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Oklahoma Water Resources Center

Final Project Report for DASNR Water Grant

Principal Investigators: Jason Warren, Scott Frazier, and Saleh Taghvaeian

Project Title: Irrigation Management and Optimization

Descriptors: Irrigation, Corn, Cotton, Wheat, Sorghum, Energy, Salinity, Water use efficiency.

Start Date: 02/01/2015

End Date: 09/30/2016

Students:

Student Status	Number	Disciplines
Undergraduate	4	BAE(2) and PaSS(2)
M.S.	3	BAE(2) and PaSS(1)
Ph.D.	1	BAE
Post Doc		
Total	8	

Outputs:

Presentations (Salinity Project):

1. Amiri, Samia; Saleh, Taghvaeian, Tyson, Ochsner, 2015, Effects of irrigation amount and quality on soil salinity dynamics, 36th Annual Oklahoma Governor's Water Conference and Research Symposium, Norman, OK.
2. Amiri, Samia; Saleh, Taghvaeian, 2016, Modeling the effects of irrigation management on soil salinity for cotton, ASABE Annual International Meeting, Orlando, FL.
3. Amiri, Samia; Saleh, Taghvaeian, 2016, Soil salinity dynamics under irrigated cotton in southwest Oklahoma, 9th International Conference on Irrigation and Drainage, Fort Collins, CO

Presentations (Subsurface Drip Project):

1. Warren, J. D. Sims, C. Murley, S. Taghvaeian, R. Kochenower and R. Taylor. 2016. Row Placement Considerations for subsurface Drip. Presented at the Oklahoma Irrigation Conference. Woodward, OK 7 March.
2. Warren, J., S. Taghvaeian, R. Taylor, D. Sims, and C. Murley. 2015. Alternative Crop Row Configuration for Subsurface Drip Irrigation. Presented at the 36th Annual Oklahoma Governor's Water Conference and Research Symposium. Norman, OK 2 Dