductive period water stress in these two studies (Figure 1). The individual treatment values of corn grain yield and kernels/area were values compared to the irrigation treatment that had no initial delay in irrigation (Trt 1) to give relative values. In a few cases, the Trt 1 values were not the highest value and, thus, relative values could be greater than one. Deviations below the 1 to 1 unity line in Figure 1 would indicate a permanent negative effect on corn grain yield of early-season water stress because of reduced kernels/area. Deviations above the line would indicate some grain yield compensation resulting from better grain filling of the reduced kernels/area.

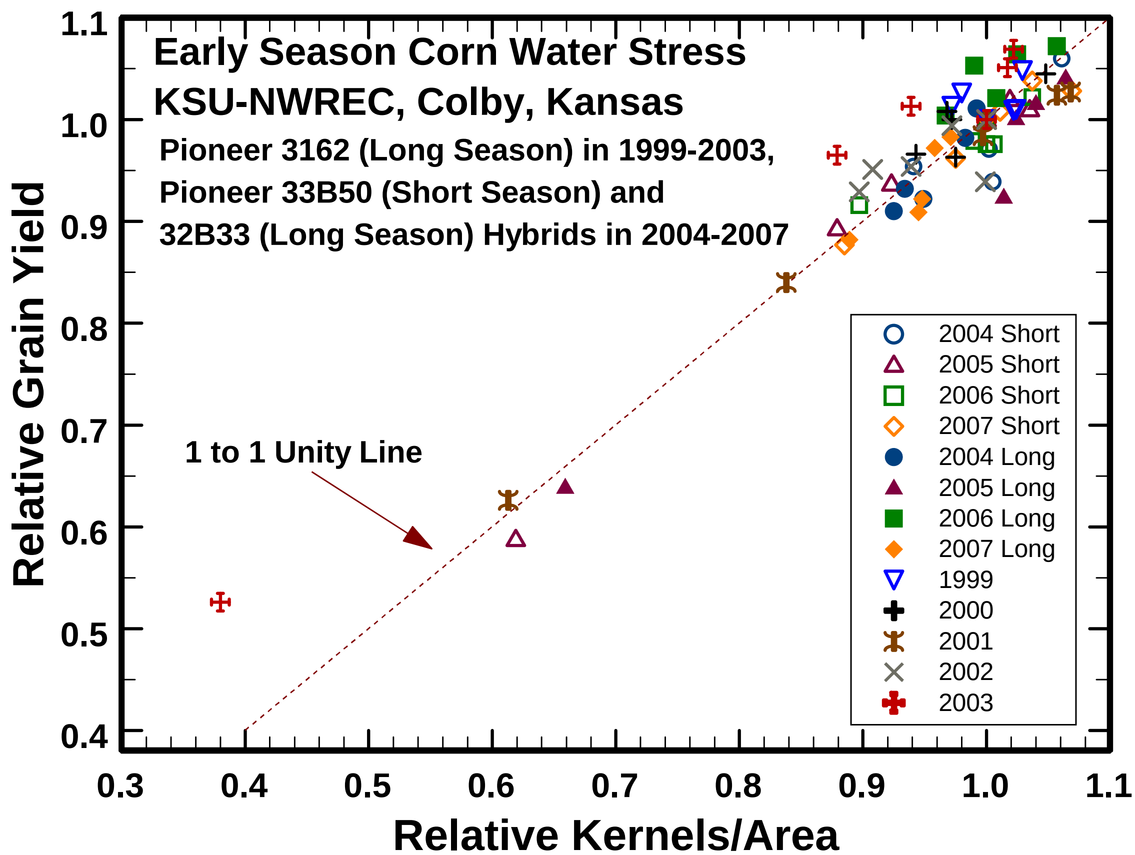


Figure 1. Relative corn grain yield as affected by relative kernels/area in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

Relative kernels/area was found to be reasonably well related to relative July water use, the minimum available soil water in the top 4 ft of the soil profile during July and to the July 1 through July 15 water deficit (Ratio of calculated well-watered corn ETc to the sum of irrigation and precipitation). Further analysis is needed to determine an improved overall relationship involving more than a single factor, but the individual factor results will be discussed here.

The 50% critical silking period for corn in this study ranged from approximately July 17 to July 22 during the study period (1999 to 2007). The short-season hybrid in the latter study would typically silk approximately one week earlier. A window of approximately two weeks on both sides around the silking period was used to compare the relative kernels/area to the relative July measured water use (sum of change in available soil water in July plus July irrigation and precipitation). Actual soil water measurements were taken on an approximately weekly basis except for equipment problems or when excessive precipitation delayed measurements, so it was not possible with the data set to always have exactly 31 days of water use. Dates used were those closest to July 1 through 31. There tended to be some reduction in relative kernels/area when relative July water use was less than 80% (Figure 2). Scatter at the lower end of relative July water use may be related to water-use differences occurring within the month or differences in evaporative demand between the years. This relationship may not result in a very good signal for procedures to determine irrigation need because the relative July water use cannot be determined until it is too late to handle the reduction in relative kernels/area.

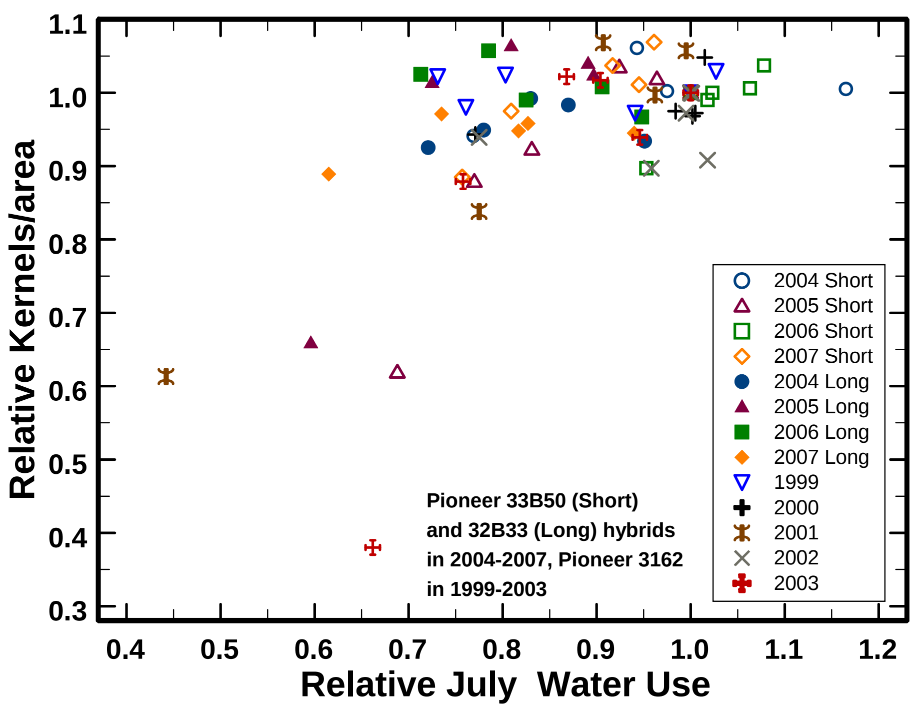


Figure 2. Relative corn grain yield as affected by relative July water use in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

The relative kernels/area tended to be reduced when July minimum available soil water in the top 4 ft (JASW) was below 0.6 (fraction) in some years (Figure 3). During years of less evaporative demand, water could be extracted from the soil profile to a further reduced level without much detriment to relative kernels/area, but severe reductions occurred for similar soil water conditions in years with large July evaporative demands. The upper and lower envelope lines of Figure 3 were manually drawn to indicate the effect of evaporative demand of the given year on relative kernels/area. These envelopes would match known theories of water stress and water flow through plants (Denmead and Shaw, 1962).

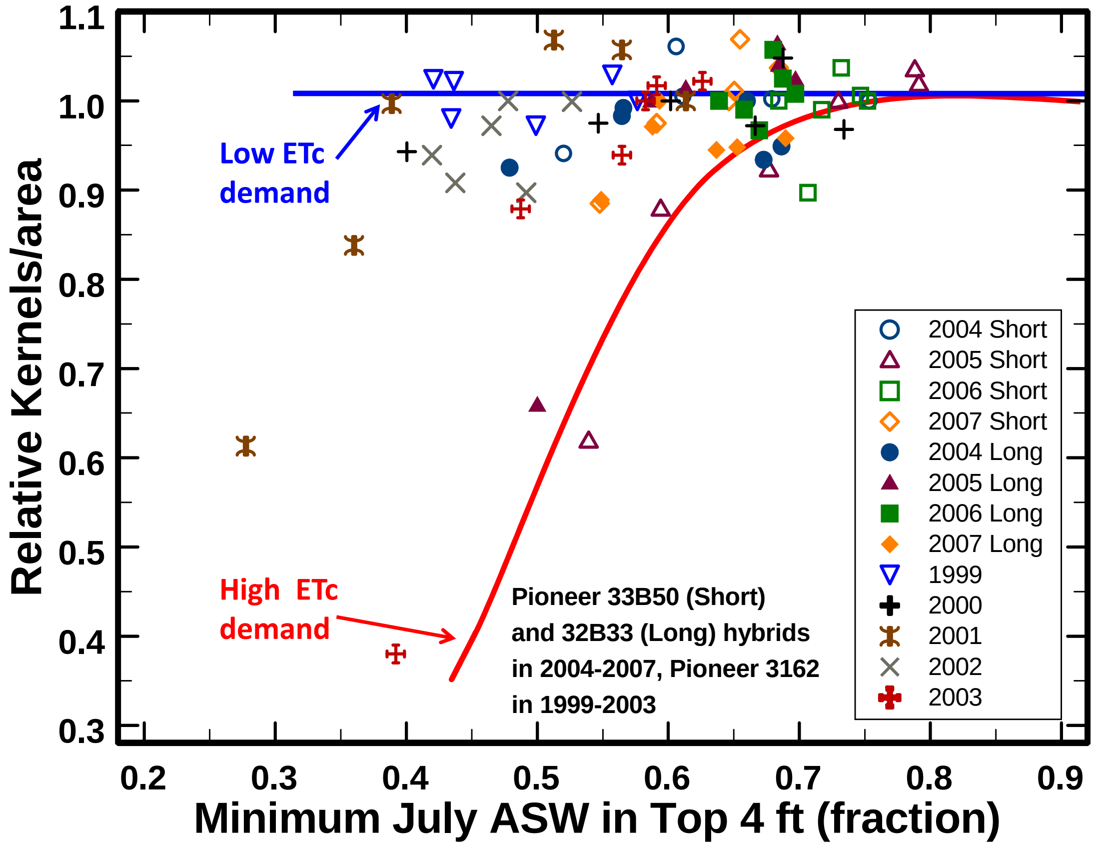


Figure 3. Relative kernels/area as affected by July minimum available soil water in the top 4 ft of soil in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007. The upper (red) and lower (blue) lines are manually drawn to illustrate years with larger and smaller July evaporative demand.

Water stress is greater both with reduced available soil water and with greater evaporative demand. The kernels/area was most sensitive to the JASW in the top 4 ft of soil as compared to both smaller and greater profile depths. This is reflecting the approximate rooting and soil water extraction depth of corn in July on this soil type. There remains considerable unexplained scatter in this graph that does not appear to be related very well to differences in evaporative demand between the years. For example, there was very little effect on relative kernels/area in 2002, although it had a moderately high evaporative demand.

The relationship of relative kernels/area to a critical level of available soil water can have some merit as a signal for determining the need for irrigation because available soil water can both be measured in real-time and the value can be projected a few days into the future.

The ratio of calculated well-watered crop ET_c to the sum of irrigation and precipitation for July 1 through 15 was also related to the relative kernels/area (Figure 4). The relative kernels/area tended to decrease when this water deficit ratio was less than 70 to 80%. Attempts were also made in varying the timeframe of the ratio (both longer and shorter and also shifting within the month of July). It appears that some of the remaining scatter in this graph is related to timing of irrigation and precipitation near the actual point of silking. For example, the isolated point from 2002 near the vertical axis may be related to a significant precipitation event that occurred near silking, but later than July 15. Further analysis should be conducted to allow the window to actually vary around the individual silking dates of each year. This might be done by computing windows based on the number of thermal units (also known as Growing Degree Days) required for silking. This relationship might also be a good signal in determining the need for irrigation because it can be determined in near real-time using the accumulated ratio to that point in time.

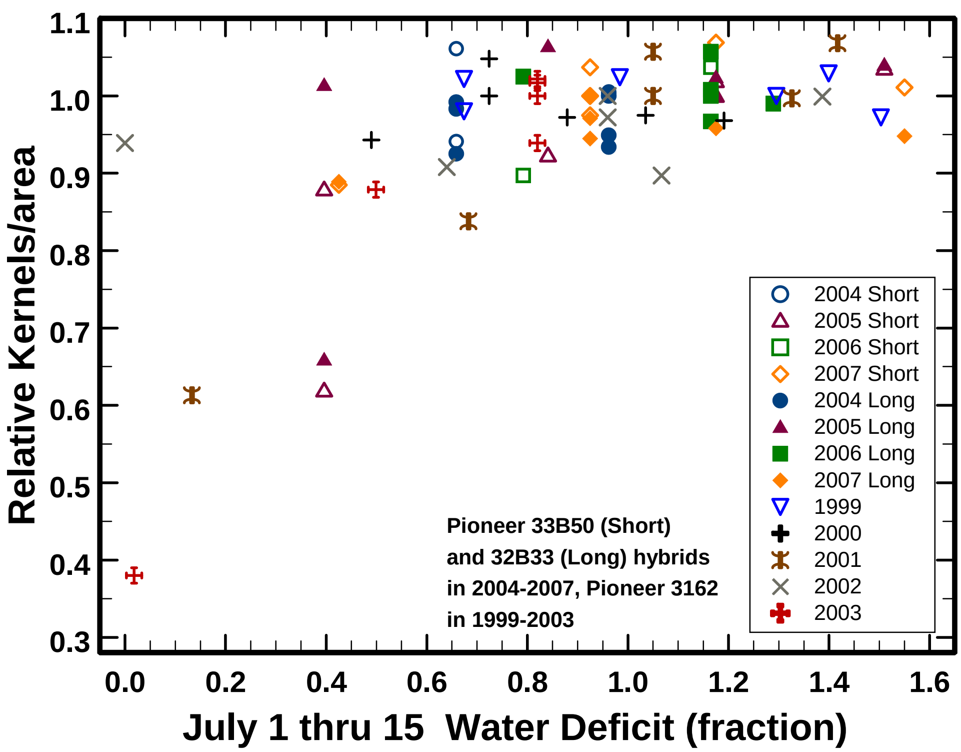


Figure 4. Relative kernels/area as affected by the July 1 through 15 water deficit (ratio of calculated well-watered crop ET_c to the sum of irrigation and precipitation) in an early-season corn water stress study, KSU-NWREC, Colby, Kansas, 1999-2007.

Further analysis should focus on attempts to combine multiple factors (e. g., measured water use, available soil water, evaporative demand, and/or timing of irrigation and precipitation) with a focus on developing irrigation signals that can be used in near real-time to make early season irrigation decisions.

Recommendations for managing pre-anthesis corn water stress

Producers should use a good method of day-to-day irrigation scheduling during the pre-anthesis period. To a large extent the information being used to make day-to-day irrigation scheduling decisions during the pre-anthesis period can also be used as in making the macromanagement decision about when to start the irrigation season. This is because even though the corn has considerable innate ability to tolerate early season water stress, most irrigation systems in the Central Great Plains do not have the capacity (e.g, gpm/acre) or practical capability (e.g., run-off or deep percolation concerns) to replenish severely depleted soil water reserves as the season progresses to periods of greater irrigation needs (i.e., greater ET_c and less precipitation). However, there is some flexibility in timing of irrigation events within the vegetative growth period. In years of lower evaporative demand, corn grown on this soil type in this region can extract greater amounts of soil water without detriment. Timeliness of irrigation and/or precipitation near anthesis appears to be important in establishing an adequate number of kernels/area. The strong linear 1:1 relationship that existed between the relative corn yield and the relative number of kernels/area (plants/area x ears/plant x kernels/ear) indicates that optimizing kernels/area is a key in optimizing grain yields. Producers growing corn on deep silt loam soils in the Central Great Plains should attempt to maintain a water deficit ratio (well watered calculated ETc divided by sum of irrigation and precipitation) during July of approximately 0.7 to 0.8 and not allow the available soil water within a 4-ft soil profile to decrease below 70%, particularly in years of greater evaporative demand.

Results for Post-Anthesis Water Stress Studies

Tabular data analysis for post-anthesis water stress studies

Results from 16 years (1993-2008) of studies indicate that anthesis for corn in Northwest Kansas varies from July 12 to July 24 with an average date of July 19 (Table 3). Physiological maturity ranged from September 14 through October 10 with an average date of September 27. The average length of the post-anthesis period was approximately 70 days. Using the corn grain yield results from the study and the individual treatment irrigation termination dates responsible for those yields, Table 3 was created to indicate the problems with using inflexible dates for determining the irrigation season termination date. Additionally, the corn grain yield results and the treatment irrigation dates were used to estimate the date when a specified percentage of maximum grain yield would occur. Because there was not an unlimited number of irrigation treatment dates there are years when the date required for a specified percentage of maximum grain yield was the same as the date for the next higher percentage. The average estimated termination date to achieve 80, 90 and 100% of maximum corn grain yield was August 2, 13, and 28, respectively, but the earliest dates were July 17, July 17 and August 12, respectively, while the latest dates were September 14, 21, and 21, respectively. Irrigators that use average or fixed dates to terminate the corn irrigation season are not realistically considering the irrigation needs of the corn that may be greater or smaller in a particular year, and thus, often will neither optimize corn production, nor minimize water pumping costs.

Table 3. Anthesis and physiological maturity dates and estimated irrigation season termination dates* to achieve specified percentage of maximum corn grain yield from studies examining post-anthesis corn water stress, KSU Northwest Research-Extension Center, Colby, Kansas, 1993-2008. Note: This table was created to show the fallacy of using a specific date to terminate the irrigation season. Note: Because there was not an unlimited number of irrigation treatment dates, there are years when the date required for a specified percentage of maximum grain yield was the same as the date for the next higher percentage.

Year	Date of Anthesis	Date of Maturity	Irrigation Season Termination Date For		
			80% Max Yield	90% Max Yield	MaxYield
1993	20-Jul	30-Sep	5-Aug	5-Aug	15-Aug
1994	20-Jul	15-Sep	5-Aug	15-Aug	15-Aug
1995	20-Jul	29-Sep	5-Aug	13-Aug	18-Aug
1996	20-Jul	3-Oct	17-Jul	17-Jul	29-Aug
1997	23-Jul	1-Oct	23-Jul	23-Jul	27-Aug
1998	20-Jul	28-Sep	20-Jul	20-Jul	24-Aug
1999	23-Jul	6-Oct	24-Jul	13-Aug	20-Sep
2000	12-Jul	20-Sep	14-Sep	20-Sep	20-Sep
2001	16-Jul	29-Sep	30-Jul	22-Sep	22-Sep
2002	22-Jul	30-Sep	4-Aug	30-Aug	7-Sep
2003	22-Jul	23-Sep	3-Aug	3-Aug	18-Aug
2004	19-Jul	28-Sep	8-Aug	21-Aug	27-Aug
2005	20-Jul	28-Sep	2-Aug	9-Aug	29-Aug
2006	17-Jul	25-Sep	30-Jul	13-Aug	13-Aug
2007	18-Jul	19-Sep	14-Aug	21-Aug	28-Aug
2008	24-Jul	10-Oct	31-Jul	6-Aug	27-Aug
Average	**19-Jul**	**27-Sep**	**2-Aug**	**13-Aug**	**28-Aug**
Standard Dev.	**3 days**	**6 days**	**13 days**	**19 days**	**13 days**
Earliest	**12-Jul**	**14-Sep**	**17-Jul**	**17-Jul**	**12-Aug**
Latest	**24-Jul**	**10-Oct**	**14-Sep**	**21-Sep**	**21-Sep**

* *Estimated dates are based on the individual irrigation treatment dates from each of the different studies when the specified percentage of yield was exceeded.*

Maximum corn yields (MY) during the 16-year period in the various studies averaged 258 bu/acre with a range of 154 to 298 bu/acre (Table 4). Extremely poor growing conditions (cold and wet) greatly reduced yields in 1993 and hail suppressed yield in 1995. The post-anthesis water use that occurred for the irrigation treatment that maximized yield ($PAWU_{MY}$) averaged 16.9 inches with a range of 14.9 to 20.2 inches (Table 4). Assuming that yield formation for the corn crop started at anthesis, the average post-anthesis water productivity (i.e., $MY/PAWU_{MY}$) was 15 bu/inch and the range of water productivity over the years was 8 to 20 bu/inch (data not shown).

Table 4. Maximum corn yields and post-anthesis water use data from studies examining post-anthesis corn water stress, KSU Northwest Research-Extension Center, Colby, Kansas, 1993-2008.

Year	**Maximum Yield (bu/a)**	**$PAWU_{MY}$* (inches)**	**$PAWU_{MY}$ (inches/d)**	**$PAWU_{MY}$ during last 30 days (inches/d)**	**$PAWU_{MY}$ during last 15 days (inches/d)**
1993	154	19.23	0.287	0.288	0.178
1994	246	15.52	0.277	0.218	0.178
1995	170	18.23	0.285	0.201	0.174
1996	280	15.38	0.220	0.161	0.137
1997	245	16.13	0.230	0.162	0.150
1998	262	16.55	0.236	0.155	0.136
1999	272	18.49	0.247	0.134	0.081
2000	259	20.24	0.289	0.276	0.302
2001	268	19.44	0.259	0.161	0.160
2002	284	16.63	0.238	0.139	0.017
2003	269	15.12	0.240	0.089	0.105
2004	283	16.25	0.229	0.181	0.164
2005	295	16.31	0.233	0.088	0.036
2006	268	16.48	0.235	0.098	0.101
2007	273	16.25	0.258	0.104	0.106
2008	298	14.85	0.190	0.115	0.091
Average	**258**	**16.94**	**0.247**	**0.161**	**0.132**
Standard Dev.	**40**	**1.65**	**0.027**	**0.061**	**0.066**
Minimum	**154**	**14.85**	**0.190**	**0.088**	**0.017**
Maximum	**298**	**20.24**	**0.289**	**0.288**	**0.302**

* *$PAWU_{MY}$ is the post-anthesis water use occurring for the irrigation treatment that achieved maximum corn grain yield within the specified year.*

$PAWU_{MY}$ averaged 0.247 inches/day during the approximately 70-day period between anthesis and physiological maturity and remained at 65 and 53% of that value (0.161 and 0.132 inches/day) during the last 30 and 15 days of the season, respectively (Table 4). This emphasizes that although crop water use is tapering off during the latter part of the season, due to maturing crop canopies and also due to lower reference evapotranspiration (ET_r), therefore, it must be considered an important factor in late season crop management. Producers should also be aware that irrigation systems with marginal or insufficient capacity may have allowed considerable soil water depletion (soil water mining) during the pre-anthesis period.

Graphical data analysis for post-anthesis water stress studies

The corn grain yield results within a given year were normalized to the maximum value occurring in that particular year to give the relative yield (RY). The post-anthesis water use within a given year was then normalized with respect to the water use that occurred for the irrigation treatment that maximized corn grain yield in that particular year. This allowed treatments receiving excessive irrigation to have relative post-anthesis water use ($RPAWU_{MY}$) values greater than one.

There was a strong relationship between relative corn yield (RY) and relative post-anthesis water use ($RPAWU_{MY}$) as shown in Figure 5.

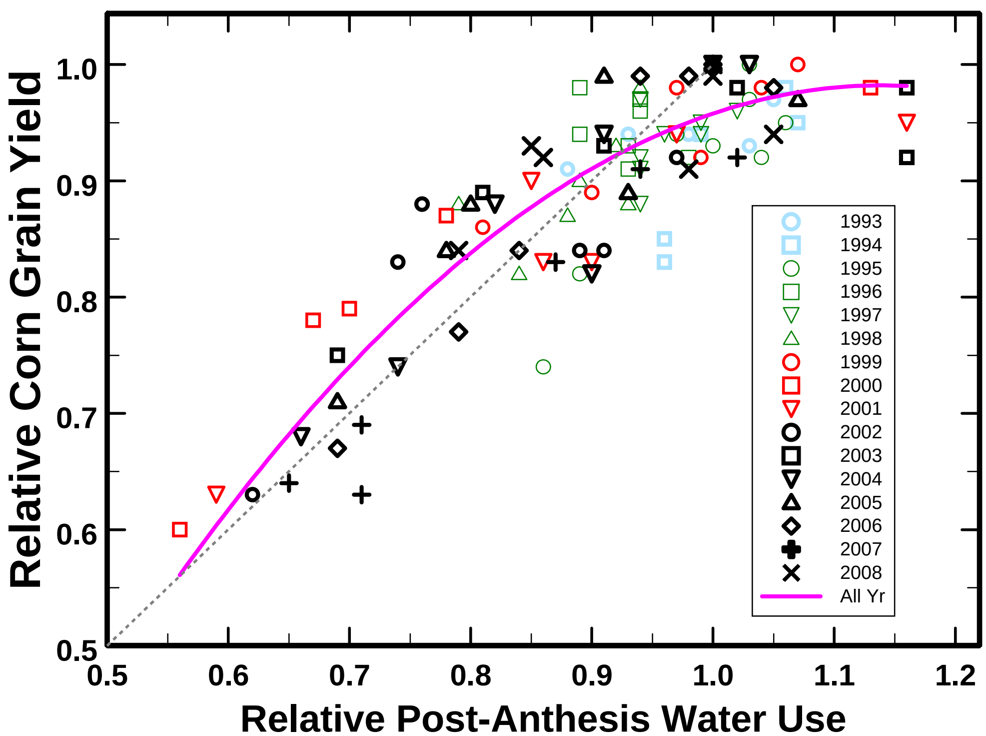


Figure 5. Relative corn grain yield (RY) as affected by relative post-anthesis water use ($RPAWU_{MY}$) for various studies examining the effect of post-anthesis water stress, KSU-NWREC, Colby, Kansas, 1993-2008. The dotted line represents a unity relationship between RY and $RPAWU_{MY}$. Note: $RPAWU_{MY}$ values can exceed one because some treatments received irrigation water in excess of the amount required to maximize corn grain yield (MY). This excessive water may have been lost in deep percolation but would have been included in the calculation procedures of post-anthesis water use.

Although there are a number of curves that can be drawn through the data (e.g., quadratic, logarithmic, etc.), there was a large portion of the data in the efficient range of $RPAWU_{MY}$ (i.e., where $RPAWU_{MY} \leq 1$) that can be adequately characterized by a one-to-one relationship between RY and $RPAWU_{MY}$. The subtle differences between assuming a curvilinear or linear relationship in the efficient range of post-anthesis water use might become important when trying to optimize corn production using water resource and economic constraints.

There was a reasonably good relationship between relative corn grain yield (RY) and the minimum post-anthesis available soil water (MPAASW, a fraction) within the 8-ft soil profile (Figure 6.) Corn yield tended to decrease for treatments having less than a minimum available soil water of approximately 55% of field capacity for any point-in- time within the post-anthesis period. Thus, the management allowable depletion (MAD) in these studies was approximately 45% as compared to the traditionally larger values often quoted in the literature (e.g., Doorenbos and Kassam, 1979; Rogers and Sothers, 1996). However, the 45% MAD value is consistent with the results of Lamm et al. (1994) and Lamm et al. (1995) from irrigated corn studies on the same soil type.

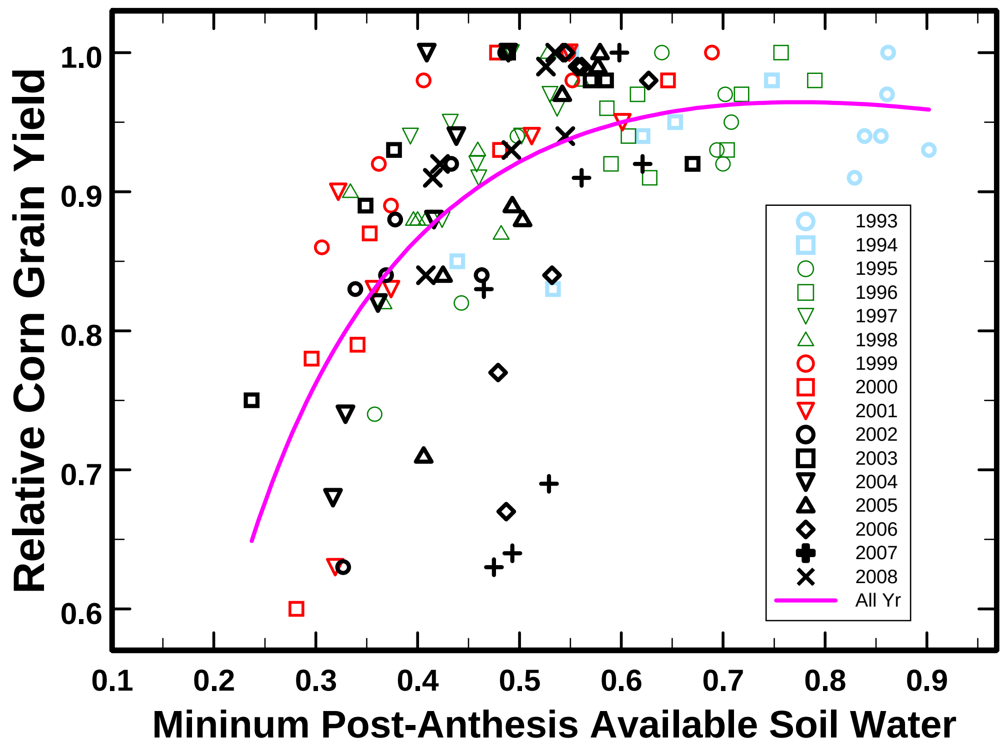


Figure 6. Relative corn grain yield (RY) as affected by the minimum value of available soil water (fraction) within the 8 ft soil profile occurring during the post-anthesis period (MPAASW). Data are from various studies examining the effect of post-anthesis corn water stress, KSU-NWREC, Colby, Kansas, 1993-2008.

There was also a relatively good relationship between $RPAWU_{MY}$ and MPAASW (Figure 7). $RPAWU_{MY}$ tended to decrease for treatments with MPAASW less than 55% of field capacity. This is to be as expected because of the strong relationship between RY and $RPAWU_{MY}$ but does provide additional evidence and rationale for a MAD value of approximately 45% for this soil type in this region as compared to the higher values in the literature.

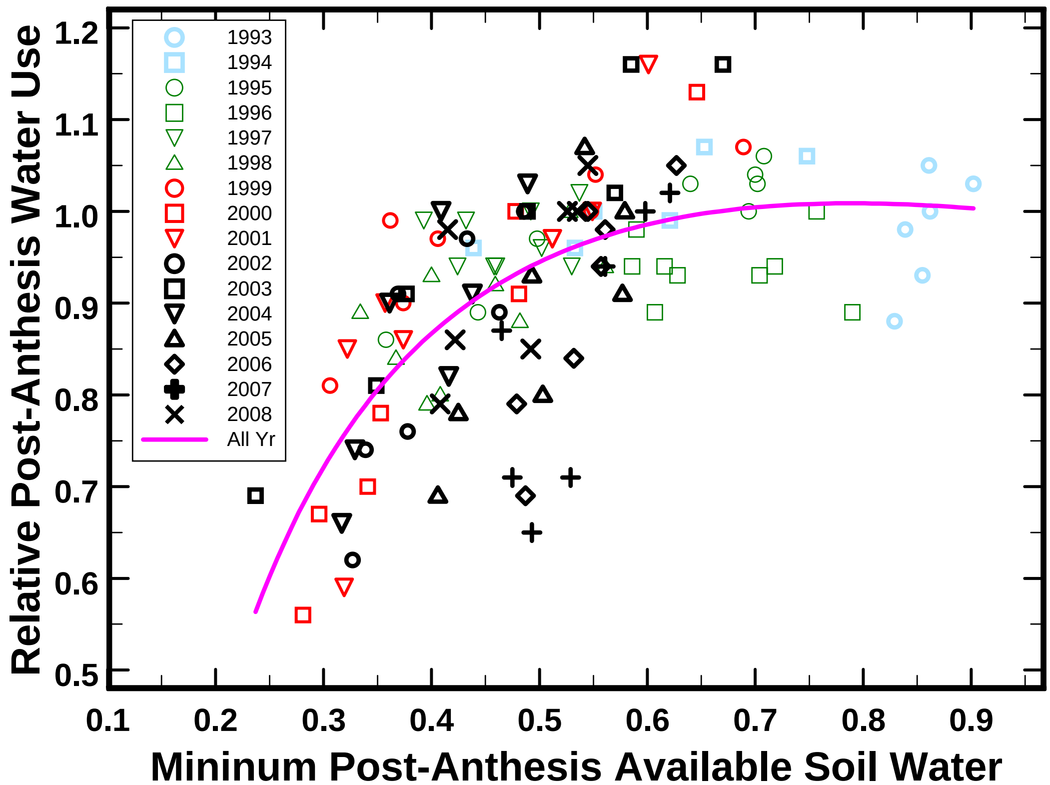


Figure 7. Relative post-anthesis water use ($RPAWU_{MY}$) as affected by the minimum value of available soil water (fraction) within the 8 ft soil profile occurring during the post-anthesis period (MPAASW). Data are from various studies examining the effect of post-anthesis corn water stress, KSU-NWREC, Colby, Kansas, 1993-2008.

Further data analysis should focus on determining the cause of increased scatter in the graph regions (Figure 6 and 7) where MPAASW is less than 0.55. Additionally, further efforts are justified in comparing the MPAASW values for different soil profile depths to see which depth has the greatest correlation and also to determine the inaccuracy associated with choosing alternative depths.

Recommendations for managing post-anthesis corn water stress

Producers should use a good method of day-to-day irrigation scheduling during the post-anthesis period. The macromanagement decision about when to terminate the irrigation season should not be based on an average or fixed date (e.g., August 31). Producers in the Central Great Plains should plan for post-anthesis water use needs of approximately 17 inches and that water use during the last 30 and 15 days of the season might average nearly 5 and 2 inches, respectively. This water use would need to come from the sum of available soil water reserves, precipitation and irrigation. When irrigation losses are minimized, a percentage decrease in post-anthesis water use will result in nearly a one-to-one percentage decrease in corn grain yield. Producers growing corn on deep silt loam soils in the Central Great Plains should attempt to limit management allowable depletion of available soil water in the top 8 ft of the soil profile to 45%.

CONCLUDING STATEMENTS

Macromanagement decisions at the seasonal boundaries should always be made in the context of having implemented appropriate day-to-day irrigation scheduling. Proper day-to-day scheduling will provide much-needed information about the crop and soil water status and evaporative demand being experienced within the given year.

Corn has greater than anticipated ability to withstand early season water stress provided that the water stress can be alleviated during the early-reproductive period. However, it should be reiterated that these results are not suggesting that irrigation can be delayed until anthesis. Most irrigation systems cannot quickly alleviate severely depleted soil water reserves as was accomplished in this pre-anthesis studies, but the results do indicate there is some flexibility in timing of irrigation events within the vegetative growth period. Timeliness of appreciable amounts of irrigation and/or precipitation near anthesis appears to be very important in maximizing yield potential.

Corn yield formation was primarily linearly related to the water use during the post-anthesis period for cases when irrigation was limited to the amount required for maximum yield. Limiting available soil water depletion to approximately 45% during the period is important in achieving maximum grain yields.

ACKNOWLEGEMENTS

Contribution No. 09-240-A from the Kansas Agricultural Experiment Station.

The authors would like to acknowledge financial support for this some of the studies discussed in this paper from Pioneer Hi-Bred Inc.

REFERENCES

Denmead, O. T. and R.H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture and meteorological conditions. Agron J. 45:385-390.

Doorenbos, J. and A H. Kassam. 1979. Yield response to water. Irrig. and Drain. Paper No. 33. Food and Agric. Org. of the United Nations, Rome Italy. 193 pp.

Lamm, F. R., D. H. Rogers, and H. L. Manges. 1994. Irrigation scheduling with planned soil water depletion. Trans. ASAE 37(5):1491-1497. Also available at http://www.oznet.ksu.edu/irrigate/Reports/ISchedPlanWD.pdf

Lamm, F. R., D. H. Rogers, and G. A. Clark. 1996. Irrigation Scheduling for Corn: Macromanagement. In: Proc. Evapotranspiration and Irrigation Scheduling Conf., San Antonio, TX, Nov. 3-6, 1996. pp. 741-748. ASAE. Also available at http://www.oznet.ksu.edu/irrigate/Reports/macro.pdf

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

Rogers, D. H. and W. Sothers. 1996. Predicting the final irrigation for corn, grain sorghum, and soybeans. Kansas State Univ. Coop. Ext. Irr. Management Series, MF2174. Manhattan, KS. 4 pp. Also available at http://www.oznet.ksu.edu/library/ageng2/MF2174.pdf

Rhoads F. M. and J. M. Bennett. 1990. Corn. Chapter 19 in Irrigation of Agricultural Crops. pp. 569-596. ASA-CSSA-SSSA, Mono No. 30, B. A. Stewart and D. R. Nielsen (Eds.). 1218 pp.

Shaw, R. H. 1988. Climate requirement. Chapter 10 in Corn and Corn Improvement. Third Edition. pp. 609-638. ASA-CSSA-SSSA, Mono No. 18, G. F. Sprague and J. W. Dudley (Eds.). 986 pp.

Yoshida, S. 1972. Physiological aspects of grain yield. Annu. Rev. Plant Physiol. 23:437-464.

Proper management of irrigated corn requires careful attention to crop water stress during both the pre-anthesis and post-anthesis growing periods.

CROP SELECTIONS AND WATER ALLOCATIONS FOR LIMITED IRRIGATION

N. L. Klocke, L. R. Stone, T. J. Dumler, S. Briggeman

Norman L. Klocke, Kansas State University, Professor, Water Resources Engineering, 4500 East Mary Street, Garden City, KS 67846, phone: 620-276-8286; fax: 620-276-6028; e-mail nklocke@ksu.edu. Loyd R. Stone, Kansas State University, Professor, Soil Physics, Throckmorton Hall, Manhattan, KS, Troy J. Dumler, Kansas State University, Extension Economist, SWREC, Garden City, KS, and Steven Briggeman, Software Developer, Sprout Software, Manhattan, KS.

INTRODUCTION

Irrigators are facing challenges with declining well yields or reduced allocations from water districts. To make reductions in water use, irrigators are considering shifts in cropping patterns that earn better net economic returns. A decision planning tool, the Crop Water Allocator (CWA), available at www.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. The model uses yield-irrigation relationships for 11-21 in. of rainfall in western Kansas as a basis to estimate yields for particular rainfall zones. The user can customize the program with crop localized crop production costs or rely on default values from typical western Kansas farming operations. Irrigators are able to plan for the optimum economic use of their limited water supply by testing their options with CWA.

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

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

The objective of this project has been to create a decision tool with user interaction to examine crop mixes and limited water allocations within land allocation constraints to find optimum net economic returns from these combinations. This decision aid is for intended producers with limited water supplies to allocate their seasonal water resource among a mix of crops. But, it may be used by others interested in crop rotations and water allocation choices.

BACKGROUND

CWA calculates net economic return for all combinations of crops selected for a rotation and water allocated to each crop. Subsequent model executions of land-split (crop rotation) scenarios can lead to more comparisons. Individual fields or groups of fields can be divided into in the following ways: 50-50; 25-75; 33-33-33; 25-25-50; 25-25-25-25. The number of crops eligible for consideration in the crop rotation could be more than the number of land splits under consideration. Optimum outcomes may recommend fewer crops than selected land splits. Fallowing part of the field is a valid option. Irrigation system parameters, production costs, commodity prices, yield maximums, annual rainfall, and water supplied to the field were held constant for each model execution, but can be changed by the user in subsequent executions.

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

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

where:

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

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

Field research results have been used to find relationships between crop yields and amounts of irrigation (figure 1). Yields from given irrigation amounts multiplied by commodity prices are used to calculate gross income. Grain yields for corn, grain sorghum, sunflower, and winter wheat were estimated by using the “Kansas Water Budget” software. Software development and use are described in Stone et al. (1995), Khan (1996), and Khan et al. (1996). Yield for each crop was estimated from irrigation amount for annual rainfall and silt loam soils. 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.

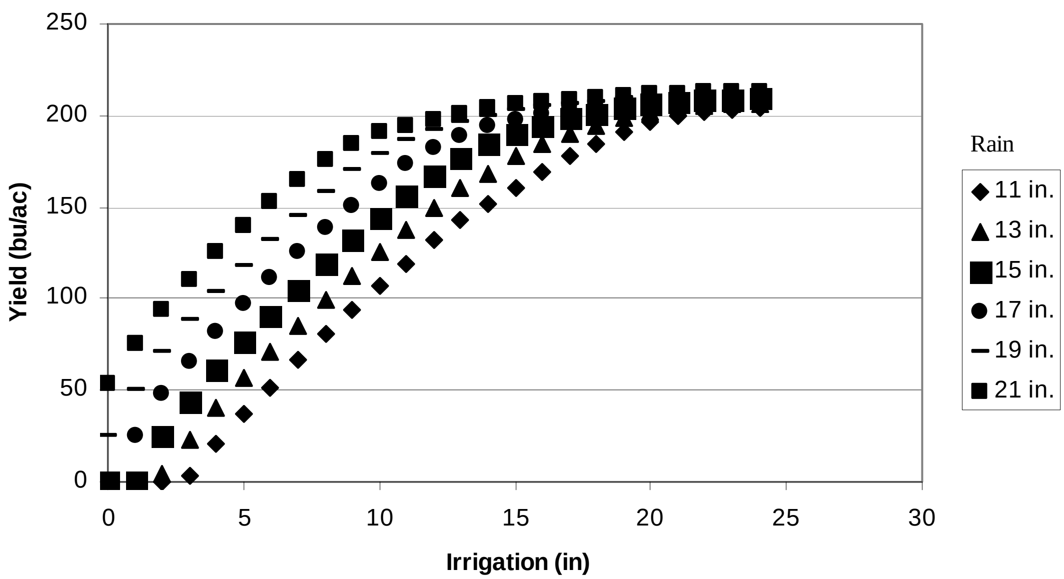


Figure 1. Yield-irrigation relationship for corn with annual rainfall from 11-21 in.

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 (www.agmanager.info/crops/) provided the basis for default production-cost values for CWA. Results can be sensitive to production costs, which require realistic production inputs.

TREND ANALYSIS

Reducing income risk is often an irrigator's motivation for switching crops as water availability declines. The Crop Water Allocator (CWA), in its present form, ranks alternative planting patterns based on mean income alone, without considering outcomes associated with changes in input variables. This risk arises from a variety of factors that are uncertain at the time of planting; the most important of these is weather conditions during the growing season. For example, although corn often generates the highest mean income, it is also likely to have a highly uncertain yield because its growth is sensitive to water stress during critical stages of the growing season. Adding trend analysis to CWA can project net returns over a range of input variables. Years with above normal, below normal and average rainfall can be simultaneously examined to find trends in net returns. The same methods can be used to project income trends for ranges of commodity prices, maximum yields, production costs, irrigation costs, and irrigation efficiency. Ranges of user input variables can be entered with ranges of net economic returns as the output. These results indicate the income risks when rainfall, irrigation costs, crop production costs, irrigation efficiencies, commodity prices, or crop maximum yields vary.

Trend analysis allows the user to find net returns over a range of possible inputs: rainfall, irrigation efficiency, commodity prices, maximum crop yields, irrigation costs, and crop production costs. For example, the program user may be interested in the response of net returns if annual precipitation varies from 13 to 21 inches and corn price ranges from $2 to $4/bu (tables 1 & 2). CWA executes a series of calculations over the range of irrigation costs, producing the corresponding range of net returns.

Two input ranges can be simultaneously processed in fixed trend analysis to find the influence of both inputs on net return.

Table 1. Net returns for $2 to $4/bu corn and 13-15 inches of annual precipitation.

	Annual Rainfall (inches)				
Crop Price - Corn ($/ bu.)	13	15	17	19	21
2	$-197 /ac	$-190 /ac	$-183 /ac	$-176/ac	$-172 /ac
3	$-76 /ac	$-50 /ac	$-25 /ac	$-4 /ac	$10 /ac
4	$46 /ac	$89 /ac	$132/ac	$168 /ac	$192 /ac
5	$168 /ac	$229 /ac	$289 /ac	$341 /ac	$375 /ac
6	$289 /ac	$369 /ac	$447 /ac	$513 /ac	$557 /ac

Table 2. Inputs for example in table 1.

Crop:	Corn
Acres:	130 acres
Gross Irrigation	12.0 inches
Total Production Costs:	$389/ac
Maximum Yield:	200 bu./ac
Irrigation Costs:	$94 /ac
Irrigation System Efficiency:	85%

ACKNOWLEDGEMENTS

This work was partly supported by the US Department of Interior, Kansas Water Resources Institute, and the USDA-ARS Ogallala Aquifer Research Initiative.

REFERENCES

Kansas State University. 2004. Crop Water Allocator (CWA): KSU Mobile Irrigation Lab. Available at: www.oznet.ksu.edu/mil .

.

Khan, A.H. 1996. KS Water Budget: Educational software for illustration of drainage, ET, and crop yield. Ph.D. diss. Kansas State Univ., Manhattan (Diss. Abstr. 96-29047).

Khan, A.H., L.R. Stone, O.H. Buller, A.J. Schlegel, M.C. Knapp, J.-I. Perng, H.L. Manges, and D.H. Rogers. 1996. Educational software for illustration of drainage, evapotranspiration, and crop yield. J. Nat. Resour. Life Sci. Educ. 25:170-174.

Stone, L.R., O.H. Buller, A.J. Schlegel, M.C. Knapp, J.-I. Perng, A.H. Khan, H.L. Manges, and D.H. Rogers. 1995. Description and use of KS Water Budget v. T1 software. Resource Manual, Department of Agronomy., Kansas State Univ., Manhattan, KS.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

IRRIGATION SCHEDULING USING KANSCHED FOR A RANGE OF WEATHER CONDITIONS

Danny H. Rogers
Professor and Extension Agricultural Engineer, Irrigation
Kansas State University Research and Extension
Department of Bio & Ag Engineering
Manhattan, KS
Voice: 785-532-5813, Email: drogers@ksu.edu

KanSched[1] is an irrigation scheduling software program developed to allow irrigation managers to use ET or crop water use information to schedule irrigation applications. ET information is available from a number of weather stations throughout Kansas. The ET information can be accessed by a variety of means including the web; such as the website of the Kansas State University Weather Data Library at www.oznet.ksu.edu/wdl.

Irrigation scheduling is a management practice to help irrigators determine when to irrigate and how much water to apply to meet crop water needs without waste of water. The scheduling concept is most often associated with irrigation systems with high irrigation capacities, meaning that water related water stress is unlikely to occur. Therefore, many irrigators discount the utility of irrigation scheduling because declining water levels have resulted in decreased well yield and therefore reduced irrigation capacity.

Irrigation capacity is the depth of water that the field would receive if entire field is watered in one day. It can be calculated as follows:

$$IC = \frac{GPM \times 24}{450 \text{ Acres}} \qquad \text{for 24 hour/day pumping}$$

GPM = gallons/minute
Acres = total irrigated acres in the field
450 gpm = 1 acre-inch/hour

As a general guideline, an irrigation capacity of at least 0.25 in/day would be considered high capacity for systems irrigating fields with high water holding capacity soils, like silt loams. Irrigated fields with sandy soils (low water holding capacity) need to have at least 0.30 inch/day to be considered high irrigation

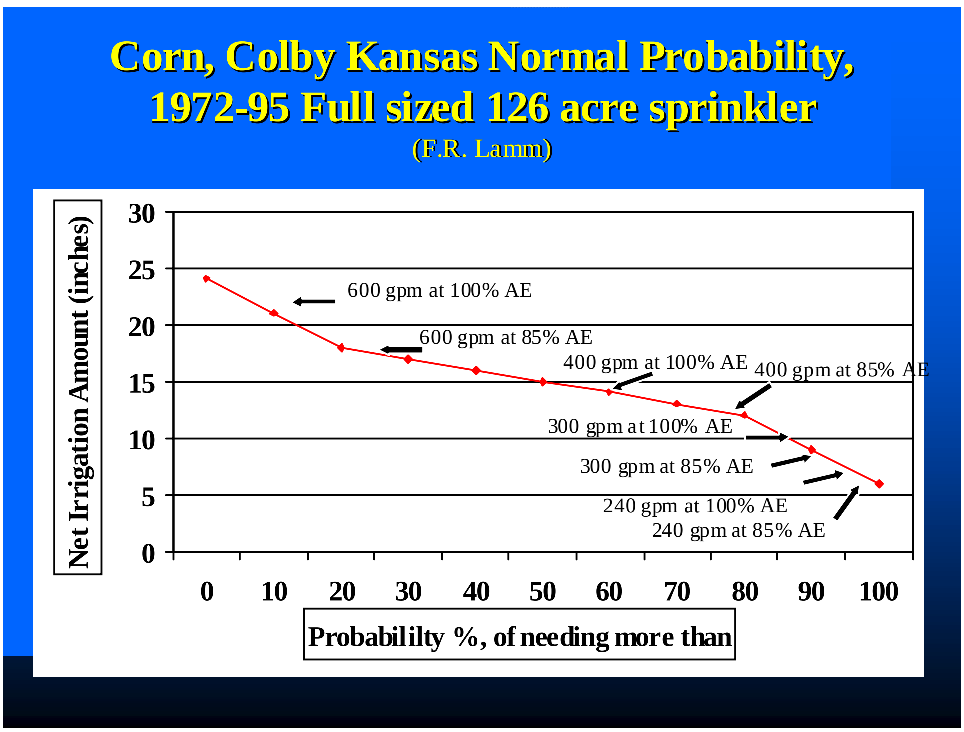
[1] KanSched is available for download for the Mobile Irrigation Lab (MIL) website at www.oznet.ksu.edu/mil or contact the author for a CD. The MIL program is supported in part by State Water Plan Funds through the Kansas Water Office.

capacity. Table 1 show the discharge rate requirement for various field sizes and efficiency values. Figure 1 shows the probability of various system capacities of meeting crop water needs for western Kansas conditions. This probability analysis also indicates lower capacity systems can meet full water needs of crops in some years, so irrigation scheduling could still benefit irrigators in determining when opportunities to save irrigation water occur.

Table 1. System flow rate required for various acreage and system efficiency

Irrigation Capacity	**1 acre**		**125 acre**	
	100% Eff	**85% Eff**	**100% Eff**	**85% Eff**
0.25 in/day	4.7 gpm	5.5 gpm	585 gpm	690 gpm
0.30 in/day	5.6 gpm	6.6 gpm	703 gpm	827 gpm

Figure 1. Effect of Irrigation Capacity on Irrigation System Reliablility.



To illustrate the use of ET-based irrigation scheduling, three years of ET and rainfall data were selected to use in KanSched and determine the irrigation schedule for two irrigation capacities (Figures 2-4). The years selected were 2002, representing high ET and low rainfall conditions; 1998, representing average or typical ET and average seasonal rainfall conditions; and 1986, representing low ET and high rainfall conditions. The data was collected at the

NW Research and Extension Center, Colby, KS. The ET and rainfall data were then mixed and matched to develop additional schedules to examine.

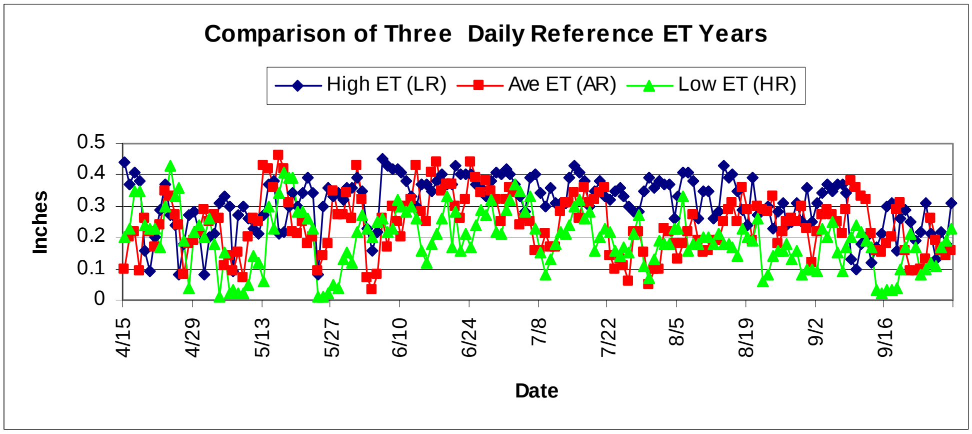


Figure 2. Daily Reference ET values for three example years.

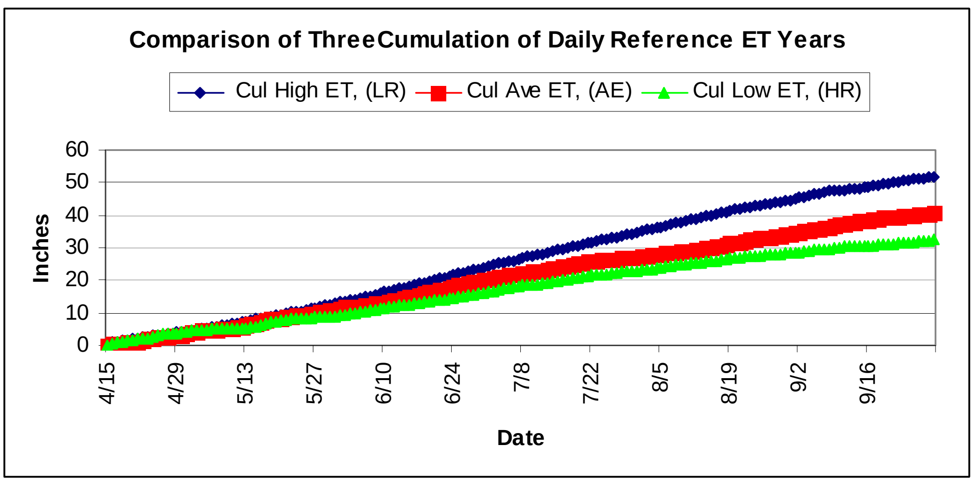


Figure 3. Cumulated Daily Reference ET values for three example years.

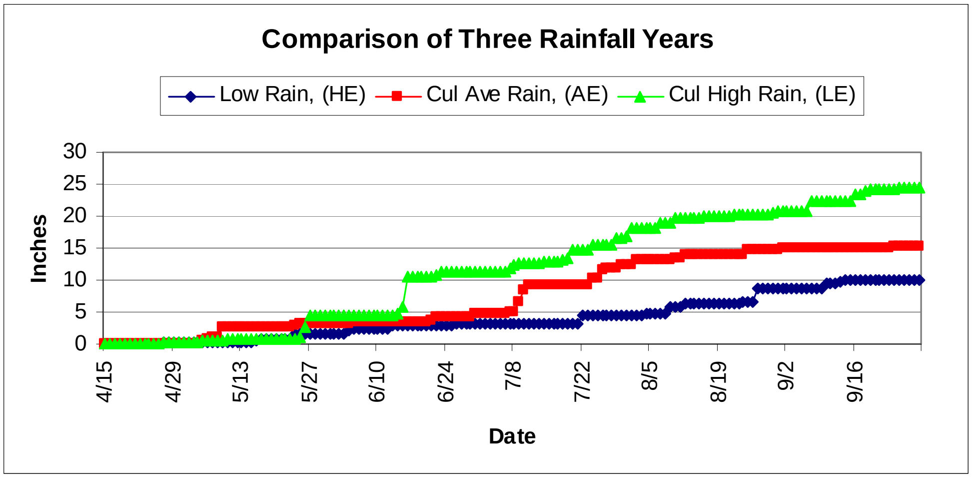


Figure 4. Cumulated rainfall events for three example years.

The test field established was for 118 day corn, emerging on May 1. Silt loam soil with a managed root zone of 42 inches was also used. The system efficiency was set at 85 percent. The irrigation capacity used was high capacity was set at 1 inch every four days (0.25 in/day) and low capacity of 1 inch every six days (0.17 in/day). Irrigation was initiated whenever the calculated root zone deficit reached one inch. Irrigation was terminated whenever the crop could reach physiologic maturity without exceeding the MAD (managed allowable deficit) of 50 percent.

The differences in the three base years are illustrated in Figures 2, 3 and 4. Figure 2 shows the daily ET plot, while Figure 3 shows the reference ET values accumulated for the period of April 15 through September 30. There is approximately 10 inches of difference between each year. Rainfall is shown in Figure 4. The low rainfall year occurred during the high ET year while the high rainfall year occurred during the low ET year.

Figure 5 shows a soil water chart for the average ET and rainfall year. Even though the rainfall for the year is near average for the season, notice the early season was dry while the later part of the season was wet. The high capacity irrigation system was easily able to maintain the soil water of the root zone above the 50 percent MAD level.

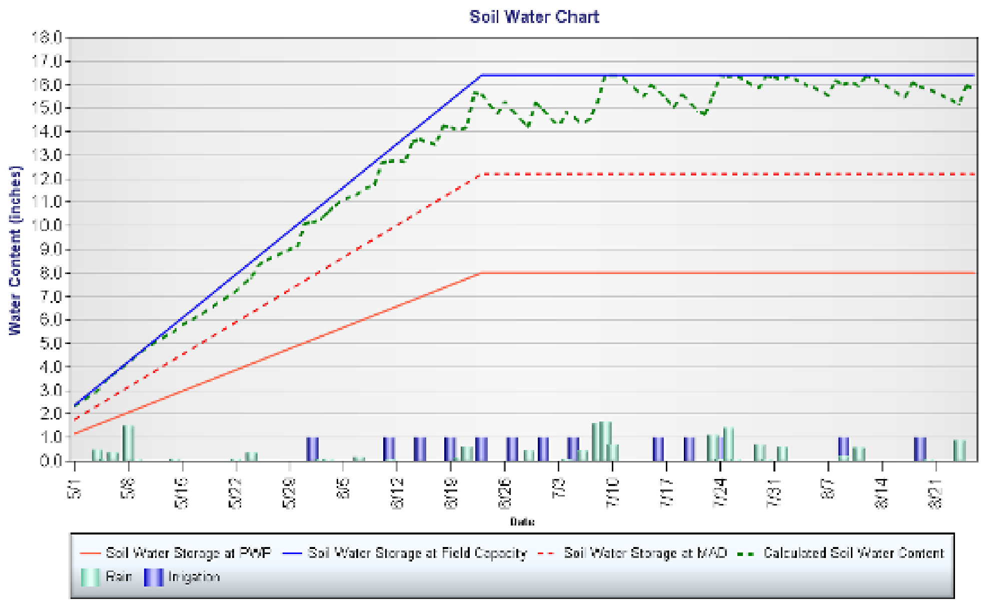


Figure 5. KanSched soil water chart for average ET and Rainfall (Field AR-AR-HC)

Tables 2, 3 and 4 show the results for the various ET years for the three rainfall years and low and high irrigation capacity.

For the high ET year (Table 2) with low rainfall, the high capacity system (Field HE-LR-HC) could not keep the root zone soil water above 50 percent MAD. For the low capacity irrigate rate, 57 days were below MAD. Many systems in western Kansas had water limiting yield stress when this year actually occurred. Notice that when high ET and high capacity were matched with average or high rainfall, no days below MAD were experienced, although the lower capacity system had some days below MAD. When the available soil water drops below MAD, crop ET begins to be suppressed and yield limited. Non crop water stress ET for the high ET year is 28.69 inches while the most stressed field (HE-LR-LC) had an ET of 23.47 inches.

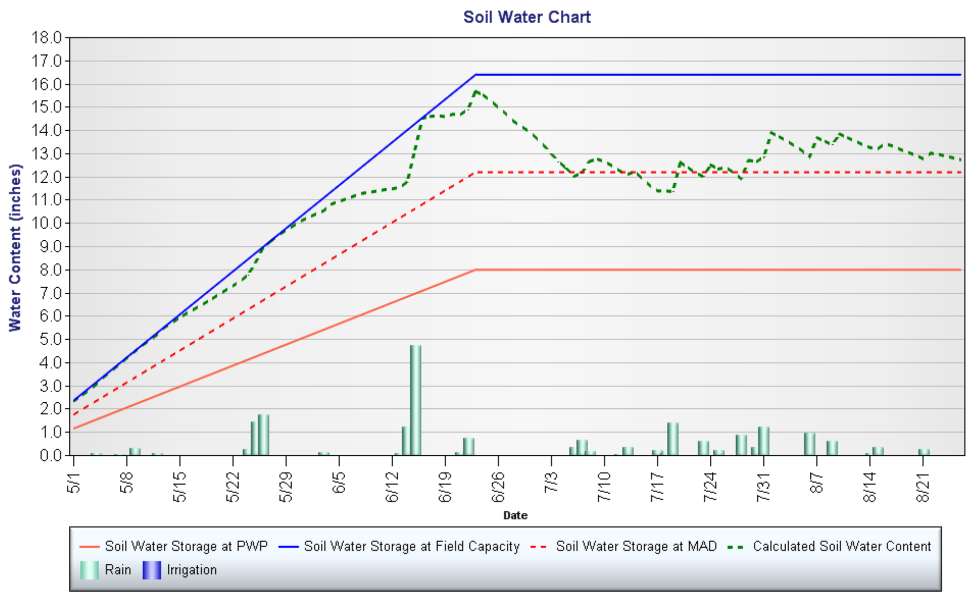


Figure 6. KanSched soil water chart for Low ET and High Rainfall with no irrigation. (Field LE-HR-NI)

Table 2. Summary of crop ET, effective rainfall, irrigation, and number of days when root zone soil water fell below 50 percent remaining for a high ET year.

Field	ET	Eff Rain	Gross Irr	Days < 50%
HE-LR-LC	23.47	8.36	14	57
HE-LR-HC	27.2	8.33	20	33
HE-AR-LC	28.35	12.71	14	8
HE-AR-HC	28.69	12.71	18	0
HE-HR-LC	28.55	13.29	14	6
HE-HR-HC	28.69	12.81	17	0

Table 3. Summary of crop ET, effective rainfall, irrigation, and number of days of root zone soil water fell below 50 percent remaining for an average ET year.

Field	ET	Eff Rain	Gross Irr	Days < 50%
AE-LR-LC	20.55	7.94	13	14
AE-LR-HC	21.13	6.62	17	0
AE-AR-LC	21.13	11.9	10	0
AE-AR-HC	21.13	8.5	14	0
AE-HR-LC	21.13	11.37	9	0
AE-HR-HC	21.13	10.52	10	0
AE-HR-LC	21.13	11.37	9	0

Table 4. Summary of crop ET, effective rainfall, irrigation, and number of days of root zone soil water fell below 50 percent remaining for a low ET year.

Field	ET	Eff Rain	Gross Irr	Days < 50%
LE-LR-LC	17.4	7.16	12	0
LE-LR-HC	17.4	7.16	12	0
LE-AR-LC	17.4	9.35	9	0
LE-AR-HC	17.4	8.08	10	0
LE-HR-LC	17.4	9.36	8	0
LE-HR-HC	17.4	8.51	9	0
LE-HR-NI	17.2	13.43	0	11

Table 3 shows the results of schedules for the average ET year. Only for the low capacity, low rainfall year did the available soil water drop below MAD. For the actual year of average ET and average rain, both high and low irrigation capacity met crop water needs.

For the low ET year, both high and low capacity was able to meet crop water needs for all rainfall years. The low ET, high rainfall year soil water chart is shown in Figure 3 and indicates that rainfall alone was nearly able to maintain MAD. Table 4 and Figure 6 show the results for field LE-HR-NI (NI = No irrigation) and indicates only 11 days below MAD occurred for the year with rainfall only. The full ET for the low ET year is 17.4 inches, only slight stress occurred with the rainfall only as the ET was 17.2 inches.

Table 5 shows the results of the three ET years combined with each rainfall year for high capacity irrigation. In this case, irrigation was to be initiated when 75 percent available soil water was reached, instead of the one inch depletion criteria. This would allow more room for rainfall storage in the soil root zone. In two cases, the strategy increased the number of days below MAD. For field HE-LR-HC, the days increased from 33 to 38; ET changed from 27.2 to 26.81 inches. The other is AE-LR-HC where two days of below MAD occurred with the improved strategy, however, ET only dropped from 21.13 to 21.11 inches. However, in all cases, gross irrigation was reduced from 1 to 4 inches. Effective rainfall, the amount of rain that could be stored in the root zone, increased in all cases except one.

Table 5. Summary of crop ET, effective rainfall, irrigation, and number of days when root zone soil water fell below 50 percent remaining for a high ET year when irrigation is initiated at a 75 percent root zone soil water contact.

Field	ET	Eff Rain	Gross Irr	Days < 50%
HE-LR-HC-I	26.81	8.36	19	38
HE-AR-HC-I	28.69	12.71	16	0
HE-HR-HC-I	28.69	14.14	14	0
AE-LR-HC-I	21.11	8.19	14	2
AE-AR-HC-I	21.13	14.78	10	0
AE-HR-HC-I	21.13	13.07	7	0
LE-LR-HC-I	17.4	7.87	11	0
LE-AR-HC-I	17.4	9.78	7	0
LE-HR-HC-I	17.4	11.85	5	0

Summary

ET-based irrigation scheduling has been effectively used by many irrigation managers, although some producers with low irrigation capacity systems feel its utility is limited. However, the examples in this presentation, illustrates that even low capacity systems can use ET-based scheduling to determine the irrigation application timing, including when to begin irrigation (sufficient root zone deficient to hold the applied depth) and when to end irrigation. In the selected years used for this analysis, rainfall at times can be sufficient to meet crop water needs without irrigation, indicating ET-based scheduling can be used effectively even for systems with limited irrigation capacity.

WATER SAVINGS FROM CROP RESIDUE MANAGEMENT

Norman L. Klocke, Water Resources Engineer
Randall S. Currie, Weed Scientist
Troy J. Dumler, Extension Economist
Kansas State University, SWREC, Garden City, KS
Email:nklocke@ksu.edu

INTRODUCTION

Corn growers who irrigate in the Great Plains face restrictions in water, either from lower well capacities or from water allocations, and/or rising energy costs. They need water management practices to maximize grain production. When there is not enough water available to produce full yields, the goal for water management is to maximize transpiration and minimize non-essential water losses. One avenue for reducing non-essential water use is to minimize soil water evaporation.

Evapotranspiration is the combination of a two processes, transpiration and soil water evaporation. Transpiration, water consumed by the crop, is essential for the plants and correlates directly with grain production. Non-productive soil water evaporation has little utility. Soil water evaporation rates from bare soil are controlled by two factors. When the soil surface is wet, atmospheric energy that reaches the ground drives evaporation rates (energy limited phase). As the surface dries, evaporation rates are limited by the movement of water in the soil to the surface. In sprinkler irrigation during the growing season, most of the evaporation results from the energy limited process because of frequent soil wetting. Crop residues insulate the surface from energy limited evaporation.

Crop residues which are left in the field have value for soil and water conservation during the following non-growing season and the growing season of the next crop. Crop residues that are removed from the field after harvest are gaining value for livestock rations, livestock bedding, and as a source of cellulous for ethanol production. The water conservation value of crop residues needs to be quantified so that crop producers can evaluate whether or not to sell the residues or keep them on their fields. Reducing soil water evaporation in sprinkler management is one of the values of crop residues. This project was designed to measure soil water evaporation with and without a growing corn crop.

For presentation at the Central Plains Irrigation Conference, Colby, KS, February 24-25, 2009. Reprinted from 2008 CPIA meeting, Greeley, CO.

OBJECTIVES

1. Determine the water savings value of crop residues in irrigated corn.
2. Measure soil water evaporation beneath crop canopy of fully and limited irrigated corn.
   a. From bare soil.
   b. From soil covered with no-till corn residue.
   c. From soil covered with standing wheat residue.
3. Calculate the contribution of evaporation to evapotranspiration.
4. Quantify soil water evaporation from partially covered soil with no crop canopy.
5. Predict potential economic savings from reducing evaporation with residues.

METHODS

Soil water evaporation was measured beneath a growing corn crop during the summers of 2004, 2005, and 2006 at Kansas State University's Research and Extension Center near Garden City, Kansas. The soil at the research site was a Ulysses silt loam. Mini-lysimeters were used for the primary evaporation measurement tool. They contained undisturbed soil cores 12 inches in diameter and 5.5 inches deep. The soil cores were extracted by pressing PVC tubing into the soil with a custom designed steel bit. The PVC tubing became the sidewalls for the mini-lysimeters. The bottom of the cores were sealed with galvanized discs and caulking. Therefore, water could only escape from the soil by surface evaporation, which could be derived from daily weight changes of the mini-lysimeters. Weighing precision produced evaporation measurements with a resolution of $\pm$ 0.002 in/day.

Volumetric soil water content was measured bi-weekly in the field plots to a depth of 8 ft in 1 ft increments with neutron attenuation techniques. The change in soil water, form the start to the end of the sampling period, plus measurements of rainfall and net irrigation were the components of a water balance to estimate crop evapotranspiration (ETc).

Measurements of crop residue coverage on the soil surface were adapted from line transect techniques. A coarse screen was laid over a mini-lysimeter. Observations of the presence or absence of residue were recorded for each intersection of screen material. The fraction of the presence of residue and total observations was converted into a percentage of coverage.

Four replications of bare, corn stover, or wheat stubble surface treatments were placed in high and low frequency irrigation treatments. High frequency irrigation was managed to meet atmospheric demand for full crop evapotranspiration (ETc). The low frequency irrigation treatment received approximately half this amount in half the irrigation events.

An additional experiment was conducted to find the soil water evaporation rates from soil surfaces that were partially covered with crop residues. A controlled area was established for the experiment where the mini-lysimeters were buried in PVC sleeves at ground level, arranged adjacent to one another in a geometric pattern. Movable shelters were available to cover the mini-lysimeters during rain events but were open during other times. There was no crop canopy over the mini-lysimeters, which were surrounded by mowed, irrigated grass. The mini-lysimeters were weighed daily. Two irrigation treatments, that approximated the companion field study, were watered with 1 or 2 per hand irrigations per week. Partial surface cover treatments had 25%, 50%, and 75% of the surface covered with corn stover which was placed on the mini-lysimeters. Mini-lysimeters with 100% coverage from corn stover and 85% coverage with standing wheat stubble were the same configuration as the field experiment. Evaporation results were normalized with reference ET (ETr) which was calculated with on-site weather factors and an alfalfa referenced ETr model (Kincaid and Heermann, 1984).

RESULTS

Within Canopy Field Results

Soil surface cover on the mini-lysimeters was measured at the start of the growing season. Corn stover and standing wheat stubble completely covered the mini-lysimeters in 2004 (table 1). Corn stover continued to completely cover the mini-lysimeters in 2005 and 2006, but the wheat stubble coverage was 91-92% in those years. The 2004 and 2005 wheat crops were shorter in stature due to less fall growth. This led to less wheat stubble coverage of the mini-lysimeters during the following year.

Table 1. Crop residue percentage cover at the end of the growing season for mini-lysimeters in corn field plots during 2004-2006 near Garden City, Kansas.

Crop Residue Cover	Dry Matter tons/ac	Residue Coverage* %
	-------------------2004-------------	
Bare	0.0	0
Corn	7.3	97
Wheat	9.8	98
	-------------------2005-------------	
Bare	0.0	0
Corn	9.5	100
Wheat	6.3	91
	-------------------2006-------------	
Bare	0	0
Corn	7.5	100
Wheat	4.3	92

*Percentage of soil surface covered by residue, determined by the modified line transect method.

When data from all years and water frequency treatments were combined, the effects of surface treatments could be isolated. Average soil water evaporation (Avg E) from the bare surface treatment was significantly more than Avg E from the two residue covered treatments (table 2). Wheat stubble surface coverage was than corn stover coverage in 2005 and 2006, resulting in more E with wheat stubble. Daily average ETc and ETr data were the same over all mini-lysimeters since the annual data was averaged over all irrigation treatments. Bare soil E for the Ulysses silt loam was 30% of ETc, which was the same result as a study with Valentine fine sandy soils in west-central Nebraska (Klocke et al., 1985). E as a ratio of ETc or ETr showed that crop residues reduced E by 50% compared with bare soil. A similar study with silt loam soils in west-central Nebraska showed that bare soil E under a corn canopy during the growing season could be reduced from 0.07 inches/day to 0.03 inches/day by adding a mulch of wheat stubble lying flat on the surface with 100% surface coverage (Todd et al., 1991).

Differences in E between bare soil and residue treatments, which were 0.02-0.03 inch per day, may seem small; however, if these daily differences were extrapolated over a 110 day growing season, total differences in E would be 2.2-3.3 inches. Similarly, E as a fraction of ETc was 0.30 for bare soil and 0.15-0.16 for the residue cover treatments. Growing season ETc values for corn can be 24-26 inches in western Kansas. Using the values of E as a fraction of ETc (table 2), potential water savings could be 3.7-4.0 inches with full soil surface coverage.

Table 2. Average soil water evaporation and evaporation as a ratio of crop evapotranspiration (ETc) and reference ET (ETr) for all bare soil and crop residue covered treatments under a corn crop canopy during 2004-2006 in Garden City, KS.

Surface Cover	Avg E in/day	ETc in/day	E/ETc*	ETr in/day	E/ETr
Bare	0.06a	0.23	0.30a	0.27	0.22a
Corn Stover	0.03c	0.23	0.15c	0.27	0.11c
Wheat Straw	0.04b	0.23	0.16b	0.27	0.12b
$LSD_{.05}$**	0.003		0.02		0.05

Means with same letters in the same columns are not significantly different for alpha=.05.

The influence of crop canopy shading canopy on soil water evaporation rates was observed by averaging data over years, surface cover treatments, and irrigation frequency treatments (table 3). Evaporation decreased as crop canopy and ground shading increased. The trend reversed as the crop matured and shading decreased. Concurrently, crop ET and reference ET increased from planting through mid-season and then decreased through the rest of the growing season. The ratio of Avg E to ETc and ETr declined during the growing season when the two factors were combined.

Table 3. Soil water evaporation (Avg E) and evaporation as a ratio of crop ET (ETc) and reference ET (ETr) during the growth stages of corn for all mini-lysimeter treatments during the 2004-2006 growing seasons at Garden City, KS.

Growth Stage	Avg Days In Growth Stage	Avg E	ETc	E/ETc	ETr	E/ETr
		in/day	in/day		in/day	in/day
Vegetative	28	0.06a	0.22b	0.27a	0.35	0.17a
Pollination	18	0.05b	0.27a	0.20b	0.33	0.15b
Seed Fill	30	0.03c	0.20c	0.15c	0.25	0.12c
$LSD_{.05}$		0.002	0.02	0.02		0.05

Means with same letters in the same columns for the same year are not significantly different for alpha = 0.05.

Partial Cover Results from Control Area

Even though average daily evaporation rates among the bare and 25%, 50%, and 75% residue covered treatments could be measured and were significantly different from one another, the magnitudes of these differences were small (table 4a). The 100% covered treatment with corn stover and the standing wheat stubble with 85% cover produced significantly less E than the other treatments. Lateral heat flow from the bare portion of the partially covered surface could have caused increased surface temperatures under the corn stover. Similarly, soil water could move from under partially covered surface to the bare portion of the surface, increasing E (Chung and Horton, 1987).

Crop residues that were distributed across the surface, needed to cover more than 75-80% to have an effect in reducing E when there was no crop canopy. Nearly complete surface coverage influenced E nearly the same with and without crop canopy.

Table 4. Soil water evaporation during Spring and Fall 2005 and Fall 2006 for full and partial crop residue surface covers at Garden City, Kansas.

a. Surface Cover	Avg E --in/day--	E/ETr*
Bare 0%	0.08a	0.26a
Corn 25%**	0.07b	0.25b
Corn 50%	0.07c	0.24c
Corn 75%	0.07a	0.26a
Corn 100%	0.04e	0.14e
Wheat 85%	0.05d	0.18d
$LSD_{.05}$	0.002	0.005

Means with same letters in the same columns for the same variable are not significantly different at alpha = 0.05.

ECONOMIC IMPACT

Crop residues can also have an effect on non-growing season. A field study in eastern Colorado during 0ctober-April of the years 2000-2004 showed that corn residues increased stored soil water by 2 inches when compared with conventional stubble mulch tillage in dryland management (Neilson, 2006). Dryland studies in Nebraska have demonstrated that wheat stubble increased non-growing season soil water storage by 2-2.5 inches when compared with bare soil (Klein, 2007).

The water savings from crop residues can have one of three impacts on income. First, if irrigation is applied in excess of water requirements of the crop in a no-till system, there could be no economic benefits from the crop residues. The excess water could leach past the root zone with no value to crop production. Second, if water supplies are adequate to grow a fully irrigated crop, pumping costs can be reduced by the difference between tilled and no-till management. Irrigators in this situation need to monitor soil water during the growing season to find the reduction in irrigation needed from crop residue management and time irrigations accordingly. Third, if the irrigation system cannot keep up with crop water requirements, the crop may be under water stress all or part of the growing season. Water savings from crop residues in no-till management can be transferred from bare soil evaporation losses to water that can be used by the crop (transpiration) for better yield returns. In this case there would be no change in irrigation pumping.

Irrigation requirements and production costs vary from year-to-year and from one irrigator to another. Commodity prices also vary from year-to-year. As demonstrated in this study, nearly full coverage of the soil surface was needed to reduce soil water evaporation and reap benefits from the crop residues. The following is one example of economic impacts on income for irrigated corn where growing season and non-growing season crop residue management combines for saving 3-5 inches of water annually:

<u>Situation 1</u>. Irrigation applications in excess of crop needs can lead to soil water leaching below the root zone and there are no benefits from the crop residues.

<u>Situation 2</u>. Irrigation requirements are reduced for a fully irrigated crop from crop residue management where pumping is reduced to account for less irrigation needs.

Pumping costs = $9 per acre for each inch pumped
Total savings for 3-5 inches less water pumped = $27-45 per acre

<u>Situation 3</u>. The irrigation system cannot provide enough water to meet the full water requirements of the crop. Three to five inches of water savings from crop residue management could shift soil water evaporation to transpiration. Corn

yields increase 12 bushels per acre for each inch of water that is transferred from evaporation to transpiration. When corn price is $4.50 per bushel, 3-5 inches of water savings from reduced evaporation would produce $162-$270 per acre additional income.

Additional growing and non-growing season benefits from crop residues include capturing precipitation, enhancing infiltration, reducing runoff, and reducing soil erosion. All of these benefits have economic value for crop production and land values, but they are more difficult to measure than direct water conservation effects of crop residue management.

ACKNOWLEDGEMENTS

Partial funding for this research was furnished by: the USDA-ARS Ogallala Aquifer Project and the US Department of Interior.

REFERENCES

Chung, S., and R. Horton.1987. Soil heat and water flow with a partial surface mulch. Water Res. Res. 23(12):2175-2186.

Kincaid, D.C., and D.F. Heermann. 1984. Scheduling irrigation using a programmable calculator. NC-12. Washington, D.C.:USDA-ARS.

Klocke, N.L., D.F. Heermann, and H.R. Duke. 1985. Measurement of evaporation and transpiration with lysimeters. Trans. of the ASAE. 28:1:183-189 & 192.

Klein, R.N. 2008. Improving you success in no-till. In Cover Your Acres Proceedings. Kansas State Research and Extension. Jan. 23-23, 2008. Oberlin, KS. p. 22-26.

Neilsen, D.C. 2006. Crop residue and soil water. In Central Plains Irrigation Conference & Exposition Proceedings. Feb. 21-22, 2006. Colby, KS. p. 136-139.

Todd, R.W., N.L. Klocke, G.W. Hergert and A.M. Parkhurst. 1991. Evaporation from soil influenced by crop shading, crop residue and wetting regime. Trans. of the ASAE. 34:2:461-466.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

CORN AND GRAIN SORGHUM PRODUCTION WITH LIMITED IRRIGATION

Norman Klocke, Water Resources Engineer
Randall Currie, Weed Scientist
Kansas State University, SWREC, Garden City, KS
Email: nklocke@ksu.edu

INTRODUCTION

Soil water management during the growing and non-growing season can be enhanced with crop residues. Capture and retention of soil water plus irrigation at critical growth stages can maximize limited irrigation resources. This research quantified the water use and irrigation requirements of corn and grain sorghum grown with optimum water management using water conservation techniques. Corn grain and forage yields declined with less than full irrigation, but sorghum grain and forage yields remained nearly constant. Net economic returns increased as more irrigation was applied to corn, but decreased with additional irrigation on sorghum. When irrigation was reduced in corn and sorghum production, there was less impact on grain and forage yield from the same proportional decrease in irrigation. For example, a 50% reduction in full irrigation caused a 20% reduction in corn grain yields. Sorghum grain yields were reduced by 8% with a 72% reduction in irrigation. However, net economic return from corn production increased at the same rate with additional irrigation. Additional irrigation decreased annual net returns from sorghum production. Irrigators, responding to economic returns form their irrigation practices, would tend to fully irrigate corn and reduce irrigation for sorghum.

OBJECTIVES

The overall goal of the project was to conduct cropping systems field research with the emphasis on crop yield response to full and limited irrigation. The objectives were to:

1. Measure grain and forage production of corn and grain sorghum with deficit irrigation and no-till management.
2. Measure grain yield and irrigation to develop production functions for corn and grain sorghum in no-till management with irrigation inputs from 2 to 3 inches to full irrigation.
3. Determine soil water during the growing-season and non-growing season to assess the impacts irrigation on soil water storage and use.
4. Find the net economic returns of corn and grain sorghum receiving irrigation from deficit to fully irrigated management.

METHODS

The cropping systems project was located at the Kansas State University's Southwest Research-Extension Center near Garden City, KS. Deficit irrigation strategies and no-till management strategies were used to test crop responses to limited water supplies. The experimental field was subdivided into strips, oriented east to west, that were irrigated by a 4-span linear move sprinkler irrigation system. Six irrigation treatments, replicated four times, ranged from 3 to 12 inches for corn and 2 to 8 inches for sorghum. If rainfall was sufficient to fill the soil profile to field capacity, irrigation was not applied. Irrigation treatments were the same for each plot from year to year so the antecedent soil water carried over to the next year. The days between irrigation events increased as irrigation decreased (table 1). The same net irrigation (1 inch) was applied for each irrigation event. Soil water was measured once every two weeks with the neutron attenuation method in increments of 12 inches to a depth of 8 feet. These measurements along with effective precipitation (no runoff), net irrigation, and soil water use were used to calculate evapotranspiration for each two-week period during the season. Ending season and beginning season soil water measurements were used to calculate soil water accumulations during the non-growing season and soil water use during the growing season. The soil was a Ulysses silt loam with an available water capacity of 2 inches/ft and volumetric water contents of 33% at field capacity and 17% at permanent wilting. Cultural practices, including hybrid selection, no-till planting techniques, fertilizer applications, weed control, were the same across irrigation treatments. Yield-irrigation relationships were used with current commodity price and crop production costs to determine net economic returns from corn and sorghum crops across irrigation treatments.

Table 1. Days between irrigation events for irrigation treatments.

Irrigation Treatment	Corn Days	Sorghum Days
1 High	4.5	4.9
2	5.5	5.6
3	6.0	6.3
4	8.3	11.1
5	10.8	13.2
Low 6	13.8	15.7

RESULTS AND DISCUSSION

Relative yields were calculated as the ratio of irrigation treatment yields and fully irrigated yields for corn and sorghum (table 2). Relative yield results were expressed as percentages of yields for the fully irrigated treatment. In the same fashion, relative irrigation was calculated as the ratio of irrigation amount of each treatment and the fully irrigated treatment. For example, the corn treatment that received 9 inches of water produced 92% of the yield of fully irrigated treatment with 74% of the irrigation. Corn grain yields decreased at a decreasing rate as irrigation was reduced. Sorghum yields from the driest irrigation treatment produced only 5 bu/acre less that the fully irrigated treatment. The driest irrigation treatment produced 96% of full yield with 28% of the water.

Table 2. Average grain yields, relative grain yields, irrigation, and relative irrigation for corn after corn and sorghum after wheat for 2004-2007.

Corn after corn 2004-2007				Sorghum after Wheat 2004-07			
Average Yield	Relative Yield	Annual Irrigation	Relative Irrigation	Average Yield	Relative Yield	Average Irrigation	Relative Irrigation
bu/ac	%	inches	%	bu/ac	%	inches	
205	100	12	100	122	100	7	100
199	99	10	85	125	100	6	86
185	92	9	74	124	100	5	72
163	81	6	52	117	100	4	48
141	70	5	39	117	96	3	34
119	59	3	29	117	96	2	28

Results for forage yields from corn and sorghum mimicked grain yields (table 3). Corn was planted at rates for predicted yield potential from each irrigation treatment, which were 19,500 plants/ac for the driest treatment to 32,000 plants/ac for the driest treatment. Sorghum was planted with 107,000 plants/ac for all irrigation treatments.

Table 3. Average forage yields (dry matter) and relative forage yields for corn after corn and sorghum after wheat for 2004-2007.

Corn after corn 2004-2007				Sorghum after Wheat 2004-07			
Average Yield	Relative Yield	Annual Irrigation	Relative Irrigation	Average Yield	Relative Yield	Average Irrigation	Relative Irrigation
T/ac	%	inches	%	T/ac	%	inches	
9.6	100	12	100	7.6	100	7	100
8.2	85	10	85	7.2	98	6	86
7.9	82	9	74	7.5	96	5	72
5.7	59	6	52	6.8	90	4	48
6.2	64	5	39	7.5	92	3	34
5.7	61	3	29	6.7	92	2	28

Results in tables 2 and 3 are four-year averages for each irrigation treatment. Variation in crop yields from year-to-year is important to evaluate income risk. Data for each irrigation treatment each year of the study are in figures 1 & 2. Regression of corn relative yields (the line in figure 1) show decreasing yields as irrigation decreased, but sorghum relative yields remained constant. The distance of the data points from the trend line indicates the variation in yields from year-to-year. Corn yield variation increased for less than 10 inches of irrigation. Variation in sorghum yields remained constant from the most to least irrigation. Yield variation can influence crop rotation choices.

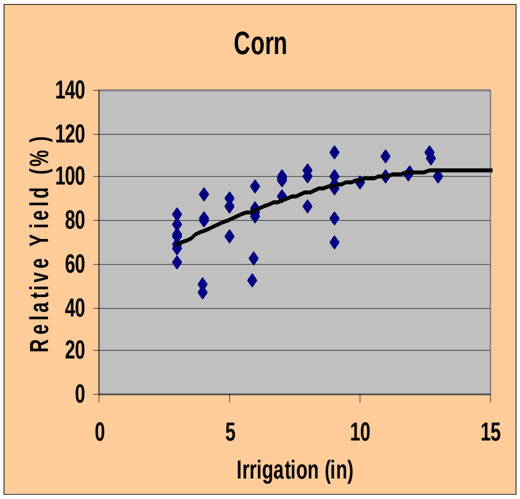


Fig. 1. Trend and variation in relative yields for corn.

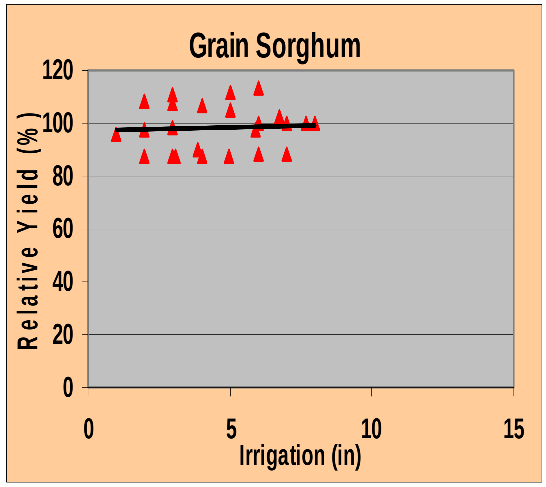


Fig. 2 Trend and variation in relative yields for sorghum.

Cropping season evapotranspiration (ETc) was calculated from the summation of net irrigation (water that infiltrated) effective precipitation (no observed runoff), and the stored soil water used during the growing season. Corn ETc (table 4) was from 25.5 the wettest irrigation treatment to 19 inches for the driest treatment for a difference of 6.5 inches. Productivity was calculated as the ratio of grain yields and ETc. Corn yields decreased relatively more than ET causing productivity to decrease with less irrigation. Plant population may have decreased potential yields for the drier treatment in 2004, which had above normal growing season precipitation. Sorghum ET (table 5) was 24.2 to 20.8 inches. Field observation and forage yields showed that the wetter treatments developed more dry matter, but the uniform plant populations did not restrict yield potential in the drier plots. Sorghum productivity increased with less irrigation causing better use of available water for grain production.

Table 4. Cropping season ETc, yield, and productivity for corn.

Irrigation	SW Use	Rainfall	ET	Yield	Productivity
Inches	inches	inches	inches	bu/ac	bu/ac-in
12	1.8	11.7	25.5	205	8.0
10	2.3	11.7	24.0	199	8.3
8	3.2	11.7	22.9	185	8.1
6	2.9	11.7	20.6	163	7.9
4.5	3.9	11.7	20.1	141	7.0
3	4.3	11.7	19.0	119	6.3

Soil water accumulated during the non-growing season and some of this water was used as component of ETc during the following growing season (table 6). As irrigation decreased, the crop developed roots deeper into the soil and extracted more soil water creating more room to store water during the following non-growing season (data not shown). There was a correspondence between

Table 5. Cropping season ETc, yield, and productivity for sorghum.

Irrigation inches	SW Use inches	Rainfall Inches	ET inches	Yield bu/ac	Productivity bu/ac-in
8	4.3	11.9	24.2	122	5.0
6.7	4.7	11.9	23.3	125	5.4
5.3	5.5	11.9	22.7	124	5.4
4	5.8	11.9	21.7	117	5.4
3	6.3	11.9	21.2	117	5.5
2	6.9	11.9	20.8	117	5.6

water stored and water used during the following season. More water soil water use followed more water storage. More water accumulated prior to sorghum than corn because soil water extraction was deeper into the soil in the sorghum crop.

Table 6. Stored soil water (SW) gains during the previous non-growing season and stored soil water use during the growing season for corn following corn and sorghum following wheat.

Irrigation Corn inches	SW Gain Corn inches		SW Use Corn inches		Irrigation Sorghum inches	SW Gain Sorghum inches		SW Use Sorghum inches	
12	3.3	b	1.8	d	8	6.8	bc	4.3	d
10	4.9	ab	2.3	cd	6.7	6.4	c	4.7	d
8	4.9	ab	3.2	ab	5.3	7.5	ab	5.5	c
6	5.9	a	2.9	abc	4	7.8	ab	5.8	bc
4.5	5.7	a	3.9	ab	3	8.0	a	6.3	b
3	6.0	a	4.3	a	2	7.9	a	6.9	a
$LSD_{0.05}$	1.7		1.1			1.1		0.5	

Fallow efficiency was calculated as the ratio of stored soil water and precipitation during the non-growing season (table 7). The time between wheat harvest and sorghum emergence was almost 11 months, but 7 months elapsed between corn harvest and emergence of the next corn crop. Soil water accumulations nearer to the time of use were more effective than early water storage. There was more time to store water in the wheat stubble that preceded sorghum planting, which refilled more of the soil profile, but there was more time for drainage. The small difference in stored soil water between the wettest irrigation treatment and the driest treatment was 1.1 inches, probably contributed to smaller differences in sorghum grain yields.

Yield results from the field study and crop prices were used to calculate gross income for corn sorghum (tables 8 & 9). Net income was calculated as the difference in gross income and production costs including irrigation costs. These commodity prices and production costs can vary over time and from one producer to the next. In this example corn could be planted on the entire field or

Table 7. Non-growing season fallow efficiency and drainage.

--Fallow Efficiency		---ET + Drainage--		---------Drainage-----	
Corn	Sorghum	Corn	Sorghum	Corn	Sorghum
%	%	inches	inches	inches	inches
33	32	6.7	14.2	3.7	7.2
49	30	5.1	14.6	2.1	7.6
49	36	5.1	13.5	2.1	6.5
59	37	4.1	13.2	1.1	6.2
57	38	4.3	13	1.3	6.0
60	38	4.0	13	1.0	6.0

or planted on half the field and rotated with sorghum. Irrigation pumping capacity can limit the irrigation amount that can be delivered to the crop. If 9 inches of irrigation were available during the growing season, the net return would be approximately $280/ac or $36,400 for a 130 ac field. If corn was rotated with sorghum and 12 in of irrigation were applied to corn, the net return would be $350/ac for corn. Sorghum would receive 6 inches of water for a net return of $125/ac. The combined net return for 130 acres would be $30,800. The difference in net return between continuous corn and the rotation is not the only consideration. Income variability from one year to the next would be less for the rotation because the corn yield would be less variable.

Table 8. Net returns (gross income – production costs) for corn after corn.

Net Irrigation	Corn Price	Grain Yield	Gross Income	Irrigation Cost	Production Costs*	Net Return
inches	$/bu	Bu/ac	$/ac	$/ac-in	$/ac	$/ac
11.5	4	205	820	9	471	349
9.8	4	199	796	9	507	289
8.5	4	185	740	9	474	266
6	4	163	652	9	427	225
4.5	4	141	564	9	380	185
3.3	4	119	476	9	344	132

Table 9. Net returns (gross income – production costs) for irrigated sorghum.

Net Irrigation	Sorghum Price	Grain Yield	Gross Income	Irrigation Cost	Production Costs*	Net Return
inches	$/bu	bu/ac	$/ac	$/ac-in	$/ac	$/ac
7.3	3.5	119	416	9	301	115
6.3	3.5	116	406	9	286	120
5.3	3.5	114	400	9	270	131
3.5	3.5	107	376	9	253	123
2.5	3.5	109	382	9	246	136
2.0	3.5	109	381	9	235	146

*Includes Irrigation costs

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

ARE OTHER CROPS BETTER THAN CORN UNDER LIMITED IRRIGATION?

Alan Schlegel, Agronomist
Loyd Stone, Soil Physicist
Troy Dumler, Extension Economist
Kansas State University
SWREC-Tribune, KS
Voice: 620-376-4761 Fax: 620-376-2278
Email:schlegel@ksu.edu

ABSTRACT

Research was initiated under sprinkler irrigation to compare limited irrigation of corn with three other summer crops (grain sorghum, soybean, and sunflower) grown under no-till practices. Corn responded the most to increased irrigation. Because of changes in growing conditions, the crop that is most profitable changes from year-to-year. Growing different crops when irrigation is limited can reduce risk and increase profitability. Averaged across the past 8 years, corn has been the most profitable crop at higher irrigation amounts, while at the lowest irrigation level, profitability was similar for all crops.

INTRODUCTION

Most groundwater pumped from the High Plains (Ogallala) Aquifer in western Kansas is used for irrigation, with corn being the predominant crop. Groundwater withdrawal from the aquifer has reduced saturated thickness and well capacities. While corn responds well to irrigation, it also requires substantial amounts of water to maximize production. Therefore, there is increased interest in reducing the amount of irrigation, and increased questions on whether crops other than corn would make more profitable use of limited amounts of irrigation.

MATERIALS AND METHODS

A study was initiated under sprinkler irrigation at the Tribune Unit, Southwest Research-Extension Center near Tribune in the spring of 2001. The objectives were to determine the impact of limited irrigation on grain yield, water use, and profitability of several summer row crops. Irrigation amounts were 5, 10, and 15 inches annually. Irrigations were scheduled to supply water at the most critical stress periods for the specific crops and limited to 1.5 inches/week. All water levels were present each year and replicated four times. The irrigation amounts for a particular plot remain constant throughout the study regardless of crop. The crops evaluated were corn, grain sorghum, soybean, and sunflower (a total of 12 treatments). The crop rotation was corn-sunflower-grain sorghum-soybean (alternating grass and broadleaf crops). All crops were grown no-till while other cultural practices (hybrid selection, fertility practices, weed control, etc.) were selected to optimize production. Seeding rate (seeds/acre) was 30,000 for corn, 80,000 for grain sorghum, 150,000 for soybean, and 23,500 for sunflower. Soil water was measured at planting, during the growing season, and at harvest in one-ft increments to a depth of 8 ft by neutron attenuation. The center four rows of each plot were machine harvested after physiological maturity with yields adjusted to 15.5% moisture for corn, 10% moisture for sunflower, and 12.5% moisture for grain sorghum and soybean. An economic analysis determined economic returns to land, management, and irrigation equipment for all crops and irrigation amounts. Custom rates were used to determine machinery operation costs. The costs of inputs (seed, fertilizer, herbicide, etc.) were based on individual year costs for the area and grain prices were harvest prices for the area. No government program payments or crop insurance costs or proceeds were included in the analyses.

RESULTS

Summer precipitation was near normal when averaged across the 8-yr period (Fig. 1). However, there were considerable differences among years. June precipitation ranged from about 1 inch to more than 5 inches. Similar variation was observed in the other months.

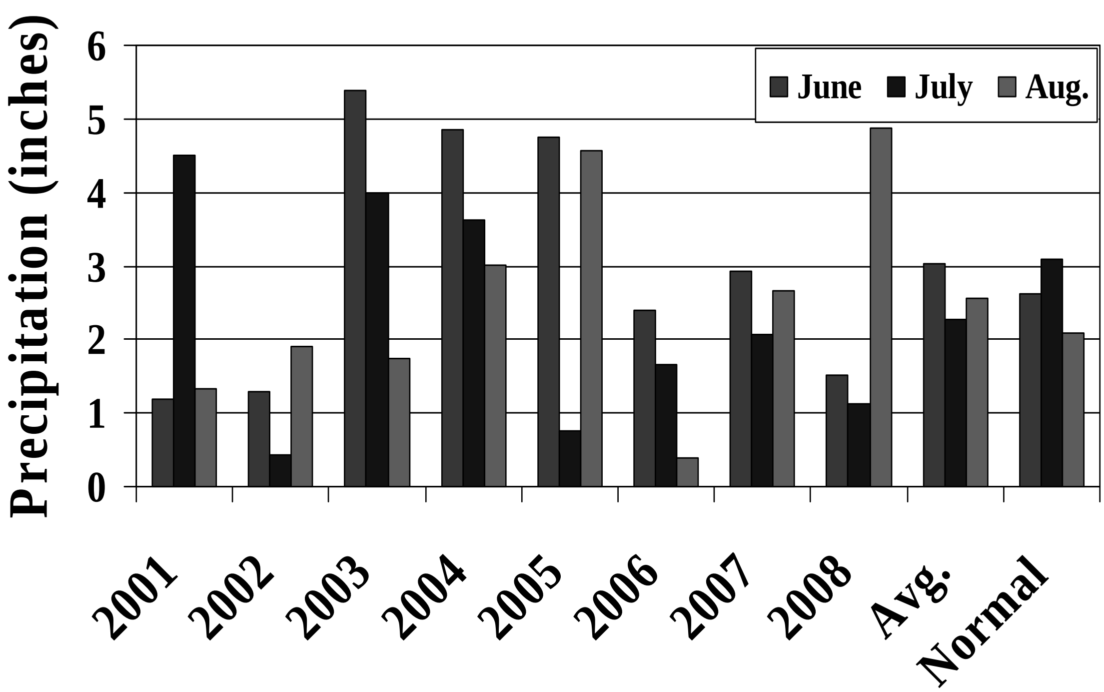


Figure 1. Summer precipitation at SWREC-Tribune Irrigation Field, 2001-2008.

Available soil water in the profile (8 ft) at planting was affected more by irrigation amount rather than crop (Fig. 2). With 5-in of irrigation, profile available water ranged from 6.5 to 8 inches. While with greater irrigation amounts profile available water was 10 to 11 inches regardless of crop.

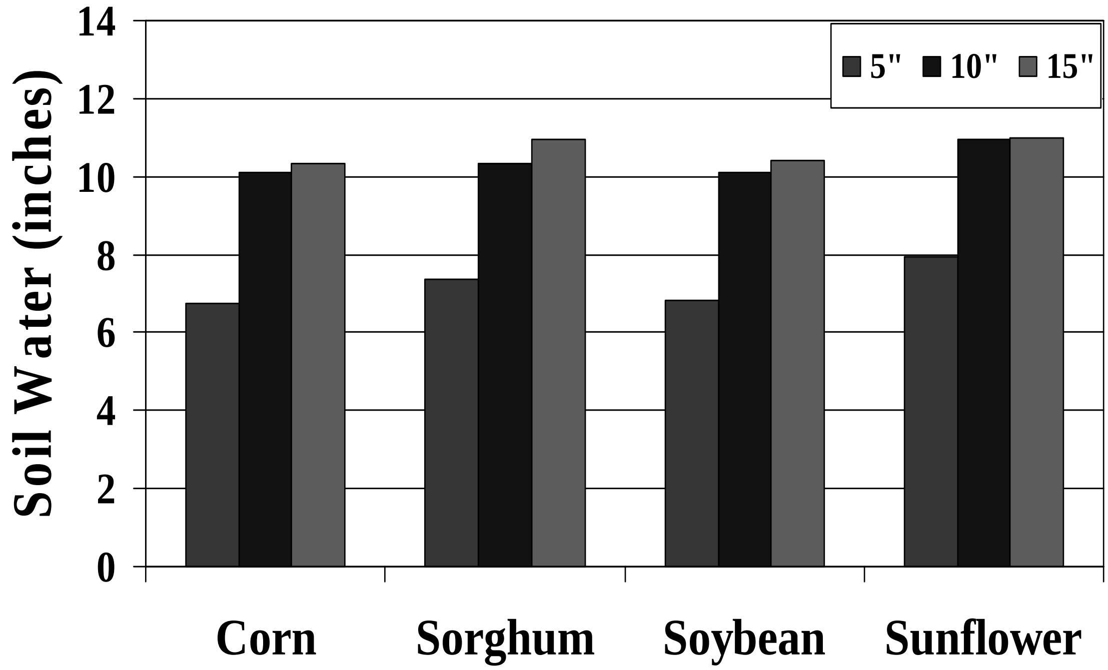


Figure 2. Available soil water at planting for four summer crops under varying irrigation levels. SWREC-Tribune, 2001-2008.

Profile available soil water at harvest was about 4 inches for all crops receiving 5 inches of irrigation (Fig. 3). With 10 inches or more of irrigation, profile available soil water at harvest was 8 to 10 inches for all crops.

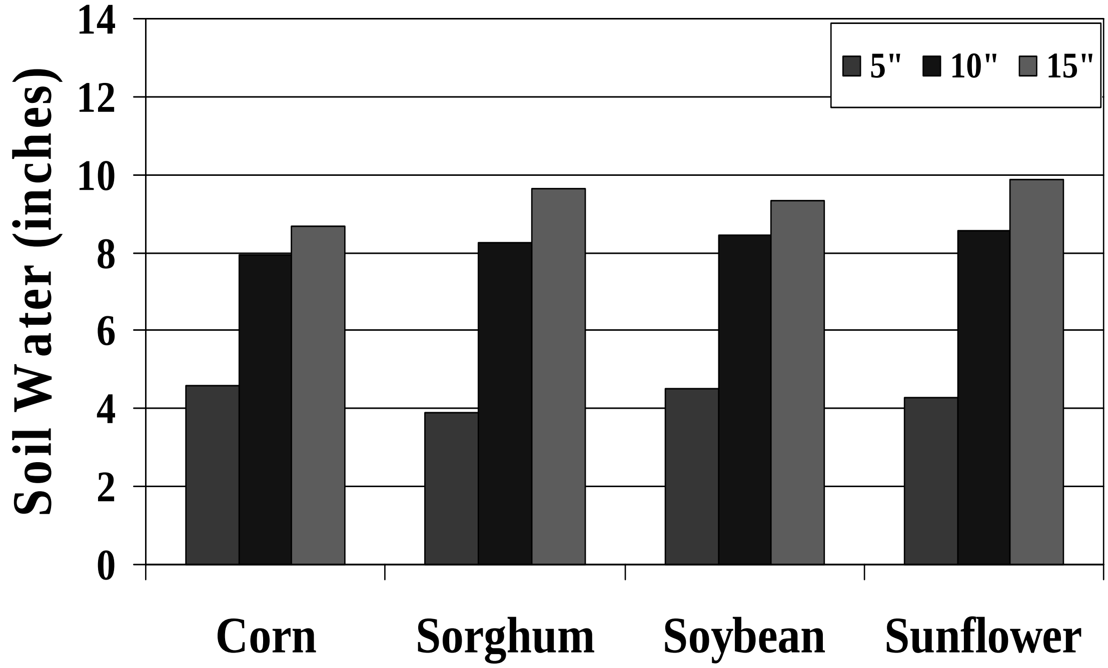


Figure 3. Available soil water at harvest for four summer crops under varying irrigation levels. SWREC-Tribune, 2001-2008.

Crop water use was more affected by irrigation amount rather than crop (Fig. 4). At higher irrigation levels, crop water use tended to be slightly greater with corn and least with sunflower.

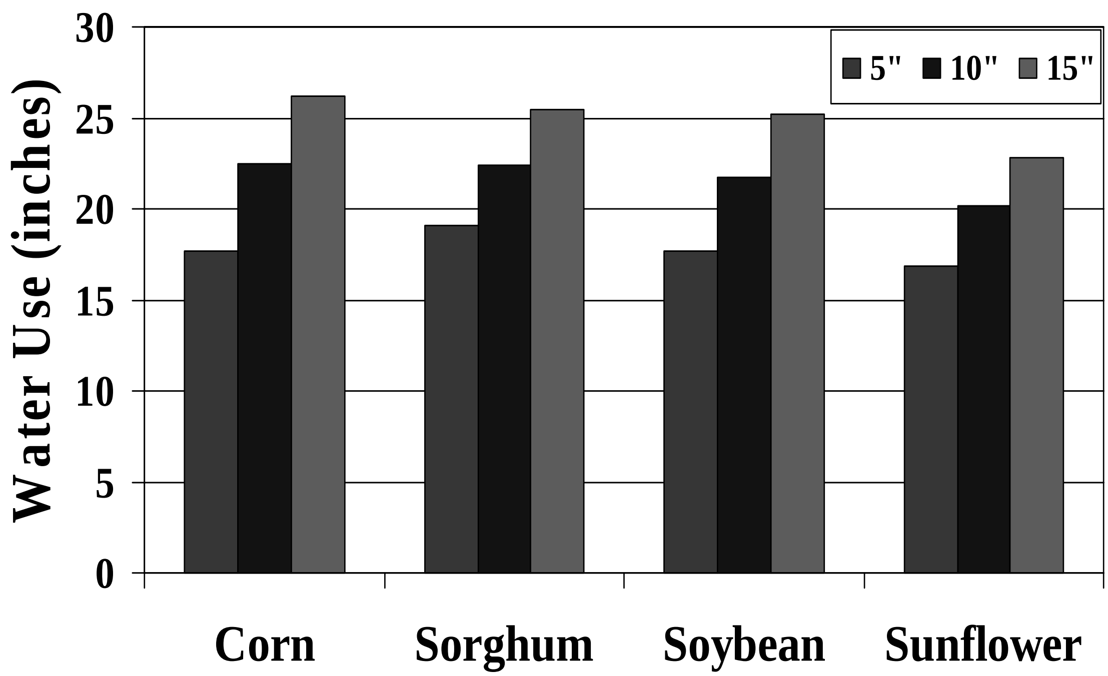


Figure 4. Crop water use for four summer crops under varying irrigation levels. SWREC-Tribune, 2001-2008.

Water use efficiency (WUE) was greater with feed grains than oilseed crops (Fig. 5). For feed grains, corn made more efficient use of water than did grain sorghum. Corn was also the only crop that had higher WUE with 10 inches of irrigation than with 5 inches of irrigation. For all other crops, WUE was similar for all irrigation amounts.

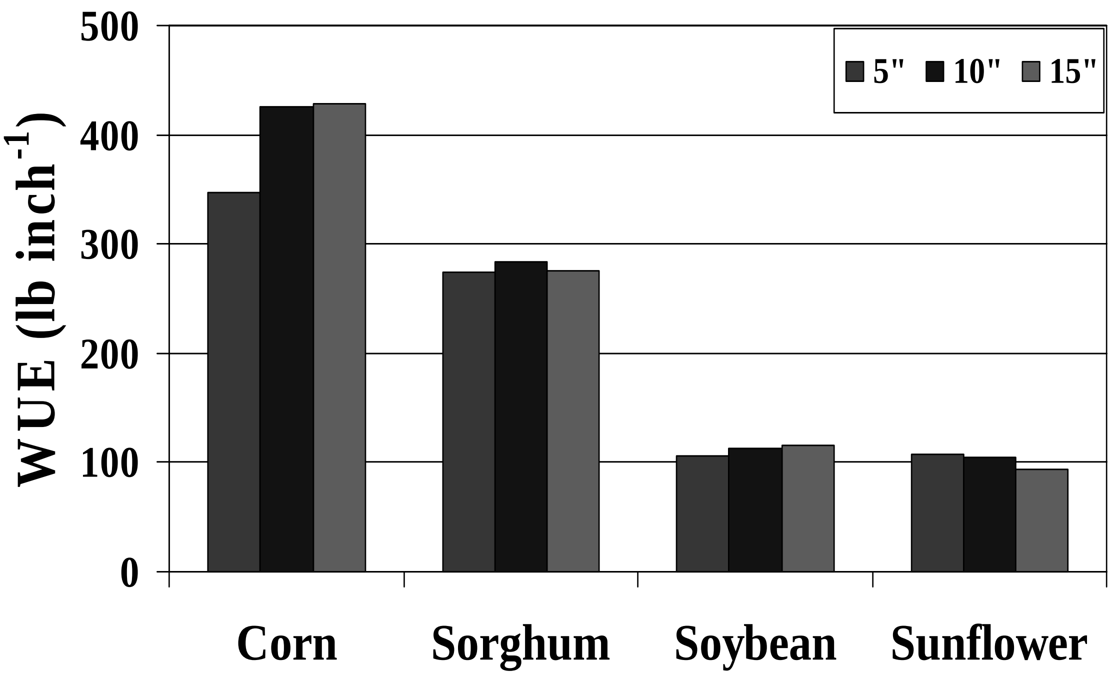


Figure 5. Water use efficiency for four summer crops under varying irrigation levels. SWREC-Tribune, 2001-2008.

Average grain yields (2001-2008) of all crops responded positively to increased irrigation (Table 1). When irrigation was increased from 5 inches to 10 inches, yield increases were 52% for corn, 18% for sorghum, 35% for soybean, and 16% for sunflower. When irrigation amounts were increased past 10 inches, yield increases were 17% for corn, 11% for sorghum, 12% for soybean and only 4% for sunflower. Corn yields increased 78% when irrigation was increased from 5 inches up to 15 inches while grain sorghum increased 31%, soybean by 52%, and sunflower by 20%.

Table 1. Average grain yield (2001-2008) of four crops as affected by irrigation amount, SWREC-Tribune, KS.

Irrigation amount	Corn	Grain sorghum	Soybean	Sunflower
acre-inch	- - - - - - - - - -	-bu/acre - - - - - - - - -		lb/acre
5	113	94	31	1800
10	172	111	42	2080
15	201	123	47	2160

An economic analysis (based on October grain prices each year and input costs from each year) found that at the lowest irrigation level, average net returns (2001-2008) were similar for all crops (Fig. 6). At the higher irrigation levels, corn was the more profitable crop. Corn was the only crop where profitability increased appreciably with more than 10 inches of irrigation.

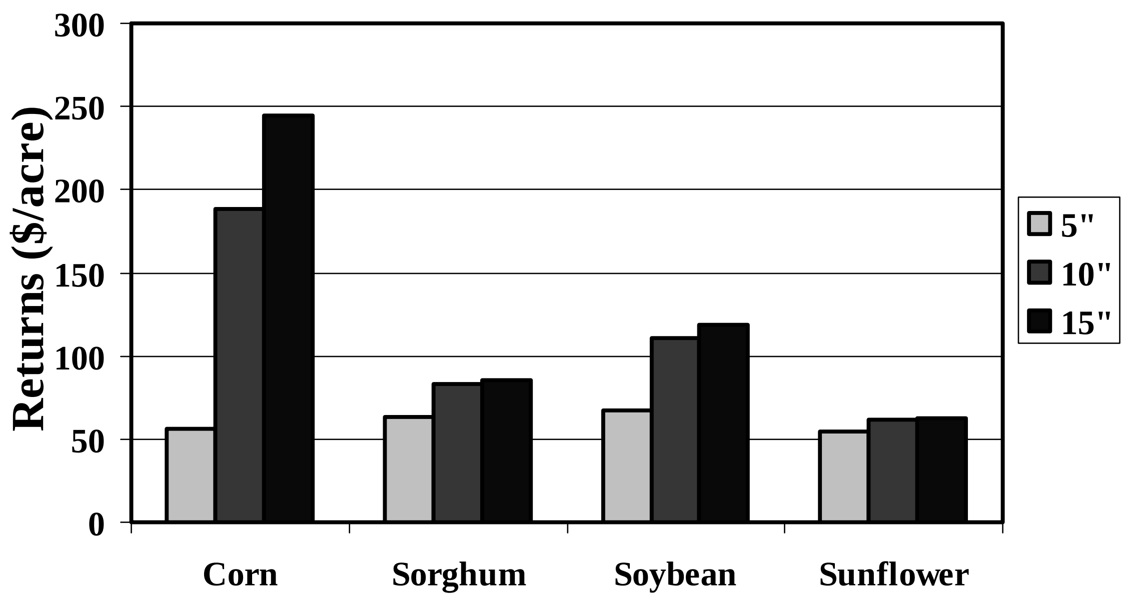


Figure 6. Average (2001-2008) net returns to land, management, and irrigation equipment, SWREC-Tribune, KS.

CONCLUSIONS

With very limited amounts of irrigation, there are several crops (grain sorghum, soybean, and sunflower) that can be grown that are as profitable as corn. These crops may also provide additional benefits in breaking pest cycles (weed, insect, and disease) that can arise with production of continuous corn. However, when irrigation amounts of 10 inches or more annually are available, corn is the most profitable crop.

Acknowledgement: Project supported in part by Kansas Corn, Grain Sorghum, and Soybean Commissions, Groundwater Management District #1, and the Ogallala Aquifer Program.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

IRRIGATION CAPACITIES IMPACT UPON LIMITED IRRIGATION MANAGEMENT AND CROPPING SYSTEMS

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

INTRODUCTION

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

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

System Capacities

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

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

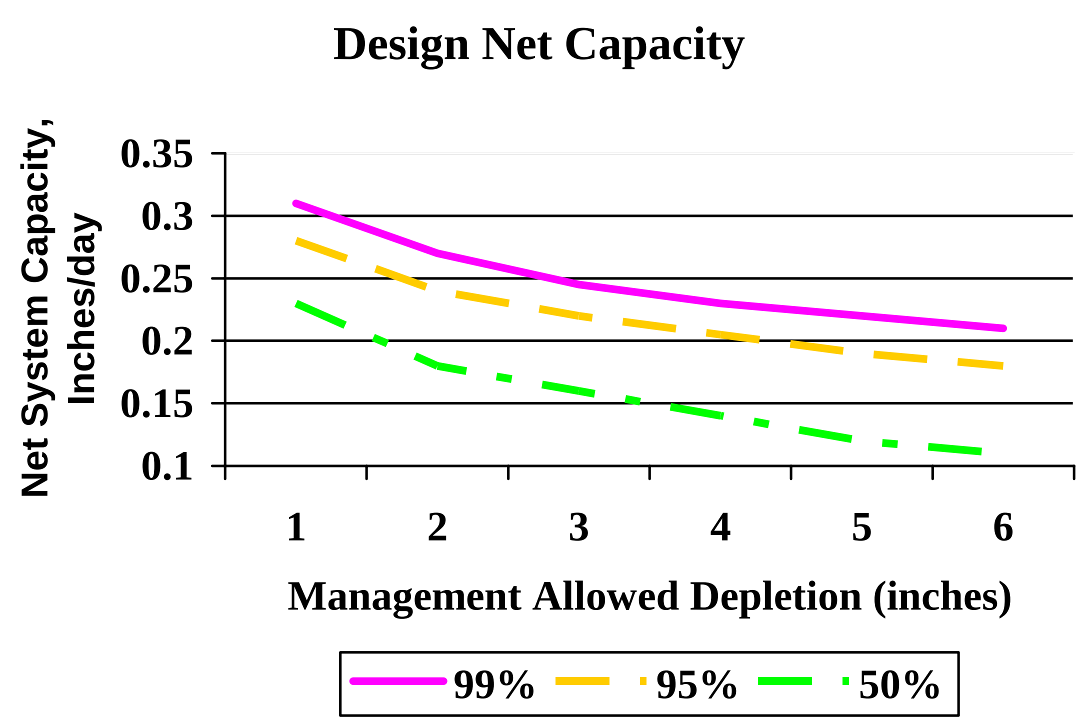


Figure 1. Net irrigation capacities for Eastern Colorado (Heermann).

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

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

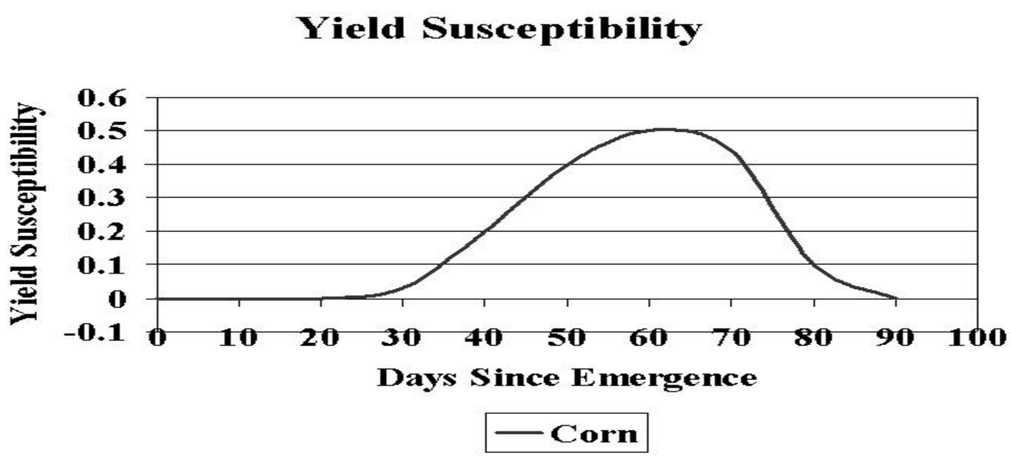


Figure 2. Yield susceptibility to water stress for corn (Sudar et al., 1981).

Management of low capacity systems generally entails by many producers running the system at times when it is not necessarily advantageous for water management but for the factor of "never wanting to fall behind and hope for the best". This type of management generally applies more water than necessary during low water use time periods, can leach nitrogen and may not alleviate water stress during periods of little or no precipitation during the high water use growth stages.

SOIL MOISTURE SIMULATION

Two locations in Colorado were chosen for simulation of multiple irrigation system capacities. Wiggins in 2007 had below average precipitation and Burlington in 2005 had above average precipitation. Precipitation in Burlington may have been above average but was concentrated in the early growing season for corn. A water balance model was used to determine crop water use and soil moisture depletion using weather data from each location and predicted irrigation maintaining soil moisture depletion between 0 and 50% if possible. Irrigation was scheduled to minimize leaching during the growing season. Beginning soil moisture was assumed to be at field capacity either from off-season precipitation or pre-irrigation. Both sites have similar water holding capacities of 1.8 to 2.0 inches per foot.

Simulated irrigation capacities include: 1 inch every 4 days (4.7 gpm/acre), 1 inch every 6 days (3.14 gpm/acre), and 1 inch every 8 days (2.36 gpm/acre). These capacities relate to a 600 gpm to a 300 gpm well for a 125 acre field. These are a typical range of well capacities within eastern Colorado.

Wiggins

Precipitation at Wiggins was below average for May and June and near average for July and August (Table 1). The majority of the precipitation in July and August was during the last 7 days of July and first 10 days of August. Average annual crop water use for corn is approximately 24 inches.

Table 1. Monthly and average precipitation for Wiggin, Co for 2007 and Burlington, CO for 2005.

	Wiggins		Burlington	
Month	Precipitation (inches)	Average (inches)	Precipitation (inches)	Average (inches)
May	1.65	2.41	4.03	2.88
June	0.31	1.98	5.08	2.50
July	2.29	1.93	2.36	2.77
August	2.49	1.58	3.15	2.28
September	0.52	1.21	0.80	1.04

Irrigation capacities had an impact upon soil moisture depletions (Figure 3). A capacity of 1 inch every 4 days was adequate for full irrigation. Soil moisture depletions did not approach 50% until the end of the growing season after the irrigation system was shut off. A system capacity of 1 inch every 6 days or less was inadequate with soil depletions greater than 50% occurring in late July.

Soil moisture depletions were critical in late July for the 1 inch in 6 and 8 days. Corn would have been in the critical growth stage of tassel and pollination during this time period. This is the time period of 60 to 80 days after emergence when Sudar determined that the greatest yield reduction would occur. This would limit yields dramatically compared to an adequate capacity that would maintain soil moisture less than 50% depletion.

Precipitation of 3.5 inches during late July and early August allowed soil depletions for both the 1 inch in 6 and 8 days to be less than 50%. However only the 1 inch in 6 days remained less than 50% depletion during the remainder of the growing season. The soil moisture depletion for the 1 inch in 8 days capacity was greater than 50% after mid-August during the grain fill time period. This water stress has less impact than during the tassel and pollination time period but still will reduce grain yields.

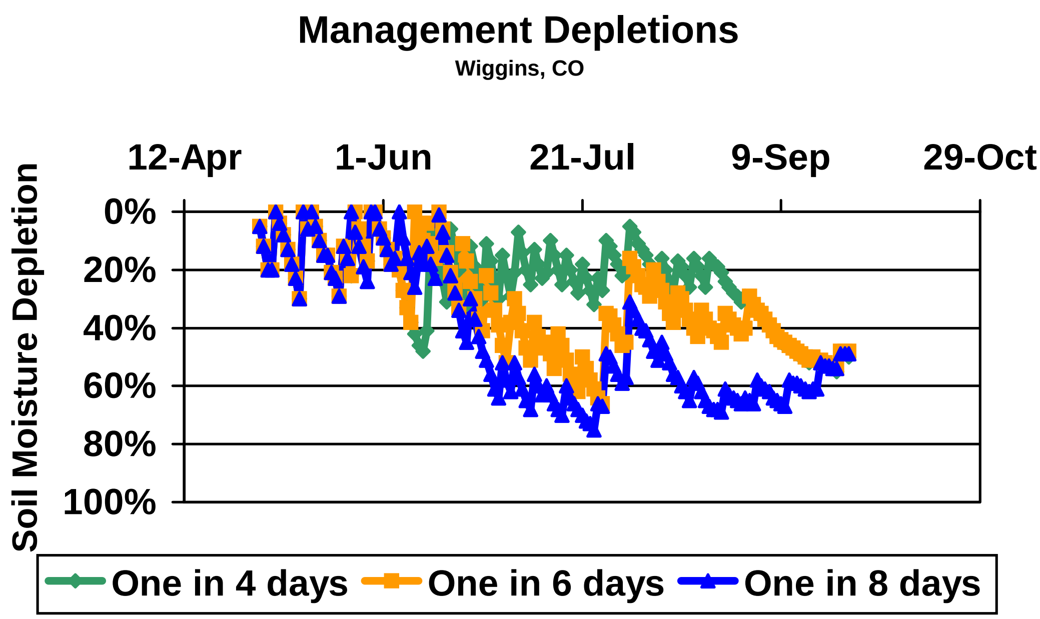


Figure 3. Soil moisture depletions for 3 irrigation capacities at Wiggins, Colorado for 2007.

With an irrigation capacity of 1 in 4 inches per day, the system was rarely turned off. Only during the time period of above average precipitation of late July and early August could the system been turn off. If irrigated acreage for corn were reduced to this capacity per acre, the only irrigation option for the remainder of the acres would be an early spring crop with the need for irrigation done by early June.

<u>Burlington</u>

Precipitation at Burlington in 2005 was above average for May and June and near average for July and August (Table 1). Precipitation in May and June totaled more than 9 inches which is 3.5 inches greater than average. During July, there was a 21 day period where little precipitation occurred. Less than 1 inch of precipitation occurred during the first 21 days of August. Average water use for corn is approximately 27 inches at Burlington.

Although precipitation was above average at Burlington, irrigation capacities had a significant impact upon soil moisture depletion (Figure 4). An irrigation capacity of 1 inch in 4 days was adequate to maintain soil moisture depletions of less than 50% during the growing season. However, soil moisture depletions during late July and early August were greater than 40%. System capacities of 1 inch in 6 days or less were inadequate with soil moisture depletions greater than 50% in late July and to late August.

Soil moisture depletions were critical in late July for the 1 inch in 6 and 8 days. Corn would have been in the critical growth stage of tassel and pollination during this time period. This is the time period of 60 to 80 days after emergence when Sudar determined that the greatest yield reduction would occur. This would limit yields dramatically compared to an adequate capacity that would maintain soil moisture less than 50% depletion.

Soil moisture depletions for system capacities of 1 inch in 6 days or less were greater than 50% during the entire reproductive growth stage. During a majority of this time period, soil moisture depletions were greater than 60% and approached 80% for the 1 inch in 8 days capacity. Soil moisture depletions were less than 50% in late August only after two precipitation events totaling more than 2 inches occurred.

Although total precipitation for the entire growing season was above average by almost 4 inches, timing of that precipitation was critical. Precipitation during July and August was near average showing the importance of adequate system capacities during the time period when crop water use was almost 14 inches.

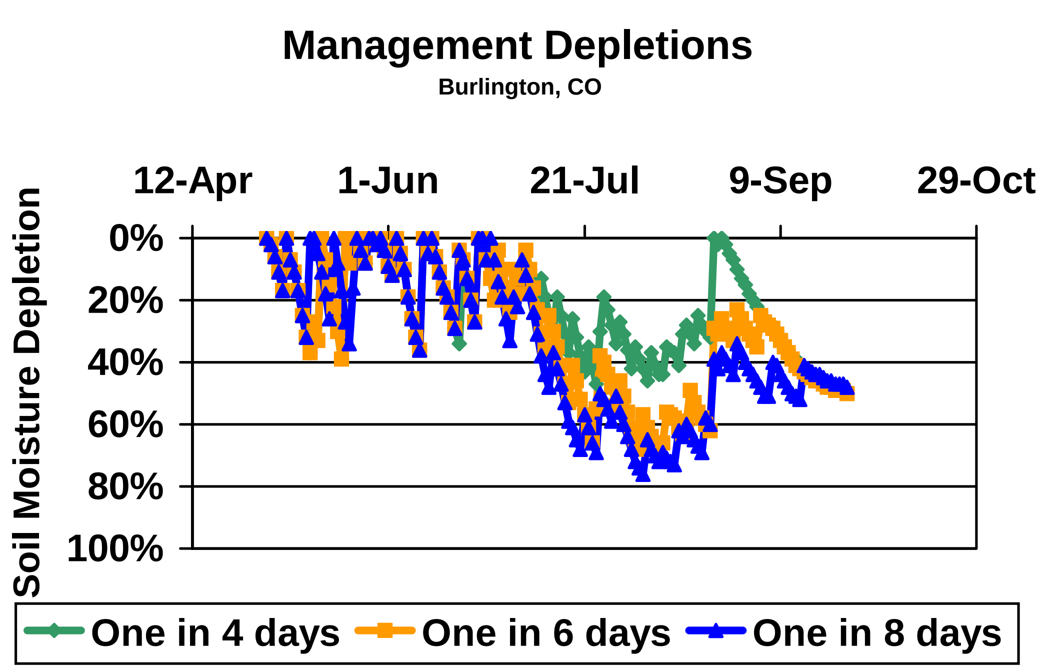


Figure 4. Soil moisture depletions for 3 irrigation capacities at Burlington, Colorado for 2005.

Alternate Strategies

Although an irrigation capacity of 1 inch in 4 days was adequate for irrigating corn during the growing season. The options for irrigating another summer crop are limited since the system rarely was off for long periods of time during July and August. The only practical option would be to irrigate an early spring crop on those acres. A second scenario was simulated including the capacity of 1 inch in 3 days and the potential to divert irrigation to the remainder of potentially irrigatable acres. Crops such as sunflower respond well to limited amounts of irrigation during critical time periods (Schneekloth). Schneekloth found that irrigating oil sunflowers during the early flower to pedal drop yielded similarly to fully irrigated sunflowers. This time period is a two to three week period that occurs in early August when sunflowers are planted in late May.

Simulating a 1 inch in 3 days system capacity, irrigation to a summer crop such as corn could be reduced during the first 3 weeks of August and with the majority of irrigation being diverted to a crop such as sunflowers (Figure 5). Soil moisture depletions increased during that time period but were still less than 50% before primary irrigation of the corn resumed.

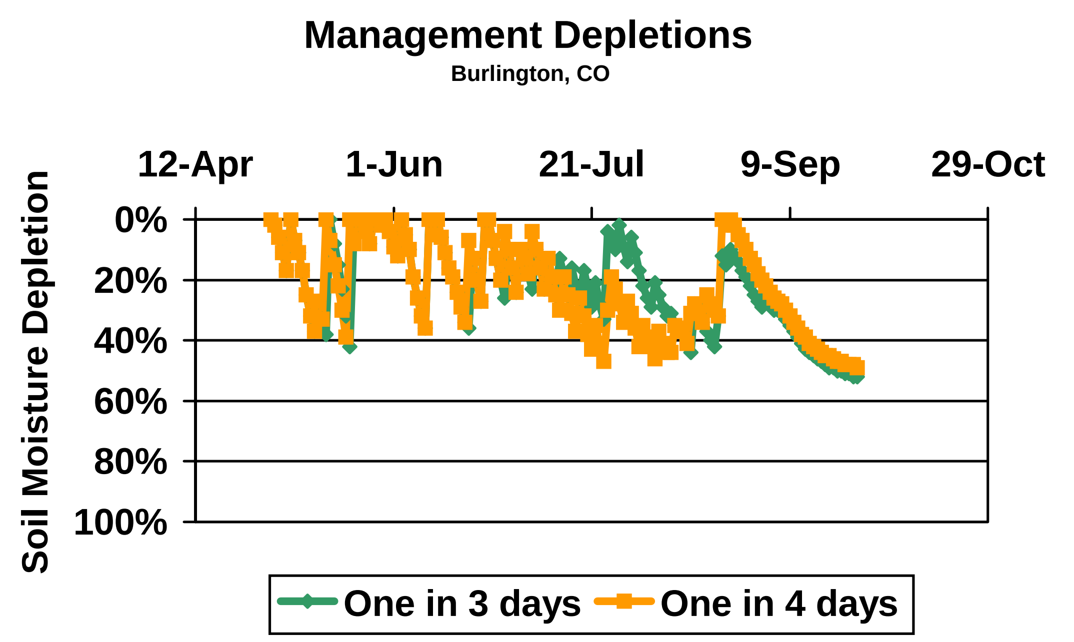


Figure 5. Soil moisture depletions for an irrigation capacity that would allow diverting irrigation to a secondary summer crop compared to an adequate capacity for full irrigation at Burlington, Colorado for 2005.

This strategy would allow for more total acres to be irrigated with more diversity but fewer acres of any one single crop.

CONCLUSION

Although both Wiggins and Burlington had dramatically different weather conditions, the minimum acceptable system capacity was similar at 1 inch in 4 days. However, this capacity may require diverting water from acres to achieve this capacity for a limited number of acres. However, spreading water over more acres with lower capacities generally will have water stress at the critical growth stages that will impact yield potential the greatest.

When dealing with system capacities that are not adequate for full irrigation management of the system, the potential for less than optimum yields increases, as does the risk involved. Alternative cropping practices must be included that diversify crops and reduce the irrigated acreage of any one crop. However, the critical time periods should not overlap unless alternative water capacity strategies are investigated.

Irrigating all of the acres with a marginal system capacity increases the reliance upon crop insurance to minimize the risk when precipitation is either below average or the distribution is not uniform. However, crop insurance in the future may limit this due to their increase exposure for risk.

References:

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

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

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

CENTER PIVOT SPRINKLER PACKAGE SURVEY RESULTS

Danny H. Rogers, Mahbub Alam, and L. K. Shaw
Extension Irrigation Engineers and MIL Project Coordinator
Kansas State University Research and Extension
Voice: 785-532-5813, or 620-275-9164
Email: drogers@ksu.edu, or malam@ksu.edu

Introduction

A road survey of center pivot irrigation systems was conducted in select counties across Kansas on two separate occasions. A county road map for the selected counties was divided into three transects north/south and three transects east/west. The survey was conducted in the fall of 2003 in Barton, Edwards, Pawnee, and Stafford counties. The counties surveyed in 2006 were Finney, Ford, Grant, Gray, Haskell, Scott, Stevens, and Thomas.

The purpose of the survey was to obtain useful information in order to characterize the types of center pivot nozzle packages currently being used and to gather baseline data for future surveys. The survey information consisted of observations on field location, degree of rotation, number of spans, nozzle type, pressure regulation, general nozzle type, nozzle height, number of spans and overhang, outlets on overhang, and end gun presence and type. Since the surveyor made observations from the road and not directly from the field, the exact type of nozzle packages could not always be determined. Therefore, they were generally characterized as impact sprinklers, fixed plate nozzles, or moving plate nozzles, which were recognizable configurations.

The results of the survey are presented in two groups: the south central survey and the western survey.

South Central Kansas Center Pivot Survey Results

The summary of observations from the south central region of Kansas is shown in Table 1 (a-f). Most of the 325 systems that were observed were typical quarter section center pivots and 95% of those systems could make a complete revolution, as shown in Table 1a. The most common type of nozzle package in the area was moving plate nozzles (rotator, I-wobbler, etc), as outlined in Table 1b, and each nozzle package was likely to be pressure-regulated, as shown in Table 1c.

Observations on the nozzle spacing and heights were divided into three height categories and five height locations. Table 1d reveals that the most common nozzle spacing was medium (8-12 feet) and Table 1e shows that the most common nozzle height was a mounting just below the center pivot truss.

The observations of primary interest for this region were the number of end guns used on the sprinkler systems. Table 1f reveals that over one-third (37.5 %) of the systems were equipped with a big gun or traditional end gun, which requires a booster pump. On the other hand, 48.9% of the systems were equipped with either double or single large impact sprinklers which are pressurized by using existing system pressure. Almost 13% of the systems did not have a different nozzle at the outer end as compared to the rest of the center pivot system.

Table 1 (a-f): Summary of Pivot Nozzle Package Survey for Barton, Edwards, Pawnee, and Stafford Counties surveyed in 2003.

Table 1a: Survey Results of Rotation Degree for Center Pivot Systems in South Central Kansas

Degree of Rotation	Number of observations	Percentage
Full Circle	309	95
Partial Circle	16	5
Total	325	100

Table 1b: Survey Results of Types of Sprinkler Nozzles on Center Pivot Systems in South Central Kansas

Nozzle Type	Number of observations	Percentage
Fixed Plate	19	5.8
Impact	22	6.8
Mixed	5	1.5
Moving Plate	244	75.1
Unknown	35	10.8

Table 1c: Survey Results of Pressure Regulators on Center Pivot Systems in South Central Kansas

Pressure Regulators	Number of observations	Percentage
Yes	90	27.7
No	91	28
Unknown	144	44.3
Total	325	100

Table 1d: Survey Results of Nozzle Spacing on Center Pivot Systems in South Central Kansas

Nozzle Spacing	Number of observations	Percentage
Close (< 8 ft)	64	19.7
Medium (8-12 ft)	187	57.5
Wide	66	20.3
Unknown	8	2.5

Table 1e: Survey Results of Nozzle Height on Center Pivot Systems in South Central Kansas

Nozzle Height	Number of observations	Percentage
< 4 ft above ground	25	7.7
> 4 ft above ground	42	12.9
Truss to 2 ft below truss	221	68.0
Within truss	1	0.3
Top of pivot	27	8.3
Unknown	8	2.5

Table 1f: Survey Results of End Gun Type on Center Pivot Systems in South Central Kansas

End Gun Type	Number of observations	Percentage
Big Gun	122	37.5
Double Large Impact	78	24.0
None	42	12.9
Single Large Impact	81	24.9
Unknown	2	0.6

Western Kansas Center Pivot Survey Results

The total number of systems observed in the western Kansas survey was 659. Center pivots larger than the typical quarter section system are more common in western Kansas, so the survey results of the number of spans ranged from 4 to 19, as shown in Table 2. Out of the total number of observations in western Kansas, 483 were either 7 or 8 spans in length, and only 10 systems were less than 6 spans in length. Seventy-six systems were either 9 or 10 spans in length, and almost 15% of the observed systems were 15 spans or larger. Approximately 50% of the systems that were 11 spans or larger were operated as partial circles, as compared to about 7% for systems of 10 spans or smaller.

Table 2: Center Pivot Survey Results of Number of Spans and Degree of Rotation

Number of Spans	Number Observed	Number of Partial Circles	Percent
4	1	1	<1
5	2	0	0
6	10	2	<1
7	276	18	2.7
8	207	19	2.9
9	26	2	<1
10	50	1	<1
11	1	1	<1
12	2	1	<1
13	4	0	0
14	4	2	<1
15	6	4	<1
16	28	14	2.1
17	20	11	1.7
18	16	10	1.5
19	6	1	<1

As Table 3 shows, 78% of the observed systems were pressure regulated and 89% used a fixed plate nozzle package.

Table 3: Center Pivot Survey Results for Pressure Regulation Use and Nozzle Type

Pressure Regulation	Number	Percentage	Nozzle Type	Number	Percent
Yes	515	78.2	Fixed Plate	589	89.4
No	136	20.7	Moving Plate	62	13.6
Unknown	8	12.1	Impact	2	<1
			Mixed	1	<1
			Unknown	5	<1

End guns, defined either as traditional big guns or impact sprinklers, accounted for only slightly more then 15% of the systems, as shown in Table 4.

Table 4: Center Pivot Survey Results of Use of End Guns

End Gun Type	Number	Percent
Big gun	7	1.1
Single large impact sprinkler	22	3.3
Double large impact sprinkler	73	11.1
None (Last nozzle same type as system)	557	84.5

Observations were also made on the placement of the nozzle for both spacing and height, as shown in Table 5. The most common observation was a mixed spacing configuration, which means that the first several spans had wider spacing than the outer spans. Only three systems were observed to have wide spacing. The majority of the systems were shown to use drop nozzles located at less than a 4 foot height, followed by systems that had heights above 4 feet but more than 2 feet below the truss.

Table 5: Center Pivot Survey Results for Nozzle Spacing and Nozzle Height

Nozzle Spacing	Number	Percent	Nozzle Height	Number	Percent
Close (< 8 ft)	214	32.7	Less than 4 foot	385	58.4
Medium (8-12 ft)	197	29.9	Greater than 4 foot	212	32.2
Mixed	245	37.2	Truss to 2 foot below	55	8.3
Wide	3	<1	Within truss	4	<1
			Top of lateral	3	<1

Survey information was also collected on the ability of the center pivot to make a full revolution. Table 6 shows that 88 systems, or 13%, could only make partial revolutions.

Table 6: Center Pivot Survey Results for Rotations

Degree of Rotation	Number	Percent
Full (360 degrees)	571	88.6
Partial (Less then 360 degrees)	88	11.4

Additional analysis looked at various combinations of observations. Table 7 shows nozzle type versus nozzle spacing, Table 8 outlines nozzle height versus nozzle type, Table 9 compares nozzle height and nozzle spacing, and Table 10 shows the number of spans versus the degree of rotation.

Table 7: Center Pivot Survey Results for Nozzle Type and Nozzle Spacing

Nozzle Type	**Nozzle Spacing**	**Observation**	**Percent**
Fixed Plate	Close (< 8 ft)	196	33.3
	Medium (8-12 ft)	155	26.3
	Wide (> 12 ft)	1	<1
	Mixed	237	40.2
Fixed Plate	**Total**	589	
Impact	Close (< 8 ft)	0	-
	Medium (8-12 ft)	0	-
	Wide (> 12 ft)	2	100
Impact	**Total**	2	
Mixed	Medium (8-12 ft)	1	100
Mixed	**Total**	1	
Moving Plate	Close (< 8 ft)	18	29.0
	Medium (8-12 ft)	38	61.3
	Mixed	6	9.7
Moving Plate	**Total**	62	
Unknown	Medium (8-12 ft)	3	60
	Mixed	2	40
Unknown	**Total**	5	

Table 8: Center Pivot Survey Results for Nozzle Height and Nozzle Spacing

Nozzle Height	**Nozzle Spacing**	**Number of Observation**
< 4 ft	Close (< 8 ft)	131
	Medium (8-12 ft)	41
	Mixed	213
< 4 ft	**Total**	385
> 4 ft above ground	Close (< 8 ft)	64
	Medium (8-12 ft)	118
	Wide (> 12 ft)	29
	Mixed	1
> 4 ft above ground	**Total**	212
Truss to 2 ft below truss	Close (< 8 ft)	18
	Medium (8-12 ft)	35
	Mixed	2
Truss to 2 ft below truss	**Total**	55
Within truss	Close (< 8 ft)	1
	Medium (8-12 ft)	2
	Mixed	1
Within truss	**Total**	4
Top of Pivot	Medium (8-12 ft)	1
	Wide (> 12 ft)	2
Top of Pivot	**Total**	3

Table 9: Center Pivot Survey Results for Nozzle Height and Nozzle Type

Nozzle Height	Nozzle Type	Observation	Percent
< 4 ft	Fixed Plate	371	96.4
	Moving Plate	12	3.1
	Mixed	2	<1
< 4 ft	**Total**	385	
> 4 ft above ground	Fixed Plate	183	86.3
	Moving Plate	27	12.7
	Unknown	2	<1
> 4 ft above ground	**Total**	212	
Top of Pivot	Impact	2	67
	Fixed Plate	1	33
Top of Pivot	**Total**	3	
Truss to 2 ft below truss	Fixed Plate	41	74.5
	Moving Plate	13	23.6
	Mixed	1	1.9
Truss to 2 ft below truss	**Total**	55	
Within truss	Fixed Plate	4	100
Within truss	**Total**	4	

Table 10: Center Pivot Survey Results for the Number of Spans versus the Degree of Rotation

Number of Spans	Number Observed	Number with Full Rotation	Number with Partial Rotation	Percent Partial
4	1	0	1	<1
5	2	2	0	0
6	10	8	2	<1
7	276	258	18	2.7
8	207	188	19	2.8
9	26	24	2	<1
10	50	49	1	<1
11	1	0	1	<1
12	2	1	1	<1
13	4	4	0	0
14	4	2	2	<1
15	6	2	4	<1
16	28	12	14	2.1
17	20	9	11	1.7
18	16	6	10	1.5
19	6	5	1	<1

Ninety percent of the observed systems had nozzles which were placed in the two lower placement categories: “less than 4 feet” or “greater than 4 feet but less then 2 feet below truss.” Sixty-three percent of all fixed plate nozzles were within 4 feet of the ground, while only 12% of moving plate nozzles fit that category. Sixty-two percent of the moving plate nozzles were observed in the “greater than 4 feet” category, as compared to 29% of the fixed plate nozzles.

Observation results revealed that moving plate nozzles tend to use higher and wider spacing configurations than the fixed plate nozzles. Approximately three-fourths of the fixed plate nozzles utilized a mixed spacing configuration. Sixty-one percent of the moving plate nozzles use medium spacing, and another 10% fit into the mixed spacing category.

The large center pivots, which have a greater number of spans, are more likely to be associated with partial rotations. For systems with 11 spans or less, only 7% did not have full rotation. For span numbers greater then 11, approximately half of the systems could do full circles. These results are expected, due to the likelihood of physical constraints in larger fields, water-right and land ownership constraints, and irrigation capacity issues for large systems.

A three-way observation of nozzle spacing, nozzle height, and nozzle type is shown in Table 11. Fixed plate nozzles are usually spaced closer and lower to the ground than moving plate nozzles, as is necessary because of the operational characteristics of the two nozzle types. Moving plate nozzles are most commonly used with medium spacing in the “greater than 4 feet” height category.

Table 11: Center Pivot Survey Results for Nozzle Spacing, Height, and Type.

Nozzle Spacing	Nozzle Height	Nozzle Type	Number	Percent
Close < 8 ft.	< 4 ft	Fixed Plate	126	98.5
		Moving Plate	5	1.5
	< 4 ft	**Total**	131	
	> 4 ft above ground	Fixed Plate	55	85.9
		Moving Plate	9	14.1
	> 4 ft	**Total**	64	
	Truss to 2 ft below truss	Fixed Plate	14	77.8
		Moving Plate	4	22.2
	Truss to 2 ft below truss		18	
	Within Truss	Fixed Plate	1	100
		Moving Plate	0	0
	Within Truss	**Total**	1	
Close <8 ft.		**Total**	214	
Medium (8-12 ft)	< 4 ft	Fixed Plate	36	87.8
	<4 ft	Moving Plate	5	12.2
	< 4 ft	**Total**	41	
	> 4 ft above ground	Fixed Plate	90	76.3
		Moving Plate	26	22.0
		Unknown	2	1.7
	> 4 ft above ground	**Total**	118	
	Truss to 2 ft below truss	Fixed Plate	26	74.2
		Moving Plate	7	20.0
		Mixed	1	2.9
		Unknown	1	2.9
	Truss to 2 ft below truss	**Total**	35	
	Within Truss	Fixed Plate	2	100
		Moving Plate	0	0
	Within Truss	**Total**	2	
	Top of Pivot	Fixed Plate	1	100
	Top of Pivot	**Total**	1	
Medium (8-12 ft)		**Total**	197	
Mixed	< 4 ft above ground	Fixed Plate	209	98.1
		Moving Plate	2	<1
		Unknown	2	<1
	< 4 ft above ground	**Total**	213	
	> 4 ft above ground	Fixed Plate	26	89.6
		Moving Plate	3	10.4
	> 4 ft above ground	**Total**	29	
	Truss to 2 ft below truss	Fixed Plate	1	50
		Moving Plate	1	50
		Mixed	0	
	Truss to 2 ft below truss	**Total**	2	
	Within Truss	Fixed Plate	1	100
		Moving Plate	0	0
	Truss to 2 ft below truss	**Total**	1	
Mixed Spacing		**Total**	245	
Wide (>12 ft)	> 4 ft above ground	Fixed Plate	1	33.3
	Top of Lateral	Impact	2	66.7
Wide (>12 ft)		**Total**	3	

Regional Survey Comparisons and Contrasts

The south central and western Kansas results were similar in that both regions predominately used systems with lengths of 7 or 8 spans. Approximately 21% of the systems in either region had span lengths of 8 or greater. However, in the south central region only two systems were greater then 10 spans in length, whereas 13% of the western systems were greater than the 10 spans. These results are expected since the terrain of the south central area requires systems that have a higher irrigation capacity for serving sandy soils. These systems are often problematic, though, because of friction losses and limitations of well capacities. In addition, more of the south central systems (95.1%) completed full circles than the western systems (86.6%), although this trend is likely related to the number of larger systems in the west.

The most common type of sprinkler package in the south central survey was a moving plate type nozzle as compared to the fixed plated nozzle in western Kansas. Higher capacity systems and sandy soils both make the use of moving plate nozzles and higher nozzle placement a preferred design selection for the general soils and slopes of south central Kansas.

End guns are commonly used on sprinkler systems in south central Kansas. Only approximately 13% of the systems in south central Kansas did not have some type of end nozzle. On the other hand, only 15% of western Kansas systems actually used an end gun on their sprinklers. Over one-third (37.5%) of the south central systems were equipped with a big gun (traditional end gun) and about half (48.9%) were equipped with either double or single large impact sprinklers.

Summary

The dominant center pivot nozzle package of western Kansas is a fixed plate nozzle positioned near to the ground using a drop tube as compared to a moving plate nozzle positioned near truss height in south central Kansas.

Acknowledgements

This work was supported in part by Kansas Water Plan Funds in support of the Mobile Irrigation Lab Project and the USDA-ARS Ogallala Aquifer Project.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N. Thompson, Colby, Kansas

CENTER PIVOT SPRINKLER APPLICATION DEPTH AND SOIL WATER HOLDING CAPACITY

D.O. Porter
Associate Professor and
Extension Agricultural Engineer
Texas AgriLife Research and
Texas AgriLife Extension Service
Lubbock, Texas
Voice:806-746-4022
Fax: 806-746-4057
Email:d-porter@tamu.edu

T.H. Marek
Senior Research Engineer
Texas AgriLife Research
Amarillo, Texas and
Superintendent, North Plains
Research Field
Etter, Texas
Voice: 806-677-5600
Fax: 806-677-5644
Email:t-marek@tamu.edu

SUMMARY

Advanced irrigation technologies, including center pivot irrigation, are excellent tools that make it possible to meet crop water requirements with a high level of water and energy efficiency and distribution uniformity. Within constraints of available water capacity and other site-specific limitations, a well designed, maintained and managed irrigation system provides for a high level of flexibility and precision to meet crop water requirements with minimal losses. The key to optimizing center pivot irrigation is management, which takes into account changing crop water requirements and the soil's permeability and water holding capacities.

LOW PRESSURE CENTER PIVOT IRRIGATION SYSTEMS

Center Pivot irrigation systems are used widely throughout the Central High Plains, including the Texas High Plains where most of the systems are low pressure systems, including Low Energy Precision Application (LEPA); Low Elevation Spray Application (LESA); Mid-Elevation Spray Application (MESA) and Low Pressure In-Canopy (LPIC).

Low pressure systems offer cost savings due to reduced energy requirements as compared with high pressure systems. They also facilitate increased irrigation application efficiency, due to decreased evaporation losses during application. Considering high energy costs and in many areas limited water capacities, high irrigation efficiency can help to lower overall pumping costs, or at least optimize crop yield/quality return relative to water and energy inputs.

LEPA irrigation applies water directly to the soil surface through drag hoses (primarily) or through "bubbler" type applicators, (such as the LEPA mode of Senninger Irrigation Inc. Quad-Spray™ products[1].) Notably LEPA involves more than just the hardware through which water is applied. It involves farming in a circular pattern (for center pivot irrigation systems) or straight rows (for linear irrigation systems). It also includes use of furrow dikes and/or residue management to hold water in place until it can infiltrate into the soil.

LEPA irrigation generally is applied to alternate furrows; reducing overall wetted surface area, and hence reducing evaporation losses immediately following an irrigation application. Because a relatively large amount of water is applied to a relatively small surface area, there is the potential of runoff losses from LEPA, especially on clay soils and/or sloping ground. Furrow dikes and circular planting patterns help reduce the runoff risk. Still, LEPA is not universally applicable as some slopes are just too steep for effective application of LEPA irrigation.

Low pressure spray systems – LESA, MESA and LPIC - offer more flexibility in row orientation, and they may be easier for some growers to manage, especially on clay soils or sloping fields. Objectives with these systems include applying water at low elevation (generally 1-2 feet from the soil surface for LESA; often 5 - 10 feet for MESA) to reduce evaporation losses from water droplets (especially important in windy conditions); applying water at a rate not exceeding the soil's infiltration capacity (preventing runoff); and selecting a nozzle package that provides good distribution uniformity and appropriate droplet size and wetting pattern.

A well designed, maintained and managed center pivot irrigation system can provide a high level of irrigation application efficiency and distribution uniformity. It offers the ability to apply a range of application rates to meet changing crop water requirements, and it can be re-nozzled if needed to adapt to changing irrigation capacities. A key to efficient irrigation management through center pivot application is optimizing irrigation scheduling (depth and timing) to meet the crop water demand with an application rate (precipitation rate) to match soil permeability.

---

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the Texas AgriLife Extension Service or Texas AgriLife Research.

IRRIGATION SCHEDULING: WHEN AND HOW MUCH?

Good irrigation management provides sufficient water to the crop to avoid drought stress, while avoiding over-irrigation which can lead to runoff and/or deep percolation losses as well as poorly aerated (anoxic) conditions. In meeting crop water demands, it is helpful to keep in mind how plants use water. Without addressing the specifics of plant physiology, plants draw water and dissolved nutrients from the root zone through their roots, xylem, plant tissues and eventually through stomata. Generally speaking, roots grow best in moist soil, since dry or saturated conditions limit root growth. Contrary to popular belief, roots do not grow in dry soil. Managing soil moisture conditions that encourage an expansive root system can in effect maximize the plant's ability to extract water and dissolved nutrients from a greater volume of soil, therefore potentially increasing nutrient use efficiency as well as water use efficiency (from rainfall, irrigation and stored soil moisture sources).

Irrigation planning should take into account crop water needs (seasonal and peak water use), soil permeability, soil moisture storage capacity, irrigation water availability (well capacity or water allocations) and equipment capabilities. Particularly in water-limited crop production systems, water use efficiency and relative economic return can be key factors in irrigation management decisions. To aid producers in irrigation resource allocation and planning, Klocke, et al. (2005) developed the Crop Water Allocator, (available at www.oznet.ksu.edu/mil) that is a user-oriented computer program for cropping system decisions based on economically optimum allocation of limited irrigation resources.

Pre-season and Early Season Irrigation Management

Where water resources and/or irrigation system capabilities are insufficient to meet full irrigation demand, and where soil moisture at planting is insufficient to ensure crop germination, it is common practice to apply a pre-season or "pre-plant" irrigation. The decision of when to apply a pre-season irrigation and how much to apply can be challenging. Research conducted at Halfway, Texas (Bordovsky and Porter, 2003) indicated that in this area known for its dry windy spring conditions, pre-season irrigation losses can be very high, with total water losses from irrigation and rainfall exceeding 47% in the 30-45 days preceding planting. In the same study, however, yield reductions were observed in fields where pre-plant irrigation was limited. Hence although starting irrigation applications too early can result in excessive losses of applied water, insufficient stored soil moisture limits crop productivity, particularly where irrigation capacities are insufficient to meet crop water requirements.

Pre-season irrigation considerations include:

- What is the soil moisture? Consider the seedbed as well as the crop's potential root zone. Soil moisture is field-specific and can be greatly affected by the crop previously grown in that field as well as off-season precipitation and atmospheric conditions.
- What is the capacity of the irrigation system and water resource? Low (gallons per minute per acre) capacity systems require more time to apply a given amount of water to the field. Table 1 relates approximate irrigation application rates according to irrigation system capacity.
- What is the target pre-season soil moisture? Consider the soil's water holding capacity, and whether the soil is to be wetted to field capacity, or if allowance should be made for the storage of anticipated rainfall before planting.
- Keep in mind that through the early part of the crop season (planting through early vegetative stages) crop water requirements may be relatively low; hence there may be opportunity to continue to build soil moisture reserve after planting.

Table 1. Approximate depths of application (inches per day or inches per week) as related to irrigation system capacity (gallons per minute per acre).

Relating irrigation system capacity to depth of application (Gallons per minute per acre to inches per day or inches per week)		
GPM/Acre	**Inches/Day**	**Inches/Week**
1	0.053	0.37
2	0.11	0.74
3	0.16	1.11
4	0.21	1.48
5	0.27	1.86
6	0.32	2.23
7	0.37	2.60
8	0.42	2.97
9	0.48	3.34
10	0.53	3.71
Note: these values do not take into account irrigation efficiency.		

In-season Irrigation Scheduling

In-season irrigation scheduling generally involves meeting crop water demand, including peak water demand, if possible. Long-term averages and research-based water use curves can be very useful in irrigation planning, and many of these are available through local or state Cooperative Extension Services. Optimal day-to-day in-season management, however, takes into account current soil moisture, crop and atmospheric demand conditions. Evapotranspiration (ET) networks provide in-season crop water demand estimates as determined by atmospheric conditions, crop(s) and growth stages. ET data sources include the Kansas State University Weather Data Library (http://www.oznet.ksu.edu/wdl/); the High Plains Regional Climate Center Automated Weather Data Network (AWDN, serving Colorado, Iowa, Kansas, Minnesota, Missouri, Montana, North Dakota, Nebraska, South Dakota and Wyoming http://www.hprcc.unl.edu/awdn/); the North Dakota Agricultural Weather Network (NDAWN, serving North Dakota, Montana and Minnesota, http://ndawn.ndsu.nodak.edu/); Oklahoma Agweather (http://agweather.mesonet.org/); the Texas High Plains Evapotranspiration Network (TXHPET, http://txhighplainset.tamu.edu); and others.

Crop water demand varies with crop and growth stage. Also the relative effect of drought stress on crop yield can vary with growth stage. For instance, the most critical period during which water stress will have the greatest effect on corn yield potential corresponds with the maximum water demand period, approximately two weeks before and after silking. Cotton yield potential is largely determined before square initiation; yet peak water demand occurs during flowering. Excess water and nitrogen late in the season can encourage excessive (undesirable) late season vegetative growth in cotton. Crop production manuals published by state Cooperative Extension services provide detailed information on crop water requirements. Examples of these materials and how they may be accessed include Kansas State University crop production handbooks for alfalfa, corn, grain sorghum, soybeans, sunflowers and wheat which are available from the KSU Mobile Irrigation Lab Tool Kit and Resources (http://www.oznet.ksu.edu/mil/ToolKit.htm).

Late Season Irrigation Management

Irrigation termination decisions involve predicting how much water will be needed by the crop from the last irrigation until physiological maturity or harvest. Long-term “average” crop water use curves from local experience or published literature; estimates of stored soil moisture; anticipated rainfall and other climate considerations; economic considerations (yield return vs. irrigation costs); and irrigation system capabilities are all factors that should be considered. Irrigation termination recommendations are often based upon local applied research programs.

MANAGING SOIL MOISTURE

Especially where irrigation capacities are insufficient to meet crop water demand, stored soil moisture is relied upon to help make up the difference. Soil moisture monitoring is a very useful complement to evapotranspiration (ET)-based information.

In many semi-arid areas, including the Texas Southern High Plains, pre-season irrigation or excess early season irrigation is used to provide moisture for crop establishment and to fill soil moisture storage capacity to augment often deficit irrigation during peak crop water use periods. Pre-season irrigation water losses through evaporation and deep percolation can be quite high. Hence it is important for growers to understand how much water their soil root zone will hold, taking into account the effective root zone depth and soil moisture storage capacity per foot of soil. Applying more water than the soil can hold can result in deep percolation losses or runoff; starting irrigation too early increases opportunity for evaporation losses. These risks need to be balanced with irrigation system capacity.

The Root Zone and Soil Water Holding Capacity

The potential root zone depth is determined by the crop; however effective root zone depth is often limited by soil conditions. Soil compaction, caliche layers, perched water tables, and other impeding conditions will limit the effective rooting depth. Roots are generally developed early in the season, and will grow in moist (not saturated or extremely dry) soil. Most crops will extract most (70% - 85%) of their water requirement from the top one to two feet of soil, and almost all of their water from the top 3 feet of soil, if water is available. Deep soil moisture is beneficial primarily when the shallow moisture is depleted to a water stress level. Commonly reported effective root zone depths by crop are listed in Table 2.

Table 2. Effective root zone depths reported for selected crops. These values represent the majority of feeder root as reported by various sources.

Crop	**Approximate Effective Rooting Depth (feet)**
Alfalfa	3.3 – 6.6+
Corn	2.6 – 5.6
Cotton	2.6 – 5.6
Sorghum	3.3 – 6.6
Vegetables	1 - 3

Deep percolation losses are often overlooked, but they can be significant. Water applied in excess of the soil's moisture storage capacity can drain below the crop's effective root zone. In some cases, periodic deep leaching is desirable to remove accumulated salts from the root zone. But in most cases, deep percolation losses can have a significant negative impact on overall water use efficiency - even under otherwise efficient irrigation practices such as low energy precision application (LEPA) and subsurface drip irrigation (SDI) irrigation. Leaching of nutrients and agricultural chemicals through deep percolation can reduce efficiency and efficacy of these inputs and present groundwater contamination risks. Coarse soils are particularly vulnerable to deep percolation losses due to their low water holding capacity. Other soils may exhibit preferential flow deep percolation along cracks and in other channels formed under various soil structural and wetting pattern scenarios.

Runoff losses occur when water application rate (from irrigation or rainfall) exceeds soil permeability. Sloping fields with low permeability soils are at greatest risk for runoff losses. Vegetative cover, surface conditioning (including furrow dikes), and grade management (land leveling, contouring, terracing, etc.) can reduce runoff losses. Irrigation equipment selection (nozzle packages) and management can also help to minimize runoff losses.

A soil’s capacity for storing moisture is affected by soil structure and organic matter content, but it is determined primarily by soil texture. **Field capacity** is the soil water content after soil has been thoroughly wetted when the drainage rate changes from rapid to slow. This point is reached when all the *gravitational water* has drained. Field capacity is normally attained 2-3 days after irrigation and reached when the soil water tension is approximately 0.3 bars (30 kPa or 4.35 PSI) in clay or loam soils, or 0.1 bar in sandy soils. **Permanent wilting point** is the soil moisture level at which plants cannot recover overnight from excessive drying during the day. This parameter may vary with plant species and soil type and is attained at a soil water tension of 10-20 bars. *Hygroscopic water* is held tightly on the soil particles (below permanent wilting point) and cannot be extracted by plant roots. **Plant available water** is retained in the soil between field capacity and the permanent wilting point. It is often expressed as a volumetric percentage or in inches of water per inch of soil depth or inches of water per foot of soil depth. Approximate plant available water storage capacities are 0.6 - 1.25 inches water per foot of soil depth for fine sandy soils; 1.2 – 1.9 inches water per foot of soil for loam soils; and 1.5 – 2.3 inches water per foot of soil for clay loam soils.

To avoid drought stress, a **management allowable depletion** is often imposed as a trigger for irrigation applications. Management allowable depletion is often in the range of 50-60% of plant available water for many agronomic crops, but may be as low as 20-30% of plant available water for drought sensitive crops.

Permeability is the ability of the soil to take in water through infiltration. A soil with low permeability cannot take in water as fast as a soil with high permeability; the permeability therefore affects the risk for runoff loss of applied water. Permeability is affected by soil texture, structure, and surface condition. Generally speaking, fine textured soils (clays, clay loams) have lower permeability than coarse soils (sand). Surface sealing, compaction, and poor structure (particularly at or near the surface) limit permeability.

Information about soil water characteristics, including plant available water, soil texture, and permeability are available for most major soils in the U.S. including the Central High Plains is available free of charge from the United States Department of Agriculture Natural Resources Conservation Service on their Web Soil Survey website at http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm.

Soil Moisture Monitoring and Soil Water Measurement

Methods used to measure soil water are classified as *direct* and *indirect*. The direct method refers to the gravimetric method in which a soil sample is collected, weighed, oven-dried and weighed again to determine the sample's water content on a mass percent basis. The gravimetric method is the standard against which the indirect methods are calibrated. Some commonly used indirect methods include electrical resistance, capacitance and tensiometry (Enciso, et al., 2001).

Electrical resistance methods include gypsum blocks or granular matrix sensors (more durable and more expensive than gypsum blocks) that are used to measure electrical resistance in a porous medium. Electrical resistance increases as soil water suction increases, or as soil moisture decreases. Sensors are placed in the soil root zone, and a meter is connected to lead wires extending above the ground surface for each reading. For most on-farm applications, small portable handheld meters are used; automated readings and controls may be achieved through use of dataloggers (Enciso, et al., 2001).

Capacitance sensors measure changes in the *dielectric constant* of the soil with a capacitor, which consists of two plates of a conductor material separated by a short distance (less than 3⁄8 of an inch). A voltage is applied at one extreme of the plate, and the material that is between the two plates stores some voltage. A meter reads the voltage conducted between the plates. When the material between the plates is air, the capacitor measures 1 (the dielectric constant of air). Most solid soil components (soil particles), have a dielectric constant from 2 to 4. Water has higher dielectric constant of 78. Hence, higher water contents in a capacitance sensor are indicated by higher measured dielectric constants. Changes in the dielectric constant provide an indication of soil water content. Sensors are often left in place in the root zone, and they can be connected to a datalogger for monitoring over time (Enciso, et al., 2001).

Tensiometers measure tension of water in the soil (soil suction). A tensiometer consists of a sealed water-filled tube equipped with a vacuum gauge on the upper end and a porous ceramic tip on the lower end. As the soil dries, soil water tension (suction) increases; in response to this increased suction, water is moved from the tensiometer through the porous ceramic tip, creating a vacuum in the sealed tensiometer tube. Water can also move from the soil into the tensiometer during or following an irrigation. Most tensiometers have a vacuum gauge graduated from 0 to 100 (centibars, cb, or kilopascals, kPa). A reading of 0 indicates a saturated soil. As the soil dries, the reading on the gauge increases. The useful limit of the tensiometer is about 80 cb. Above this tension, air enters through the ceramic cup and causes the instrument to break suction with the soil and fail reading on the gauge. Therefore, these instruments are most useful in sandy soils and with drought-sensitive crops because they have narrower operational soil moisture ranges (Enciso, et al., 2001).

Alternately, a soil's moisture condition can be assessed by observing its **feel and appearance**. A soil probe, auger, or spade may be used to extract a small soil sample within each foot of root zone depth. The sample is gently squeezed manually in the palm of a hand to determine whether the soil will form a ball or cast, and whether it leaves a film of water and/or soil in the hand. Pressing a portion of the sample between the thumb and forefinger allows one to observe whether the soil will form a ribbon. Results of the sample are compared with guidelines described by the USDA-NRCS (1998).

Soil water monitoring methods have advantages and limitations. They vary in cost, accuracy, ease of use, and applicability to local conditions (soils, moisture ranges, etc.) Most require calibration for accurate moisture measurement. Proficiency of use and in interpreting information results from practice and experience under given field conditions.

CONCLUSIONS AND RECOMMENDATIONS

Crop water requirements are crop-specific, and they vary with weather and growth stage. Water management is especially important for critical periods in crop development. Knowledge of the root zone should be applied to optimize irrigation management taking into account the crop’s effective rooting depth, the soil moisture storage capacity, and field-specific conditions (shallow soils, caliche layers, etc.). In the use of irrigation scheduling, soil moisture monitoring, evapotranspiration information, and/or plant indicators can be used to fine-tune water applications to meet crop needs.

REFERENCES

Bordovsky, James P. and Dana O. Porter. 2003. Cotton response to pre-plant irrigation level and irrigation capacity using spray, LEPA and subsurface drip irrigation. ASAE Paper No. 032008. Presented at: 2003 Annual International Meeting of the American Society of Agricultural Engineers, Las Vegas, Nevada, July 27-30, 2003.

Enciso, Juan, Dana Porter, and Xavier Peries. 2007. Irrigation Monitoring with Soil Water Sensors. Fact Sheet B-6194. Texas AgriLife Extension Service, Texas A&M System, College Station, TX.

Klocke, Norman L., Loyd R. Stone, Gary A. Clark, Troy J. Dumler, and Steven Briggeman. 2005. Crop water allocation for limited groundwater. ASAE Paper No. 052187. Presented at: 2005 Annual International Meeting of the American Society of Agricultural Engineers, Tampa, Florida, July 17-20-2005.

Porter, D.O., T.H. Marek, T.A. Howell, and L. New. 2005. The Texas High Plains Evapotranspiration Network (TXHPET) User Manual v. 1.01. Texas A&M University Agricultural Research and Extension Center Rep. 03-37. Available at: http://txhighplainset.tamu.edu/usermanual.pdf (accessed 01/28/09).

High Plains Regional Climate Center Automated Weather Data Network (AWDN). University of Nebraska-Lincoln. http://www.hprcc.unl.edu/awdn/ (accessed 01/28/09).

Kansas State University Mobile Irrigation Laboratory. Kansas State University Research and Extension. http://www.oznet.ksu.edu/mil/ (accessed 01/28/09).

Kansas State University Mobile Irrigation Laboratory Tool Kit and Resources. Kansas State University Research and Extension. http://www.oznet.ksu.edu/mil/ToolKit.htm (accessed 01/28/09).

Kansas State University Weather Data Library. Kansas State University Research and Extension. http://www.oznet.ksu.edu/wdl/ (accessed 01/28/09).

North Dakota Agricultural Weather Network. North Dakota State University Department of Soil Science. http://ndawn.ndsu.nodak.edu/ (accessed 01/28/09).

Oklahoma Agweather / Oklahoma Mesonet. Oklahoma State University and the University of Oklahoma. http://agweather.mesonet.org/ (accessed 01/28/09).

USDA-NRCS. 1998. Estimating soil moisture by feel and appearance. United States Department of Agriculture Natural Resources Conservation Service Program Aid Number 1619.

USDA-NRCS. 2008. Web Soil Survey. United States Department of Agriculture Natural Resources Conservation Service. http://websoilsurvey.nrcs.usda.gov/ (accessed 01/28/09).

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N. Thompson, Colby, Kansas

COMPARISON OF GRAIN SORGHUM, SOYBEAN, AND COTTON PRODUCTION UNDER SPRAY, LEPA, AND SDI

Paul D. Colaizzi
Agricultural Engineer
Phone: 806-356-5763
paul.colaizzi@ars.usda.gov

Steven R. Evett
Research Soil Scientist
Phone: 806-356-5775
steve.evett@ars.usda.gov

Terry A. Howell
Research Leader (Agric. Engr.)
Phone: 806-356-5746
terry.howell@ars.usda.gov

R. Louis Baumhardt
Research Soil Scientist
Phone: 806-356-5766
r.louis.baumhardt@ars.usda.gov

USDA-ARS
P.O. Drawer 10
Bushland, Texas 79012-0010
FAX: 806-356-5750

ABSTRACT

Crop production was compared under subsurface drip irrigation (SDI), low energy precision applicators (LEPA), low elevation spray applicators (LESA), and mid elevation spray applicators (MESA) at the USDA-Agricultural Research Service Conservation and Production Research Laboratory, Bushland, Tex., USA. Each irrigation method was compared at irrigation rates meeting 25, 50, 75, and 100% of full crop evapotranspiration (ET_c). Crops included three seasons of grain sorghum, one season of soybean (planted following a cotton crop that was destroyed by hail), and four seasons of upland cotton. For grain sorghum, SDI followed by LEPA, MESA, and LESA resulted in greater grain yield, water use efficiency, and irrigation water use efficiency at the 25- and 50% irrigation rates, whereas MESA followed by LESA outperformed LEPA and SDI at the 75- and 100% irrigation rates. For soybean, the same trend was observed at the 25- and 50% irrigation rates, whereas SDI followed by MESA, LEPA, and LESA resulted in the best crop response at the 75% irrigation rate, and MESA followed by SDI, LESA, and LEPA resulted in the best crop response at the 100% irrigation rate. Cotton response was consistently best for SDI, followed by LEPA, and either MESA or LESA at all irrigation rates. Within each irrigation rate, few significant differences were observed among irrigation methods in total seasonal water use for all crops.

INTRODUCTION

Irrigation is practiced on approximately 4 million of the 8.5 million cultivated acres in the semiarid Texas High Plains. Irrigation results in substantially greater crop productivity and water use efficiency compared with dryland production where precipitation is limited or sporadic (Howell, 2001). The Ogallala Aquifer is the primary water resource for irrigated agriculture in the U.S. Great Plains, including the Texas High Plains, and is one of the largest freshwater resources in the world. However, the Ogallala Aquifer has been declining in many areas because withdrawals (the vast majority being for irrigation) have greatly exceeded recharge. The Ogallala is the major part of the High Plains aquifer, which underlies 175,000 square miles across eight Great Plains states, representing 27 percent of U.S. irrigated land. The practice of efficient irrigation is therefore imperative to simultaneously prolong the life of the Ogallala and High Plains aquifers, conserve energy used for pumping, and sustain rural economies.

Center pivot irrigation systems equipped with low-pressure application packages and subsurface drip irrigation (SDI) can be highly efficient in terms of uniformity, application efficiency, and crop water productivity compared with gravity irrigation (Schneider, 2000; Camp, 1998). In the Texas High Plains, about 75 percent of the irrigated area is by center pivot, with gravity and SDI comprising about 20 and 5 percent, respectively (Colaizzi et al., 2009). Center pivot application packages initially included impact sprinklers, but these have been supplanted by packages that operate at lower pressure and hence reduce energy consumption, including mid elevation spray applicators (MESA), low elevation spray applicators (LESA), and low energy precision applicators (LEPA) (Lyle and Bordovsky, 1983). Surface and subsurface drip irrigation were first adopted in Texas during the mid-1980s for cotton production (Henggeler, 1995); SDI has greatly expanded in the Trans Pecos and Southern High Plains cotton producing regions (Enciso et al., 2007; Bordovsky et al., 2008).

There is anecdotal evidence that SDI results in greater crop yield, greater water use efficiency, and earlier cotton maturity relative to center pivot systems equipped with spray or LEPA packages. Cotton earliness under SDI is thought to be related to reduced evaporative cooling from the soil surface and plant canopy relative to that under center pivot systems. Reduced evaporation could result in warmer soil temperatures and encourage more vigorous early-season plant development. However, this may be countered somewhat by the greater cooling effect on the soil from the more frequent irrigation inherent with SDI (Wanjura et al., 1996). In any case, warmer soil temperatures would be a critical advantage for cotton production in thermally-limited climates where corn is traditionally produced, such as the northern Texas Panhandle and southwestern Kansas (Howell et al., 2004; Colaizzi et al., 2005). In addition, SDI has been shown to be technically feasible and economically advantageous over center pivot under certain circumstances for corn production in western Kansas (Lamm et al., 1995; Lamm and Trooien, 2003; O’Brien et al., 1998). Despite these apparent advantages, the initial capital expense, greater maintenance and management requirements, and difficulty with crop germination in dry soil (Bordovsky and Porter, 2003; Enciso et al., 2005; Thorburn et al., 2003), have been persistent barriers to greater adoption of SDI.

The objective of this paper was to compare crop production under MESA, LESA, LEPA, and SDI in a multi-year experiment at Bushland, Tex., USA. Crops included grain sorghum, soybean, and cotton. Production parameters measured included crop yield, seasonal water use (irrigation applied + rain + change in soil water storage), water use efficiency (WUE), and irrigation water use efficiency (IWUE). WUE was defined as the ratio of economic yield (Y) to seasonal water use, or WUE = Y $(ET)^{-1}$. IWUE was defined as the increase in irrigated yield (Y_i) over dryland yield (Y_d) due to irrigation (IR), or IWUE = $(Y_i\text{-}Y_d)\ IR^{-1}$ (Bos, 1980). Loan value and gross returns were also reported for cotton.

MATERIALS AND METHODS

This research was conducted at the USDA Agricultural Research Service Conservation and Production Research Laboratory at Bushland, Texas (35° 11′ N lat., 102° 06′ W long., 3,894 ft elevation above MSL). The soil is a Pullman clay loam (fine, superactive, mixed, thermic torrertic Paleustoll; USDA-NRCS, 2009) with slow permeability due to a dense B21t horizon that is 6- to 20-in. below the surface. A calcic horizon begins at approximately 4 ft below the surface.

The relative performance of mid elevation spray applicators (MESA), low elevation spray applicators (LESA), low energy precision applicator (LEPA), and subsurface drip irrigation (SDI) were compared for irrigation rates ranging from near dryland to meeting full crop evapotranspiration (ET_c) in a strip-split block design. The irrigation rates were designated I_0, I_{25}, I_{50}, I_{75}, and I_{100}, where the subscripts were the percentage of irrigation applied relative to meeting full ET. The I_0 plots were similar to dryland production, in that they received only enough irrigation around planting to ensure crop establishment, except irrigated fertility and seeding rates were used. The MESA, LESA, and LEPA methods (see Table 1 for details on application devices) were applied with a hose-fed, three-span Valmont[1] lateral-move irrigation system, where each span contained a complete block (i.e., a replicate). Irrigation rates were imposed by varying the speed of the lateral. The SDI method consisted of laterals chiseled beneath alternate furrows at the 12-in. depth, where irrigation rates were imposed by varying emitter flow rates and spacing (Table 2).

Cropping seasons included grain sorghum (2000, 2001, and 2002; Table 3), soybean (2005; Table 3), and cotton (2003, 2004, 2006, and 2007; Table 4). Soybean was planted after the 2005 cotton crop was destroyed by hail. All crops

---

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

were planted in east-west oriented raised beds on 30-in. centers. Dikes were installed in all furrows after crops had developed true leaves to control run on and runoff of irrigation water and rain (Schneider and Howell, 2000; Howell et al., 2002). Crop varieties and cultural practices were similar to those practiced in the region for high crop yields (Tables 3 and 4).

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

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

[a] All sprinkler components manufactured by Senninger Irrigation, Inc., Orlando, Fla., except where noted.
[b] All devices equipped with 10 psi pressure regulators and No. 17 (0.27-in) plastic spray nozzles, giving a flow rate of 6.5 gpm.
[c] Manufactured by A. E. Quest and Sons, Lubbock, Tex.

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

Irrigation rate	Emitter Flow Rate (gph)	Emitter Spacing (in.)	Emitter Application Rate (in. h^{-1})
I_0 [b]	--	--	--
I_{25}	2.6	36	0.019
I_{50}	3.3	24	0.038
I_{75}	3.3	16	0.057
I_{100}	3.3	12	0.076

[a] All SDI dripline manufactured by Netafim USA, Fresno, Calif.
[b] Smooth tubing, no emitters

Volumetric soil water was measured by gravimetric samples to the 6 ft depth in 1-ft increments at planting and harvest. Soil water was also measured during the crop season by neutron scattering to the 7.5-ft depth in 8-in. increments (Evett and Steiner, 1995) using a depth control stand (Evett et al., 2003). Neutron moisture meters were field-calibrated and achieved accuracies better than 0.005 $m^3 m^{-3}$ (or 0.06 in. ft^{-1}). Near-surface soil water and temperatures were also measured with time-domain reflectometry and copper-constantan thermocouples, respectively (Evett et al., 2006) during the soybean and last two cotton seasons (Colaizzi et al., 2006a; 2006b). Irrigations for grain sorghum were scheduled using the Texas High Plains Evapotranspiration Network (Porter et al., 2005). Irrigations for soybean and cotton were scheduled when measured soil water deficit (by neutron scattering) averaged 1 in. in the I_{100} plots. The I_{100} plots received sufficient irrigation to bring the soil profile to field capacity; the I_{75}, I_{50}, and I_{25} plots received proportionately less. In some years, all plots received a uniform 1-in. spray application to ensure germination.

Table 3. Agronomic data for grain sorghum (2000, 2001, and 2002 seasons; Colaizzi et al., 2004) and soybean (2005 season; Colaizzi et al., 2006a).

Year	2000	2001	2002	2005
Crop	Grain sorghum	Grain sorghum	Grain sorghum	Soybean [c]
Variety	Pioneer 84G62	Pioneer 8966	Pioneer 84G62	Pioneer 94M90
Plant density (seeds ac^{-1})	121,000	93,000	89,000	182,000
Planting date	26-May	22 June[b]	31-May	20-Jun
Harvest date	21-Sep	29-Oct	14-Nov	26-Oct
Precipitation (in.)	5.5	4.9	12.5	5.5
Fertilizer applied	68 lb ac^{-1} preplant P		51 lb ac^{-1} preplant P	102 lb ac^{-1} preplant P
	52 lb ac^{-1} preplant N	160 lb ac^{-1} preplant N	143 lb ac^{-1} preplant N	158 lb ac^{-1} preplant N [c]
	40 lb ac^{-1} irr. N (I_{100}) [a]	16 lb ac^{-1} irr. N (I_{100}) [a]		
Herbicide applied	2.0 qt ac^{-1} Bicep	2.0 qt ac^{-1} Bicep	1.4 lb ac^{-1} Atrazine	1.0 qt ac^{-1} Treflan
Insecticide applied	0.25 qt ac^{-1} Lorsban	None	None	None

[a] Liquid urea 32-0-0 injected into irrigation water; deficit irrigation treatments received proportionately less.
[b] Two previous plantings on 22 May and 5 June failed to emerge.
[c] Replaced cotton that was destroyed by hail.

Table 4. Agronomic data for cotton (2003, 2004, 2006, and 2007 seasons; Colaizzi et al., 2005; 2006b).

Year	2003	2004	2006	2007
Crop	Cotton	Cotton	Cotton	Cotton
Variety	Paymaster 2280 BG, RR	Paymaster 2280 BG, RR	Paymaster 2280 BG, RR	Paymaster 2280 BG, RR
Plant density (seeds ac^{-1})	70,000	80,000	80,000	60,000
Planting date	10-Jun [a]	20-May	17-May	29-May
Harvest date	21-Nov	14-Dec	13-Dec	5-Nov
Total heat units (DD60's, F)	1940	1560	2280	1980
Precipitation (in.)	6.6	19.5	14.3	8.0
Fertilizer applied	95 lb ac^{-1} preplant P	102 lb ac^{-1} preplant P	74 lb ac^{-1} preplant P	78 lb ac^{-1} preplant P
	28 lb ac^{-1} preplant N	30 lb ac^{-1} preplant N	16 lb ac^{-1} preplant N	17 lb ac^{-1} preplant N
	43 lb ac^{-1} irr N (I_{100}) [b]	45 lb ac^{-1} irr N (I_{100}) [b]	70 lb ac^{-1} irr N (I_{100})[b]	120 lb ac^{-1} irr N (I_{100}) [b]
Herbicide applied	1.0 qt ac^{-1} Treflan	1.0 qt ac^{-1} Treflan	1.0 qt ac^{-1} Treflan	1.0 qt ac^{-1} Treflan
				1.0 qt ac^{-1} Round Up
Insecticide applied	NONE	NONE	0.5 qt ac^{-1} Lorsban	0.5 qt ac^{-1} Lorsban
Growth regulator applied	NONE	NONE	NONE	NONE
Defoliant applied	NONE	NONE	NONE	0.5 qt ac^{-1} Paraquat
Boll opener applied	NONE	NONE	NONE	0.5 qt ac^{-1} Gin Star

[a] The first planting on 21-May sustained severe hail damage on 3-Jun.
[b] Liquid urea 32-0-0 injected into irrigation water; deficit irrigation treatments received proportionately less.

Crop yield (derived from hand sampling a 108 ft^2 area in each plot), seasonal water use, water use efficiency (WUE), and irrigation water use efficiency (IWUE) were compared using the SAS PROC MIXED procedure (Littell et al., 2006). Loan value and gross return were also compared for cotton. Any differences in these parameters were tested using least squared differences ($\alpha \leq 0.05$), and means were separated by letter groupings using a macro by Saxton (1998).

RESULTS AND DISCUSSION

Grain Sorghum

The relative performance of the irrigation methods changed with the irrigation rate for grain sorghum (Table 5). For the lower irrigation rates (I_{25} and I_{50}), grain yield was greatest for SDI, followed by LEPA, MESA, and LESA. For the higher irrigation rates (I_{75} and I_{100}), grain yield was greatest for MESA, followed by LESA. The only significant difference ($\alpha \leq 0.05$) occurred at I_{25}, where grain yield under SDI was significantly greater than for the other irrigation methods. The other differences were only numerical, although some additional significant differences did occur within individual seasons (Colaizzi et al., 2004). Grain yield was significantly different for each irrigation rate average (except between I_{75} and I_{100}), and was positively correlated with the irrigation rate as expected. For irrigation method averages, grain yield was greatest for SDI, followed by MESA, LEPA, and LESA, where the only significant difference was observed between SDI and LESA. For seasonal water use, the only significant differences observed were between irrigation rate averages. WUE and IWUE followed the same trends observed for grain yield among irrigation rates and for irrigation method averages. For irrigation rate averages, however, WUE was greatest at I_{75}, followed by I_{50}, I_{100}, I_{25}, and I_0, and IWUE was greatest at I_{50}, followed by I_{25}, I_{75}, and I_{100}. The least WUE occurred at I_0, which was only about 38 percent of WUE at I_{50}, and shows the impact of irrigation on WUE (Howell, 2001). It appears that diminishing crop response to water was reached around I_{75}, as yield was not much greater at I_{100} and maximum WUE occurred at I_{75}.

We speculate that different factors, depending on irrigation rate, may have influenced the relative performance of the irrigation methods that were observed for grain sorghum. One rationale of SDI and LEPA is that evaporative losses from the plant canopy and air above the canopy and losses to wind drift are virtually eliminated, and that evaporative looses from the soil are greatly reduced (because of less soil wetting) compared with spray applicators. This would allow a greater proportion of irrigation water to be available for plant transpiration (assuming no other losses occurred such as runoff or deep percolation) and hence increase crop productivity. This hypothesis was supported by the greater grain yield observed for SDI compared with the other methods at the I_{25} and I_{50} irrigation rates (Table 5). Grain yield with LEPA was only slightly greater than MESA, suggesting both had similar total evaporative losses. However, MESA loss pathways may have also included evaporation from the canopy and overlying air and wind drift (which probably were not present under LEPA), but less loss pathways by soil water evaporation compared with LEPA. Grain yield was greater for MESA compared with LESA at all irrigation rates, but more so at I_{25} and I_{50}. This may have been caused by greater erosion of furrow dikes and runoff away from the center of the plot (where grain yield was measured by hand samples) under LESA. The spray applicator height of LESA was 1 ft, whereas it was 5 ft for MESA (Table 3). Therefore, the plant canopy would be expected to intercept more irrigation water with MESA, whereas greater risk of furrow dike erosion may result with the low applicator height of LESA, which does not divert water away from furrow dikes like the double-ended drag sock used with LEPA.

At the I_{75} and I_{100} irrigation rates, the lack of soil aeration and nutrient leaching by deep percolation may have reduced grain sorghum yield for SDI (and to a lesser extent LEPA) compared with MESA and LESA (Table 5). Colaizzi et al. (2004) observed increases in volumetric soil water between the 6- and 10-ft depths over successive measurements with neutron scattering for SDI at I_{75} and I_{100}, LEPA at I_{100}, but not for MESA or LESA. This was attributed to deep percolation rather than upward capillary movement, since the depth to saturated thickness of the Ogallala Aquifer was approximately 250 ft. Lamm et al. (1995) reported that corn yield with SDI was lower at 125% of full ET compared with 100% ET in two out of three years in a study at Colby, Kan., and also attributed this to poor soil aeration and leaching of nutrients by deep percolation. In that study, Darusman et al. (1997) deduced deep percolation using tensiometer measurements for the 100% and 125% irrigation rates. In the grain sorghum study at Bushland, Tex., the presence of deep percolation suggests that irrigation rates exceeded 100% in some cases for LEPA and SDI. The irrigations were scheduled using the Texas High Plains Evapotranspiration (TXHPET) Network (Porter et al., 2005), which used crop coefficients derived from large weighing lysimeters (Marek et al., 1988; Howell et al., 1995) for several crops including grain sorghum (Howell et al., 1997). The crop coefficients reflect crops irrigated with MESA, and probably have larger values (to compensate for greater evaporation and wind drift) compared with crop coefficients that might have resulted had the coefficients been determined using LEPA or SDI. Consequently, the subsequent studies with soybean and cotton used neutron scattering as the basis for irrigation scheduling.

Table 5. Grain sorghum response, average of 2000, 2001, and 2002 seasons; Colaizzi et al., 2004.

Irrigation Rate [a]	Irrigation method	Grain yield [b] (bu ac^{-1})		Seasonal water use (in.)		WUE (bu ac^{-1} $in.^{-1}$)		IWUE (bu ac^{-1} $in.^{-1}$)	
I_{25}	MESA	60.8	b [c]	18.1	a	3.80	b	8.57	b
(7.0 in.)	LESA	49.7	b	18.5	a	3.07	b	6.37	b
	LEPA	65.3	b	18.5	a	3.97	b	9.49	b
	SDI	99.5	a	18.9	a	5.96	a	16.32	a
I_{50}	MESA	123.3	a	22.1	a	6.12	ab	11.77	a
(10.8 in.)	LESA	109.3	a	22.5	a	5.36	b	10.36	a
	LEPA	127.0	a	22.2	a	6.24	ab	12.23	a
	SDI	140.7	a	22.3	a	7.02	a	13.74	a
I_{75}	MESA	152.3	a	25.0	a	6.71	a	10.48	a
(14.7 in.)	LESA	144.5	a	25.7	a	6.12	a	9.92	a
	LEPA	141.5	a	25.3	a	6.09	a	9.63	a
	SDI	142.1	a	24.8	a	6.33	a	9.55	a
I_{100}	MESA	162.7	a	28.6	a	6.14	a	8.69	a
(18.6 in.)	LESA	155.9	a	28.5	a	5.90	a	8.26	a
	LEPA	146.6	a	28.0	a	5.67	a	7.69	a
	SDI	144.8	a	28.6	a	5.47	a	7.47	a
Irrigation rate averages									
I_0 (3.1 in.)		18.1	d [d]	14.9	e	1.59	c	----	
I_{25} (7.0 in.)		68.8	c	18.5	d	4.20	b	10.19	ab
I_{50} (10.8 in.)		125.1	b	22.3	c	6.19	a	12.03	a
I_{75} (14.7 in.)		145.1	a	25.2	b	6.31	a	9.90	bc
I_{100} (18.6 in.)		152.5	a	28.4	a	5.80	a	8.03	c
Irrigation method averages									
	MESA	124.8	ab [e]	23.4	a	5.69	ab	9.88	ab
	LESA	114.9	b	23.8	a	5.11	b	8.73	b
	LEPA	120.1	ab	23.5	a	5.49	b	9.76	b
	SDI	131.8	a	23.6	a	6.20	a	11.77	a

[a] Numbers in parenthesis are average seasonal irrigation totals for each irrigation rate.
[b] Yields were converted from dry mass to 14% moisture content by mass; 1 bu = 55 lb.
[c] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within an irrigation rate.
[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation rate averages.
[e] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation method averages.

Soybean

Soybean response was generally more favorable under SDI compared with other irrigation methods at the I_{25}, I_{50}, and I_{75} irrigation rates (Table 6). At I_{25}, SDI resulted in significantly greater crop yield, WUE, and IWUE compared with MESA and LESA; at I_{50}, these parameters were all significantly greater for SDI compared with MESA, LESA, and LEPA. Seasonal water use was not significantly different among irrigation methods at I_{25}; however, seasonal water use was significantly greater for MESA compared with LESA at I_{50} due to an outlying value in a MESA plot, the cause of which could not be determined. At I_{75}, SDI also resulted in the largest yield, WUE, and IWUE values, followed by MESA, LEPA, and LESA, whereas the ranks of greatest seasonal water use were in opposite order (i.e., SDI had the least but LESA had the most seasonal water use). At I_{100}, however, MESA resulted in the largest yield and IWUE, followed by SDI, LESA, and LEPA. SDI did result in the largest WUE at I_{100}, followed by MESA, LESA, and LEPA. As expected, yield and seasonal water use increased significantly as irrigation rate increased, but maximum WUE and IWUE both occurred at I_{50}, and the smallest WUE occurred at I_0. For irrigation method averages, SDI resulted in significantly greater yield, WUE, and IWUE compared with other methods (except yield with SDI was only numerically greater than MESA). Here, no significant differences were observed for seasonal water use; however, SDI resulted in numerically less seasonal water use compared with other methods.

Soybean yield, WUE, and IWUE followed the same trends as those observed for grain sorghum at I_{25}, I_{50}, and irrigation method averages. At all irrigation rates, MESA outperformed LESA, a result also observed for grain sorghum. These results suggest that similar loss pathways occurred for soybeans as did for grain sorghum, except that poor soil aeration and nutrient leaching may not have been as prevalent at the I_{75} and I_{100} irrigation rates, since irrigations were scheduled using direct measurements of the soil water profile, and no increases in volumetric soil water were observed below the root zone (data not shown). In addition, soil temperatures were greater with SDI compared with other methods during early development stages (Colaizzi et al., 2006a). This may have promoted pod development, and further suggests that SDI results in less evaporative loss (by lack of evaporative cooling) from the soil, a result that was predicted by Evett et al. (1995) for corn.

Table 6. Soybean response, 2005 season; Colaizzi et al., 2006a.

Irrigation Rate [a]	Irrigation method	Yield [b] (bu ac^{-1})		Seasonal water use (in.)		WUE (bu ac^{-1} in.$^{-1}$)		IWUE (bu ac^{-1} in.$^{-1}$)	
I_{25}	MESA	31.4	b [c]	14.7	a	2.15	b	2.41	bc
(2.8 in.)	LESA	29.9	b	15.5	a	1.93	b	1.87	c
	LEPA	33.1	ab	15.1	a	2.19	b	3.00	b
	SDI	36.9	a	14.7	a	2.52	a	4.34	a
I_{50}	MESA	42.1	b	19.2	a	2.20	b	3.11	b
(5.7 in.)	LESA	38.2	b	17.6	b	2.18	b	2.42	b
	LEPA	42.3	b	17.9	ab	2.36	b	3.14	b
	SDI	49.8	a	18.0	ab	2.77	a	4.47	a
I_{75}	MESA	51.2	ab	21.4	ab	2.39	ab	3.14	a
(8.5 in.)	LESA	46.6	b	22.5	a	2.09	c	2.60	a
	LEPA	48.4	ab	22.1	ab	2.18	bc	2.80	a
	SDI	52.7	a	20.9	b	2.53	a	3.32	a
I_{100}	MESA	58.6	a	24.7	a	2.37	ab	3.01	a
(11.3 in.)	LESA	55.2	ab	24.3	a	2.27	ab	2.71	a
	LEPA	51.5	b	24.4	a	2.11	b	2.38	a
	SDI	57.6	a	23.8	a	2.43	a	2.92	a
Irrigation rate averages									
I_0 (0 in.)		24.6	e [d]	12.4	e	1.98	b	----	
I_{25} (2.8 in.)		32.8	d	15.0	d	2.21	b	2.91	a
I_{50} (5.7 in.)		43.1	c	18.2	c	2.38	a	3.28	a
I_{75} (8.5 in.)		49.7	b	21.7	b	2.30	ab	2.96	a
I_{100} (11.3 in.)		55.7	a	24.3	a	2.30	ab	2.76	a
Irrigation method averages									
	MESA	45.8	ab [e]	20.0	a	2.28	b	2.92	b
	LESA	42.5	b	19.9	a	2.14	b	2.40	b
	LEPA	43.8	b	19.9	a	2.21	b	2.83	b
	SDI	49.3	a	19.3	a	2.56	a	3.76	a

[a] Numbers in parenthesis are average seasonal irrigation totals for each irrigation rate.
[b] Yields were converted from dry mass to 13% moisture content by mass; 1 bu = 60 lb.
[c] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within an irrigation rate.
[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation rate averages.
[e] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation method averages.

Cotton

Cotton response was most favorable with SDI, followed by LEPA for all irrigation rates and irrigation method averages (Table 7). SDI resulted in the largest lint yield, WUE, and IWUE values compared with all other irrigation methods for all irrigation rates, followed by LEPA, LESA, and MESA (a minor exception occurred at the I_{50} and I_{75} irrigation rates, where MESA resulted in slightly greater WUE and IWUE compared with LESA). In many cases these differences were significant, with SDI usually being significantly greater than MESA and/or LESA. Seasonal water use, however, was not significantly different among irrigation methods, although SDI resulted in slightly greater numerical values. Preliminary soil temperature data during the 2006 season indicated that SDI maintained warmer soil temperatures early in the season compared with LEPA, LESA, or MESA, which was probably due to reduced evaporative cooling, and supported the hypothesis that SDI may enhance early cotton establishment and growth compared with other irrigation methods (Colaizzi et al., 2006b). Lint yield, seasonal water use, WUE, and IWUE were all significantly greater with increasing irrigation rate, with the largest values observed at I_{100}. This result for WUE and IWUE differed from those for soybean and grain sorghum, where maximum WUE and IWUE occurred below I_{100}.

The fiber quality of cotton has become increasingly important as textiles have adopted high spin technology that requires longer and stronger fibers (e.g., Yu et al., 2001). Fiber quality is comprised of several parameters (micronaire, length, strength, uniformity, color, etc.), and cotton producers receive a premium or discount, called *loan value*, based on overall fiber quality. The irrigation method generally did not result in significant differences in loan value (except at I_{50} where LEPA was significantly greater than LESA); for irrigation amount only I_{100} was significantly greater than I_{25} (Table 8). This would result in gross returns being mostly correlated to lint yield rather than loan value, and SDI resulted in the largest gross returns for all irrigation rates, followed by LEPA. Both SDI and LEPA resulted in significantly greater gross returns compared with MESA and LESA when irrigation methods were averaged.

The relative performance of SDI, LEPA, and spray for cotton were consistent with results of studies at Halfway, Tex. (Segarra et al., 1999; Bordovsky and Porter, 2003). Halfway is approximately 75 miles south of Bushland with lower elevation (3569 ft above MSL), and typically has greater heat units during the cotton season, resulting in greater lint yield and loan value compared with Bushland. Lint yield and loan values herein were similar to those reported by Marek and Bordovsky (2006), who evaluated several cotton varieties (including Paymaster 2280 BG/RR) at Etter, Tex., which is approximately 60 miles north of Bushland but has similar heat units available for cotton production.

Table 7. Cotton response, average of 2003, 2004, 2006, and 2007 seasons; Colaizzi et al., 2005; Colaizzi et al., 2006b.

Irrigation Rate [a]	Irrigation method	Lint yield (lb ac^{-1})		Seasonal water use (in.)		WUE [b] (lb ac^{-1} in.$^{-1}$)		IWUE [b] (lb ac^{-1} in.$^{-1}$)	
I_{25} (2.6 in.)	MESA	413	a [c]	16.4	a	14.5	b	26.7	b
	LESA	441	a	16.8	a	18.6	b	27.6	b
	LEPA	492	a	16.8	a	25.6	ab	29.9	ab
	SDI	572	a	16.9	a	37.1	a	34.8	a
I_{50} (4.4 in.)	MESA	497	b	18.8	a	14.2	b	27.1	b
	LESA	500	b	18.7	a	13.8	b	27.0	b
	LEPA	660	ab	19.4	a	36.7	a	34.4	a
	SDI	715	a	19.5	a	40.8	a	36.4	a
I_{75} (6.2 in.)	MESA	697	b	21.2	a	32.5	b	32.6	bc
	LESA	674	b	21.2	a	29.5	b	31.3	c
	LEPA	777	ab	20.7	a	42.9	ab	37.3	ab
	SDI	911	a	21.5	a	59.6	a	42.8	a
I_{100} (7.9 in.)	MESA	778	b	23.2	a	37.2	b	33.3	b
	LESA	791	ab	23.2	a	37.9	b	33.9	b
	LEPA	885	ab	23.3	a	45.3	ab	37.2	ab
	SDI	951	a	22.8	a	57.3	a	42.1	a
Irrigation rate averages									
I_0 (0.9 in.)		354	e [d]	14.5	e	25.6	c	----	
I_{25} (2.6 in.)		479	d	16.7	d	29.8	bc	23.9	b
I_{50} (4.4 in.)		593	c	19.1	c	31.2	b	26.4	b
I_{75} (6.2 in.)		765	b	21.1	b	36.0	a	41.1	a
I_{100} (7.9 in.)		851	a	23.1	a	36.6	a	44.4	a
Irrigation method averages									
	MESA	596	b [e]	19.9	a	29.9	c	24.6	c
	LESA	601	b	19.9	a	30.0	c	24.9	c
	LEPA	703	a	20.1	a	34.7	b	37.6	b
	SDI	787	a	20.2	a	39.0	a	48.7	a

[a] Numbers in parenthesis are average seasonal irrigation totals for each irrigation rate.
[b] WUE and IWUE were computed based on lint yield.
[c] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within an irrigation rate.
[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation rate averages.
[e] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation method averages.

Table 8. Cotton loan value and gross return, average of 2003, 2004, 2006, and 2007 seasons.

Irrigation Rate [a]	Irrigation method	Loan Value [b] (cents lb^{-1})		Gross return ($ ac^{-1})	
I_{25}	MESA	46.39	a [c]	$192	a
(2.6 in.)	LESA	46.96	a	$209	a
	LEPA	48.59	a	$240	a
	SDI	49.23	a	$284	a
I_{50}	MESA	48.13	ab	$240	bc
(4.4 in.)	LESA	45.77	b	$228	c
	LEPA	49.53	a	$334	ab
	SDI	49.29	ab	$354	a
I_{75}	MESA	49.20	a	$347	b
(6.2 in.)	LESA	49.41	a	$336	b
	LEPA	49.40	a	$390	ab
	SDI	49.45	a	$453	a
I_{100}	MESA	48.94	a	$388	a
(7.9 in.)	LESA	49.29	a	$395	a
	LEPA	50.05	a	$452	a
	SDI	50.35	a	$481	a
Irrigation rate averages					
I_0 (0.9 in.)		48.11	ab [d]	$173	d
I_{25} (2.6 in.)		47.79	b	$231	d
I_{50} (4.4 in.)		48.18	ab	$289	c
I_{75} (6.2 in.)		49.37	ab	$382	b
I_{100} (7.9 in.)		49.65	a	$429	a
Irrigation method averages					
	MESA	48.16	a [e]	$292	b
	LESA	47.86	a	$292	b
	LEPA	49.39	a	$354	a
	SDI	49.58	a	$393	a

[a] Numbers in parenthesis are average seasonal irrigation totals for each irrigation rate.
[b] Base loan value was 51.60 cents lb^{-1} for all years, from International Textile Center, Lubbock, Texas
[c] Numbers followed by the same letter are not significantly different (α ≤ 0.05) within an irrigation rate.
[d] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation rate averages.
[e] Numbers followed by the same letter are not significantly different (α ≤ 0.05) between irrigation method averages.

SUMMARY AND CONCLUSIONS

Crop production was compared under four irrigation methods and four irrigation rates in the Southern High Plains, Tex., USA. Crops included three seasons of grain sorghum, one season of soybean (planted after a cotton crop was destroyed by hail), and four seasons of upland cotton. Irrigation methods included subsurface drip irrigation (SDI), low energy precision applicators (LEPA), low elevation spray applicators (LESA), and mid elevation spray applicators (MESA). For each irrigation method, irrigation was applied at rates of 25, 50, 75, and 100% of meeting the full crop water requirement (i.e., crop evapotranspiration), and an additional near-dryland rate (0%) was included to compute irrigation water use efficiency.

Grain sorghum and soybean response to irrigation method changed with irrigation rate, with SDI and LEPA generally outperforming MESA and LESA at low irrigation rates, and vice-versa at high irrigation rates. For grain sorghum at high irrigation rates, deep percolation was observed for SDI and to a lesser extent LEPA. The yield depressions at high irrigation rates may have resulted from nutrient leaching and lack of soil aeration. Cotton response was consistently best for SDI, followed by LEPA, and either MESA or LESA at all irrigation rates. Preliminary soil temperature data for soybean and cotton indicated that SDI maintained warmer soil temperatures compared with the other irrigation methods early in the season. Warmer soil temperatures may have been the result of less soil water evaporation. Thus, SDI may have partitioned more soil water to plant transpiration, which enhanced crop yields, especially at low irrigation rates. Warmer soil temperatures would make SDI advantageous for cotton production in thermally-limited climates. LEPA may also result in greater partitioning to plant transpiration compared with MESA or LESA, as crop response to LEPA was generally almost as favorable as SDI. Despite possible differences in evaporation pathways, there were few significant differences in total seasonal water use among irrigation methods within an irrigation rate for all crops. This, along with the potential for deep percolation and other losses (e.g., runoff), underscores the need for proper irrigation management if the full benefits of advanced irrigation technology are to be realized.

Beginning in the 2009 season, this experiment will continue with corn, which is also a major crop in the Southern Great Plains. The cost and return of crop production under each irrigation method will be assessed to determine the long-term economics of SDI, LEPA, LESA, and MESA with various irrigation rates. It is hoped that these results will assist producers in selecting the irrigation technology that will result in the greatest profit potential while prolonging the life of the Ogallala Aquifer.

ACKNOWLEDGEMENTS

This research was supported by the Ogallala Aquifer Program and USDA-ARS National Program 211, Water Availability and Watershed Management. We thank the numerous biological technicians and student workers for their meticulous and dedicated efforts in executing experiments and obtaining and processing data. Thanks also to Dr. Arland Schneider, USDA-ARS, Ret., for initiating the grain sorghum study, and to Drs. Sara Duke and Kathy Yeater, USDA-ARS, Statisticians, for their assistance with the statistical analysis.

REFERENCES

Bordovsky, J. P., and D. Porter. 2008. Effect of subsurface drip irrigation system uniformity on cotton production in the Texas High Plains. *Applied Engineering in Agriculture.* 24(4): 465-472.

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

Bos, M. G. 1980. Irrigation efficiencies at crop production level. *ICID Bull.* 29: 18-25, 60.

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

Colaizzi, P. D., P. H. Gowda, T. H. Marek, and D. O. Porter. 2009. Irrigation in the Texas High Plains: A brief history and potential reductions in demand. *In press, Irrig. and Drain.* DOI:10.1002/ird.418.

Colaizzi, P. D., A. D. Schneider, S. R. Evett, T. A. Howell. 2004. Comparison of SDI, LEPA, and spray irrigation performance for grain sorghum. *Trans. ASAE.* 47(5):1477-1492.

Colaizzi, P. D., S. R. Evett, and T. A. Howell. 2005. Cotton production with SDI, LEPA, and spray irrigation in a thermally-limited climate. CD-ROM. Irrigation Association Annual Meeting, 6-8 Nov, Phoenix, AZ.

Colaizzi, P. D., S. R. Evett, and T. A. Howell. 2006a. Crop emergence and near-surface soil temperature for SDI, LEPA, and spray irrigation. Paper Number: 062278. 2006 ASABE Annual International Meeting, Sponsored by American Society of Agricultural and Biological Engineers, 9-12 July, Portland, OR.

Colaizzi, P. D., S. R. Evett, and T. A. Howell. 2006b. Near-surface soil water and temperature for SDI, LEPA, and spray irrigation. CD-ROM. Irrigation Association Annual Meeting, 5-7 Nov, San Antonio, TX.

Darusman, A. H. Khan, L. R. Stone, W. E. Spurgeon, and F. R. Lamm. 1997. Water flux below the root zone vs. irrigation amount in drip-irrigated corn. *Agron. J.* 89(3): 375-379.

Enciso-Medina, J. M., P. D. Colaizzi, W. L. Multer, and C. R. Stichler. 2007. Cotton response to phosphorus fertigation using subsurface drip irrigation. *Applied Engineering in Agriculture.* 23(3): 299-304.

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

Evett, S. R., T. A. Howell, and A. D. Schneider. 1995. Energy and water balances for surface and subsurface drip irrigated corn. pp. 135-140. In F. R. Lamm (ed.) *Microirrigation for a Changing World: Conserving Resources/Preserving the Environment. Proc. Fifth International Microirrigation Congress.* Am. Soc. Agric. Engr., St. Joseph, MI.

Evett, S. R., J. A. Tolk, and T. A. Howell. 2003. A depth control stand for improved accuracy with the neutron probe. *Vadose Zone J.* 2(4): 642-649.

Evett, S. R., and J. L. Steiner. 1995. Precision of neutron scattering and capacitance-type soil water content gauges from field calibration. *Soil Sci. Soc. Am. J.* 59(4): 961-968.

Evett, S. R., J. A. Tolk, and T. A. Howell. 2006. Soil profile water content determination: Sensor accuracy, axial response, calibration, temperature dependence, and precision. *Vadose Zone J.* 5: 894-907.

Henggeler, J. C. 1995. A history of drip-irrigated cotton in Texas. In *Microirrigation for a Changing World: Conserving Resources/Preserving the Environment. Proc. Fifth International Microirrigation Congress.* F. R. Lamm (ed.). pp. 669-674. ASAE, St. Joseph, MI.

Howell, T. A., A. D. Schneider, D. A. Dusek, T. H. Marek, and J. L. Steiner. 1995. Calibration and scale performance of Bushland weighing lysimeters. *Trans. ASAE* 38(4): 1019-1024.

Howell, T. A., J. L. Steiner, A. D. Schneider, S. R. Evett, and J. A. Tolk. 1997b. Seasonal and maximum daily evapotranspiration of irrigated winter wheat, sorghum, and corn: Southern High Plains. *Trans. ASAE* 40(3): 623-634.

Howell, T. A. 2001. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* 93(2): 281-289.

Howell, T. A., A. D. Schneider, and D. A. Dusek. 2002. Effects of furrow diking on corn response to limited and full sprinkler irrigation. *Soil Sci. Soc. Am. J.* 66(1): 222-227.

Howell, T. A., S. R. Evett, J. A. Tolk, and A. D. Schneider. 2004. Evapotranspiration of full-, deficit-irrigation, and dryland cotton on the Northern Texas High Plains. *J. Irrig. Drain. Engrg., Am. Soc. Civil Engrs.* 130(4): 277-285.

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

Lamm, F. R., H. L. Manges, L. R. Stone, A. H. Khan, and D. H. Rogers. 1995. Water requirement of subsurface drip-irrigated corn in northwest Kansas. *Trans. ASAE* 38(2): 441-448.

Littell, R. C., G. A. Milliken, W. W. Stroup, R. D. Wolfinger, and O. Schabenberger. 2006. SAS® for Mixed Models, 2nd ed. Cary, N.C.: SAS Institute, Inc.

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

Marek, T. H., and D. Bordovsky. 2006. Performance of ten cotton varieties in the Northern Texas High Plains. *Texas Journal of Agricultural and Natural Resources.* 19: 48-61.

Marek, T. H., A. D. Schneider, T. A. Howell, and L. L. Ebeling. 1988. Design and construction of large weighing monolithic lysimeters. *Trans. ASAE* 31(2):477-484.

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1998. An economic comparison of subsurface drip and center pivot irrigation systems. *Applied Engineering in Agriculture.* 14(4): 391-398.

Porter, D. O., T. H. Marek, T. A. Howell, and L. L. New. 2005. The Texas High Plains Evapotranspiration Network (TXHPET) User Manual v. 1.01. Texas A&M University Agricultural Research and Extension Centre Rep. 03-37. Available at: http://txhighplainset.tamu.edu/usermanual.pdf (accessed 23 January 2009).

Saxton, A. M. 1998. A macro for converting mean separation output to letter groupings in proc mixed. In *Proc. 23rd SAS Users Group Intl*., 1243-1246. Cary, N.C.: SAS Institute, Inc.

Schneider, A. D. 2000. Efficiency and uniformity of the LEPA and spray sprinkler methods: A review. *Trans. ASAE* 43(4): 937-944.

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

Segarra, E., L. Almas, and J. P. Bordovsky. 1999. Adoption of advanced irrigation technology: LEPA vs. drip in the Texas High Plains. In *Proc. Beltwide Cotton Conf.*,1:324-328. Memphis, Tenn.: National Cotton Council.

Thorburn, P. J., F. J. Cook, and K. L. Bristow. 2003. Soil-dependent wetting from trickle emitters: implications for system design and management. *Irrig. Sci.* 22: 121-127.

USDA-Natural Resources Conservation Service. 2009. Web Soil Survey, Soil Survey TX375, Potter County, Texas. Available at: http://websoilsurvey.nrcs.usda.gov. (accessed 23 January 2009).

Wanjura, D. F., J. R. Mahan, and D. R. Upchurch. 1996. Irrigation starting time effects on cotton under high-frequency irrigation. *Agron. J.* 88(4): 561-566.

Yu, J., Kohel, R. J., and Zhang, T. 2001. Evaluation of cotton fiber quality QTLs for molecular breeding. In *Proc. Genetic Control Of Cotton Fiber And Seed Quality Workshop*, 5-6 Dec. 2000, San Antonio, TX, 175-180.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

KEYS TO SUCCESSFUL ADOPTION OF SDI: MINIMIZING PROBLEMS AND ENSURING LONGEVITY

Danny H. Rogers
Extension Engineer, Irrigation
K-State Research and Extension
Biological & Ag Engineering
Manhattan, Kansas
drogers@ksu.edu

Freddie R. Lamm
Research Irrigation Engineer
K-State Research and Extension
Northwest Research-Extension Center
Colby, Kansas
flamm@ksu.edu

INTRODUCTION

Since 1989, research studies and demonstration studies at the Northwest and Southwest Research-Extension Centers of Kansas State University have indicated that subsurface drip irrigation (SDI) systems can be efficient, long-lived, and adaptable for irrigating corn and other deep-rooted crops. A survey of all Kansas SDI users in 2003 revealed an estimated 14,000 acres were irrigated with SDI systems (Rogers, unpublished data). Though system usage has grown steadily over the years, SDI systems are currently used on less than 1% of total irrigated acres. The 2006 Kansas Irrigation Water Use Report indicated that 10,250 acres were exclusively irrigated by SDI systems and an additional 8,440 acres were irrigated partially by SDI in combination with another system type, such as an irrigated SDI corner of a center pivot sprinkler or a surface gravity-irrigated field partially converted to SDI.

Many producers have had successful experiences with SDI systems despite minor technical difficulties during the adoption process. In a 2005 survey of SDI users, nearly 80% of Kansas producers indicated they were at least satisfied with the performance of their SDI system, and less than 4% indicated they were not satisfied (Alam & Rogers 2005). However, even satisfied users indicated a need for additional SDI management information. The most noted concern was the damage and repairs caused by rodents. A few systems had failed or had been abandoned after a short-use period due to inadequate design, inadequate management or a combination of both.

Design and management are closely linked in a successful SDI system. Research studies and on-farm producers both indicate that SDI systems result in high-yielding crops and water-conserving production practices only when the systems are properly designed, installed, operated and maintained. A system that is improperly designed and installed 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 also be operated according to design specifications and utilize good irrigation water management procedures to achieve high uniformity and efficiency. An SDI system is also destined for early failure without proper maintenance. This paper will review key factors for successful adoption of SDI for Kansas irrigated agriculture.

MINIMUM SDI COMPONENTS FOR EFFICIENT WATER DISTRIBUTION AND SYSTEM LONGEVITY

SDI system design must consider individual management restraints and goals, as well as account for specific field and soil characteristics, water quality, well capabilities, desired crops, production systems, and producer goals. However, certain basic features are a part of all SDI systems, as shown in Figure 1. The long-term ability of the producer to operate and maintain the system in an efficient manner is seriously undermined if any of the minimum components are omitted during the design process. Minimum SDI system components should not be sacrificed as design and installation cost-cutting measures. If minimum SDI components cannot be included as part of the system, an alternative type of irrigation system or a dryland production system should be considered.

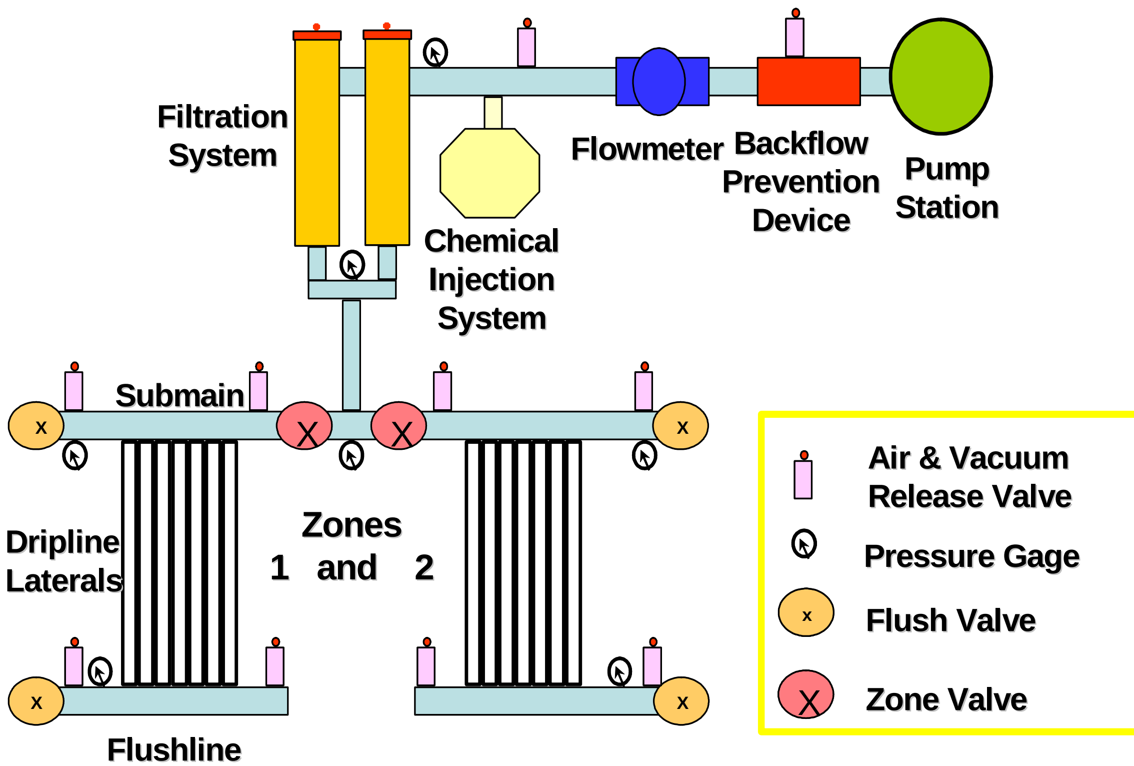


Figure 1. Minimum components of an SDI system. (Components are not to scale) K-State Research and Extension Bulletin MF-2576, Subsurface Drip Irrigation (SDI) Component: Minimum Requirements

Water distribution components of an SDI system include the pumping station, the main, submains and dripline laterals. Sizing requirements for the mains and submains are somewhat similar to underground service pipe to center pivot sprinklers or main pipelines for surface-irrigated gravity systems and are determined by the flow rate and acceptable friction loss within the pipe. In general, the flow rate and friction loss determines the dripline size (diameter) for a given dripline lateral length and 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. In addition to basic water distribution components, additional components allow the producers to monitor SDI system performance, allow flushing, and protect or maintain performance by injection of chemical treatments. The injection equipment can also be used to provide additional nutrients or chemicals for crop production. A backflow prevention device is required to protect the source water from accidental contamination if backflow should occur.

The actual characteristics and field layout of an SDI system vary from site to site, but irrigators often add additional capabilities to their systems. For example, the SDI system in Figure 2 shows additional valves that allow the irrigation zone to be split into two flushing zones. When the well or pump does not have the capacity to provide additional flow and pressure to meet the flushing requirements for the irrigation zone, splitting the zone into two parts may be an important design feature. The American Society of Agricultural and Biological Engineers (ASABE) recommends a minimum flushing velocity of 1 ft/s for microirrigation lateral maintenance (ASAE EP-405, 2008). This flushing velocity requirement needs to be carefully considered at the design stage, and may dictate larger sizes for submains and flushlines to assure that maximum operating pressures for the driplines are not exceeded (Lamm and Camp, 2007).

Filter systems are generally sized to remove particles that are approximately 1/10 the diameter of the smallest emitter passageway. However, small particles still pass through the filter and into the driplines, and over time, they can clump together. Also, biological or chemical processes produce materials that need to be removed to prevent emitter clogging or a build-up of material at the outlet or distal end of the system. Opening the flushline valves allows water to rapidly pass through the driplines, carrying away any accumulated particles. A good design should allow flushing of all pipeline and system components.

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 flushing event. When only a small amount of debris is found, the flushing interval may be increased. Heavy accumulations of debris, however, mean more frequent flushing is needed.

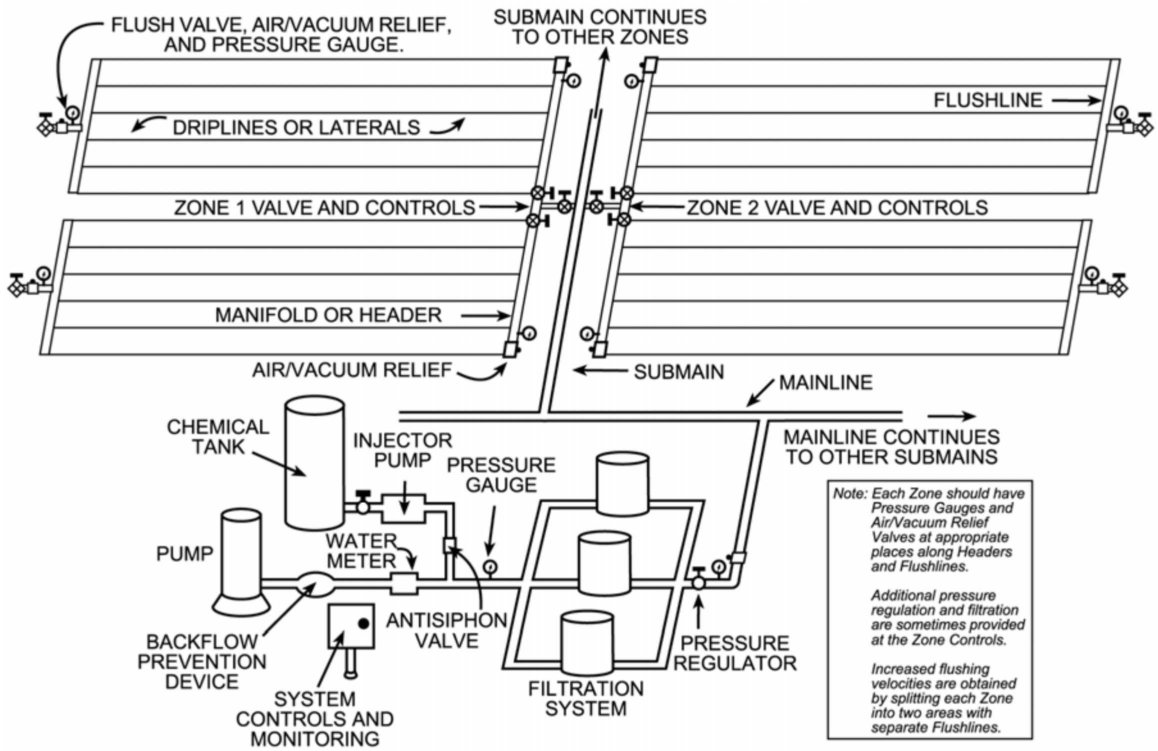


Figure 2. Layout for a well-designed SDI system (Lamm and Camp, 2007).

In SDI systems, all water application is underground. Because no surface wetting occurs in properly installed and operated systems, no visual cues of system operation are available to the manager. Therefore, the flow meter and pressure gauges act as operational feedback cues. The pressure gauges along the submain of each zone measure the inlet pressure to driplines. Decreasing flow rates and/or increasing pressure may indicate clogging, and increasing flow rates with decreasing pressure may indicate a major line leak. The inlet pressure gauges along with those at the distal ends of the dripline laterals at the flushline valve help establish the baseline performance characteristics of the system. Good quality pressure gauges should be used at each of these measurement locations and the gauges should be periodically replaced or inspected for accuracy. The flow rate and pressure measurements should be recorded and retained for the life of the system. A time series of flow rate and pressure measurements can be used as a diagnostic tool to discover operational problems and determine appropriate remediation techniques, as illustrated in Figure 3.

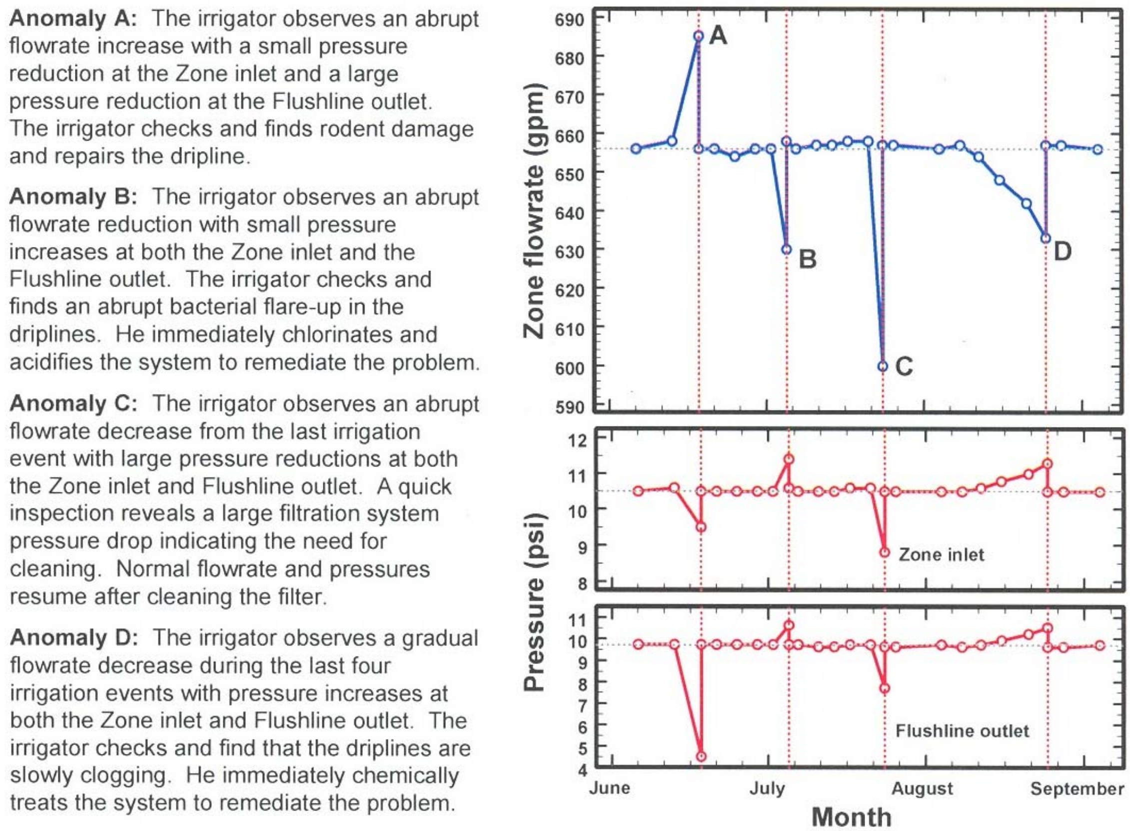


Figure 3. Hypothetical example of how pressure and flowrate measurement records could be used to discover and remediate operational problems (Lamm and Camp, 2007).

FILTRATION SYSTEM

The heart of the protection system for the dripline emitters is the filtration system. The type of filtration system depends on the quality characteristics of the irrigation water and the clogging hazards. The illustration in Figure 1 depicts a pair of screen filters, while Figure 2 shows a series of sand media filters. Screen filters are the simplest type of filtration and provide a single plane of filtration. They are most often used in situations where the water source is relatively clean. Sand media filtration systems, which consist of two or more large pressure tanks with specially graded filtration sand, provide three dimensional filtration and are well-suited for surface water sources. Surface water supplies may require settling basins and/or several layers of bar screen barriers at the intake site to remove large debris and organic matter. Another common type of filtration system is the disc filter which can also be considered as providing three dimensional filtration. In some cases, the filtration system may be a combination of filtration components. For example, a well that produces a large amount of sand in the pumped water may require a cyclonic sand separator in advance of the main filter. Examples of the different types of filters are shown in Figure 4.

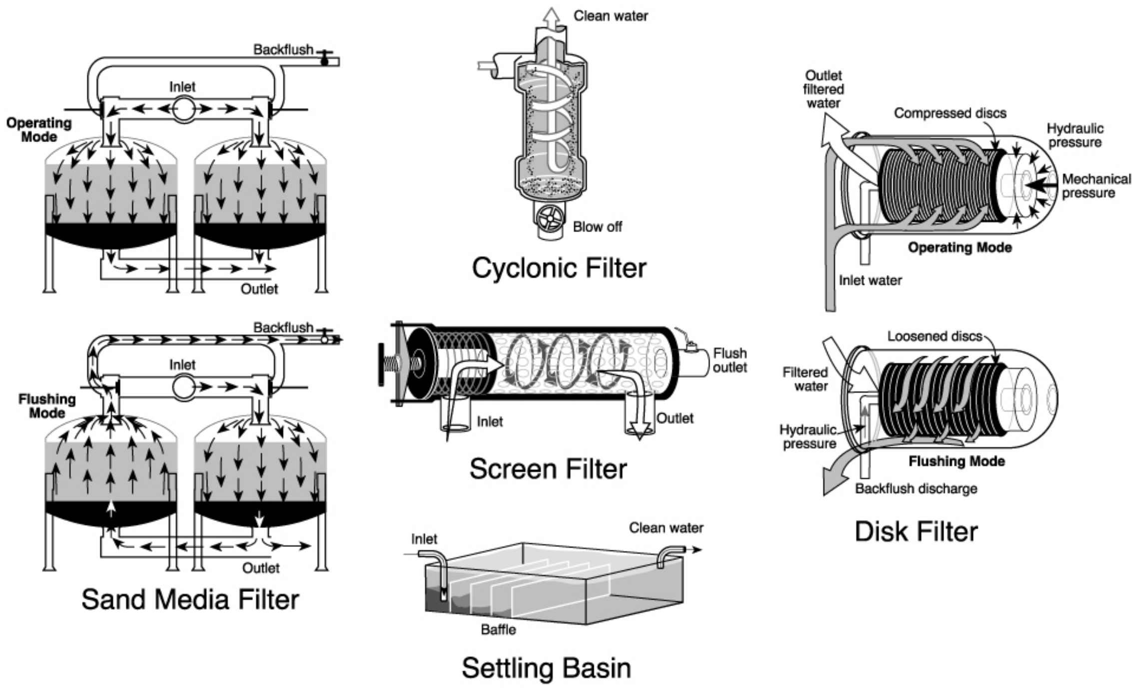


Figure 4. Schematic description of various filtration systems and components. (Courtesy of Kansas State University).

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

INJECTION SYSTEM

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

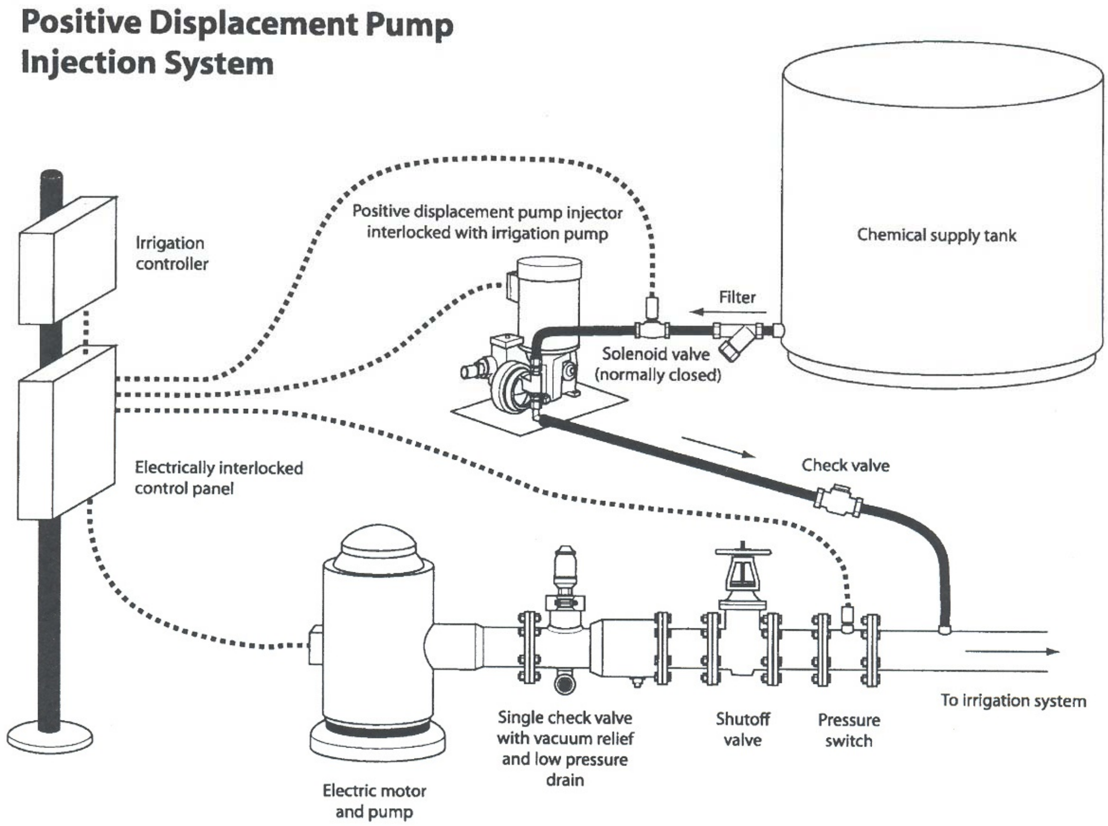


Figure 5. Layout of an Injection System with Safety Interlocks and Backflow Prevention Devices (Courtesy of L.J. Schwankl, Univ. of California-Davis)

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

The injection systems in Figures 1 and 2 have a single injection point located upstream of the main filter, but some agrochemicals may require an injection point downstream from the filter to prevent filter damage. Care needs to be exercised in the location of the injection port to prevent system problems such as corrosion within the filters or chemical precipitation beyond the filter resulting in emitter clogging.

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

WATER QUALITY ANALYSIS

Water quality also has a significant effect on SDI system performance and longevity. In some instances, poor water quality causes soil and crop growth problems. However, with proper treatment and management, water high in minerals, nutrient enrichment or salinity can be used successfully in SDI systems. No SDI system should be designed and installed without first assessing the quality of the proposed irrigation water supply.

Clogging prevention is the key to SDI system longevity and requires understanding of the potential problems associated with a particular water source. Table 1 details important water quality information that all designers and irrigation managers should consider in the early stages of the planning process. With this information in mind, suitable management, maintenance plans, and system components, like the filtration system, can be selected.

Table 1. Recommended water quality tests to be completed before designing an SDI system.

1. **Electrical Conductivity (EC)**, a measure of total salinity or total dissolved solids, measured in dS/m or mmho/cm.
2. **pH**, a measure of acidity, where a value of 1 is very acid, 14 is very alkali, and 7 is neutral.
3. **Cations** include Calcium (Ca), Magnesium (Mg), and Sodium (Na), measured in measured in meq/L, (milliequivalent/liter).
4. **Anions** include Chloride (Cl), Sulfate (SO_4), Carbonate (CO_3), and Bicarbonate (HCO_3), measured in meq/L.
5. **Sodium Absorption Ratio (SAR)**, a measure of the potential for sodium in the water to develop sodium sodicity, deterioration in soil permeability and toxicity to crops. SAR is sometimes reported as Adjusted (Adj) SAR. The Adj. SAR value better accounts for the effect on the HCO_3 concentration and salinity in the water and the subsequent potential damage to the soil because of sodium.
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****

* The boron test would be for crop toxicity concern.

** Oil in water would be a 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 should 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 the presence of oil may be helpful in oil-producing areas of the state or if the well to be used for SDI has experienced surging, which causes existing drip oil in the water column to mix with the pumped water. The fee schedule for Tests 1 through 11 varies from lab to lab and may total a few hundred dollars. The cost is minor, however, in comparison to the value offered by the test in determining proper design and operation of the SDI system.

RODENT MANAGEMENT

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

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

PRODUCER RESPONSIBILITIES

The decision to invest in an SDI system is ultimately up to the investor. Good judgments require a thorough understanding of the fundamentals of the opportunities and challenges and/or the recommendations from a proven expert. A network of SDI industry support is still in early development in the High Plains region, even though the microirrigation industry is over 40 years old and application in Kansas has been researched since 1989. Individuals considering SDI should carefully determine if the system is a viable option for their situation by taking the following actions:

1. Getting educated 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 www.oznet.ksu.edu/sdi and the Microirrigation forum at 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. Visiting other producer sites that have installed and used SDI. Most current producers are willing to show their systems to others.

2. Interviewing at least two companies.
    a. Ask 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 successful adoption 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. Obtaining 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 (SDI) offers a number of agronomic production and water conservation advantages but these advantages are only achieved with proper design, operation, and maintenance. With proper care the SDI system can have an efficient, effective and long life. One necessary change from the current irrigation systems, however, is the need to understand SDI's sensitivity to clogging by physical, biological and/or chemical agents.

Before designing or installing an SDI system, a comprehensive water quality assessment should be conducted on the source water supply. Once this assessment is completed, 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 the management needs may seem daunting at first, most managers quickly become familiar with the SDI system and its operational needs.

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

OTHER AVAILABLE INFORMATION

The above discussion is a brief summary prepared 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

ACKNOWLEGEMENTS

Contribution No. 09-241-A from the Kansas Agricultural Experiment Station.

REFERENCES

Alam, M. and D. H. Rogers. 2005. Field Performance of Subsurface Drip Irrigation (SDI) in Kansas. In: Proc: Irrigation Assoc. International Irrigation Technical Conf., IA 05-1209. November 6-8, 2005. Phoenix, AZ. 5 pp.

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

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

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

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

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

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

A LOOK AT TWENTY YEARS OF SDI RESEARCH IN KANSAS

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

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 20 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. Additional crops that have been studied at the NWREC SDI site are soybean, sunflower, grain sorghum, alfalfa and demonstration trials of melons and vegetables.

GENERAL STUDY PROCEDURES

This report summarizes several studies conducted at the KSU Northwest and Southwest Research-Extension Centers at Colby and Garden City, Kansas, respectively. A complete discussion of all the employed procedures lies beyond the scope of this paper. For further information about the procedures for a particular study the reader is referred to the accompanying reference papers when so listed. These procedures apply to all studies unless otherwise stated.

The two study sites were located on deep, well-drained, loessial silt loam soils. These medium-textured soils, typical of many western Kansas soils, hold approximately 18.9 inches of plant available soil water in the 8 ft profile at field capacity. Study areas were nearly level with land slope less than 0.5% at Colby and 0.15% at Garden City. The climate is semi-arid, with an average annual precipitation of 17 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).

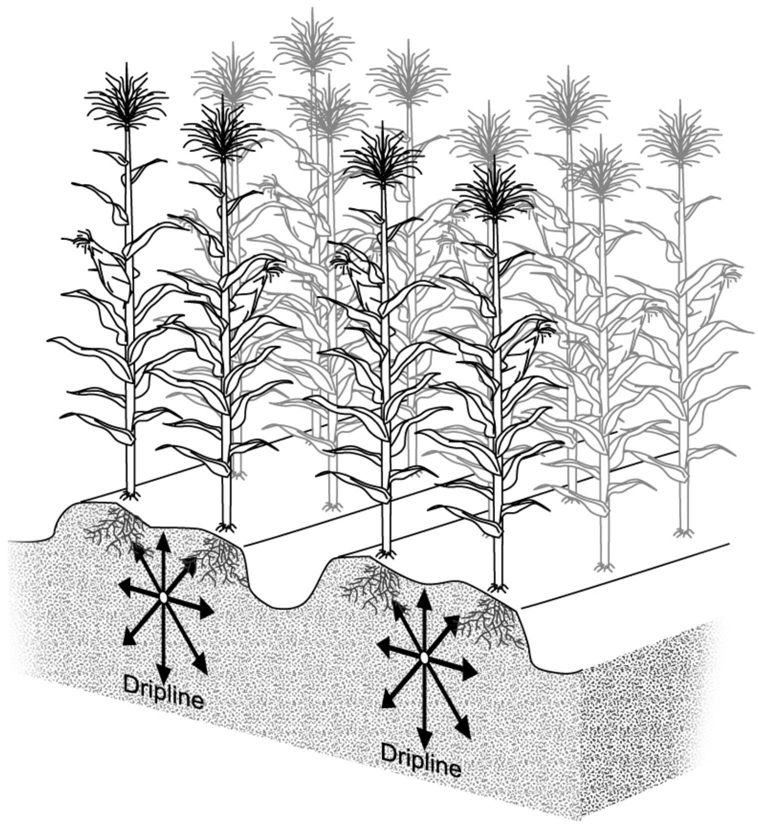


Figure 1. Physical arrangement of the subsurface dripline in relation to the corn rows.

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 inch of water used above a threshold of 12.9 inches (Lamm et al., 1995). The relationship between corn yields and irrigation is curvilinear (Figure 2.) primarily because of greater drainage for the heavier irrigation amounts (Figure 3).

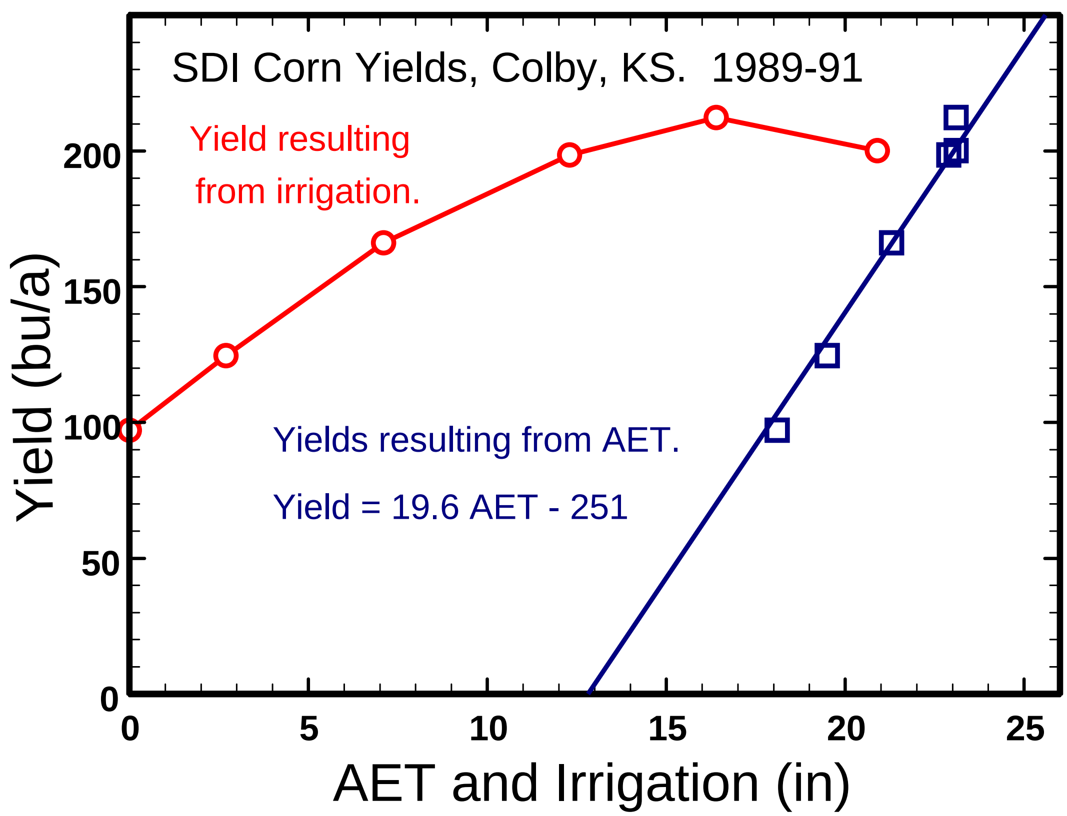


Figure 2. Corn yield as related to irrigation and calculated evapotranspiration (AET) in a SDI water requirement study, Colby, Kansas, 1989-1991.

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.

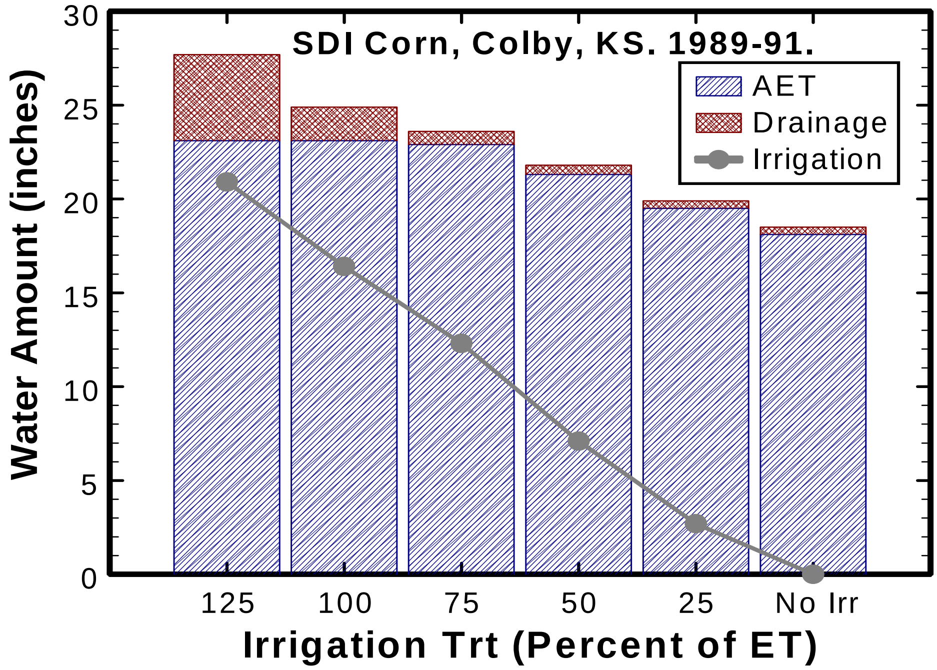


Figure 3. Calculated evapotranspiration (AET) and seasonal drainage as related to irrigation treatment in a SDI water requirement study, Colby, Kansas, 1989-1991.

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 densities (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 soil water depletion during this period will have a large effect on final kernel weight and ultimately, corn grain yield. Increasing plant density from 22,500 to 34,500 plants/acre generally increased corn grain yields, particularly in good corn production years. There was very little yield penalty for increased plant density even when irrigation was severely limited or eliminated.

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.

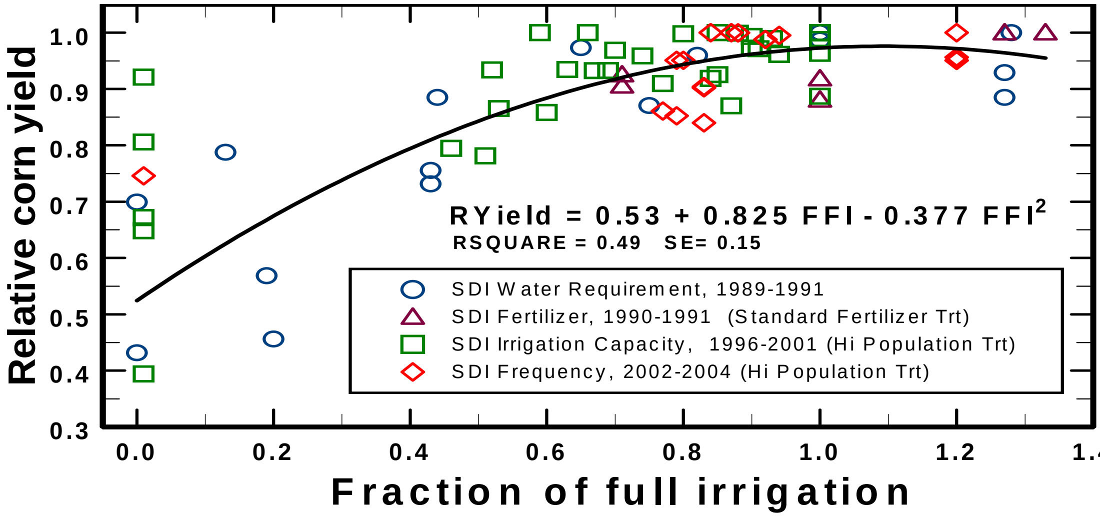


Figure 4. Relative corn grain yield for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

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.

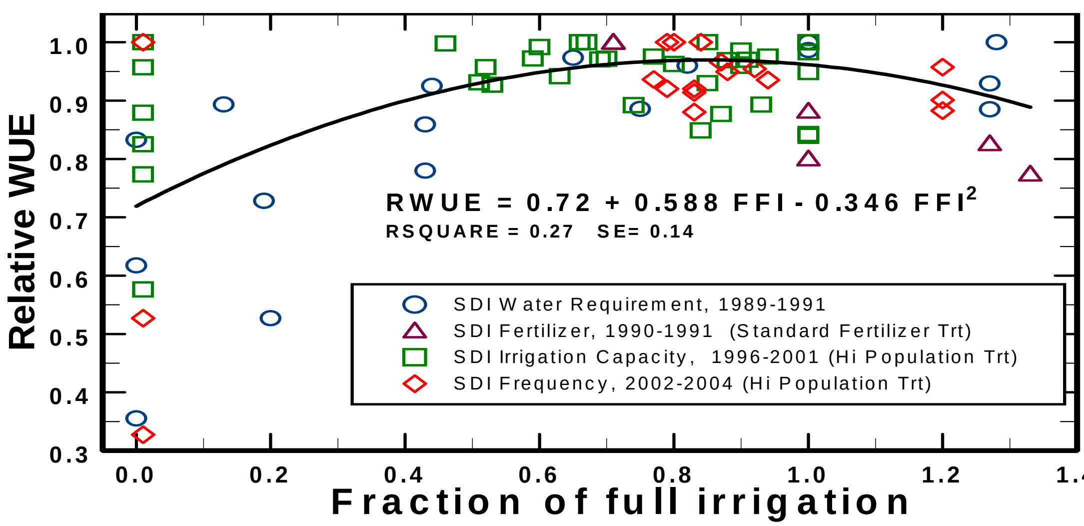


Figure 5. Relative water use efficiency of corn for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

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 SDI frequencies had little or no effect on corn yields provided soil water was managed within acceptable stress ranges (Howell et al., 1997).

In a 2002-2004 study at Colby, Kansas, four irrigation frequencies at a limited irrigation capacity were compared against fully irrigated and non-irrigated treatments (Lamm and Aiken, 2005). The hypothesis was that under limited irrigation, higher frequency with SDI might be beneficial during grain filling and the latter portion of the season as soil water reserves become depleted. The four irrigation frequencies were 0.15 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 sprinkler irrigated corn in this region 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.

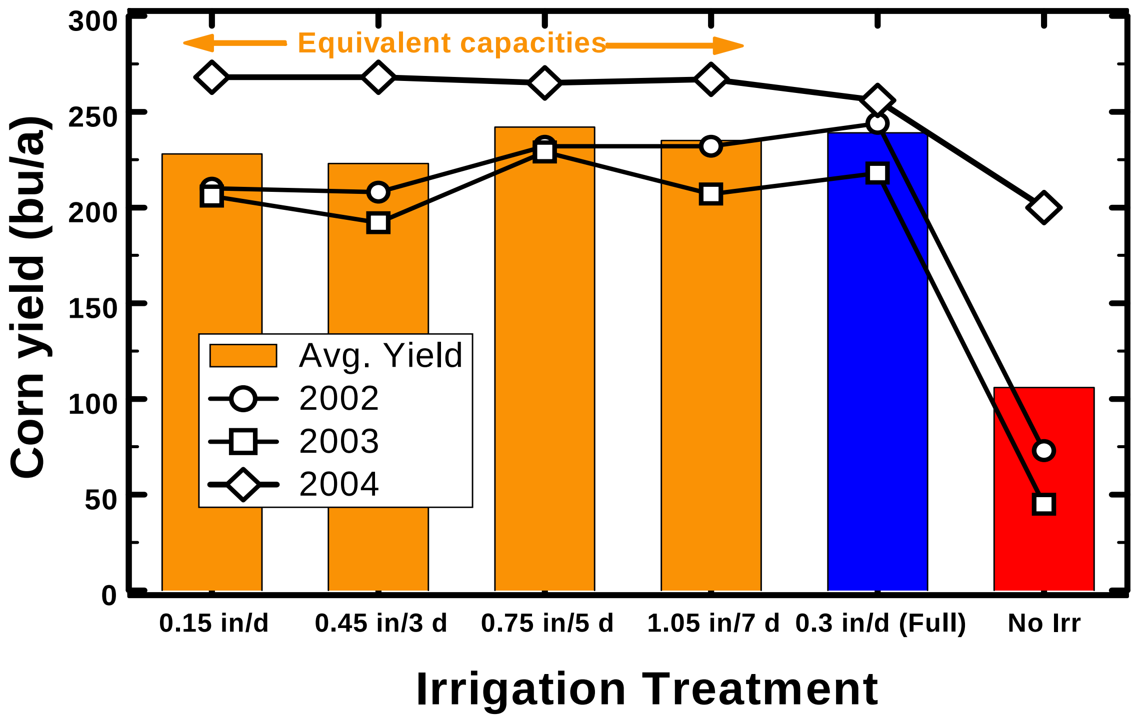


Figure 6. Corn grain yields as affected by irrigation treatment in a study examining SDI frequency under limited irrigation, Colby, Kansas, 2002 to 2004.

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 (Spurgeon, et al., 1991; Manges et al., 1995; Darusman et al., 1997; Lamm et al., 1997a). The first study at the KSU Southwest Research-Extension Center at Garden City, Kansas evaluated 4 dripline spacings (2.5, 5, 7.5, and 10 ft) with corn planted in 30 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	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.

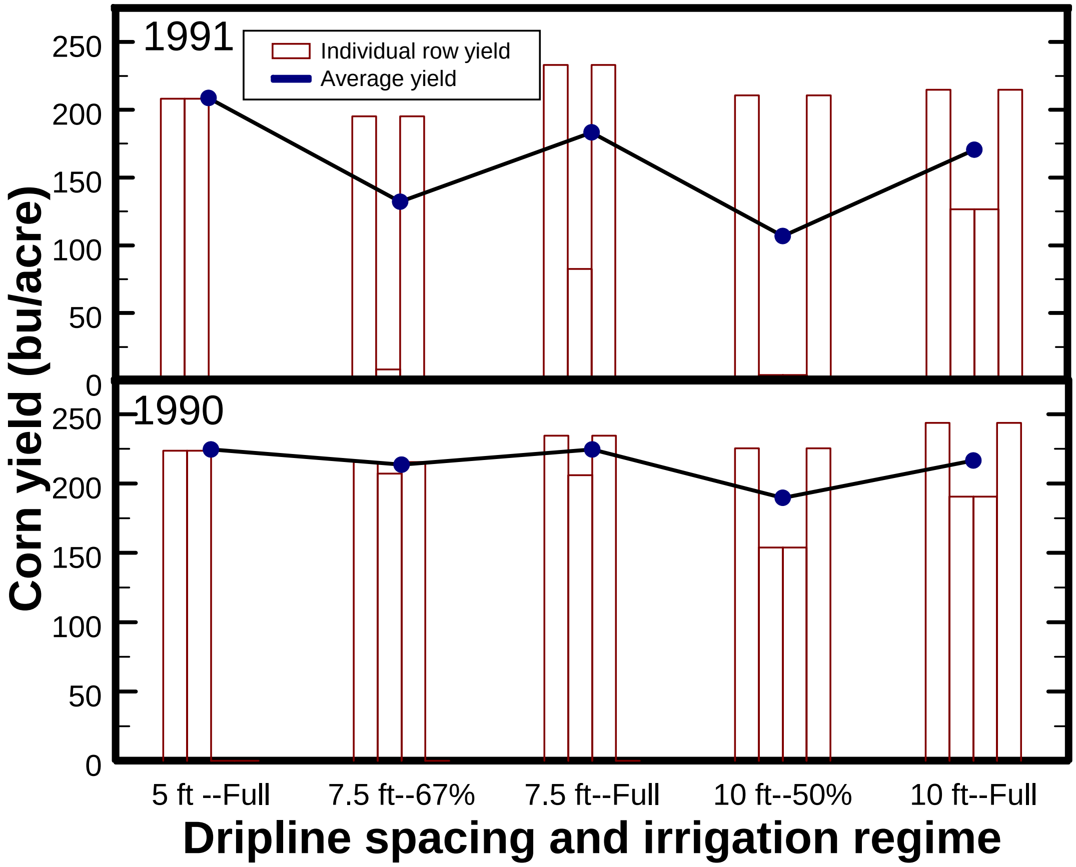


Figure 7. Corn yield distribution as affected by dripline spacing and irrigation regime, Colby, Kansas, 1990-1991. Note: Individual row yields are mirrored about a centerline half way between two adjacent driplines for display purposes.

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

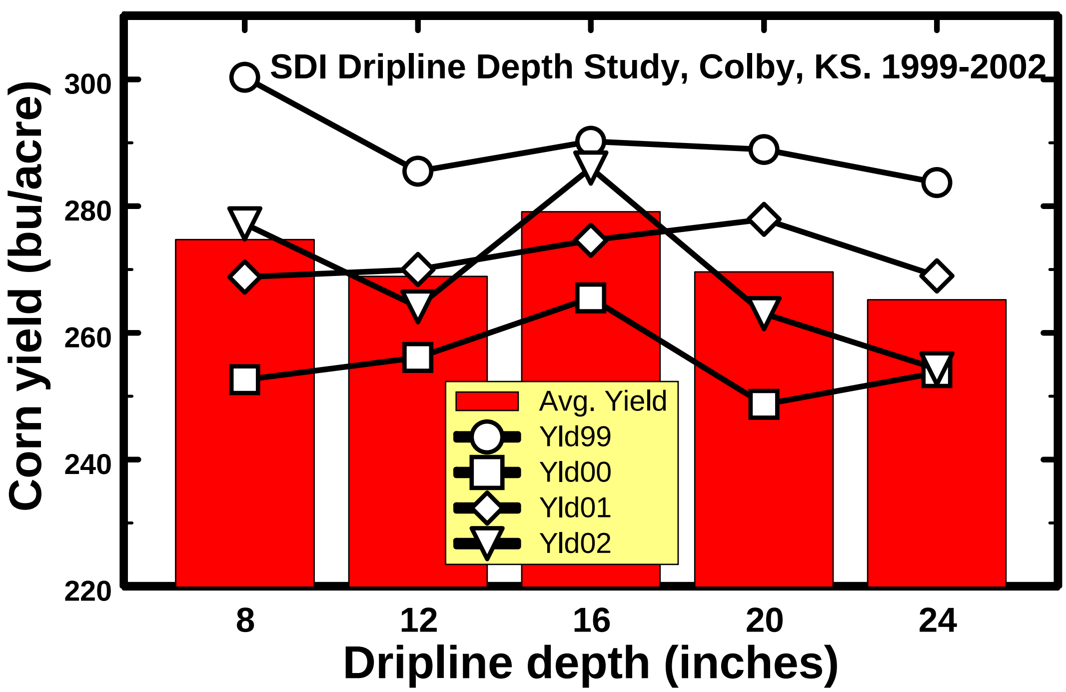


Figure 8. Corn grain yields as affected by dripline depth, 1999-2002, Colby, Kansas.

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

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

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

NITROGEN FERTILIZATION WITH SDI

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

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

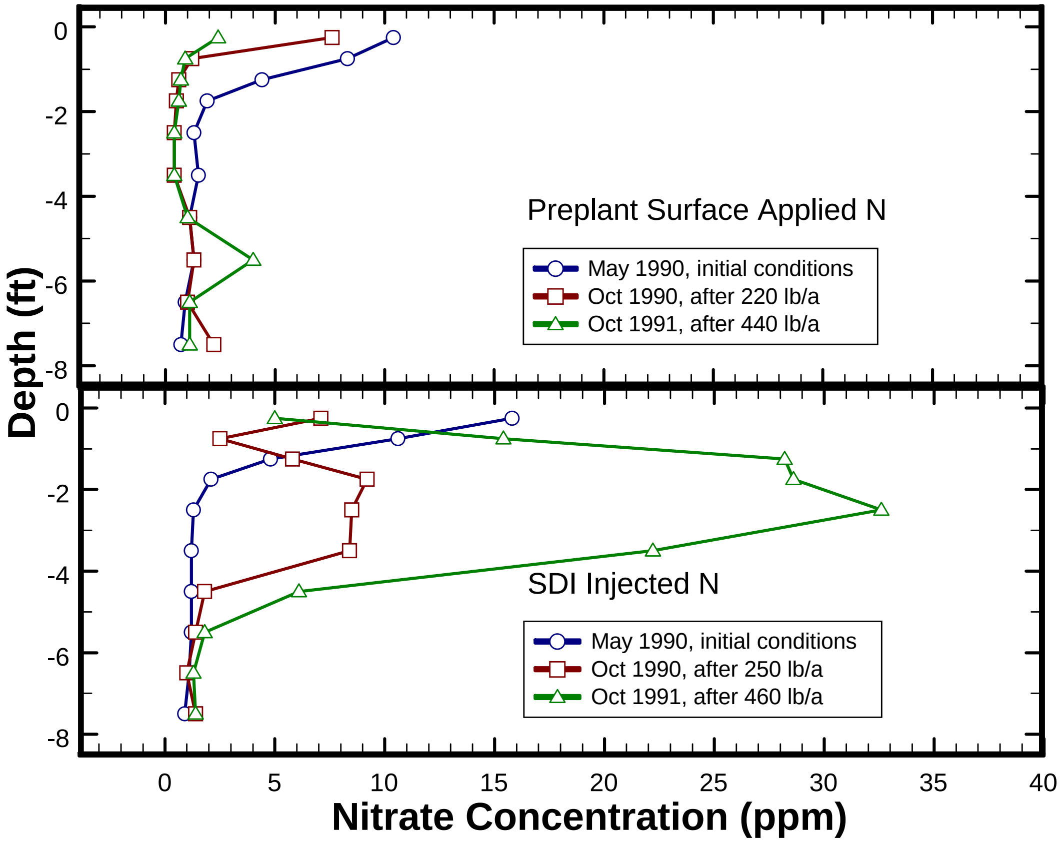


Figure 9. Nitrate concentrations in the soil profile for preplant surface-applied and SDI injected nitrogen treatments, Colby, Kansas, 1990-91. Data is for selected nitrogen fertilizer rate treatments with full irrigation (100% of AET).

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.

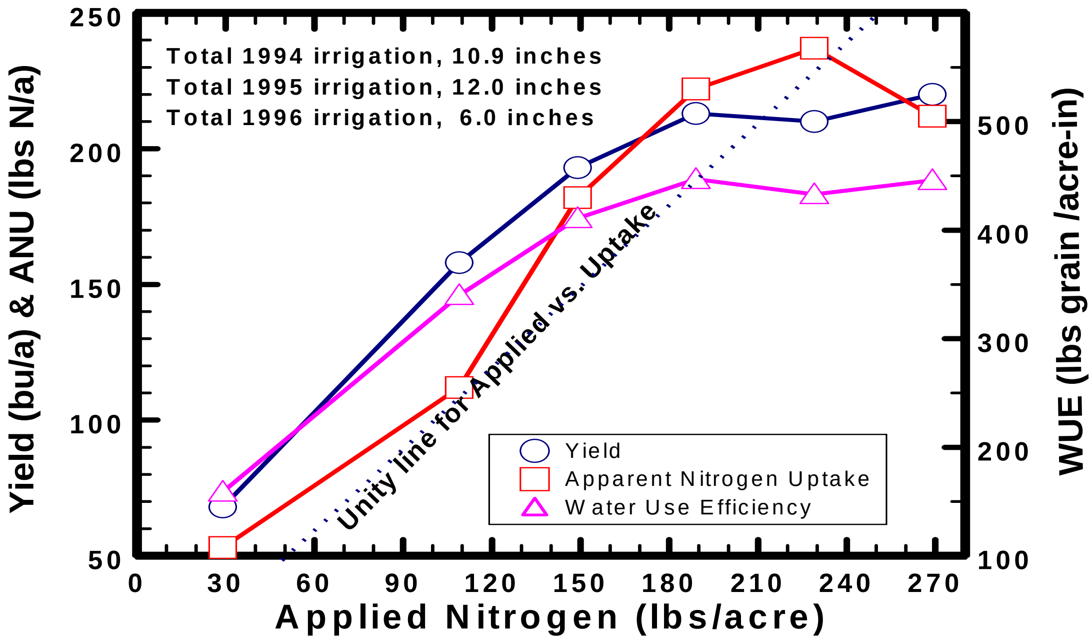


Figure 10. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water use efficiency as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded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

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.

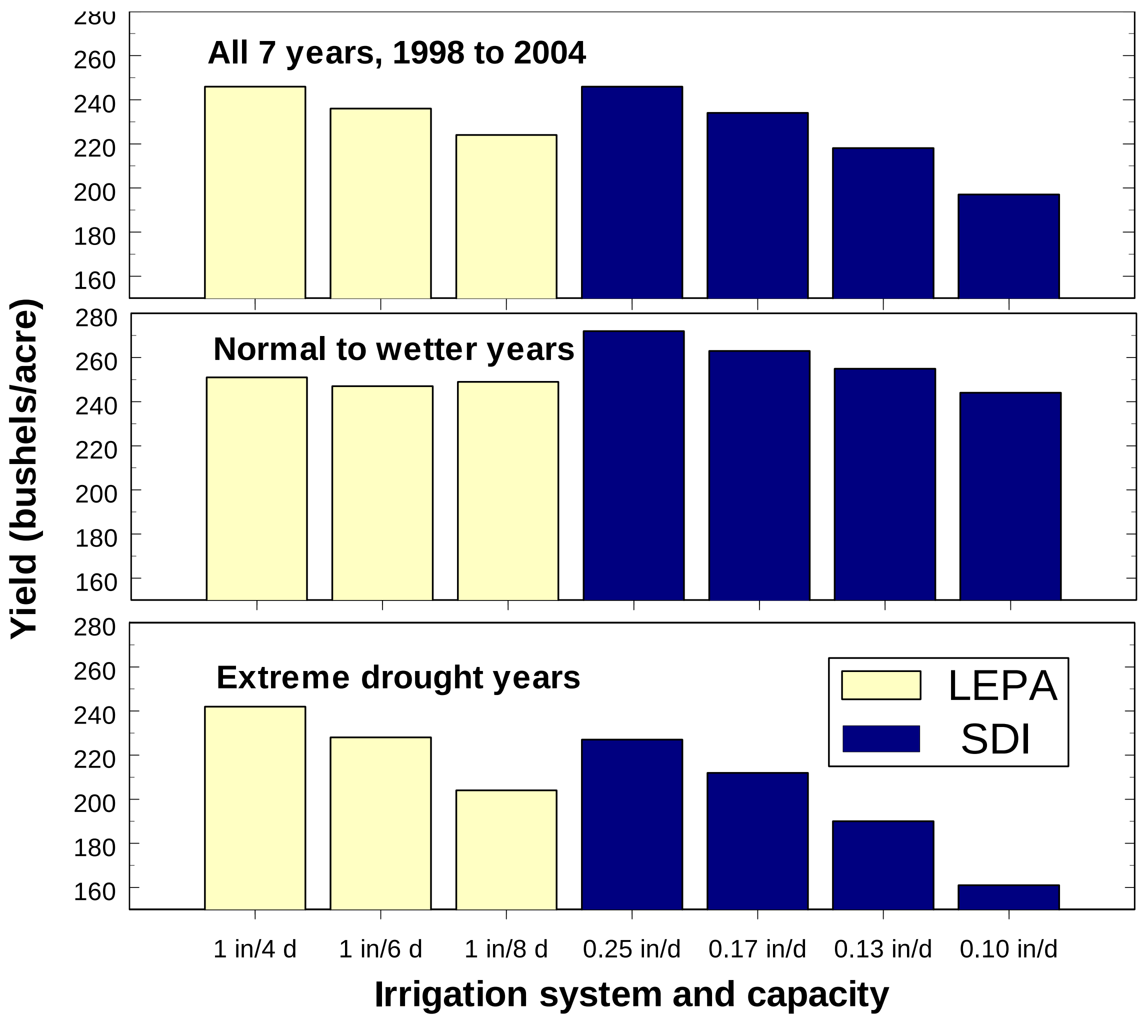


Figure 11. Variation in corn yields across years and weather conditions as affected by irrigation system type and capacity, Colby Kansas.

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

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

Table 3. Crop yield of soybean, grain sorghum and sunflower as affected by irrigation method and irrigation treatment, KSU Northwest Research-Extension Center, Colby Kansas, 2004-2008.

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

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

ALFALFA PRODUCTION WITH SDI

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

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

There were not large differences in annual yield between irrigation levels but over the course of each season there would tend to be a slight reduction in alfalfa yield with increasing distance from the dripline. This reduction was greater for the 70% ET treatment and resulted in reduced overall annual yields (Figure 12). However, crude protein (a measure of alfalfa quality) and digestibility was greater at the greater distances and reduced ET (Figure 13 and 14). This helped compensate for the yield reduction.

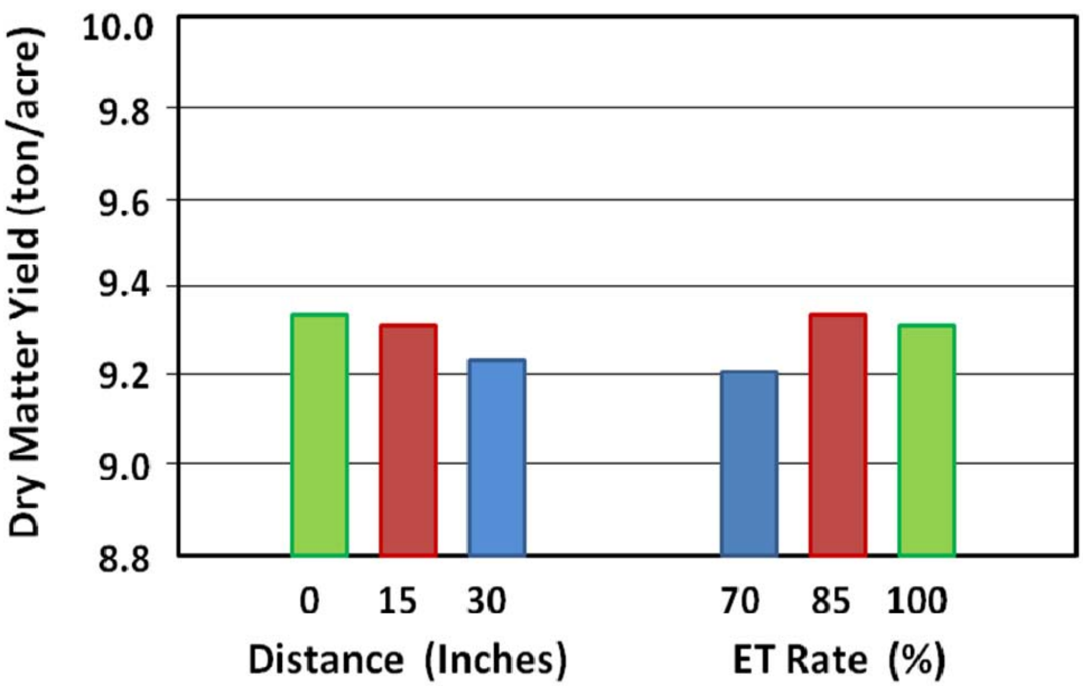


Figure 12. Dry matter yield of alfalfa as affected by perpendicular horizontal distance from dripline and irrigation level, KSU Northwest Research-Extension Center, Colby Kansas. Data is averaged over the years, 2005 through 2007.

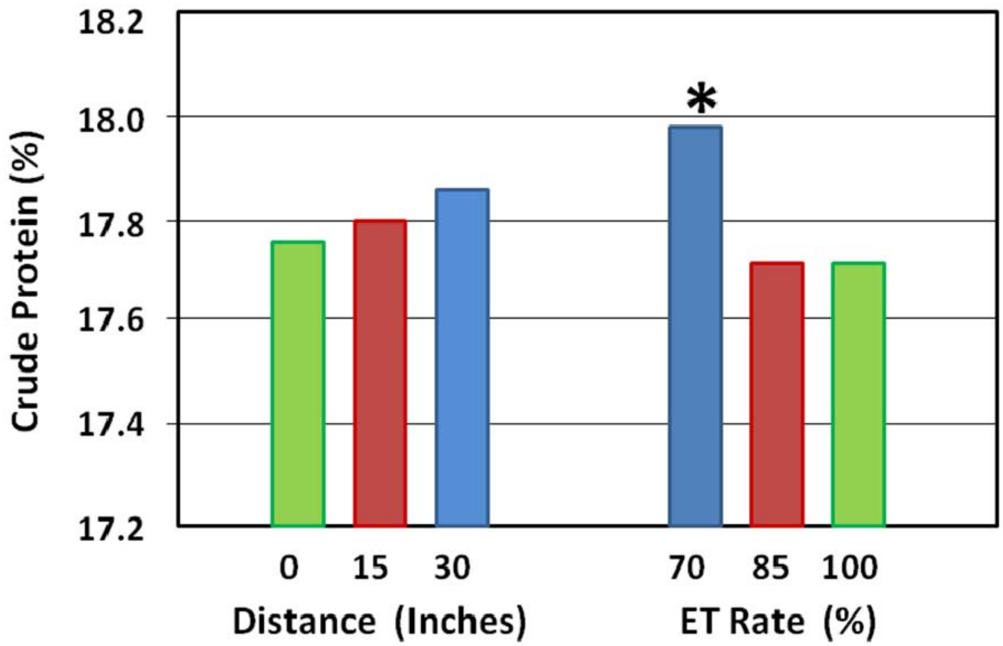


Figure 13. Crude protein percentage of alfalfa as affected by perpendicular horizontal distance from dripline and irrigation level, KSU Northwest Research-Extension Center, Colby Kansas. Data is averaged over the years, 2005 through 2007.

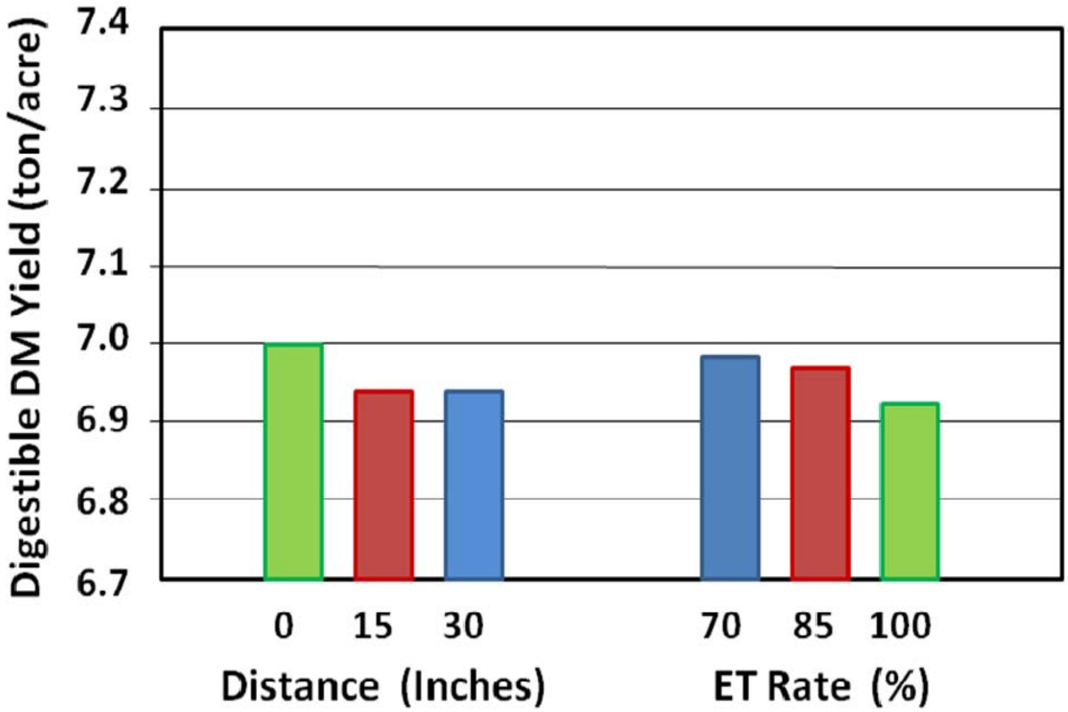


Figure 14. Digestible dry matter yield of alfalfa as affected by perpendicular horizontal distance from dripline and irrigation level, KSU Northwest

Research-Extension Center, Colby Kansas. Data is averaged over the years, 2005 through 2006.

APPLICATION OF LIVESTOCK EFFLUENT WITH SDI

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

An engineering feasibility study (1998 to 2002, commercial beef feedlot in Gray County, Kansas) conducted by Kansas State University with beef feedlot effluent has indicated that driplines with discharge of 0.4 to 1 gal/hr-emitters can be used successfully with little clogging. However, the smaller emitter sizes normally used with high quality groundwater in the Central Great Plains may be risky for use with beef feedlot effluent. The discharge of the two smallest emitter sizes, 0.15 and 0.24 gal/hr-emitter decreased approximately 40% and 30%, respectively, during the four seasons, indicating considerable emitter clogging (Figure 15). The three driplines with the highest flow rate emitters (0.40, 0.60, and 0.92 gal/hr-emitters) have had approximately 7, 8, and 13% reductions in flow rate, respectively. Following an aggressive freshwater flushing, acid and chlorine injections in April of 2002, the flowrates of the lowest two emitter sizes (0.15 and 0.24 gal/hr-emitter) were restored to nearly 80 and 97% of their initial flowrates, respectively.

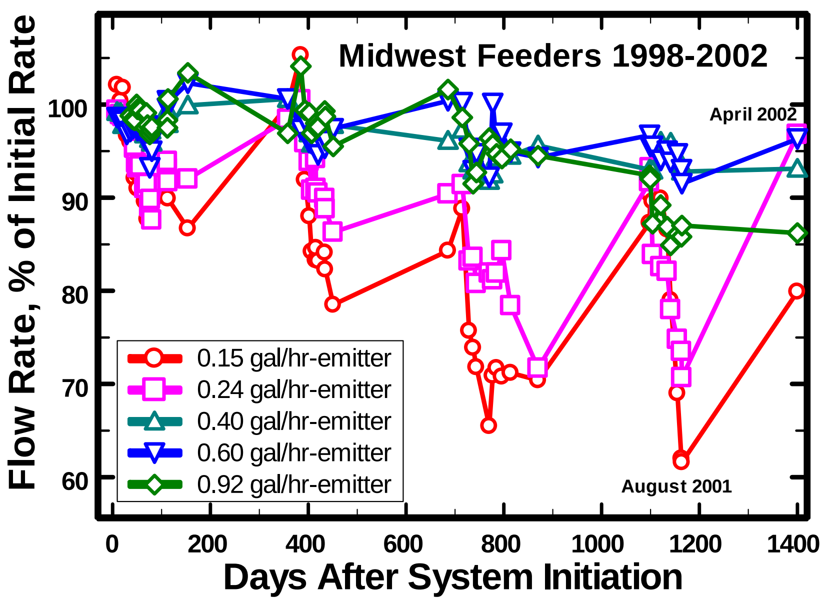


Figure 15. Decrease in emitter discharge during four seasons of operation of an SDI system with biological effluent at Midwest Feeders, Ingalls, Kansas, 1998 to 2002.

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

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

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

1 Total applied N-P-K from the three sources: starter treatment at planting (30 lbs N/acre + 45 lbs/a P205), wastewater application, and the amount naturally occurring in the irrigation water (0.75 lbs/acre-inch).

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

3 Water use efficiency (WUE) is defined as grain yield in lb/acre divided by total water use in inches.

ECONOMICS OF SDI

SDI has not been typically used for row crop production in the Central Great Plains. Typically, SDI has much higher investment costs as compared to other pressurized irrigation systems such as full size center pivot sprinklers. However, there are realistic scenarios where SDI can directly compete with center pivot sprinklers for corn production in the Central Great Plains. As field size decreases, SDI can more directly compete with center pivot sprinklers because of increasing higher ratio of center pivot sprinkler (CP) costs to irrigated acres (Figure 15). Small and irregular shape fields may be ideal candidates for SDI.

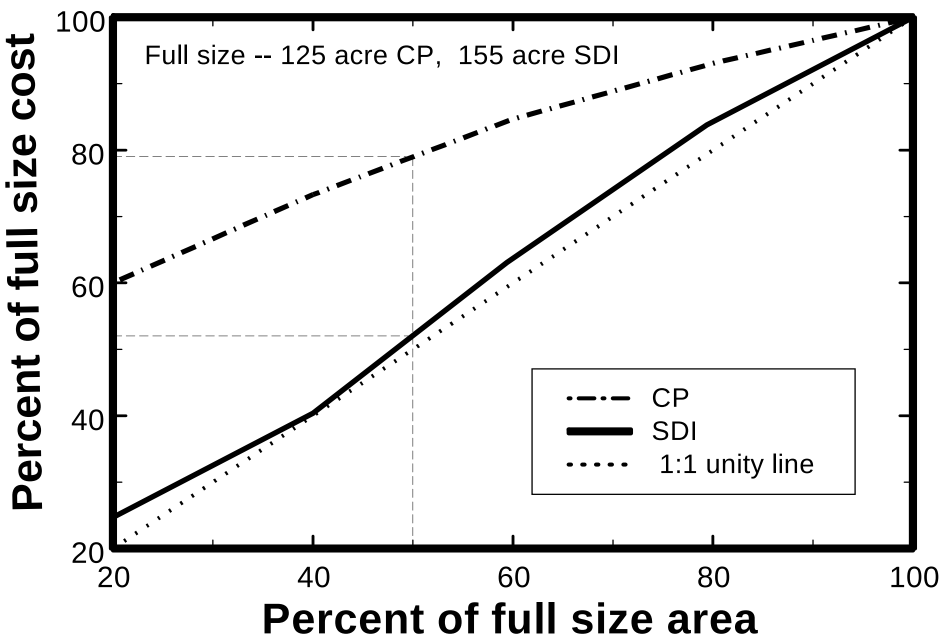


Figure 15. Center pivot sprinkler (CP) and SDI system costs as related to field size. (after O'Brien et al., 1997)

Economic comparisons of CP and SDI systems are sensitive to the underlying assumptions used in the analysis (Lamm et. al., 2003). The results show that these comparisons are very sensitive to size of CP irrigation system, shape of field (full vs. partial circle CP system), life of SDI system, SDI system cost with advantages favoring larger CP systems and cheaper, longer life SDI systems. The results are moderately sensitive to corn yield, corn harvest price, yield/price combinations and very sensitive to higher potential yields with SDI with advantages favoring SDI as corn yields and price increase. A Microsoft Excel spreadsheet template has been developed for comparing CP and SDI economics and is available for free downloading from the internet at http://www.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 16). 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.

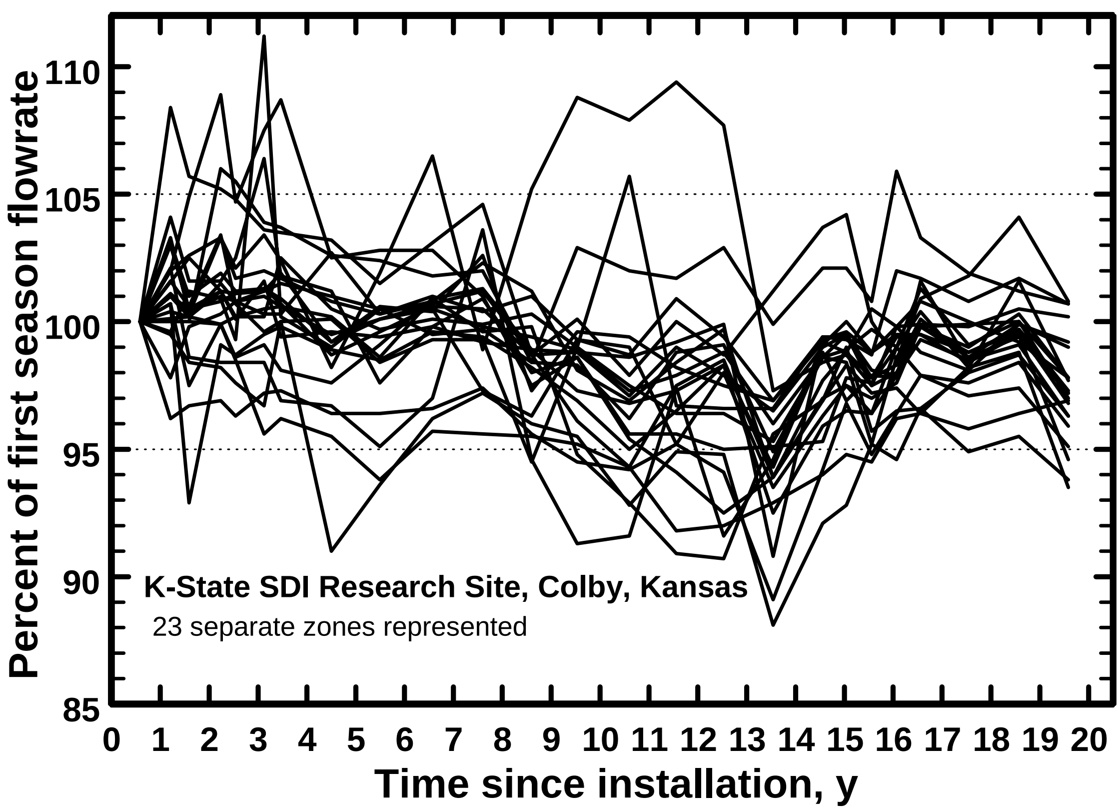


Figure 12. Stability in zone flowrates from the initial first season as related to time for an SDI system installed at Kansas State University, Colby, Kansas, 1989-2007.

CONCLUDING STATEMENTS

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

ACKNOWLEGEMENTS

Contribution No. 09-243-A from the Kansas Agricultural Experiment Station.

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

REFERENCES

Caldwell, D. S., W. E. Spurgeon and H. L. Manges. 1994. Frequency of irrigation for subsurface drip-irrigated corn. Trans. ASAE 37(4):1099-1103.

Camp, C. R., F. R. Lamm, R. G. Evans and C. J. Phene. 2000. Subsurface drip irrigation – Past, present and future. In Proc. Fourth Decennial Nat'l Irrigation Symp., Nov. 14-16, 2000, Phoenix, AZ. Sponsored by ASAE. pp. 363-372. Also available at http://www.oznet.ksu.edu/sdi/Reports/2000/K-StateRep/campis.htm

Camp, C.R. 1998. Subsurface drip irrigation: A review. Trans. ASAE 41(5):1353-1367. Also available at http://www.florence.ars.usda.gov/publist/sw_3247_.pdf

Darusman, A. H. Khan, L. R. Stone, and F. R. Lamm. 1997. Water flux below the root zone vs. drip-line spacing in drip-irrigated corn. Soil Sci Soc. Am. J. 61:1755-1760. Also available at http://www.oznet.ksu.edu/sdi/Reports/1997/WaterFluxSpacing.pdf

Hengeller, J. 1995. Use of drip irrigation on alfalfa. In: Proc. Central Plains Irrigation Shortcourse, Feb. 7-8, 1995, Garden City, Kansas. Kansas State Univ. Extension Biol. and Agric. Engr. Dept., Manhattan, KS. pp. 160-167.

Howell, T. A. 2001. Enhancing water use efficiency in irrigated agriculture. Agron J. 93(2):281-289. Also available at http://www.cprl.ars.usda.gov/wmru/pdfs/howell 2001.pdf

Howell, T. A., A. D. Schneider, and S. R. Evett. 1997. Subsurface and surface microirrigation of corn—Southern High Plains. Trans. ASAE 40(3):635-641.

Kincaid, D. E. and D. F. Heerman. 1974. Scheduling Irrigation Using a Programmable Calculator. USDA Pub. ARS-NC-12, February, 1974. 55 pp.

Lamm, F. R. 2004. Comparison of SDI and Simulated LEPA Sprinkler Irrigation for Corn. In Proc. Irrigation Assn. Int'l. Irrigation Technical Conf., November 14-16, 2004, Tampa, FL. Available from Irrigation Assn., Falls Church VA. IA Paper No. IA04-1098. pp 475-485. Also available at http://www.oznet.ksu.edu/sdi/Reports/2004/LS100104.pdf

Lamm, F. R. 2005. SDI for conserving water in corn production In Proc. ASCE-EWRI Water Congress, May 15-19, 2005, Anchorage, AK. 12 pp. Also available at http://www.oznet.ksu.edu/sdi/Reports/2005/ASC000557.pdf

Lamm, F. R. and R. M. Aiken. 2005. Effect of irrigation frequency for limited subsurface drip irrigation of corn. In Proc. Irrigation Assn. Int'l. Irrigation Technical Conf., November 6-8, 2005, Phoenix, AZ. Available from Irrigation Assn., Falls Church VA. IA Paper No. IA05-1264. Also available at http://www.oznet.ksu.edu/sdi/Reports/2005/SDIFreqIA.pdf

Lamm, F. R. and T. P. Trooien. 2001. Irrigation capacity and plant population effects on corn production using SDI. In Proc. Irrigation Assn. Int'l. Irrigation Technical Conf., Nov. 4-6, 2001, San Antonio, TX. Pages 73-80. Available from Irrigation Assn., Falls Church VA. Also available at http://www.oznet.ksu.edu/sdi/Reports/2001/icpp.pdf

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

Lamm, F. R., A. J. Schlegel, and G. A. Clark. 2004. Development of a Best Management Practice for Nitrogen Fertigation of Corn Using SDI. Appl. Engr in Agric. 20(2):211-220. Also available at http://www.oznet.ksu.edu/sdi/Reports/2004/SDIFert04.pdf

Lamm, F. R., T. P. Trooien, and A. J. Schlegel. 2006. Applying swine effluent with SDI and LEPA sprinkler irrigation. Proc. 27th Annual Int'l. Irrig. Assoc. Tech. Conf., San Antonio, Texas, Nov. 5-7, 2008. Available from Irrig. Assoc., Falls Church, VA. Paper No. IA06-1517. pp. 513-526. Also available at http://www.oznet.ksu.edu/sdi/Reports/2006/LammIA.pdf

Lamm, F. R. T. P. Trooien, and A. J. Schlegel. 2007. Application and utilization of livestock effluent through SDI systems. Intr'l Symposium on Air Quality and Waste Management for Agriculture, Broomfield, CO. Sept. 15-19, 2007. ASABE. 8 pp. Also available at http://www.oznet.ksu.edu/sdi/Reports/2007/AppUtlSDIWW.pdf

Lamm, F. R., D. M. O'Brien, D. H. Rogers, and T. J. Dumler. 2003. Center pivot sprinkler and SDI economic comparisons. In Proc. of the Central Plains Irrigation Conf., February 4-5, 2003, Colby Kansas. Proceedings available from CPIA, 760 N. Thompson, Colby, Kansas. pp. 199-211. Also available at http://www.oznet.ksu.edu/sdi/Reports/2003/CPSDI03.pdf

Lamm, F. R., L. R. Stone, H. L. Manges, and D. M. O'Brien. 1997a. Optimum lateral spacing for subsurface drip-irrigated corn. Trans. ASAE, 40(4)1021-1027. Also available at http://www.oznet.ksu.edu/sdi/Reports/1997/OptSpacing.pdf

Lamm, F. R. T. P. Trooien, H. L. Manges, and H. D. Sunderman. 2001. Nitrogen fertilization for subsurface drip-irrigated corn. Trans ASAE 44(3):533-542. Also available at http://www.oznet.ksu.edu/sdi/Reports/2001/dfert.pdf

Lamm, F. R., H. L. Manges, D. H. Rogers, W. E. Spurgeon, and M. H. Farmer. 1990. Design and installation of a drip irrigation system for research purposes. Presented at the international winter meeting of the ASAE, Chicago, IL, Dec. 18-21, 1990. ASAE Paper No. 902530, ASAE, St. Joseph, MI. 21 pp. Also available at http://www.oznet.ksu.edu/sdi/Reports/1990/Design&Instal.pdf

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

Lamm, F. R., T. P. Trooien, G. A. Clark, L. R. Stone, M. Alam, D. H. Rogers, and A. J. Schlegel. 2002. Using beef lagoon wastewater with SDI. In Proc. Irrig. Assoc. Int'l. Irrigation Technical Conf., October 24-26, 2002, New Orleans, LA. Available from Irrig. Assoc., Falls Church, VA. 8 pp. Also available at http://www.oznet.ksu.edu/sdi/Reports/2002/MWIAPaper.pdf

Manges, H. L., W. E. Spurgeon, Z. M. Huang, and D. J. Tomsicek. 1995. Subsurface dripline spacing and plant population for corn production. In Proceedings of the Fifth Int'l Microirrigation Congress, Orlando, Florida, April 2-6, 1995. pp 388-394. ASAE, St. Joseph, MI, USA. 978 pp.

Nakayama, F. S. and D. A. Bucks. 1986. Trickle irrigation for crop production. Edited by F. S. Nakayama, and D. A. Bucks. Elsevier Publications, Netherlands. 383 pp.

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

Powell, N. L. and F. S. Wright. 1993. Grain yield of subsurface microirrigated corn as affected by irrigation line spacing. Agron. J. 85:1164-1170.

Spurgeon, W. E., H. L. Manges, and T. P. Makens. 1991. Drip line spacing and plant population for corn. Presented at the int'l winter meeting of the ASAE. ASAE Paper No. 912592, ASAE, St. Joseph, MI. 12 pp.

Trooien, T. P., F. R. Lamm, L. R. Stone, M. Alam, D. H. Rogers, G. A. Clark, and A. J. Schlegel. 2000. Subsurface drip irrigation using livestock wastewater: Dripline flow rates. Appl. Engr. in Agric. 16(5):505-508. Also available at http://www.oznet.ksu.edu/sdi/Reports/2000/SDILWaste.pdf

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

USING THE K-STATE CENTER PIVOT SPRINKLER AND SDI ECONOMIC COMPARISON SPREADSHEET - 2009

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

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

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

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

Kansas State University

INTRODUCTION

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

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

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

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

Field description and irrigation system estimates	Total	Suggested	CP	Suggested	SDI	Suggested
Field area, acres	160	← 160	125	← 125	155	← 155
Non-cropped field area (roads and access areas), acres	5	← 5				
Cropped dryland area, acres (= Field area - Non-cropped field area - Irrigated area)			30		0	
Irrigation system investment cost, total $			$73,450	← $73,450	$186,000	← $186,000
Irrigation system investment cost, $/irrigated acre			$587.60		$1,200.00	
Irrigation system life, years			25	← 25	20	← 20
Interest rate for system investment, %	8.0%	← 8.0%				
Annual insurance rate, % of total system cost			1.60%	← 1.60%	0.60%	← 0.60%
Production cost estimates			CP	Suggested	SDI	Suggested
Total variable costs, $/acre (See CF Tab for details on suggested values)			$585.92	← $585.92	$559.29	← $559.29
Additional SDI variable costs (+) or savings (-), $/acre			Additional Costs →		$0.00	← $0.00
Yield and revenue stream estimates			CP	Suggested	SDI	Suggested
Corn grain yield, bushels/acre		Suggested	220	← 220	220	← 220
Corn selling price, $/bushel	$4.00	← $4.00				
Net return to cropped dryland area of field ($/acre)	$36.00	← $36.00				

Advantage of SDI over Center Pivot Sprinkler *	**$/total field each year**	**$1,065.25**
*** Advantage in net returns to land and management**	**$/acres each year**	**$6.66**

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

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

ANALYSES METHODS AND ECONOMIC ASSUMPTIONS

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

Field & irrigation system assumptions and estimates

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

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

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

Irrigation system costs are highly variable at this point in time due to rapid fluctuations in material and energy costs. Cost estimates for the 125 acre CP system and the 155 acre SDI system are provided on the current version of the spreadsheet template based on discussions with dealers and Dumler et al. (2007), but since this is the overall basis of the comparison, it is recommended that the user apply his own estimates for his conditions. In the base analyses, the life for the two systems is assumed to be 25 and 20 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 20 and 25 years and typical financial interest rates, the zero salvage value is a very minor issue in the analysis. System life is a very important factor in the overall analyses. However, the life of the SDI system is of much greater economic importance in analysis than a similar life for the CP system because of the much higher system costs for SDI. Increasing the system life from 20 to 25 years for SDI would have a much greater economic effect than increasing the CP life from 20 to 25 years.

When the overall field size decreases, thus decreasing system size, there are large changes in cost per irrigated acre between systems. SDI costs are nearly proportional to field size, while CP costs are not proportional to field size (Figure

2). Quadratic equations were developed to calculate system costs when less than full size 160 acre fields were used in the analysis (Obrien et al., 1998):

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

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

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

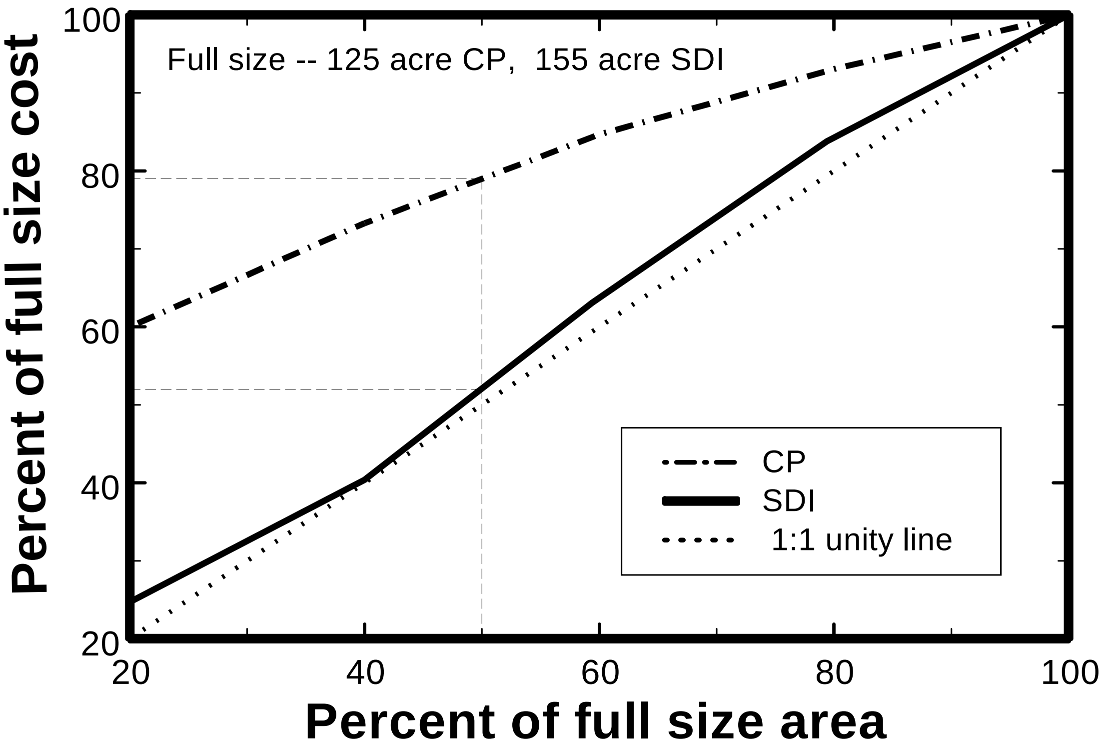


Figure 2. CP and SDI system costs as related to field size. (after O'Brien et al., 1998)

The annual interest rate can be entered as a variable, but is currently assumed to be 8.0%. The total interest costs over the life of the two systems were converted to an average annual interest cost for this analysis. Annual insurance costs were assumed to be 1.6% of the total system cost for the center pivot sprinkler and 0.6% for the SDI system, but can be changed if better information is available. The lower value for the SDI was based on the assumption that only about 40% of the system might be insurable. Many of the SDI components are not subject to the climatic conditions that are typically insured hazards for CP systems. However, system failure risk is probably greater with SDI systems which might influence any obtainable insurance rate. The cost of insurance is a minor factor in the economic comparison when using the current values.

Production cost assumptions and estimates

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

Production costs were adapted from KSU estimates (Dumler et al., 2008). A listing of the current costs is available on the CF worksheet (tab) (Figure 3) and the user can enter new values to recalculate variable costs that more closely match their conditions. The sum of these costs would become the new suggested Total Variable Costs on the Main worksheet (tab), but the user must manually change the input value on the Main worksheet (White input cell box) for the economic comparison to take effect. *The user may find it easier to just change the differential production costs between the systems on the Main tab rather than changing the baseline assumptions on the CF tab. This will help maintain integrity of the baseline production cost assumptions.*

Factors for Variable Costs			CP	Suggested	SDI	Suggested
Seeding rate, seeds/acre	$/1000 S	Suggested	34000	← 34000	34000	← 34000
Seed, $/acre	$2.24	← $2.24	$76.16		$76.16	
Herbicide, $/acre			$28.68	← $28.68	$28.68	← $28.68
Insecticide, $/acre			$35.30	← $35.30	$35.30	← $35.30
Nitrogen fertilizer, lb/acre	$/lb	Suggested	242	← 242	242	← 242
Nitrogen fertilizer, $/acre	$0.40	← $0.40	$96.80		$96.80	
Phosphorus fertilizer, lb/acre	$/lb	Suggested	50	← 50	50	← 50
Phosphorus fertilizer, $/acre	$0.35	← $0.35	$17.50		$17.50	
Crop consulting, $/acre			$6.50	← $6.50	$6.50	← $6.50
Crop insurance, $/acre			$37.00	← $37.00	$37.00	← $37.00
Drying cost, $/acre			$0.00	← $0.00	$0.00	← $0.00
Miscellaneous costs, $/acre			$0.00	← $0.00	$0.00	← $0.00
Custom hire/machinery expenses, $/acre			$150.14	← $150.14	$150.14	← $150.14
Other non-fieldwork labor, $/acre			$0.00	← $0.00	$0.00	← $0.00
Irrigation labor, $/acre			$6.50	← $6.50	$6.50	← $6.50
Irrigation amounts, inches			17	← 17	13	← 13
Fuel and oil for pumping, $/inch			$5.80	← $5.80	$5.80	← $5.80
Fuel and oil for pumping, $acre			$98.60		$75.40	
Irrigation maintenance and repairs, $/inch			$0.60	← $0.60	$0.60	← $0.60
Irrigation maintenance and repairs, $/acre		Suggested	$10.20		$7.80	
1/2 yr. interest on variable costs, rate	8.0%	← 8.0%	$22.54		$21.51	
Total Variable Costs			**$585.92**		**$559.29**	

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

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

Yield and revenue stream estimates

Corn grain yield is currently estimated at 220 bushels/acre in the base analysis with a corn price of $4.00/bushel (See values on Main worksheet). Net returns for the 30 cropped dryland acres for the CP system (corners of field) were assumed to be $36.00/acre which is essentially the current dryland crop cash rent estimate for Northwest Kansas. Government payments related to irrigated crop production are assumed to be spread across the overall field size, and thus, do not affect the economic comparison of systems.

Sensitivity analyses

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

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

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

The results are very sensitive to

- any additional production cost savings with SDI.

The results are moderately sensitive to

- corn yield
- corn price
- yield/price combinations

and very sensitive to

- higher potential yields with SDI

with advantages favoring SDI as corn yields and price increase.

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

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

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

Field size	160	127	95	64	32	80	
CP Size	125	100	75	50	25	64	← Wiper 1/2 circle
CP Cost	$587.60	$685.38	$827.22	$1,077.78	$1,763.15	$1,147.66	
CP Dry	30	24	18	12	6	14	
SDI Size	155	124	93	62	31	78	
SDI Cost	$1,200.00	$1,226.70	$1,255.60	$1,299.00	$1,400.40	$1,273.72	
SDI life years	Note: This sensitivity valid only if full-sized CP (125 acres) and SDI (155 acres) costs exist on Main worksheet (tab) !!!!!!!						
5	**$167.72**	**$168.06**	**$164.71**	**$154.55**	**$127.31**	**$146.23**	
10	**$51.47**	**$48.29**	**$41.79**	**$28.71**	**-$8.36**	**$22.05**	
15	**$12.72**	**$8.36**	**$0.82**	**-$13.24**	**-$53.58**	**-$19.35**	
20	**-$6.66**	**-$11.60**	**-$19.66**	**-$34.21**	**-$76.19**	**-$40.05**	
25	**-$18.28**	**-$23.58**	**-$31.96**	**-$46.80**	**-$89.75**	**-$52.47**	

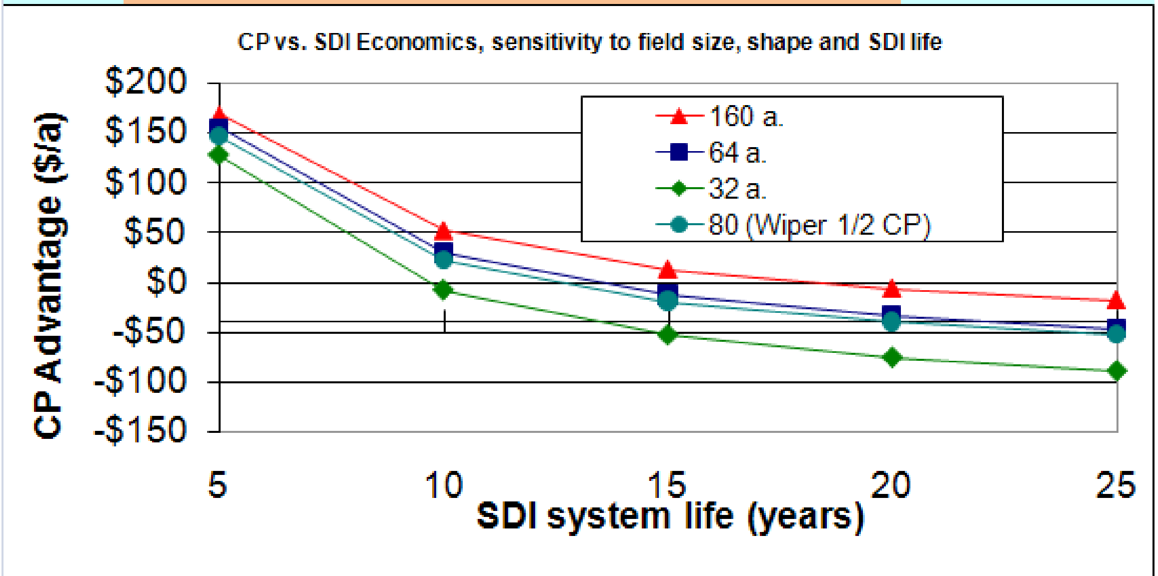


Figure 4. The Field size & SDI life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

SOME KEY OBSERVATIONS FROM PREVIOUS ANALYSES

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

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

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

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

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

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

SDI Cost $/acre	SDI system life, years: 5	10	15	20	25	30
900	$96.22	$9.04	-$20.03	-$34.56	-$43.28	-$49.09
1000	$120.05	$23.18	-$9.11	-$25.26	-$34.95	-$41.40
1100	$143.89	$37.32	$1.80	-$15.96	-$26.61	-$33.72
1200	$167.72	$51.47	$12.72	-$6.66	-$18.28	-$26.03
1300	$191.55	$65.61	$23.63	$2.64	-$9.95	-$18.35
1400	$215.38	$79.75	$34.55	$11.94	-$1.62	-$10.66
1500	$239.21	$93.90	$45.46	$21.24	$6.71	-$2.98

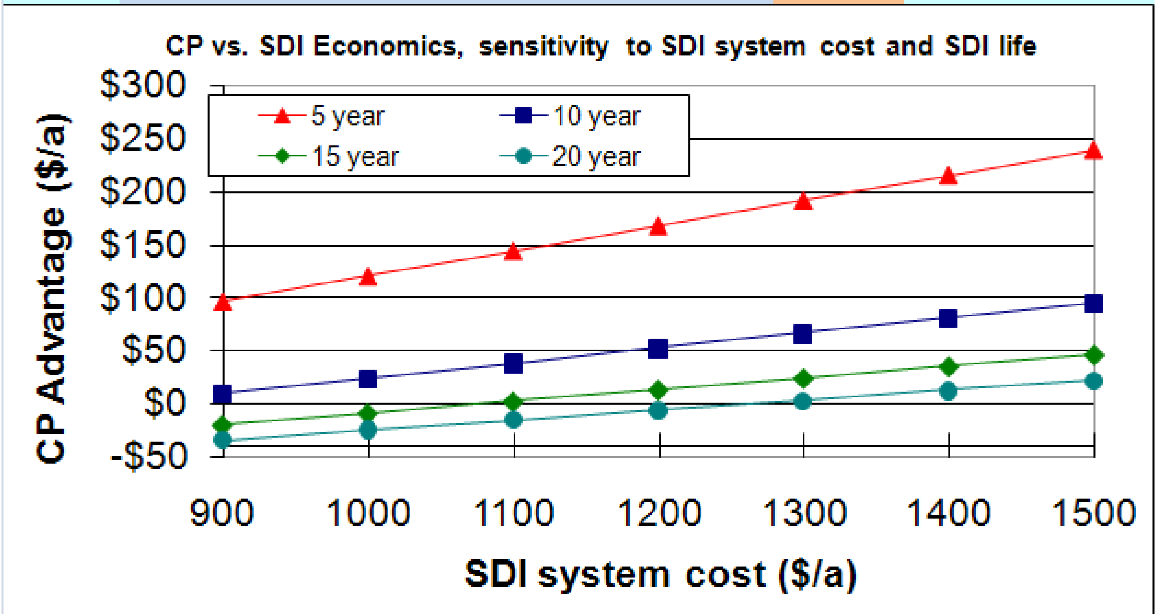


Figure 5. The SDI cost and life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

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

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

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

	Corn cash price, $/bu						
Corn Yield	$2.80	$3.20	$3.60	$4.00	$4.40	$4.80	$5.20
160	$74.34	$62.34	$50.34	$38.34	$26.34	$14.34	$2.34
170	$69.09	$56.34	$43.59	$30.84	$18.09	$5.34	-$7.41
180	$63.84	$50.34	$36.84	$23.34	$9.84	-$3.66	-$17.16
190	$58.59	$44.34	$30.09	$15.84	$1.59	-$12.66	-$26.91
200	$53.34	$38.34	$23.34	$8.34	-$6.66	-$21.66	-$36.66
210	$48.09	$32.34	$16.59	$0.84	-$14.91	-$30.66	-$46.41
220	$42.84	$26.34	$9.84	-$6.66	-$23.16	-$39.66	-$56.16
230	$37.59	$20.34	$3.09	-$14.16	-$31.41	-$48.66	-$65.91
240	$32.34	$14.34	-$3.66	-$21.66	-$39.66	-$57.66	-$75.66
250	$27.09	$8.34	-$10.41	-$29.16	-$47.91	-$66.66	-$85.41
260	$21.84	$2.34	-$17.16	-$36.66	-$56.16	-$75.66	-$95.16
270	$16.59	-$3.66	-$23.91	-$44.16	-$64.41	-$84.66	-$104.91

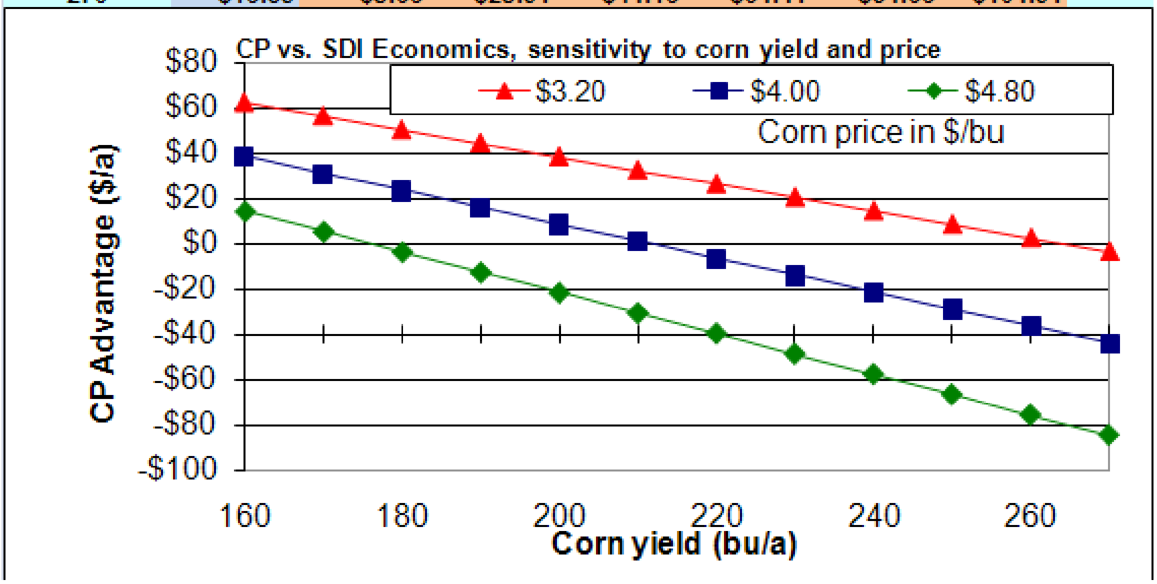


Figure 6. The Yield and Price worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

AVAILABILITY OF FREE SOFTWARE

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

ACKNOWLEGEMENTS

Contribution No. 09-242-A from the Kansas Agricultural Experiment Station.

REFERENCES

Dumler, T. J., D. M. O'Brien, and B. L. S. Olson. 2008. Center-pivot-irrigated corn cost-return budget in Western Kansas. KSU Farm Management Guide, MF-585. Manhattan, Kansas. 4 pp. Also available at http://www.oznet.ksu.edu/library/agec2/MF585.pdf

Dumler, T. J., D. M. O'Brien, and D. H. Rogers. 2007. Irrigation capital requirements and energy costs. KSU Farm Management Guide, MF-836. Manhattan, Kansas. 4 pp. Also available at http://www.oznet.ksu.edu/library/agec2/mf836.pdf

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

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

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

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

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

REDUCING THE COST OF PUMPING IRRIGATION WATER

Derrel L. Martin,
Professor
University of Nebraska-Lincoln
Biological Systems Engineering
Lincoln, Nebraska
402-472-1586
dlmartin@unlnotes.unl.edu

William L. Kranz,
Associate Professor
University of Nebraska-Lincoln
Biological Systems Engineering
Haskell Agricultural Laboratory
Concord, Nebraska
402-584-3857
wkranz@unl.edu

Tom W. Dorn,
Extension Educator
University of Nebraska-Lincoln
Extension
Lincoln, Nebraska
402-441-7180
tdorn@unl.edu

Steve R. Melvin,
Extension Educator
University of Nebraska-Lincoln
Extension
Curtis, Nebraska
308-367-4424
smelvin@unl.edu

Alan J. Corr,
Extension Educator
University of Nebraska-Lincoln
Extension
North Platte, Nebraska
308-696-6781
acorr@unl.edu

Energy Use in Irrigation

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

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

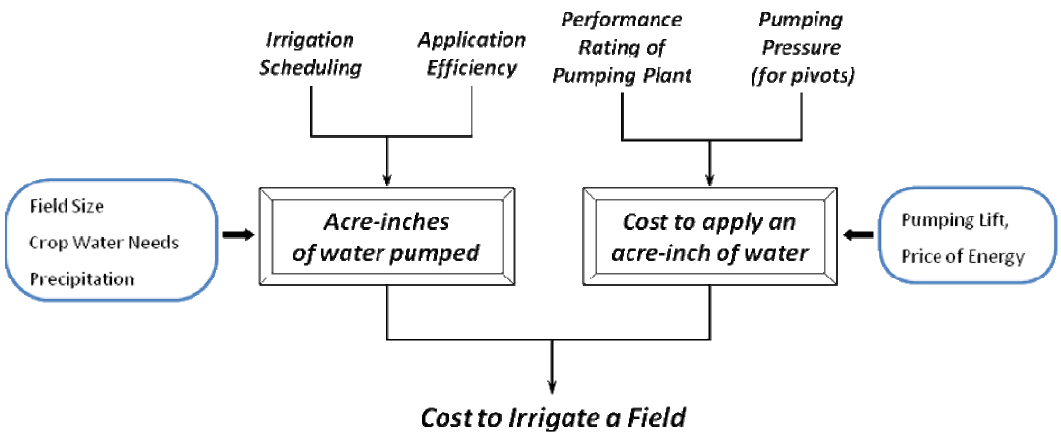


Figure 1. Diagram of factors affecting irrigation pumping costs

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

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

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

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

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

Energy Requirements

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

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

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

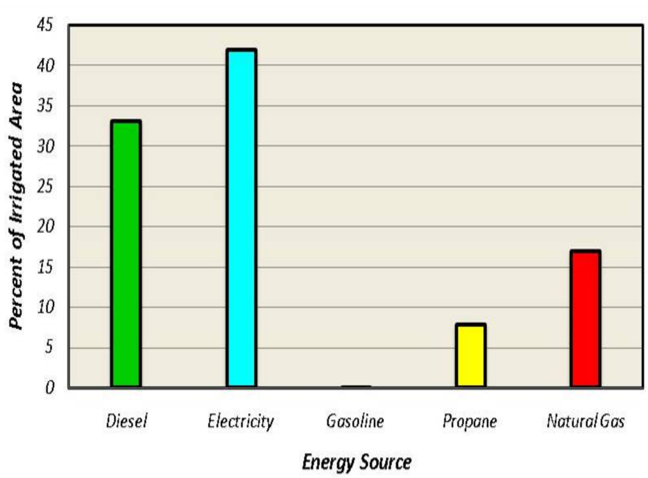


Figure 2. Percent of land irrigated in Nebraska by type of energy source (from USDA Farm and Ranch Irrigation Survey, 2003).

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

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

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

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

whp stands for water horsepower

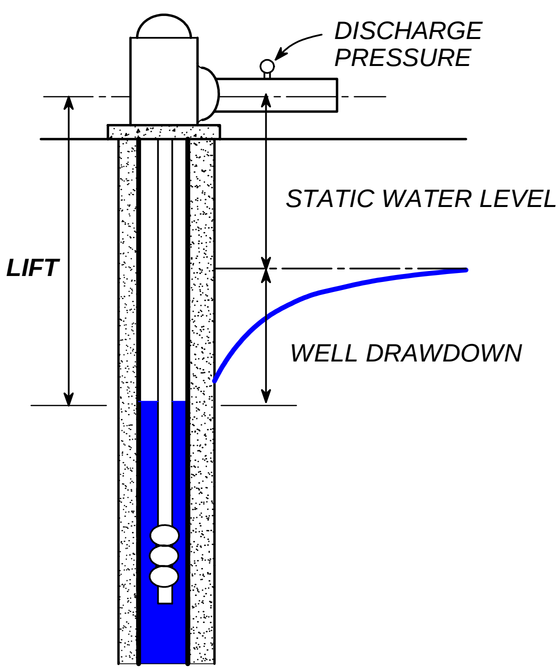


Figure 3. Diagram of pumping lift and discharge pressure measurements needed to assess pumping plant efficiency.

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

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

Pumping Plant Efficiency

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

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

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

Table 3. Conversions for other energy sources.

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

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

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

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

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

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

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

Table 5. Volume of water pumped per hour.

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

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

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

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

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

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

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

Paying for Repairs

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

Table 6. Series Present Worth Factor

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

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

Examples

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

Example 1

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

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

Example 2

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

Example 3

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

Summary

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

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

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

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

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

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

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

Figure 4. Pumping Cost Worksheet

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

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

ENERGY SAVINGS USING VARIABLE FREQUENCY DRIVES ON CENTRIFUGAL PUMPING APPLICATIONS

John Whaley
Channel Sales Engineer
Rockwell Automation
Wichita, Kansas
Voice:316-641-9050
Email:jwwhaley@ra.rockwell.com

Modern Electric Motor Starting Means

There are three primary methods used to start and operate induction AC motors: Full voltage direct across the line starters, reduced voltage soft starts, and Variable frequency drives (VFD's). The three methods all have distinctly different effects on both the mechanical system but also the power distribution networks.

Both the full voltage and reduced voltage starting means are only capable of running AC motors at the motor's synchronous speed of 60Hz. Full voltage cross the line starters allows the utility's full wave form to start the motor. This method will see a 600% to 800% of full load current in-rush during the starting of the motor. Many utility providers have begun to limit this starting means to only smaller motor loads due to the effects of the high in-rush current required to start the motor. Reduced Voltage soft starts will allow for more control of starting ramp rates of the system, but will have a typical in-rush current during starting of 350% to 450% of the motor's full load current and not allow for speed control. Both of these starting means do not allow for power factor correction within an induction AC motor system.

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

Affinity's Law Effects on Power consumption

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

Comparing the Cost to Traditional Engines

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

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

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

MONITORING IRRIGATION WATER APPLICATION WITH COMPUTERIZED CONTROLLERS

William Kranz
Associate Professor Biological Systems Engineering
University of Nebraska
Haskell Agricultural Laboratory
Concord, Nebraska
VOICE: 402-584-3857 FAX: 402-584-3859
wkranz1@unl.edu

INTRODUCTION

In the Central Plains area of Colorado, Kansas and Nebraska, approximately 9 million acres of cropland are irrigated by center pivot irrigation systems (2003 Census of Agriculture). Existing systems span the generations of center pivot technology evolution from water to electric and hydraulically driven machines. Due to their design, center pivots are operating on varying topography, and often have a range in soil textures present under a single machine. Perched water tables challenge managers of standard machines with the need to provide little or no irrigation water to some areas while fully irrigating others. Each of these factors represents a reason for using some sort of monitor/controller to manage water applications based upon need. In the process, altering machine speed of travel and irrigation cycles is the first step in site specific irrigation. Precision application and site specific irrigation are techniques to maximize the value of the water applied via a center pivot.

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

SITE SPECIFIC IRRIGATION

Over the last two decades research has been conducted by public and private groups seeking to development methodology and decision making tools necessary for application of water and plant nutrients based upon the physical limitations of a tract of land. In essence this work was adding center pivot irrigation systems to the list of variables that can be considered on a site-specific basis. As the technology has evolved so has the list of terminology used to help lay claim to unique ways standard center pivot controls are replaced and/or enhanced to allow variation in the center pivot's application depth and water application rate.

Initial steps to define decision making tools used for site-specific irrigation began in the early 1980's. Technologies such as Low Energy Precision Application (LEPA) were developed based on the early efforts to define optimum flow rates for sprinkler heads operating within inches of the soil surface (Lyle and Bordovsky, 1981). A series of control manifolds were used deliver different flow rates. Later work by Roth and Gardner (1989) sought to use the irrigation system to apply different amounts of nitrogen fertilizer with irrigation water.

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

Individual sprinkler control of water application depth can be accomplished by using a series of on-off time cycles or as it has become known as 'pulsing' the sprinkler (Karmeli and Peri, 1974). Reducing the on time is effective and reducing both the application depth and the water application rate. This is accomplished using either direct-acting or pilot-operated solenoid valves. Direct acting valves have a linkage between the plunger and the valve disc while the pilot-operated solenoid uses irrigation pipeline pressure to activate the valve.

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

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

As with any new technology, there are positives and negatives associated with each of these three methods of controlling sprinkler flow rates. Certainly long term maintenance is an issue. However, the biggest factor limiting their use is installation cost that ranges from around $2000 for a system monitor to over $20,000 for control of individual sprinklers.

CONTROLLERS

Center pivot manufacturers have developed proprietary means of monitoring and controlling center pivots using a variety of technologies under the trade names:, OnTrac IPAC, Tracker, and Grow Smart. The computerized control panels provide center pivot operators with the potential to monitor and control center pivots using telephones, radio telemetry, internet connections and satellite communication. In addition, there are a few private venture monitors and/or controllers that are available under the trade names: Farmscan, AgSense, and Pivotrac. Farmscan is the only company providing equipment for total VRI at this time.

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

Part two includes monitoring the center pivot control circuitry. This is accomplished directly at the main pivot panel. But can also be done using a Programmable Logic Controller (PLC) device. The main panel houses control circuitry for the end gun, system speed of travel and direction, and on/off controls. Since most of this circuitry terminates at the end tower, center pivot monitors and controllers also can be mounted near the last tower control box.

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

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

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

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

SYSTEM REQUIREMENTS

Selecting the method of sprinkler control may be the easiest decision to make since the main factor of concern is: Will it pay to install the controls? However, once the decision is made to use a variable rate sprinkler application system-based upon some predetermined management zone size, design of the remaining portions of the irrigation system become interdependent.

How will the pumping plant respond to changes is system flow rate requirements? As sprinklers turn on and off, the flow rate required by the system varies. The response of a standard system is that the pump output will follow the pump curve to the right or left depending on whether more or less sprinklers are operating. More significant is that sprinklers near the end gun have flow rates that are significantly greater than sprinklers near the pivot point. Consequently, turning off sprinklers on the first 200 feet of the system will have much less effect than turning off a 200 foot section near the end gun. The correct design response is to install a pumping plant with variable revolutions per minute (RPM) so that as more sprinklers are added, the pumping RPM is increased and visa versa. In this way the pumping plant can supply water at the design pressure regardless whether 50 or 150 sprinklers are in operation.

The difficulty arises when the motor used to supply power the pump is the same one used to supply power to the center pivot. Changes is pump RPM require changes in engine RPM. So a separate energy supply may be required for the center pivot.

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

How accurately can I determine system position if application rate changes are desired? Center pivot position on most systems (without special equipment) is determined by the resolver that is located at the pivot point. Alignment systems typically have an accuracy of $\pm 1.5^{o}$ of where the first tower is located. Thus, at a distance of 1320 feet from the pivot point, the position of the last sprinkler could be off by 34 feet or more. Research conducted by Peters and Evett (2005) found that resolver determined position errors could be up to 5 degrees or over 100 feet on a 1320 foot long center pivot. Installation of a WAAS enabled digital GPS system can increase the accuracy of determining the location of the pivot lateral to errors of less than 10 feet. The net effect of being able to accurately determine the pivot lateral location is that management zone size can be reduced without increasing the potential for a misapplication.

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

Information Requirements

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

Field maps of each of these variables (field slope and soil texture, fertility level, grain or forage yield) represent information that make up levels in a Graphic Information System (GIS) analysis. It is important that these maps provide information on a management zone size basis. Limitations in the ability to collect point measurements due to cost or response time of sensors all impact the spatial resolution of the application map. For example, an 8-row combine operating at 6 mph and collecting yield estimates every 3-seconds provides a different spatial picture than a center pivot with control of banks of 5 sprinkler heads. Consequently, variable rate irrigation controls will typically be at less resolution than any of the other crop production inputs.

SUMMARY

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

TERMINOLOGY

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

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

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

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

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

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

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

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

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

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

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

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

REFERENCES

Karmeli, D and G. Peri. 1974. Basic principles of pulse irrigation. Journal of Irrigation and Drainage Division, ASCE 100(IR3):309-319.

King, B. A., and D. C. Kincaid. 2004. A variable flow rate sprinkler for site-specific irrigation management. Applied Engineering in Agriculture 20(6):765-770.

Lyle, W.M., and J.P. Bordovsky, 1981. Low energy precision application (LEPA) irrigation system. Transactions of ASAE 26(5):1241-1245.

Peters, T. R., S. R. Evett. 2005. Using low-cost GPS receivers for determining field position of mechanical irrigation systems. Appl. Engr in Agriculture 21(5):841-845.

Roth, R.L., and B.R. Gardner. 1989. Modified self-moving irrigation system for water-nitrogen crop production studies. ASAE paper No.89-0502, St. Joseph, MI: ASAE.

Sadler, E.J., R. G. Evans, G.W. Buchleiter, B. A. King, and C.R. Camp. 2000. Design considerations for site specific irrigation. *In*: Proc. 4th National Irrigation Symp.. (eds.) R. G. Evans, B. L. Benham and T. P. Trooien. ASABE St. Joseph, MI. pp. 304-315.

Sadler, E.J., R.G. Evans, K.C. Stone, and C.R. Camp. 2005. Opportunities for conservation with precision irrigation. J. Soil and Water Conservation (60(6):371-379.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby, Kansas, February 24-25, 2009
Available from CPIA, 760 N. Thompson, Colby, Kansas

UPDATE ON NORTHWEST KANSAS WATER CONSERVATION EFFORTS

Wayne Bossert
Manager
Northwest Kansas Groundwater Management District No. 4
Colby, Kansas
Voice: 785-462-3915 Fax: 785-462-2693
Email: wab@gmd4.org

1. ENHANCED MANAGEMENT PROTOCOL

(Reference link: http://www.gmd4.org/EnhancedMgt/protocol.htm)

In late 1999 the Kansas Legislature asked the Kansas Water Authority (KWA) to study several issues and make recommendations. Two of these issues were groundwater related and included: The long-term prospects for transitioning groundwater irrigation to dry land farming in specific areas to maintain sustainable yields; and the competition for future water (both ground and surface) and suggestions on addressing the expected competition. Also at this time the state water plan adopted a future objective for the High Plains Aquifer (Ogallala) to slow the current groundwater decline rates and extend the economic life of the aquifer. This future objective begins to drive the entire process.

In response, the Kansas Water Office (KWO) formed a Management Advisory Committee (MAC) for the Ogallala Aquifer that included all local stakeholders and asked this group to devise an approach to declining groundwater levels. In October 2001, the MAC agreed on 5 recommendations and 17 guiding principals on how this should be accomplished. The 5 recommendations were:

1. Delineate Ogallala Aquifer into subunits for enhanced management;

2. GMDs identify subunits in decline and set goals to extend and conserve aquifer;

3. Set subunit priorities to extend aquifer's life and sustain region's vitality;

4. Support and expand programs and activities to extend and conserve aquifer's life;

5. Support and expand research and education regarding aquifer conservation.

All applicable areas in the state began to address these recommendations. The Northwest Kansas Groundwater Management District No. 4 (GMD 4) in early 2006 included a High Priority Area (HPA) process into its management plan and began its enhanced management process which included (and still includes) seven tasks:

Task 1 - Cluster Aquifer Sub-units (Completed)
Task 2 - Prioritize Aquifer Sub-units (Completed)
Task 3 - Verify data for each high priority aquifer sub-unit (Completed)
Task 4 - Set water goals and management for HPA sub-units after public input
Task 5 - Assess management program per board decisions based on Task 4
Task 6 - Develop plans to transition to dryland for appropriate acreages
Task 7 - Review, evaluate and reiterate

In designating the GMD 4 HPAs the board decided that any section experiencing 9% or more decline between 1996 and 2002, OR, a 2-mile, reported water use density exceeding 275 AF per section, would be designated a “high priority section”. Furthermore, any 1/4 Township (9 square miles) having 2 or more high priority sections would be designated a “high priority area”. These would be the hydrological-derived HPAs. The board also decided that any area from which a local request of involved persons came that desired additional management, could also be designated a HPA.

The process is now on Task 4 – the public meetings. The board has been conducting public meetings within each high priority aquifer sub-unit in order to: a) inform the land owners and water users of the district’s process and findings; b) to discuss the area’s future outlook based on the district findings; c) to request input from the attendees about preferred future actions - specifically including preferences for a groundwater budget for the next 20 years; and d) what management policies/actions/strategies should be considered by the board to achieve the preferred groundwater budget.

Following the public meetings, the board will decide what groundwater use goals (groundwater budgets) are appropriate for each HPA and what management approaches should be implemented. These decisions will be incorporated into the management program before being undertaken. If new regulatory authorities are considered necessary or prudent, either by the public or the board, they will be further explored at this step in the process.

(NOTE: In both the public meeting venue and the final board decision process, the following methods for reducing water use might be discussed: 1) targeting funding for water use efficiency improvements, water right set asides, or water right buyouts; 2) stricter regulation of water rights to include both negative and positive incentives concerning: a) overpumpage; b) tailwater control and reuse; and c) unreasonable pumpage; and 3) Intensive groundwater use control areas

(IGUCAs) or other special management areas. Any other ideas brought up by the district members within either venue will also be considered.)

Three main points regarding Task 4 are:

1) There are no pre-conceived problems or solutions by the GMD 4 board as Task 4 is undertaken – everything is open for discussion including problems or solutions offered by the local participants.

2) There is no specific deadline on the Task 4 process – multiple meetings may be needed due to the complexity of the issues and the data that must be presented. However, non-action (or the perception thereof) may change the expectations of anyone watching this process.

3) Both voluntary and/or regulatory approaches (in fact all approaches) can be considered.

2. WATER TRANSITION ASSISTANCE

A relatively new conservation program authorized by the 2006 Legislature is the Water Transportation Assistance Program (WTAP). The reference link (from which the following overview has been excerpted) is:

http://www.scc.ks.gov/images/stories/pdf/wtap_%2009_leg_report.pdf

"WTAP is a voluntary, incentive-based water conservation program whereby a participating landowner permanently retires (dismisses) water rights in exchange for compensation by the State of Kansas. WTAP is administered by the State Conservation Commission (SCC) for "the purpose of reducing consumptive use in the target or high priority areas of the state..."

The pilot project is authorized for 5 years (beginning July 1, 2007) with an annual budget from federal and state funds not allowed to exceed $1.5 million. Unexpended fund balances can be carried over to successive fiscal years with the approval of the Legislature. Although it is a "stand-alone" project, WTAP was envisioned to be consistent with, and complimentary to, the water management policies and programs of other federal, state, local, and private entities operating on a statewide basis. As such, it does allow for cooperative cost-sharing from the federal or state government, or private sources, for water right retirement grants.

Mutually agreeable compensation is paid to a landowner in the form of a financial assistance "grant" which can be distributed in installments of up to 10 years. The grant is available to aid willing sellers in the transition from irrigation to dryland farming. The amount of the compensation is largely determined by a fixed price point value determined annually by the SCC in conjunction with other agencies, *and many other relevant factors such as the seniority of the water right, its historic consumptive water use quantity, the proximal relationship of the water right within the targeted water supply, and a competitive bid price submitted by the owner. WTAP grants are tied to obligations of permanent water right dismissals which ensure tax dollars are invested wisely and efficiently. They are only available in areas closed to new appropriations of water which have been determined to be "in need of aquifer restoration and stream flow recovery.""*

The Legislature designated two eligible areas via statute – the Rattlesnake Creek (HUC 11030009) and the Prairie Dog Creek (HUC 10250015) and provided a process for other areas to be designated as program eligible. Part of this process required each eligible area to set a "retirement goal of historic consumptive water use". Once this retirement goal was reached, WTAP funds would no longer be used therein.

Throughout 2008 calendar year GMD 4 worked to make its six designated high priority areas eligible for this program. These areas were formally closed to new appropriations and determined to be in need of aquifer restoration by the chief engineer on September 22, 2008. As a result, the six designated areas became the state's third eligible area. The retirement goals for the six HPAs in GMD 4 are: SH-1: 6,000 Acrefeet (AF); SH-2: 4,000 AF; CN-3: 2,000 AF; TH-4: 600 AF; TH-5: 15,000 AF; and SD-6: 12,000 AF. The GMD 4 board also agreed to provide an additional $50.00 per historic consumptive water use for every successful WTAP application within its six eligible areas.

The first signup period for the FY 2009 program began October 1, 2008 and ran through November 15, 2008. During this enrollment period, SCC received a total of 41 applications totaling $9,799,400 in competitive bids and representing 5,753 AF of annual appropriation authorization which could be permanently retired – three applications from the Rattlesnake Creek Sub-basin and 38 from the GMD 4 HPAs.

WTAP, being a 5 year pilot program, will have the opportunity to assist these eligible areas in reaching their designated retirement goals. The Kansas Legislature appropriates WTAP funding annually, so whether or not the 4th and 5th years will get any funding is still under debate, as is the continuance of the program beyond its pilot status.

WTAP was designed to work in concert with other conservation efforts – most notably the Environmental Quality Incentive Program (EQIP) under the 2002 and 2008 Farm Bills. In fact several of the GMD 4 WTAP applications are also enrolled in EQIP.

The WTAP program for FY 2009 had available approximately $3.4 million which had been accrued over the first 3 years of the program. This funding was sufficient to fund 20 of the 41 applications filed – resulting in 2,294 AF of historic consumptive water use being retired permanently. Of these 20 applications, the three Rattlesnake Creek applications and 17 of the 38 GMD 4 applications were slated for approval. Due to the state budget shortfalls projected in 2009 and 2010, some or all of these funds may be swept by the Governor and Legislature for other projects.

3. CONSERVATION PROJECTS ALLIANCE

(Reference link: http://www.gmd4.org/Alliance/Alliance.htm)

Anticipating passage of a Kansas statute dealing with the possibility of award monies from the Republican River Compact Settlement Agreement coming to Kansas from either Colorado or Nebraska, the GMD 4 board decided to look into a possibility of forming a conservation projects alliance.

As anticipated, the Kansas legislature did pass Substitute for SB 89 in the 2008 session - specifying how any award monies would be utilized by Kansas. After the state's interstate litigation fund is restored to its $20 million target level, Sub. for SB 89 created two new conservation funds - the "Republican River Conservation Projects - Nebraska" fund and the "Republican River Conservation Projects - Colorado" fund.

One-third of any monetary Nebraska award received will go to the state water plan fund for water conservation projects - with priority given to projects that will directly enhance Kansas' ability to stay in compliance with the compact. Two-thirds of any Nebraska funds received will be administered by the Kansas Water office for conservation projects in the Lower Republican River basin in Kansas.

Two-thirds of any Colorado award funds received will be administered by the Kansas Water office for conservation projects in the Upper Republican basin in Kansas while one-third will go to the state water plan fund for water conservation projects anywhere in the Kansas.

The new statute lists ten types of conservation projects for which funds could be approved, but these ten designations are broad and include many possibilities.

In August, 2007 GMD 4 contacted approximately 80 Upper Republican Basin leaders and suggested the idea of a conservation projects alliance whose goal would be to craft a unified, cooperative and comprehensive water conservation projects application for consideration by the Kansas Water Office (KWO). These persons included representatives of County Commissions; Cities; Irrigation Districts; GMD 4; production agriculture; economic development; Resource Conservation & Development areas; financial institutions; area Industry; animal feeding operations; the Upper Republican Basin Advisory Committee; county farm bureau 's and the environment. The Alliance was formed.

Through this process, each "stakeholder group" (commissioners, cities, etc.) appointed one representative to sit on the Alliance. The following persons currently sit on the Alliance:

Wayne Bossert; GMD 4; Colby; Chair
John Arford; Economic Development; Norton
Sandy Rogers; RC&Ds; Goodland
Matt Bain; Environment; Colby
Spencer Schlepp; Conservation Districts; St. Francis
Dick Kelly; Industry; Oberlin
Larry Maxwell; Financial; Colby
Robert Binning; County Farm Bureaus; Atwood
Currently vacant; Cities;
Ralph Unger; County Commissions; Oberlin
Sid Metcalf; URBAC; Atwood
Harlan House; Animal Feeders; Goodland
Herb Mattson; Production Ag; Colby

The Alliance continues to meet and discuss potential conservation projects for the Upper Republican River Basin - eventually to settle on a suite of projects to be further evaluated before submitting its cooperative application to the KWO. Some of the ideas being discussed currently are:

1) Develop a “WTAP-like” program to further reduce historic consumptive water use. While this program may be applied basin-wide within the Upper Republican River basin, approximately 1/3 of the GMD 4 area (and all or parts of three GMD 4 HPAs) are included.

2) Enhance and extend a CRP set aside program for irrigated or dry land acres.

3) Develop a small irrigation project to use compact surface water that may be provided by Colorado – either to irrigate new acres or replace Ogallala Aquifer irrigation water on existing irrigated acres. These new water rights could be term permits allowing for alternative (non-irrigation) uses of this water in the future.

4) Enhancement program for playa lakes for recharge and environmental benefits.

5) Develop a reverse osmosis (RO) facility for a basin community using Dakota Aquifer water to replace the existing supply.

6) Construct a streambank recovery and storage project to use compact surface water that may be provided by Colorado.

4. NORTHWEST KANSAS GROUNDWATER CONSERVATION FOUNDATION

The Northwest Kansas Groundwater Conservation Foundation (Foundation) (reference link: http://www.groundwaterfoundation.com/) is a private corporation in the state of Kansas organized in cooperation with the public Northwest Kansas Groundwater Management District No. 4 (GMD 4). The Foundation board of directors intends to use public and private funding contributions to achieve all stated missions. The Foundation was formally incorporated in August, 2003 and obtained its IRS status in July, 2004.

The Foundation will incent existing water right owners to set aside - temporarily or permanently - consumptive groundwater use within priority areas of the local groundwater district. Funding will come from a variety of public and private sources and will be approved pending an application and evaluation process based on owner bids. Permanent water right reductions will be given priority.

From its inception, the Foundation has been seeking private grants to reduce consumptive water use within the district to achieve the state water plan goal of reduced water use. GMD 4 has also been putting approximately $75,000.00 per year toward the Foundation in order to entice additional private grant monies – unsuccessfully thus far.

To date the Foundation has agreed to contribute $50.00 per AF of historic consumptive water use for all successful WTAP applications.

For questions about any Northwest Kansas Groundwater Management District No.4 program – conservation or otherwise – please contact the district.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

WATER POLICIES THAT STOOD THE TEST OF TIME: A MATTER OF PERSPECTIVE

Paul Graves, P.E.
Assistant Chief Engineer
Kansas Department of Agriculture, Division of Water Resources
Topeka, Kansas
Voice: 785-296-2683   Fax: 785-296-1176
Email: paul.graves@kda.ks.gov

ABSTRACT

This paper examines the effectiveness of several water policies in Kansas: 1) limiting appropriation of water to safe yield quantities (and a closely related policy of closing fully appropriated areas); 2) monitoring water use through metering points of diversion and requiring annual water use reporting; and 3) providing the opportunity to manage groundwater through Intensive Groundwater Use Control Areas, in which corrective controls can be tailored to address specific problems.

These policies were selected on the basis of their profound effects on water resource management; their adoption more than 10 years ago, which provides a suitable period of record to judge their performance; and the ability to assess their performance in quantifiable ways. (In addition, these policies are likely to be of interest to individuals attending an irrigation conference.) The policies were evaluated and deemed to have continued relevancy, a record of accomplishing their objectives, and public acceptance.

INTRODUCTION

The importance of water for all human endeavors and the natural world cannot be overstated. Since there are competing demands for finite water supplies, government policies are necessary to ensure fair allocation and protection of water resources.

Three principal water policies of the state of Kansas are examined in this paper, with the objective being to determine if the policies have "stood the test of time", that is, if they have achieved their purposes and continue to be useful.

The following sections describe the methodology, analysis, and conclusions of this evaluation.

Disclaimer: The opinions and statements expressed in this paper are the personal opinions and statements of the author. Although informed by the author's work for the Kansas Department of Agriculture's Division of Water

Resources, the opinions and statements expressed herein do not necessarily reflect the agency's official policy or position on these issues.

METHODOLOGY

Scope of Examination

Merriam-Webster's Online Dictionary contains several definitions for the word "policy"; the meanings that appear to be most relevant to this discussion are:

> *2 a: a definite course or method of action selected from among alternatives and in light of given conditions to guide and determine present and future decisions;*
> *b: a high-level overall plan embracing the general goals and acceptable procedures especially of a governmental body*[1]

These definitions reflect the purposeful nature of policies. Water policies, then, are deliberate courses of action adopted by entities to achieve objectives involving water.

Entities establishing water policies range from the United Nations to sovereign nations, states, local governments, corporations, other organizations, and individuals. An example of federal water policy is EPA drinking water standards. An example of individual water policy is the decision to install low-flow fixtures in one's home (assuming it is optional and not mandated by government).

Water is a very broad subject. There are many different facets to consider, including supply and demands, quality, ecosystems, infrastructure, various uses, and so on. Due to the author's particular role in state government, this paper focuses on Kansas' water resources policies, that is, policies guiding the management of surface water and groundwater.

There is some debate over what constitutes an official policy, or when a policy must be followed. For example, some argue that policies set by an appointed body such as the Kansas Water Authority (KWA) do not have the same weight as statutes passed by the state Legislature, and as such are not mandatory. Others point to the makeup of KWA – which consists of voting members appointed by the Governor and Legislative leadership – and that its recommendations may effectively become law if/when the Legislature approves the State Water Plan budget, which is designed to implement KWA's policies.

This paper does not attempt to settle the aforementioned debate. Instead, it will focus on water policies implemented through state statutes, regulations, or

[1] http://www.merriam-webster.com/dictionary/policy

agency decisions under the statutes and regulations. Most people seem to accept these as enforceable water resources policy.[2]

Basis for Selection

Several criteria were used to select water resources policies for an examination as to whether they have "stood the test of time":

- First, the policies must have significant implications. It would not be worthwhile to spend time on trivial considerations.

- Second, the policies must have been in place for at least 10 years. Ten years may be the minimum span of time necessary to assess a water resource policy given the multi-year time frame ordinarily required for implementation and some noticeable response, and considering the normal variability in precipitation (i.e., 10 years is usually considered to be the minimum period of record needed to include representative wet, dry, and average years).

- Third, the policies must be measureable in some objective manner. Although it is beyond the scope of this paper to comprehensively quantify the effects of water policies, it is the author's intent to examine policies that have quantifiable effects.

The Kansas Water Appropriation Act (K.S.A. 82a-701 *et seq.*) and the Groundwater Management District Act (K.S.A. 82a-1020 through 1040) would seem to present the best opportunities to identify policies for this examination since as state laws governing water resources they unquestionably represent state water policy. Some of the policies established in these statutes (and their associated regulations) are listed below:

- Safe yield
- Ogallala mining
- Water conservation plans
- Waste of water
- Minimum desirable streamflow
- Well spacing
- Metering
- Water use reporting
- Water banking

[2] Article X in the Bill of Rights effectively grants states authority over management of water resources. According to the Tenth Amendment, since the U.S. Constitution does not ascribe that power to the federal government nor specifically withhold it from the states, it is delegated to the states (that is, the people). "*The powers not delegated to the United States by the Constitution, nor prohibited by it to the states, are reserved to the states respectively, or to the people". (Article X, Bill of Rights)*

- Intensive Groundwater Use Control Areas (IGUCAs)

Some policies established in other state laws, which seem to have objectives related to the above-listed policies, include the following:

- Grants for irrigation efficiency improvements
- Incentive payments for water right retirements
- Water marketing
- Water assurance districts

These lists are not intended to be exhaustive, and are just a selection of some of the more obvious choices for policies to examine.

Of the policies listed above, three were selected for further examination in this paper, for the reasons noted below:

1. <u>Safe yield</u> – This is a fundamental principle mentioned once in the Kansas Water Appropriation Act[3] and nearly 50 times in the associated rules and regulations.[4] *"'Safe yield' means the long-term sustainable yield of the source of supply, including hydraulically connected surface water or groundwater."*[5] For example, safe yield of an aquifer is typically regarded as the annual average recharge of the aquifer by the portion of precipitation that percolates into the ground and replenishes the aquifer. It has been a standard criterion in the issuance or dismissal of water appropriation applications since 1993, with some exceptions.[6] Some "Administrative Policies" which preceded the regulations required the application of safe yield principles in certain watersheds as early as 1983.[7] The policy of limiting appropriations to safe yield obviously has had profound effects on water resources in Kansas. One can estimate the quantitative and qualitative effects of this policy through analysis of water appropriation trends before and after the policy was adopted. One can also judge the effects of this policy by considering locations where a safe yield policy was not adopted in as timely a manner.

2. <u>Metering/water use reporting</u> – Measuring the amount of water used and reporting the amount of water used are closely related, and are therefore considered together in this paper. Both requirements are addressed in the

---

[3] K.S.A. 82a-711(b): *"In ascertaining whether a proposed use will prejudicially and unreasonably affect the public interest, the chief engineer shall take into consideration...(2) the area, safe yield and recharge rate of the appropriate water supply."*
[4] K.A.R. 5-1-1 *et seq.*
[5] K.A.R. 5-1-1(ttt).
[6] Exceptions to safe yield include appropriations approved prior to adoption of safe yield policy; appropriations in some Groundwater Management Districts which use an allowable depletion approach; as well as domestic use, some temporary permits, and some term permits.
[7] Policies and Procedures of the Chief Engineer, Kansas Department of Agriculture, Division of Water Resources.

Kansas Water Appropriation Act[8] and the associated rules and regulations. These requirements date from 1957 (meters) and 1988 (water use reports), respectively. Without these tools, it would be much more difficult to effectively regulate and manage Kansas' water resources. As a result of its metering and water use reporting policy, Kansas is widely regarded as having very good water use data on which to base regulatory decisions. One can estimate the quantitative and qualitative outcomes of this policy by considering the impacts on water use when meters are installed, as well as the amount of water involved in enforcement activities that rely on data obtained through metering and water use reporting. One can also judge the effects of this policy by considering other states that do not have equivalent policies.

3. IGUCAs – In recent years, the chief engineer's authority to establish Intensive Groundwater Use Control Areas has come under increased scrutiny by stakeholders, agencies, and the state legislature. This apparently resulted from dissatisfaction with the Pawnee Valley IGUCA proceedings of 2007, although it may stem from a more general opposition to increased regulation of groundwater. In any case, the IGUCA authorities[9], which were added to the Groundwater Management Act in 1978, significantly increased the options for managing groundwater resources in Kansas. IGUCAs provide flexibility and the ability to tailor solutions to a wide variety of groundwater resource problems. One can estimate the quantitative and qualitative outcomes of this policy by considering the number of water rights curtailed by IGUCAs as compared with the number that would have been curtailed to achieve the same objectives (e.g., delivering water to a senior water right holder) if first in time, first in right administration under the Kansas Water Appropriation Act had been the only option. (The resource may also be better protected under an IGUCA than with priority administration; however, this paper will not analyze this hypothesis.) One can also judge the effects of this policy by considering other states that do not have equivalent policies.

Basis for Evaluation

Several criteria were used to evaluate whether the selected water resources policies have "stood the test of time":

- First, is the policy still relevant and still applied? It would not be worthwhile to examine antiquated laws which are no longer enforced.

- Second, does the policy accomplish its objectives? This presupposes a clear intent which, if not explicitly stated, should be readily apparent.

[8] Measuring water use: K.S.A. 82a-706c; reporting water use: K.S.A. 82a-732.
[9] K.S.A. 82a-1036 through 1040.

- Third, do a majority of people agree with the policy? This may be difficult to assess quantitatively without the benefit of a proper survey, but one can at least gauge public opinion based on comments from stakeholders and legislators.

An evaluation of the three selected policies is provided in the next section of this paper.

ANALYSIS

The following analysis of the three selected policies applies the metrics noted above under “Basis for Selection” and the criteria listed above under “Basis for Evaluation”:

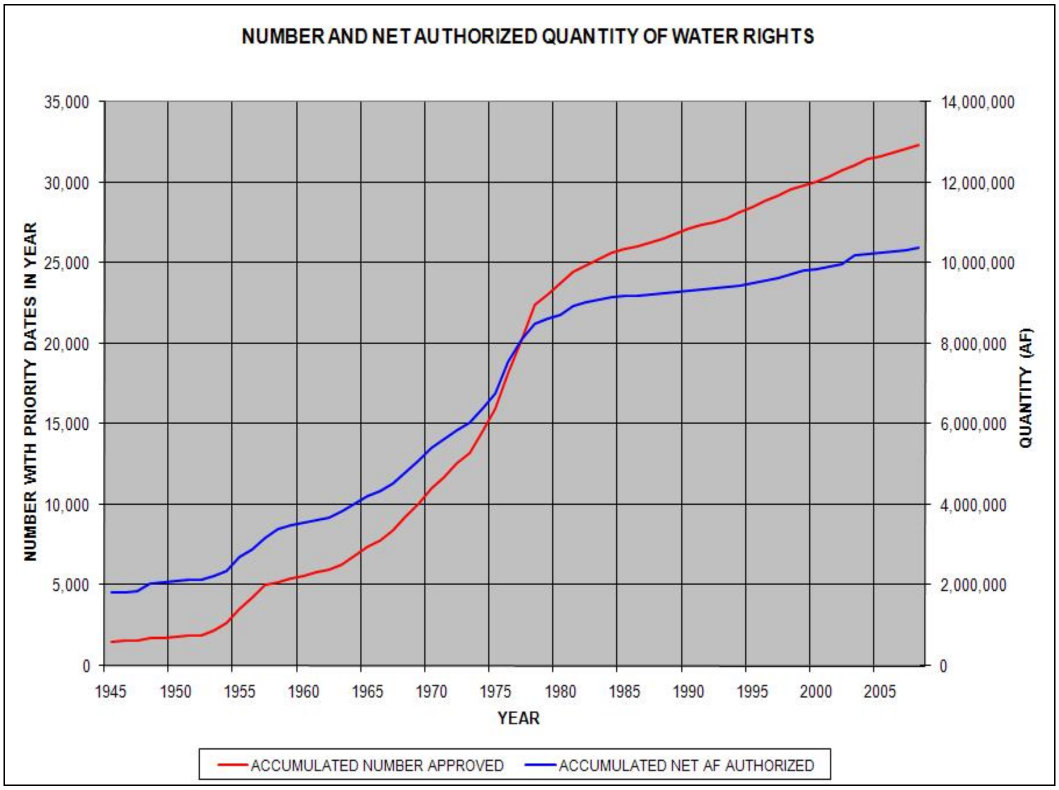
1. <u>Safe yield</u> – As illustrated in Figure 1 below, the number of water rights and the cumulative authorized quantity of water rights in Kansas grew exponentially from the mid-1940s through about 1980. From about 1980 through present the growth was linear, at a significantly slower rate.

   There are several main reasons for the shape of the graph in Figure 1. Water rights that were developed prior to 1945, when the Kansas Water Appropriation Act was enacted, became “vested rights” with a priority date of June 28, 1945. The increasing use of irrigation systems during the 1950s-1970s fueled much of the growth in water use, as did population growth and industry to lesser extents. In 1978, the Kansas Water Appropriation Act was amended making it mandatory for individuals to apply for water appropriation permits, whereas previously it had been optional. And in the early 1980s, the chief engineer began closing some areas of the state to new appropriation and establishing safe yield requirements for areas still open to appropriation (with some exceptions previously noted).

   Since the decelerated growth of the volume of appropriated water in the 1980s was due both to closing areas to new appropriations and limiting appropriations to safe yield quantities, it is difficult to quantify the amount of deceleration attributable to safe yield – at least, based solely on the information in Figure 1. Based on the fact that most “closed” areas were locations where the majority of water right development and water use occurred (Ogallala-High Plains aquifer and alluvial valleys), it may be that closing areas to new appropriations had the greater effect on reducing the rate of water appropriation.

   However, in a way the closing of these areas was akin to implementing a safe-yield policy, since either approach is grounded in the recognition of a finite resource and would have the effect of eliminating most additional appropriations of water in fully developed areas. From Figure 1, it appears that the cumulative total authorized quantity of water rights would have been at least double its present value if the growth rate of the mid-to-late 1970s were linearly extrapolated, that is, if the safe yield/closure policy had not been applied when it was.

Figure 1: Historical Development of Water Rights in Kansas

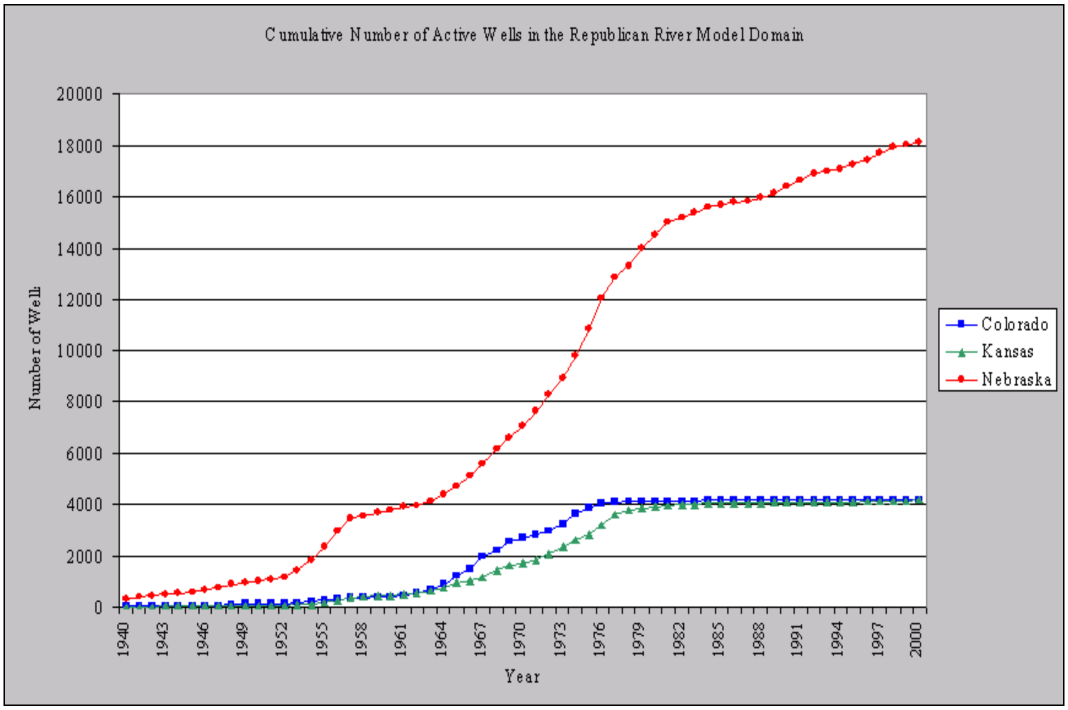


(Source: Kansas Department of Agriculture, Water Rights Information System Database, 2008)

Obviously, there is a finite amount of renewable water supply in Kansas. If safe yield (and its relative, closing over-appropriated areas) had not been implemented, and had water appropriation continued to grow at 1970s rates, it is probable that groundwater declines and streamflow depletions would have accelerated and the adverse impacts on vested/senior water rights and the public interest would be substantially greater than they are today.

A striking example of what could have happened in Kansas is the growth of wells in Nebraska’s Republican River Basin long after Kansas and Colorado closed areas to new appropriation and established safe yield requirements. As shown in Figure 2 below, approximately 4,000 additional wells (a 30% increase) were installed in Nebraska’s portion of the basin after 1980, whereas the number of wells leveled out in the other states’ portions of the basin. A consequence of this continued development of the water resource is that Nebraska has been unable or unwilling to comply with the Republican River Compact, which may end up costing the state tens of millions of dollars in litigation, restitution and penalties as well as significant challenges in curtailing groundwater use to achieve compact compliance in the future.

Figure 2: Historical Development of Wells in the Republican River Basin



(Source: Kansas Department of Agriculture, 2008)

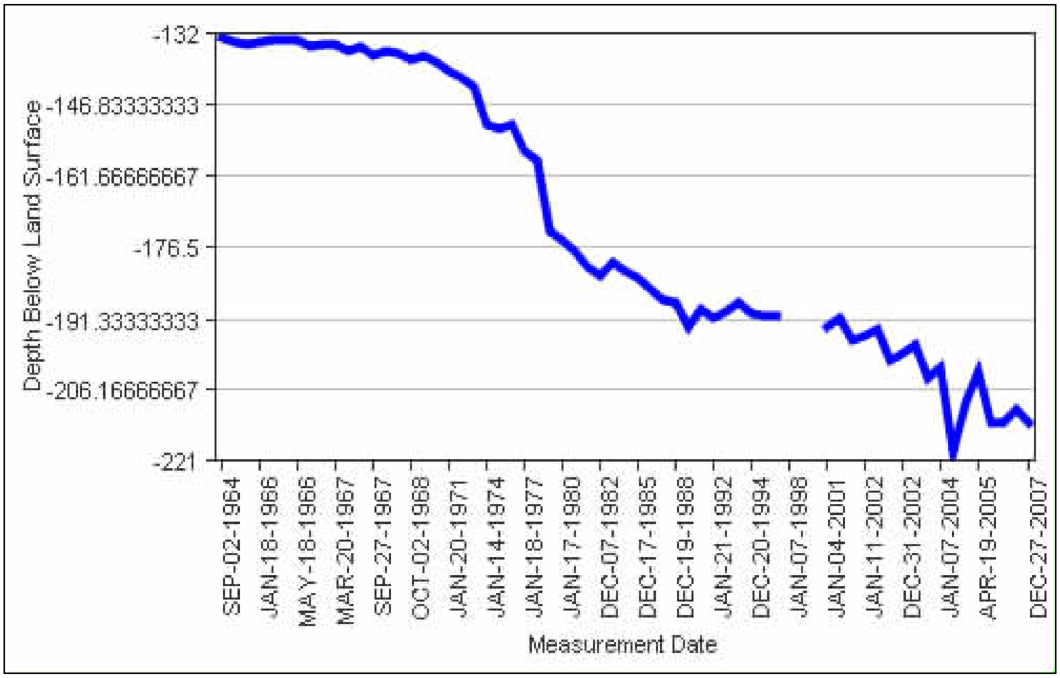
Clearly, Kansas' safe yield policy and its closely-related closure of over-appropriated areas have had profound effects on the management of water resources. This policy is still relevant and applied today.

The intent of the policy, based on the statutory and regulatory language, is presumed to be preventing over-appropriation of water resources. Stated another way, in the classical mass balance equation inflows minus outflows equals change in storage; the intent of the safe yield policy is to have long-term average inflows equal outflows (including pumping) so that the long-term average change in storage is negligible.

Based on streamflow records and groundwater measurements exhibiting stable water supplies, it appears that the safe-yield policy has been successful in accomplishing this objective in areas of the state where it was applied before over-appropriation occurred. In other areas that were closed to new appropriation of water, the policy has not reversed the trend of groundwater declines or streamflow depletions but has apparently kept the rate of declines from accelerating further and in some cases has led to decreasing rates of decline.

Figure 3 below shows an example of this. Rates of groundwater decline accelerated dramatically during the period of heavy development during the late 1960s and 1970s, and then became more gradual in the 1980s and subsequent decades. The well hydrograph illustrated in Figure 3 is in a high-decline area of Sheridan County.

Figure 3: Groundwater Level Changes in a High Plains Aquifer Well (Well No. 392210100384601, Sheridan County)



(Source: Kansas Geological Survey, WIZARD Water Well Database, 2009)

It should be noted that while this well exhibits the expected trends as previously described, hydrographs from other wells in the same area show different trends over time – from a uniform rate of decline over the period of record to increasing rates of decline through present or in some cases increasing water levels. This underscores an important fact that the Ogallala-High Plains aquifer is not homogeneous – local conditions can vary considerably.

The data presented above suggest that the safe yield/closure policy has been effective in accomplishing its objectives of balancing supply and demand, or avoiding increases in imbalances that may have prefigured the policy in some areas of the state.

Based on anecdotal evidence many stakeholders, organizations, officials and legislators agree with the safe yield/closure policy as evidenced in comments at meetings and hearings and the lack of any noticeable effort to repeal the policy. It is generally considered a fair and prudent policy for stewardship of the resource and protection of existing water rights.

However, there are examples of some discontent with the policy. For instance, Big Bend Groundwater Management District No. 5 has indicated that it wants to review whether some areas of the district could be opened to new appropriations. A hydrologic model is being developed that will help answer this question. This may not reflect disagreement with the safe yield policy per se, so much as a desire to revisit previous decisions applying the policy using more comprehensive data and analytical tools available today.

Another example involves water appropriation applications filed before certain townships in Southwest Kansas Groundwater Management District No. 3 were closed to new appropriation. In a number of cases the chief engineer has ruled that the applications cannot be approved on the basis of allowable appropriation specified in the regulations at the time of filing, or that the additional appropriations would impair existing water rights. These considerations are corollaries to safe yield. Some of the applicants appealed these rulings, signifying that at some level they disagree with the safe yield policy although ostensibly the appeal may be based on questioning the specific facts and analyses.

2. <u>Metering/water use reporting</u> – Studies have confirmed an intuitive outcome – the accuracy of water use reporting increases when meters are installed. This came about because the requirement to report water use in many cases pre-dated the requirement to install meters, although the authority to require meters pre-dated the requirement for water use reporting (see citations under Basis for Selection, item 2). Typically, meter requirements have been imposed for various areas through orders of the chief engineer or through permit conditions. In fact, this process is still ongoing today. Most of the water rights in the western half of Kansas are fully metered, and meter requirements for the eastern half continue to be issued.

   Since the majority of water use in Kansas (about 85%) is for irrigation, and the majority of irrigation occurs in the western half of Kansas, most water use in Kansas is already metered. In addition, most of the large municipal and industrial uses in eastern Kansas are already metered for other reasons even if the chief engineer has not ordered it.

   The most common method for estimating water use without a meter is to track the hours of pumping and multiply it by the pumping rate. However, the hours and rate method was shown to significantly underestimate or overestimate the actual amount of water pumped for irrigation, in some cases by as much as 30%.[10]

Meters and water use reports are essential for accurate enforcement of water rights, management of the state's water resources, interstate compact compliance, and other purposes. In 2008, the Kansas Department of Agriculture performed thousands of compliance inspections for a number of reasons including to determine if authorized points of diversion were acceptably metered and to ascertain whether water use was within the authorized quantities. A total of 65 civil penalty orders were issued for over-pumping and meter violations. As part of the civil penalties, these water rights were assessed reductions in their 2009 authorized use totaling nearly 2,000 acre-feet. These penalties will be enforceable in part because of the meters installed on these points of diversion. (Faulty meters identified in the compliance checks will be repaired or replaced with acceptable meter installations.)

A 2008 preliminary analysis indicated that it would cost approximately $376,000 per year to monitor consumptive use of water on irrigated farmland in Kansas using Landsat thermal imagery.[11] Based on a 2005 cost estimate, the Kansas Department of Agriculture's water use monitoring program – which relies on meters or estimation methods, annual water use reports, compliance inspections and enforcement – costs the state about $170,000 per year, less than half the cost of the alternative method.

Not only is Kansas' water metering/water use reporting policy cost effective, it is widely recognized as a model for other states. Time and again Kansas water resources officials have heard from their counterparts in other states about their desire to have a water use monitoring program as efficient and effective as Kansas'. The author has heard similar statements from U.S. Geological Survey staff, which compiles water use data from all 50 states in a national report.[12] They have to estimate water use in states that do not collect this data as Kansas does, and even in states that collect water use data it is often not as comprehensive and useful as Kansas'.

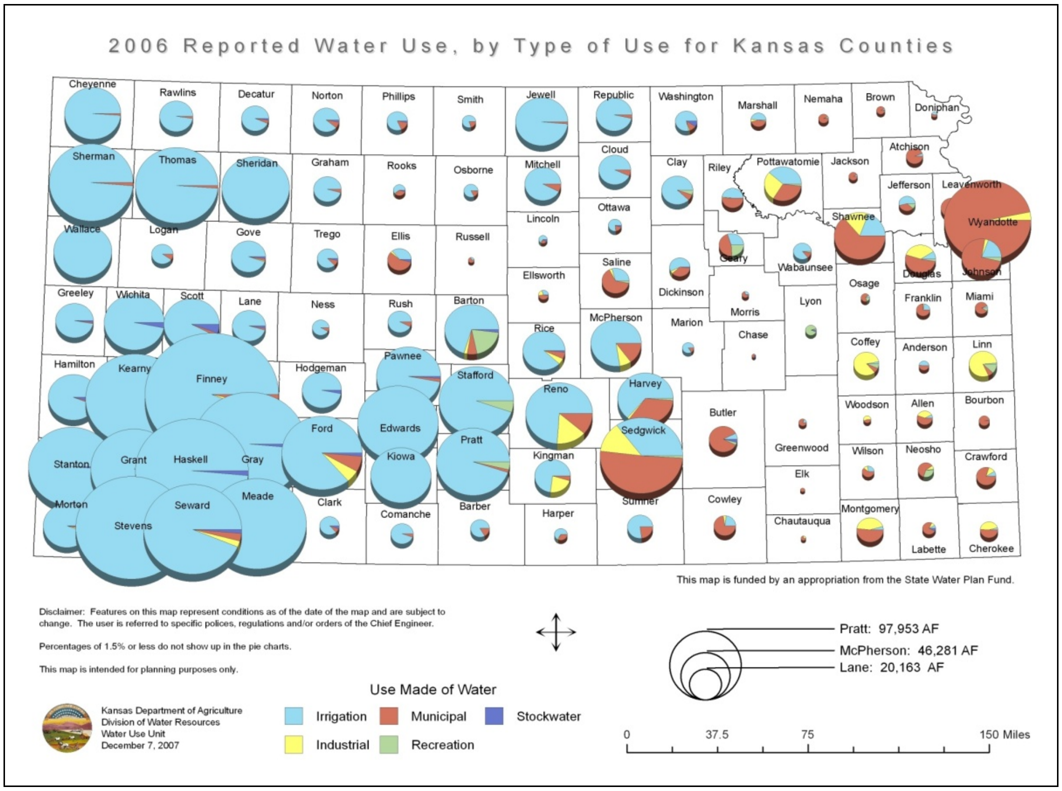
In 2007, the Western States Water Council asked member states (the 18 states from North Dakota to Texas and westward) to complete a survey of

[10] *1997 Kansas Irrigation Water Use*; Kansas Water Office and Kansas Department of Agriculture; pp. 45-47 and Table 16.
[11] "Cost Estimate for Monitoring Consumptive Use of Water from Irrigation Wells in Kansas"; Idaho Department of Water Resources (May 9, 2008).
[12] *Estimated Use of Water in the United States in 2000*, U.S. Geological Survey Circular 1268 (2004). According to USGS' website their 2005 water use report is due to be issued in 2009.

their water supplies and demands. Several states were unable to provide meaningful responses because they do not collect this type of information. Kansas was able to provide detailed information in response to the survey.

Figure 4 below illustrates the type of data available to the state for water resource management as a result of metering and water use reporting.

Figure 4: Reported Water Use by County and Type of Use, 2006



(Source: Kansas Department of Agriculture, 2007)

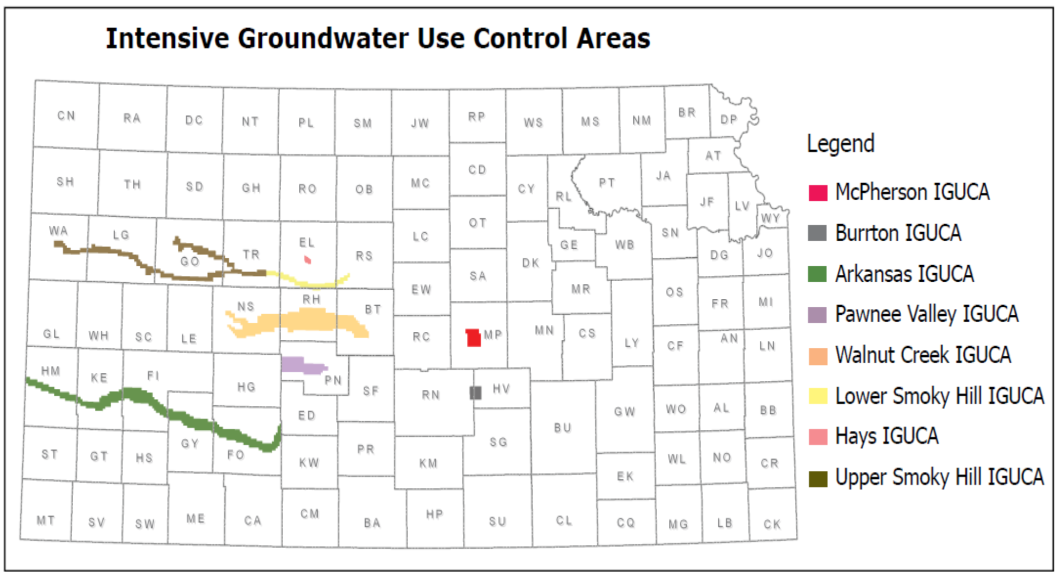
Attached in Appendix A is Kansas' response to a 2008 survey from the Western States Water Council on methods and costs to monitor water use from irrigation wells. This provides additional details on Kansas' water use monitoring program and puts in perspective the magnitude and importance of the data collected. Also, the data provided in the survey response may be of interest to attendees at this conference.

Besides the benefits to state and federal agencies charged with managing water resources, the Kansas policy on monitoring water use also directly benefits water users by enabling them to actively manage their own water use and avoid violations. In some cases, irrigators and other users have installed sophisticated equipment to remotely monitor their use and make adjustments in real-time from their office computers in response to changing weather conditions, changing demands, and coordination of multiple irrigation systems and water rights.

Kansas' water use monitoring policy remains a viable and necessary practice that accomplishes the state's objectives including water right compliance and enforcement, water resource management, interstate compact compliance, and other purposes. While some individual water right holders or groups might object to the costs of metering and water use reporting, by and large there is round support for this policy due to the recognition that without this data the state's efforts to manage our precious water resources, including administration of the Kansas Water Appropriation Act, would be severely impeded.

3. IGUCAs – Eight intensive groundwater use control areas (IGUCAs) have been established in Kansas and are still in effect. These are shown on Figure 5 below.

Figure 5: Intensive Groundwater Use Control Areas in Kansas



(Source: Kansas Department of Agriculture, 2009)

These IGUCAs were established for a number of reasons including groundwater declines, deteriorating groundwater quality, and other public interest issues. IGUCAs are designed to address a variety of groundwater problems with customized solutions. An example of a specific solution is the City of Hays IGUCA which requires city residents with domestic water wells to comply with the city's summer lawn watering ordinance in order to avoid waste of water.

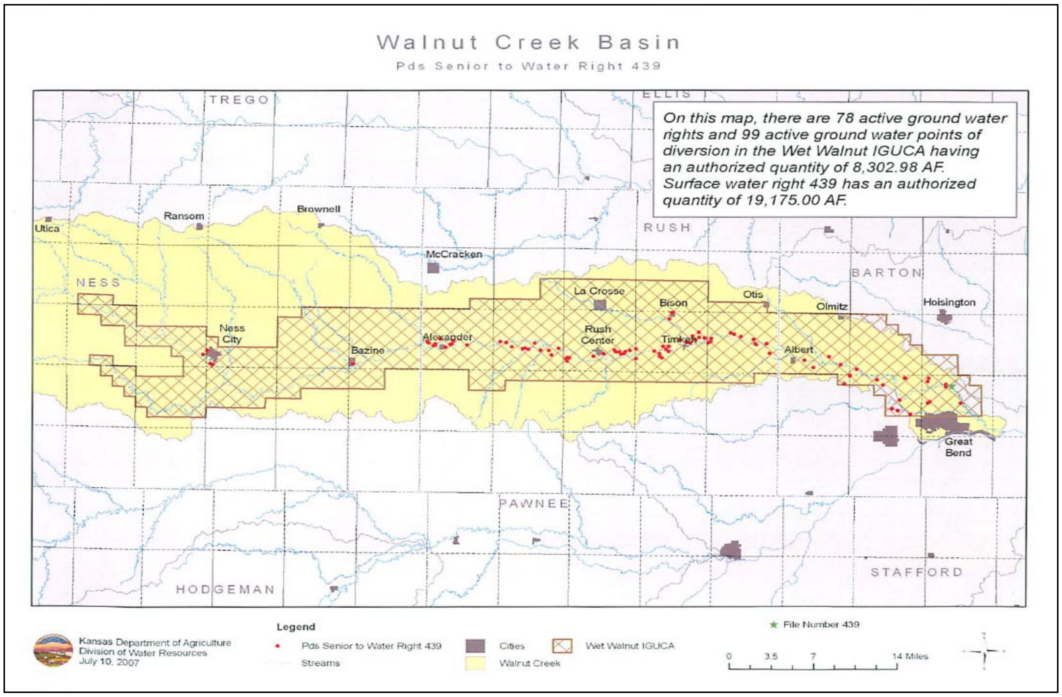
Two examples vividly illustrate the benefits of IGUCAs: the Walnut Creek IGUCA in Kansas, and by contrast a case in Colorado, which lacks

IGUCA-type authority and flexibility, where the curtailment of irrigation under priority administration of water rights over a large area had devastating effects.

One of the main impetuses for initiation of the Walnut Creek IGUCA was the possibility of a call for administration of water rights by the Kansas Department of Wildlife and Parks in the event their early water right for Cheyenne Bottoms would become impaired. (Cheyenne Bottoms is a wetland wildlife refuge that is a major stopover for migratory birds and an important recreational attraction for Kansas.) Figure 6 below illustrates this scenario. In concept, 78 groundwater rights (17% of total) senior to the Cheyenne Bottoms surface water right would not be curtailed; conversely, 389 groundwater rights (83% of total) could be curtailed in this scenario – with presumably disastrous effects on the local economy and livelihood of the agricultural community.

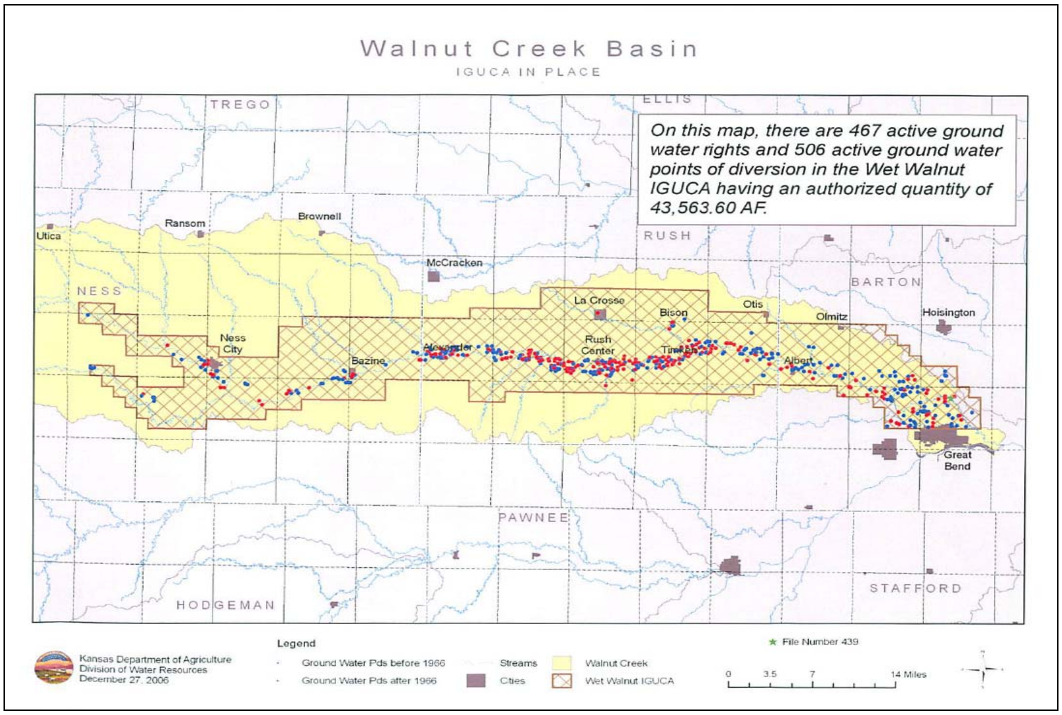
Among the principle findings in the Walnut Creek IGUCA hearing was quantification of the long-term sustainable yield of the basin as 22,700 acre-feet of groundwater. Rights developed before the date when 22,700 acre-feet of water was appropriated in the basin were considered “senior rights” while those that were developed after that date were defined to be “junior rights”. The corrective controls apportioned 22,700 acre-feet among the existing groundwater rights: vested rights were allotted their full authorized quantities; senior rights were allotted reasonable use (12 inches to 14 inches per year for irrigation rights); and junior rights were allotted 44% of the senior right allocations (5.25 inches to 6.25 inches for irrigation rights). Five year allocations were developed so that junior irrigators could meet reasonable needs at least two or three out of five years. While this approach resulted in partial curtailment of many water rights in the basin, remarkably it allowed all water rights to continue operating. Figure 7 below illustrates this scenario.

Figure 6: Active Water Rights Under Hypothetical Water Right Administration by Priority



(Source: Kansas Department of Agriculture, 2007)

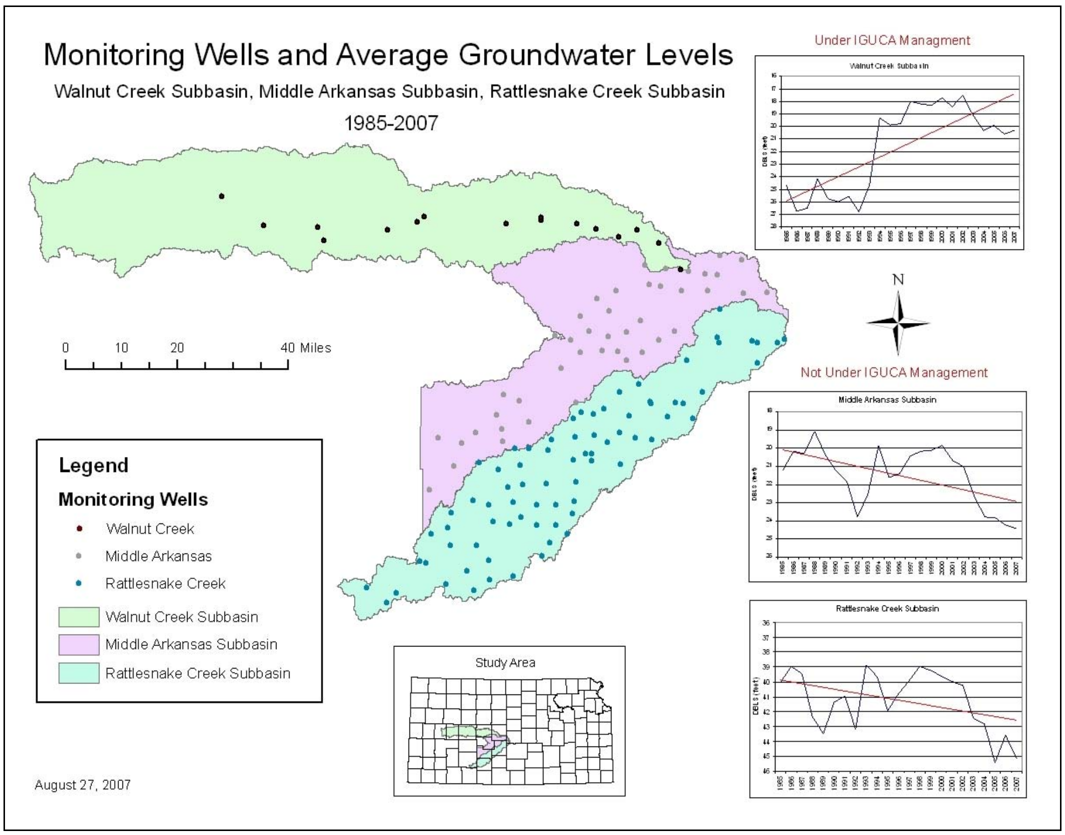
Figure 7: Active Water Rights Under IGUCA Corrective Control Provisions



(Source: Kansas Department of Agriculture, 2006)

Over the years since the Walnut Creek IGUCA was established, groundwater levels have risen with an overall trend of about one foot per three years. This represents a return to a hydrologic system with a reasonable balance between recharge and withdrawals. Water users can rely on the long-term sustainability of the aquifer because rising groundwater levels in wetter years will offset declining water levels in drier years. Surface water users dependent upon discharge from the aquifer to the stream again have a relatively reliable source from which to exercise their rights. Figure 8 below contrasts the Walnut Creek basin with two neighboring basins that continue to exhibit long-term declining groundwater trends.

Figure 8: Groundwater Trends in Three Basins



(Source: Kansas Department of Agriculture, 2007)

A recent situation in Colorado underscores the value of IGUCAs. In May 2006, Colorado ordered more than 400 irrigation wells shut down to protect senior water rights on the South Platte River. This affected 200 farms that had already planted crops. Farmers estimated their potential losses in the hundreds of thousands of dollars. Also shut down were two drinking water wells for a trailer park with about 300 residents.[13] A

[13] “Farmers Sweat Lack of Water”; Rocky Mountain News (May 10, 2006).

newspaper article included in Appendix B of this paper provides more details about this curtailment of water rights and its adverse effects.

In 2008, the Kansas Department of Agriculture conducted an informal survey of western states to determine which ones have authorities for groundwater management tools similar to IGUCAs. Of the 18 western states (not including Hawaii), 10 have authorities for groundwater management options similar to IGUCAs in varying degrees.

Colorado is one of the 10 states that have authority for special management of groundwater areas, called Designated Ground Water Basins. However, it appears that Colorado's rules for Designated Ground Water Basins focus on aspects such as allowable appropriation, metering and operating plans, and apparently do not provide the flexibility for creative solutions such as IGUCAs in Kansas.[14] Hence, Colorado seems to have no other option than administration (curtailment) of junior water rights in times of shortage.

Kansas' IGUCA policy continues to serve as a viable tool for implementing groundwater management strategies tailored to address specific problems. As described above for one of the eight existing IGUCAs, this policy has been exceptionally effective, particularly when contrasted with the severe water use curtailment in states such as Colorado which do not have the IGUCA alternative.

IGUCAs remain timely because they can be modified over time as necessary to adjust for changing conditions or better data. In fact, five of the eight IGUCAs have been amended at least once. The Walnut Creek IGUCA has been amended three times since it was initially established in 1992.

The most recent IGUCA proceeding was in 2007, related to possible expansion of the Pawnee Valley IGUCA. During the hearing, several parties expressed opposition to expanding the IGUCA. Some organizations and legislators also expressed opposition to the IGUCA expansion, for various reasons.

However, during the 2007 IGUCA proceedings and in the legislative hearings and stakeholder meetings that followed it, there has been widespread support by virtually all groups and individuals involved that the IGUCA policy is fundamentally sound and must be preserved so that creative solutions can be applied in areas where strict administration of

[14] *Rules and Regulations for the Management and Control of Designated Ground Water*; State of Colorado Ground Water Commission (Amended December 30, 2008). http://www.water.state.co.us/cgwc/rules-regs/DBRulesWithFigs.pdf

water rights by priority would have more severe adverse impacts on the community and economy.

The above analysis indicates a positive finding that the three policies in question have indeed stood the test of time based on their continued effectiveness and public acceptance. This naturally leads to the follow-up question: Are there examples of water policies which have not stood the test of time? The answer is yes. Several examples are noted below for consideration:

- Not limiting appropriations, etc: This is the opposite of the safe yield policy including closure of fully-appropriated or over-appropriated areas. Since evidence presented in this paper (and common sense) suggests that the safe-yield/closure policy is a prudent action for stewardship of resources and protection of water rights, it stands to reason that the opposite policy is antiquated and ineffective. The same rationale would suggest that policies to not monitor water use or not provide appropriate groundwater management alternatives would be counter-productive. On the other hand, there are always exceptions to the rule. There may be instances when it makes sense not to limit appropriations, monitor water use, or have alternatives to first-in-time/first-in-right administration.

- Irrigation efficiency improvements as a means to reduce water use: Until a couple of years ago, the state of Kansas had a cost-share program to promote irrigation efficiency improvements. A main purpose of the program was to reduce water use in areas with declining water resources. However, over time it became apparent that improving the efficiency of irrigation did not appreciably conserve water, but rather improved crop yields.[15] While efficiency is important and to be encouraged, the state decided to discontinue this type of cost-share program since it was not achieving a reduction in water use.

- Non-conjunctive management of water resources: Kansas has recognized the interconnected, interdependent nature of groundwater and surface water since at least 1945 when the Kansas Water Appropriation Act was passed, regulating both sources in a coordinated manner. However, to this day there are still states that do not routinely manage groundwater

---

[15] *Effects of Irrigation Practices on Water Use in the Groundwater Management Districts Within the Kansas High Plains, 1991-2003*; Scientific Investigations Report 2006-5069; U.S. Geological Survey (2006). "The best estimator of irrigation water use incorporated total acres irrigated and annual average or March–October regional precipitation. A conclusion that can be drawn from the trend analyses described in this report is that, although irrigation water use for all GMDs showed no statistically significant trend, an apparent increased efficiency of center pivots irrigation systems with drop nozzles has allowed more water-intensive crops to be grown on more irrigated acres." (Abstract, p.1)

and surface water conjunctively, that is, together. Nebraska is a notable example of non-conjunctive management – the state of Nebraska is responsible for management of surface water resources while Natural Resource Districts are supposed to manage groundwater. In practice, it appears that the two have largely operated independently. One of the most dramatic outcomes of this disconnect is Nebraska's current noncompliance with the Republican River Compact. Their violations stem from overuse of groundwater which in turn led to streamflow depletions. The outcome of this has not been determined, but the matter is in non-binding arbitration and if that fails to resolve the violations could return to the U.S. Supreme Court. The consequences of Nebraska's dichotomous regulation of groundwater and surface water could be severe sanctions such as monetary reparations and shutting down hundreds or thousands of wells.

CONCLUSIONS

The objective of this exercise was to evaluate whether some of the more prominent water resource policies in Kansas have "stood the test of time" as signified by their continued relevance, effectiveness, and public acceptance. By these measures, based on the analyses herein, the author concludes that the three policies listed below have indeed met this standard:

- Limiting appropriation of water to safe yield quantities, and closure of fully-appropriated or over-appropriated areas
- Monitoring water use through metering and water use reporting
- Establishing intensive groundwater use control areas where necessary to implement creative solutions to groundwater problems

By observation, some of the key attributes of these time-tested water policies include:

- Consistent with basic laws of nature, e.g., conservation of mass
- Reasonable, in the public interest
- Provides essential data for resource management
- Provides flexibility rather than a one-size-fits-all approach

A well-known saying is, "Laws are like sausages – it is better not to see them being made", referring to the often messy process. Nevertheless, public policy makers usually try to make sure that laws are designed for long-term applicability and effectiveness. Reflecting on laws that have achieved time-tested status is one way to identify characteristics and principles which can be applied in crafting new policies for achieving present and future objectives.

Appendix A

Kansas' Response to a 2008 Survey on Irrigation

Western States Water Council

Survey on the Methods and Costs to Monitor Pumping from Irrigation Wells

1. State: **Kansas**

2. Do you agree with the numbers in table 1, below, for your state? **No. Based on information from annual water use reports compiled in the Water Rights Information System (WRIS) maintained by the Kansas Department of Agriculture's Division of Water Resources, as of March 20, 2008 the requested quantities are as follows:**

   1995 Total water use (MGD): 3,946
   1995 Irrigation water use (MGD): 3,364
   1995 Irrigation as percent of total water use: 85
   2003 Number of irrigation wells: 27,770
   2003 Total irrigated acreage: 3,151,754 (3,078,034 from groundwater; 73,720 from surface water)

3. Is there a program in your state to monitor pumpage from irrigation wells? **Yes**

   a. If yes

      i. How many irrigators participate in the program? **6,511 (2005 data)**
      ii. How much does the average irrigator spend on the program? **Cost of a postage stamp per year**
      iii. How much does the state spend on the program? **$170,000 per year (2005 estimate)**
      iv. How many wells are monitored by flow meters? **21,054 (2005 data)**
         1. what is the average cost of a flow meter? **$1,000**
         2. what is the average lifespan of a flow meter? **8 years (repairs can extend it)**
         3. what is the cost to install a flow meter? **$300 to $2,000 (depending on difficulty)**
         4. what is the cost to calibrate a flow meter? **$400 average**

v. How many wells are monitored by power consumption? **Data not available; anecdotally relatively few use this method**

vi. How many wells are monitored by some other method? **5,887 (hours x rate)**

vii. How long does it take before a year's data are analyzed? **1 to 2 years**

viii. How does the state use the pumpage data? **A partial list follows:**

- **Safe yield analyses in processing water appropriation applications**
- **Certification of water rights**
- **Compliance & enforcement of water rights**
- **Abandonment determinations**
- **Impairment investigations**
- **Water use accounting**
- **Compact administration**
- **Administration of water right flex accounts and water banking**
- **Basin planning**
- **Hydrologic modeling**
- **Water management**
- **Technical assistance**
- **Conservation plans**
- **National water use reporting**
- **Technical reports**
- **Property valuation**
- **Irrigation efficiency evaluation**

ix. What are the three things you would most like to change about the way pumpage data are gathered, reported, and processed, without regard to the cost or practicality of making the changes?

- **Statewide metering of all non-domestic points of diversion by 2015 (significant progress has been made and work continues)**
- **Online water use reporting (development of web-based reporting is underway); eventually real-time reporting through data loggers and telemetry (at least in areas with active water rights administration)**
- **Electronic reporting in the future is anticipated to reduce dependence on**

manual data entry and allow improved quality- control

b. If no, would such a program be useful?

4. Can you provide a paragraph or two summarizing the program?

Regulations under the Kansas Water Appropriation Act (http://www.ksda.gov/appropriation/statutes) establish requirements for:

- **Installation of a water flowmeter or other suitable water measuring device**
- **Water flowmeter specifications**
- **Water flowmeter installation specifications**
- **Water flowmeter maintenance**
- **Water use reporting**
- **Other criteria**

The Kansas Department of Agriculture's Division of Water Resources and several groundwater management districts share responsibility for compliance & enforcement of these requirements. Meters are inspected following installation, tested for accuracy, and readings are checked for water right compliance and other reasons.

All non-domestic water right holders are required to annually report their water use to the Division of Water Resources. DWR receives approximately 15,000 paper reports each year, many of which include information for multiple water rights. These data are manually entered into the Water Rights Information System (WRIS) database, quality-control checked, and used for a variety of purposes (see 3.a.viii above). More information on Kansas' water use reporting is available at http://www.ksda.gov/appropriation/content/116.

State	Total Water Use (million gal/day) 1995[1]	Irrigation Water Use million gal/day 1995[2]	Irrigation as Percent of Total Water Use	Number of Irrigation Wells 2003[2]	Total Irrigated Acreage 2003[3]
Alaska	25	0.3	1	57	2,252
Arizona	3,830	3,180	83	5,149	836,587
California	25,200	23,500	93	67,637	8,471,936
Colorado	5,230	4,910	94	11,793	2,562,329
Idaho	4,340	4,310	99	6,924	3,126,857
Kansas	3,620	3,220	89	19,526	2,543,950
Montana	1,960	1,820	93	1,810	2,131,955
Nebraska	7,020	6,740	96	71,506	7,516,171
Nevada	1,340	1,060	79	1,986	639,310
New Mexico	1,980	1,680	85	8,430	769,787
North Dakota	105	181	58	1,734	207,772
Oklahoma	716	401	56	4,540	508,842
Oregon	3,210	3,070	96	7,855	1,731,660
South Dakota	249	175	70	1,872	390,406
Texas	10,500	8,140	77	63,602	4,947,745
Utah	2,200	1,930	88	2,632	1,082,213
Washington	3,080	2,800	91	5,626	1,806,782
Wyoming	2,800	2,660	95	985	1,415,037
TOTAL	**77,405**	**69,777.03**		**283,664**	**40,691,591**

Table 1. Comparison of total water use and irrigation water use for the 18 member states of the Western States Water Council in 1995 and the number of irrigation wells in 2003. Both dates are the most recent available.

1 http://water.usgs.gov/watuse/pdf1995/pdf/summary.pdf
2 http://water.usgs.gov/watuse/pdf1995/pdf/irrigation.pdf
3 http://www.agcensus.usda.gov/Publications/2002/FRIS/tables/fris03_14.pdf
4 http://www.agcensus.usda.gov/Publications/2002/FRIS/tables/fris03_02.pdf

Appendix B

Article about Colorado Curtailing Water Use

Farmers sweat lack of water
Growers mop brows after state edict to shut down wells

Jerd Smith, Rocky Mountain News
Published May 10, 2006 at midnight

The state ordered more than 400 powerful irrigation wells shut down this week to protect the South Platte River, triggering a crisis for about 200 farms from Brighton to Fort Morgan.

"It's the toughest decision I've ever had to make," said State Engineer Hal Simpson, Colorado's top water regulator.

Farmers who've already planted this year say they stand to lose hundreds of thousands of dollars as a result of Simpson's ruling. The decree may mean bankruptcy for some. But others, such as La Salle potato grower Harry Strohauer, are gearing up for battle.

"I'm going to fight like crazy," Strohauer said.

Strohauer is losing the use of 14 wells that normally irrigate 1,100 acres of potatoes and onions. He's invested $700,000 in seed and fertilizer so far this spring.

"To get hit with this ruling after we've all planted is ludicrous," Strohauer said.

A spokesman for Gov. Bill Owens said the state may declare an emergency in the counties affected by the shutdown.

But the shutdown was precipitated by a new state law that requires farmers who use deep irrigation wells - which draw down the aquifer that also nourishes the river - to replace that water.

The law is meant to stabilize the river by reducing the impact of deep wells.

The law was passed after the 2002 drought, when farmers who relied solely on the river's surface water for irrigation saw their fields burn up, while well-dependent farmers continued irrigating.

Surface-water farmers and some cities successfully sued the state for allowing the deep wells to harm the river.

Under the new law, well-dependent farmers were given several years to find additional water supplies, either by securing water leases or with permanent purchases of water.

In 2002, roughly 5,000 irrigation wells were operated in the South Platte basin. Under the new law, more than 1,500 have already been shut down, while the users of several hundred others have developed new water plans that allow them to legally operate their wells.

But Simpson's ruling signals that time is up for farmers who have been unable to line up sufficient new water supplies.

"This is a wreck," said Tom Cech, manager of the Central Water Conservancy District.

The district has been working frantically since 2003, raising property taxes to lease and buy water and to build small reservoirs to aid this last group of farms. All told, the district has raised $21 million to help comply with the new law, Cech said, but the lingering drought and competition for water between fast-growing Front Range cities and farmers has made water scarce and expensive.

Cech said the district had projected it would have enough water this year to operate the wells at 15 percent of their capacity.

But the state engineer's decision, prompted by a dry spring and the district's loss of several key water leases, doomed the farmers' efforts just as the new growing season got under way.

The law also stipulates that farmers must show they have enough incoming water to cover future water debts to the river.

Because of the lingering dry spell, the state required that they use a worst-case drought scenario to calculate future needs, which meant finding more water.

"It's a brutal standard," Cech said.

Bob Sakata is a veteran vegetable grower in Brighton and an elder statesman on the South Platte River.

Sakata already has spent $264,000 planting 300 acres in onions, broccoli, sweet corn and carrots. The three wells he planned to use on that land won't operate this year, and the crops in the ground probably won't survive.

Sakata is a large grower, with 19 other wells and the rights to river water. Still, he said he was caught off guard by the ruling.

Farmers had expected to be able to use their wells at least for a short period of time this summer. But to be shut down completely was a surprise.

"There has to be a better solution than this," Sakata said. "I've put out calls to the governor, to the commissioner (of agriculture) and director of natural resources. There's just got to be a way."

North of Brighton, two wells that supply drinking water to Page's Trailer Park will also be shut down as a result of the ruling.

Bernie Pagel, who has owned the park since 1969, said about 70 families live there and depend on the wells for 90 percent of their water.

"I'm just wondering what we're supposed to do," Pagel said.

He's talking to other nearby water providers to see if he can purchase water.

"We're also wondering if there's any emergency exemption," he added, noting that more than 300 residents will be without water if the wells are shut off.

Glen Kobobel is a corn grower outside Wiggins. He, too, had expected to have at least a small amount of well water to use on his crops this summer. Tuesday afternoon, he had yet to finish calculating how much money he will lose as those crops dry out.

"Our family will be able to survive this shutdown," Kobobel said. "I don't know about next year, though. And I just can't figure out why the state is doing this to us. I think we're so few in number, our voices mean nothing."

Simpson, the state engineer, had a different take. "There just wasn't enough water in their plan," he said of the farmers' efforts to comply with the new law.

"We're very sorry it came to this."

How trouble got started

The crisis in the South Platte River basin took root more than 70 years ago, when hundreds of farm families from Brighton to Fort Morgan started digging wells in a shallow aquifer that also supplies the river.

Water engineering was in its infancy, and state agriculture and water officials encouraged the drilling, hopeful that the wells would drought-proof the lush, irrigated high plains region.

No one understood back then that the wells were pulling water from the same aquifer that helped supply the river. By 1969, the science was clear. The wells were depleting the river. The state began requiring farmers to put back into the river some of what their wells had drawn down.

Under the new law, farmers must put about 80 percent of the total water they pump from the ground back into the river. Previously, their obligation had been as low as 5 percent in some years.

http://www.rockymountainnews.com/news/2006/may/10/farmers-sweat-lack-of-water/

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby, Kansas, February 24-25, 2009.
Available from CPIA, 760 N. Thompson, Colby, Kansas

STATE POLICY ON CONSERVING GROUND WATER IN KANSAS

SUSAN STOVER, L.G.
MANAGER, HIGH PLAINS UNIT
KANSAS WATER OFFICE
TOPEKA, KS 66614
PHONE: 785-296-0876 FAX: 785-296-0878
SUSAN.STOVER@KWO.KS.GOV

The policy to conserve and extend the life of the Ogallala – High Plains aquifer was first adopted into the Kansas Water Plan in 2001. The Kansas Water Plan also has the objective to reduce the water level decline rate within the Ogallala and implement enhanced water management in targeted areas by 2010. Management of ground water outside the low-recharging Ogallala is to be guided by the Kansas Water Plan objective to achieve sustainable yield management of Kansas surface and ground water sources by 2015.

There are a number of efforts on-going to implement the guidance, particularly in the High Plains aquifer. One aspect is improving the knowledge about the aquifers. Hydrologic computer modeling of the High Plains and interconnected alluvial aquifers and streams helps define the water budget and project future conditions. Models are done or under development in Northwest Kansas GMD4, Southwest Kansas GMD3, Big Bend GMD5, and the North and South Fork of the Solomon River. Practical saturated thickness is also being defined in many areas of the High Plains aquifer. There are the on-going annual water level measurements, which indicate the decline trends. Complimenting that information are three index wells in the High Plains aquifer which provide hourly, year round data on aquifer levels. Under development is a Master Well Inventory to link all state databases for any individual fresh water well.

Voluntary, incentive based programs are available to help conserve ground water. These include the Upper Arkansas River Conservation Reserve Enhancement Program (CREP), a federal-state program; the state funded Water Right Transition Assistance Program (WTAP); a USDA program to convert irrigated lands to dryland agriculture through Environmental Quality Incentive Program (EQIP). In the new Farm Bill, EQIP also has an Agricultural Water Enhancement Program (AWEP), that can be used for water quantity or quality concerns, with the Ogallala cited as a priority area. Efforts are also underway, led by Kansas State University, to develop crop response yield curves that could be used by USDA Risk Management Agency, to allow them to offer crop insurance for limited irrigated fields.

Proceedings of the 21st Annual Central Plains Irrigation Conference, Colby Kansas, February 24-25, 2009
Available from CPIA, 760 N.Thompson, Colby, Kansas

2009 IRRIGATION CROPLAND LEASE ARRANGEMENTS

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

Todd Ziegler & Mark Wood
Extension Agricultural Economists
Northwest Kansas Farm Management Association
Colby, Kansas
Voice: 785-462-6664 Fax: 785-462-3863
Email: toddziegler@agecon.ksu.edu & mawood@ksu.edu

Grain price volatility and changing crop input costs have affected the equitability of existing irrigated cropland leasing arrangements during the 2006 through 2009 period. It has been challenging for tenants and landowners to maintain equitable cropland leasing arrangements in response to both the historic increases and the following decrease that have occurred in agricultural commodity and crop input prices over the last 3-4 years.

This paper utilizes western Kansas crop enterprise cost of production estimates in the **KSU Lease.xls** program to estimate equitable cropland leasing arrangements for 2009. Cost of production estimates for irrigated corn, sunflowers, grain sorghum, soybeans and wheat were taken from K-State Farm Management Guide budget projections and Kansas Farm Management Association Farm Enterprise budgets. Non-irrigated cost of production estimates for wheat and other crops were used from the same sources. The **KSU Lease.xls** program is a spreadsheet budgeting program developed by Kansas State University Extension Specialists Kevin Dhuyvetter and Terry Kastens that can be used to determine equitable crop share and cash lease rental arrangements. Information on common irrigated and nonirrigated crop leasing arrangements were taken from K-State surveys of irrigated and nonirrigated crop leasing arrangements published in November-December 2008.

The crop budgets, leasing arrangement surveys, and the KSU Lease.xls program are available at www.Agmanager.info, the website for K-State Extension Agricultural Economics educational information.

SCENARIO #1: CENTER PIVOT OWNED BY LANDOWNER, SHARING OF SELECTED CROP INPUT EXPENSES

The first analysis of how equitable a common irrigated cropland leasing arrangement is focused on the scenario in which the Landowner owns the center pivot irrigation system and shares the cost of selected crop input expenses. On a 160 acre field, it is assumed that a center pivot irrigation system is used covering 125 acres of irrigated corn. For the nonirrigated corners (35 acres) it was assumed that a wheat-fallow rotation was used.

In this scenario the tenant owned and paid 100% of the cost of the irrigation power unit used. The landowner shared 33% of the cost of fertilizer, herbicides, insecticides, and crop insurance with the tenant. The tenant paid 100% of all other expenses, including seed, crop consulting, machinery, labor, and energy costs. The opportunity cost of farmland ownership for 125 acres of irrigated farmland and 35 acres of nonirrigated farmland (corners) was calculated to be a 5% rate of return. Farmland values were assumed to be those reported in the August 2008 Kansas Farmland Values publication from Kansas Agricultural Statistics. The grain prices used represent bids for the Colby – Goodland area on January 21, 2009. Following are the 2009 crop budgets used for this 160 acre scenario on which irrigated corn is grown.

CROP BUDGETS SHOWING TOTAL COSTS AND RETURNS

Link to KSU Farm Management Guides (crop budgets)

Crop/System	Corn	Soybean	Oil SF	Milo	Wheat	Wht-Flw	Total	Per	Per
Planted acres of each crop	125.0	0.0	0.0	0.0	0	17.5	142.5	Acre	Acre
Tillable acres per planted acre	1.00	1.00	1.00	1.00	1.00	2.00	160.0	Planted	Tillable
INCOME PER ACRE									
A. Yield per acre	200.0	55.0	22.0	120.0	70.0	45.0	---	---	---
B. Price per unit	$3.57	$9.15	$14.25	$2.83	$5.38	$5.38	---	---	---
C. Net government payments	$32.53	$32.53	$32.53	$32.53	$32.53	$16.26	$4,351	$30.53	$27.19
D. Indemnity payments	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0	$0.00	$0.00
E. Miscellaneous income	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0	$0.00	$0.00
F. Returns/acre ((A x B) + C + D + E)	$746.53					$258.36	$97,838	$686.58	$611.48
COSTS PER ACRE									
1. Seed	$67.20					$10.40	$8,582	$60.22	$53.64
2. Herbicide	35.54					12.07	4,653	32.65	29.08
3. Insecticide / Fungicide	35.30					0.00	4,412	30.96	27.58
4. Fertilizer and Lime	247.64					73.37	32,239	226.24	201.49
5. Crop Consulting	6.50	6.25	6.50	6.25	6.00	0.00	813	5.70	5.08
6. Crop Insurance	50.00	20.00	20.00	20.00	20.00	12.50	6,469	45.39	40.43
7. Drying	0.00					0.00	0	0.00	0.00
8. Miscellaneous	10.00	10.00	10.00	10.00	10.00	5.50	1,346	9.45	8.41
9. Machinery Expense	148.38					103.98	20,367	142.93	127.30
10. Non-machinery Labor	16.77					11.70	2,301	16.15	14.38
11. Irrigation	210.33					0.00	26,291	184.50	164.32
12. Land Charge / Rent	80.00					83.00	11,453	80.37	71.58
G. SUB TOTAL	$907.65					$312.51	$118,926	$834.57	$743.29
13. Interest on 1/2 Nonland Costs	27.38					7.79	3,559	24.97	22.24
H. TOTAL COSTS	$935.03					$320.30	$122,484	$859.54	$765.53
I. RETURNS OVER COSTS (F - H)	($188.50)					($61.94)	($24,647)	($172.96)	($154.04)
J. TOTAL COSTS/UNIT (H/A)	$4.68					$7.12	---	---	---
K. RETURN TO TOTAL COST (I+13)/G	-17.75%					-17.33%	-20.12%	-20.12%	-20.12%
		Delete inputs in columns not being used!							
M. Breakeven price (w/ base crop)	$3.89	-$2.87	-$7.17	-$1.31	-$2.25	$3.97			
N. Breakeven yield (w/ base crop)	220.4	7.0	3.1	18.7	5.7	32.6			
Base crop for breakeven analysis	1	0	0	0	0	1			

[1] All "blue values" are inputs, black values are calculated from those inputs — 8:38 AM 01/23/09

Crop production input, machinery, labor, and land costs are shown below.

TABLE 1. Production Inputs Used for Budgets

ITEM	Corn					Wht-Flw	$/unit
Seeding rate (lbs, seeds, etc)	30	150	23.4	6.5	90	65	
Seed price, $/unit	$2.24	$0.25	$0.91	$3.16	$0.16	$0.16	
Fertilizer:							
82-0-0	270	0	120	150	122	79	$0.570 /lb
N (dry/liquid)	0	0	0	0	0	0	$0.850 /lb
P	86	48	44	53	39	26	$1.090 /lb
K	0	0	0	0	0	0	$0.620 /lb
Lime	0	0	0	0	0	0	$0.010 /lb
Herbicide							
RT3	44						$0.40 /oz
+ Bicep Lite II Magnum	1.5			1.5			$11.29 /qt
+ Additives	1						$1.00 /ac
Prowl		3.6					$3.65 /oz
Glyphosate + Adjuvants		2					$9.64 /ac
Prowl H2O			3				$4.19 /pt
Spartan			4				$3.53 /oz
Marksman				2			$4.26 /pt
Ally (0.1 oz/ac) + Banvel (4 oz/ac)					1	1	$2.85 /ac
RT3 (16.5 oz/ac) + 2, 4-D (1 pt/ac)						1	$9.22 /ac
Insecticide / Fungicide							
Force 3G	5.4						$4.64 /lb
Capture 2EC	0.08						$128.00 /lb
Warrior 1 EC			0.05				$258.46 /lb
Tilt					4		$3.00 /oz
Irrigation water, inches/acre	18	15	10	12	10	0	$5.80 /in
Irrigation repairs, $/acre-inch							$0.33 /in
Drying cost, $/unit (bu, cwt, etc)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	
	Delete inputs in columns not being used!						8:38 AM 01/23/09

TABLE 2. Machinery and Land Resources Used for Budgets

ITEM	Corn					Wht-Flw	$/unit
Drill/Plant, $/acre	$12.48	$12.52	$12.39	$12.18	$10.91	$10.91	
Tillage and Chemical Applications:							
Chisel	1	1	1	1	0	0	$11.04 /ac
Disk	1	1	1	1	2	0	$9.07 /ac
Field cultivate	1	1	1	1	1	1	$8.29 /ac
Sweep	0	0	0	0	0	3	$7.62 /ac
Anhydrous application	1	0	1	1	1	1	$9.68 /ac
Fertilizer application	0	0	0	0	0	0	$4.80 /ac
Herbicide application	2	2	1	2	1	4	$5.15 /ac
Insecticide application	1	0	2	0.5	1	0	$5.14 /ac
Harvest							
Base charge, $/acre	$25.33	$25.87	$23.89	$19.96	$19.28	$19.28	
Charge for high yields, $/unit	$0.188	$0.181	$0.002	$0.182	$0.183	$0.183	
High yield	71	28	14	36	21	21	
Hauling, $/unit	$0.164	$0.164	$0.003	$0.175	$0.177	$0.177	
Non-machinery labor, hr/acre	1.29	0.79	0.80	1.04	0.85	0.90	$13.00 /hr
Irrigation labor, hr/acre	0.50	0.50	0.50	0.50	0.50	0.00	$13.00 /hr
Average land value, $/acre /A	$1,600	$1,600	$1,600	$1,600	$1,600	$830	
Annual return to land, % /A							5.0%
Interest on capital, %							8.0%
	Investment, $					Salvage	
Irrigation Equipment	Total	$/wet ac		Years		value, %	
Well, pump and gearhead value	$53,000	$424		25		0%	
Power unit and meter	$12,250	$98		7		0%	
Irrigation system	$59,500	$476		20		25%	

Price scenarios to consider	Corn					Wht-Flw	Use (Y=1, N=0)
Long-run prices (MF-1013)	$3.36	$7.36	$13.33	$3.02	$5.02	$5.02	0
Short-run prices (MF-1013)	$4.44	$8.39	$13.33	$4.10	$5.86	$5.86	0
2009 bids (Colby Cash – 1/21/09)	$3.57	$9.15	$14.25	$2.83	$5.38	$5.38	1

/A -- The annual cost associated with land can either be entered as a Land Value x Rent-to-Value OR as a Cash Rent x 100%. For example, if cash rent in region is $42 per acre, this can be entered as $42 in row 94 and 100% in cell K95 OR as $840 in row 94 and 5% in cell K95 [$42 x 100% = $840 x 5%].

The operator's share of production inputs are shown. Here, "-100%" indicates that an expense is equitably shared in the same % as resource contributions.

Landowner ==================>	Landowner, Northwest KS, 123-456-8888		01/23/09
Operator ==================>	Tenant, Northwest KS, 123-456-9999		8:38 AM
Basis for equitable share calculations: For the entire rotation (L4 = 0), Crop-by-crop (L4 = 1)		L4 ==>	0

OPERATOR'S share of production inputs (enter -100% if equitably shared)							
Crop/System	Corn	---	---	---	---	Wht-Flw	Total
Planted acres	125.0	---	---	---	---	17.5	142.5
Seed	100%	100%	100%	100%	100%	100%	
Fertilizer:							
82-0-0	67%	67%	67%	67%	67%	67%	
N (dry/liquid)	67%	67%	67%	67%	67%	67%	
P	67%	67%	67%	67%	67%	67%	
K	67%	67%	67%	67%	67%	67%	
Lime	67%	67%	67%	67%	67%	67%	
Herbicide							
RT3	67%	67%	67%	67%	67%	67%	
+ Bicep Lite II Magnum	67%	67%	67%	67%	67%	67%	
+ Additives	67%	67%	67%	67%	67%	67%	
Prowl	67%	67%	67%	67%	67%	67%	
Glyphosate + Adjuvants	67%	67%	67%	67%	67%	67%	
Prowl H2O	67%	67%	67%	67%	67%	67%	
Spartan	67%	67%	67%	67%	67%	67%	
Marksman	67%	67%	67%	67%	67%	67%	
Ally (0.1 oz/ac) + Banvel (4 oz/ac)	67%	67%	67%	67%	67%	67%	
RT3 (16.5 oz/ac) + 2, 4-D (1 pt/ac)	67%	67%	67%	67%	67%	67%	
Insecticide / Fungicide							
Force 3G	67%	67%	67%	67%	67%	67%	
Capture 2EC	67%	67%	67%	67%	67%	67%	
Warrior 1 EC	67%	67%	67%	67%	67%	67%	
Tilt	67%	67%	67%	67%	67%	67%	
Crop consulting	100%	100%	100%	100%	100%	100%	
Crop insurance	-100%	-100%	-100%	-100%	-100%	-100%	
Drying cost	-100%	-100%	-100%	-100%	-100%	-100%	
Operator's equitable share (OS%)	68.0%					60.7%	67.7%

Crop/System	Corn	---	---	---	---	Wht-Flw	Total
Planted acres	125.0	---	---	---	---	17.5	142.5
OPERATOR'S share of machinery, labor, irrigation, and land (enter -100% if shared equitably)							
Drill/Plant	100%	100%	100%	100%	100%	100%	
Tillage and Chemical Applications:							
Chisel	100%	100%	100%	100%	100%	100%	
Disk	100%	100%	100%	100%	100%	100%	
Field cultivate	100%	100%	100%	100%	100%	100%	
Sweep	100%	100%	100%	100%	100%	100%	
Anhydrous application	100%	100%	100%	100%	100%	100%	
Fertilizer application	100%	100%	100%	100%	100%	100%	
Herbicide application	100%	100%	-100%	-100%	-100%	-100%	
Insecticide application	100%	100%	100%	100%	100%	100%	
Harvest							
Harvest	100%	100%	100%	100%	100%	100%	
Hauling	100%	100%	100%	100%	100%	100%	
Miscellaneous	100%	100%	100%	100%	100%	100%	
Non-machinery labor	100%	100%	100%	100%	100%	100%	
Irrigation expenses							
Labor	100%	100%	100%	100%	100%	100%	
Fuel and oil	100%	100%	100%	100%	100%	100%	
Repair and maintenance	100%	100%	100%	100%	100%	100%	
Irrigation investment							
Well, pump and gearhead	0%	0%	0%	0%	0%	0%	
Motor	0%	0%	0%	0%	0%	0%	
Irrigation system	0%	0%	0%	0%	0%	0%	
Land	0%	0%	0%	0%	0%	0%	
Cash payment to landowner, $/acre	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0
Operator's equitable share (OS%)	68.0%					60.7%	67.7%
Landowner's equitable share (LS%)	32.0%					39.3%	32.3%

Pre-defined operator's share for income (crop sales and government payments)[1]	
Operator's share (if > 0, OS% will be over-ridden)	0.0%

[1] By entering a pre-defined share for the operator (landowner share is calculated as 100% minus operator share), the calculated equitable share percentage (cell L70) will be over-ridden and not used in the ***Lease Budgets*** tab.

Operator and Landowner's income shares are based on the equitable concept.

KSU-Lease.xls -- Developed by Kevin C. Dhuyvetter and Terry L. Kastens
Extension Agricultural Economists, Kansas State University

Shares page

This analysis indicates that the operator is contributing 67.7% and the landowner 32.3% of total resources in this example where the landowner also owners the center pivot. The operator's and landowners costs and returns for this particular crop share leasing arrangement are shown below.

CROP BUDGETS SHOWING OPERATOR'S COSTS AND RETURNS

Tenant, Northwest KS, 123-456-9999				8:38 AM	01/23/09
Equitable share (OS%) =========>	67.7%	67.7%	67.7%		
Crop/System	Corn	Wht-Flw	Total	Per	Per
Total tillable acre	==>		160.0	Planted	Tillable
Planted acres of each crop	125.0	17.5	142.5	Acre	Acre
Harvested yield per acre	200.0	45.0	---	---	---
INCOME PER ACRE					
A. Yield per acre	135.3	30.4	---	---	---
B. Price per unit	$3.57	$5.38	---	---	---
C. Net government payments	$22.01	$11.00	$2,944	$20.66	$18.40
D. Indemnity payments	$0.00	$0.00	$0	$0.00	$0.00
E. Miscellaneous income	$0.00	$0.00	$0	$0.00	$0.00
F. Returns/acre ((AxB) + C + D + E)	$505.11	$174.81	$66,198	$464.55	$413.74
COSTS PER ACRE					
1. Seed	$67.20	$10.40	$8,582	$60.22	$53.64
2. Herbicide	23.81	8.08	3,118	21.88	19.48
3. Insecticide / Fungicide	23.65	0.00	2,956	20.74	18.48
4. Fertilizer and Lime	165.92	49.16	21,600	151.58	135.00
5. Crop Consulting	6.50	0.00	813	5.70	5.08
6. Crop Insurance	33.83	8.46	4,377	30.71	27.36
7. Drying	0.00	0.00	0	0.00	0.00
8. Miscellaneous	10.00	5.50	1,346	9.45	8.41
9. Machinery Expense	148.38	97.32	20,251	142.11	126.57
10. Non-machinery Labor	16.77	11.70	2,301	16.15	14.38
11. Irrigation	116.84	0.00	14,605	102.49	91.28
12. Land Charge / Rent	0.00	0.00	0	0.00	0.00
G. SUB TOTAL	$612.90	$190.62	$79,948	$561.04	$499.68
13. Interest on 1/2 Nonland Costs	22.53	6.32	2,927	20.54	18.29
H. TOTAL COSTS	$635.43	$196.94	$82,875	$581.58	$517.97
I. RETURNS OVER COSTS (F - H)	($130.31)	($22.13)	($16,676)	($117.03)	($104.23)
J. TOTAL COSTS/UNIT (H/A)	$4.70		---	---	---
K. RETURN TO TOTAL COST (I/H)	-20.51%	-11.24%	-20.12%	-20.12%	-20.12%

CROP BUDGETS SHOWING LANDOWNER'S COSTS AND RETURNS

Landowner, Northwest KS, 123-456-8888				8:38 AM	01/23/09
Equitable share (100 - OS%) ====>	32.3%	32.3%	32.3%		
Crop/System	Corn	Wht-Flw	Total	Per	Per
Total tillable acre	==>		160.0	Planted	Tillable
Planted acres of each crop	125.0	17.5	142.5	Acre	Acre
Harvested yield per acre	200.0	45.0	---	---	---
INCOME PER ACRE					
A. Yield per acre	64.7	14.6	---	---	---
B. Price per unit	$3.57	$5.38	---	---	---
C. Net government payments	$10.52	$5.26	$1,407	$9.87	$8.79
D. Indemnity payments	$0.00	$0.00	$0	$0.00	$0.00
E. Miscellaneous income	$0.00	$0.00	$0	$0.00	$0.00
F. Returns/acre ((AxB) + C + D + E)	$241.42	$83.55	$31,639	$222.03	$197.74
COSTS PER ACRE					
1. Seed	$0.00	$0.00	$0	$0.00	$0.00
2. Herbicide	11.73	3.98	1,536	10.78	9.60
3. Insecticide / Fungicide	11.65	0.00	1,456	10.22	9.10
4. Fertilizer and Lime	81.72	24.21	10,639	74.66	66.49
5. Crop Consulting	0.00	0.00	0	0.00	0.00
6. Crop Insurance	16.17	4.04	2,092	14.68	13.07
7. Drying	0.00	0.00	0	0.00	0.00
8. Miscellaneous	0.00	0.00	0	0.00	0.00
9. Machinery Expense	0.00	6.66	117	0.82	0.73
10. Non-machinery Labor	0.00	0.00	0	0.00	0.00
11. Irrigation	93.49	0.00	11,686	82.01	73.04
12. Land Charge / Rent	80.00	83.00	11,453	80.37	71.58
G. SUB TOTAL	$294.75	$121.90	$38,978	$273.53	$243.61
13. Interest on 1/2 Nonland Costs	4.85	1.47	632	4.44	3.95
H. TOTAL COSTS	$299.61	$123.36	$39,610	$277.96	$247.56
I. RETURNS OVER COSTS (F - H)	($58.19)	($39.82)	($7,970)	($55.93)	($49.81)
J. TOTAL COSTS/UNIT (H/A)	$4.63		---	---	---
K. RETURN TO TOTAL COST (I/H)	-19.42%	-32.27%	-20.12%	-20.12%	-20.12%

KSU Lease.xls -- Developed by Kevin C. Dhuyvetter and Terry L. Kastens
Extension Agricultural Economists, Kansas State University

Lease budgets page

The final summary comparison of alternative estimates of equitable irrigated crop leasing arrangements are shown below.

ALTERNATIVE METHODS OF ESTIMATING CASH RENT					8:38 AM	01/23/09
Crop/System	Corn		Wht-Flw	Total	Per	Per
Total tillable acre	==>			160.0	Planted	Tillable
Planted acres of each crop	125.0		17.5	142.5	Acre	Acre
A. Landowner's COST						
Land	$80.00		$83.00	$11,453	$80.37	$71.58
Irrigation equipment	$93.49		$0.00	$11,686	$82.01	$73.04
Total	$173.49		$83.00	$23,139	$162.38	$144.62
B. Landowner's EQUITABLE SHARE RENT ---- risk adj factor		3.0%				
Total income	$746.53		$258.36	$97,838	$686.58	$611.48
Landowner's share	32.3%		32.3%	32.3%	32.3%	32.3%
Landowner's income	$241.42		$83.55	$31,639	$222.03	$197.74
Landowner operating expense	126.12		40.36	16,471	115.58	102.94
Income less operating expense	$115.30		$43.18	$15,168	$106.44	$94.80
Less risk adjustment	3.46		1.30	455	3.19	2.84
Cash rent equivalent	$111.84		$41.89	$14,713	$103.25	$91.96
C. Amount tenant CAN AFFORD TO PAY						
Total income	$746.53		$258.36	$97,838	$686.58	$611.48
Total operating expense	$761.54		$237.30	$99,345	$697.16	$620.91
Return to land and irr equip	($15.01)		$21.06	($1,508)	($10.58)	($9.42)
Comparison of alternative cash rent methods						
Low	($15.01)		$21.06	($1,508)	($10.58)	($9.42)
Average	$90.11		$48.65	$12,115	$85.02	$75.72
High	$173.49		$83.00	$23,139	$162.38	$144.62
Returns above all costs (profit)	($188.50)		($61.94)	($24,647)	($172.96)	($154.04)

Part A of this table shows that the landowner's costs for this land, including both the cash and opportunity cost of the irrigation equipment and the opportunity cost of farmland ownership (5% target rate of return) amount to $144.62 per acre.

Part B indicates that for this example in which the landowner owns the center pivot irrigation system and contributes a 1/3 share of selected crop input costs (fertilizer, herbicides, insecticides and crop insurance), with a 3% risk adjustment factor, the landowner's equivalent share rent is $91.96 per tillable acre.

Part C shows that the amount the tenant can afford to pay if all resources are valued at their full economic opportunity cost is actually negative (i.e., -$9.42 per acre). That said, full economic opportunity costs for irrigation equipment, labor and farmland are often not fully covered in such leasing arrangements.

In a comparison of the alternative cash rent calculation methods, the average rent per tillable acre is $75.72 for the full 160 acre field, with an average of $90.11 on the irrigated corn acres and of $45.38 per acre on the dryland acres.

SCENARIO #2: CENTER PIVOT OWNED BY OPERATOR, SHARING OF SELECTED CROP INPUT EXPENSES

The second analysis of how equitable a common irrigated cropland leasing arrangement is focused on the scenario in which the Operator (i.e., tenant) owns the center pivot irrigation system and shares the cost of selected crop input expenses. All other aspects of the lease are unchanged from the first scenario.

OPERATOR'S share of machinery, labor, irrigation, and land (enter -100% if shared equitably)							
Drill/Plant	100%	100%	100%	100%	100%	100%	
Tillage and Chemical Applications:							
Chisel	100%	100%	100%	100%	100%	100%	
Disk	100%	100%	100%	100%	100%	100%	
Field cultivate	100%	100%	100%	100%	100%	100%	
Sweep	100%	100%	100%	100%	100%	100%	
Anhydrous application	100%	100%	100%	100%	100%	100%	
Fertilizer application	100%	100%	100%	100%	100%	100%	
Herbicide application	100%	100%	-100%	-100%	-100%	-100%	
Insecticide application	100%	100%	100%	100%	100%	100%	
Harvest							
Harvest	100%	100%	100%	100%	100%	100%	
Hauling	100%	100%	100%	100%	100%	100%	
Miscellaneous	100%	100%	100%	100%	100%	100%	
Non-machinery labor	100%	100%	100%	100%	100%	100%	
Irrigation expenses							
Labor	100%	100%	100%	100%	100%	100%	
Fuel and oil	100%	100%	100%	100%	100%	100%	
Repair and maintenance	100%	100%	100%	100%	100%	100%	
Irrigation investment							
Well, pump and gearhead	0%	0%	0%	0%	0%	0%	
Motor	0%	0%	0%	0%	0%	0%	
Irrigation system	100%	100%	100%	100%	100%	100%	
Land	0%	0%	0%	0%	0%	0%	
Cash payment to landowner, $/acre	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0
Operator's equitable share (OS%)	72.7%					60.7%	72.2%
Landowner's equitable share (LS%)	27.3%					39.3%	27.8%

Pre-defined operator's share for income (crop sales and government payments)[1]	
Operator's share (if > 0, OS% will be over-ridden)	0.0%

[1] By entering a pre-defined share for the operator (landowner share is calculated as 100% minus operator share), the calculated equitable share percentage (cell L70) will be over-ridden and not used in the ***Lease Budgets*** tab.

Operator and Landowner's income shares are based on the equitable concept.

Part A of the following table shows that the landowner's costs for this land, including both the cash and opportunity cost of the irrigation equipment and the opportunity cost of farmland ownership (5% target rate of return) amount to $112.08 per acre.

Part B indicates that for this example in which the operator owns the center pivot irrigation system with the landowner contributing a 1/3 share of selected crop input costs (fertilizer, herbicides, insecticides and crop insurance), with a 3% risk adjustment factor, the landowner's equivalent share rent is $67.14 per tillable acre.

Part C shows that the amount the tenant can afford to pay if all resources are valued at their full economic opportunity cost is actually negative (i.e., -$42.96 per acre). As in the previous illustration, full economic opportunity costs for irrigation equipment, labor and farmland are often not fully covered in such leasing arrangements.

In a comparison of the alternative cash rent calculation methods, the average rent per tillable acre is $45.75 for the full 160 acre field, with an average of $52.21 on the irrigated corn acres and of $45.38 per acre on the dryland acres.

ALTERNATIVE METHODS OF ESTIMATING CASH RENT				11:46 AM	01/23/09	
Crop/System	Corn		Wht-Flw	Total	Per	Per
Total tillable acre	==>			160.0	Planted	Tillable
Planted acres of each crop	125.0		17.5	142.5	Acre	Acre
A. Landowner's COST						
Land	$80.00		$83.00	$11,453	$80.37	$71.58
Irrigation equipment	$51.84		$0.00	$6,480	$45.47	$40.50
Total	$131.84		$83.00	$17,933	$125.84	$112.08
B. Landowner's EQUITABLE SHARE RENT ---- risk adj factor		3.0%				
Total income	$746.53		$258.36	$97,838	$686.58	$611.48
Landowner's share	27.8%		27.8%	27.8%	27.8%	27.8%
Landowner's income	$207.73		$71.89	$27,225	$191.05	$170.15
Landowner operating expense	123.77		38.82	16,151	113.34	100.94
Income less operating expense	$83.96		$33.07	$11,074	$77.71	$69.21
Less risk adjustment	2.52		0.99	332	2.33	2.08
Cash rent equivalent	$81.45		$32.08	$10,742	$75.38	$67.14
C. Amount tenant CAN AFFORD TO PAY						
Total income	$746.53		$258.36	$97,838	$686.58	$611.48
Total operating expense	$803.19		$237.30	$104,552	$733.70	$653.45
Return to land and irr equip	($56.66)		$21.06	($6,714)	($47.12)	($41.96)
Comparison of alternative cash rent methods						
Low	($56.66)		$21.06	($6,714)	($47.12)	($41.96)
Average	$52.21		$45.38	$7,320	$51.37	$45.75
High	$131.84		$83.00	$17,933	$125.84	$112.08
Returns above all costs (profit)	($188.50)		($61.94)	($24,647)	($172.96)	($154.04)

CONCLUSIONS

These illustrations of equitable leasing arrangements are intended for general illustration purposes. They may or may not be representative of a particular farm or equitable farmland leasing relationship, depending on the degree to which that a particular field, irrigation system, or set of production costs does or does not accurately fit other situations.

Alternative leasing scenarios can be calculated for the irrigated crops, including sunflowers, soybeans, grain sorghum and wheat. In this session at the 2009 Central Plains Irrigation Conference, we will give closer scrutiny to the cost estimates used in these examples, and show the effect of using alternative crops and cropping systems upon the bottom line equitable lease returns. We will also show a number of nonirrigated / dryland crop leasing arrangement examples, and discuss some relevant irrigated equipment – related tax planning issues.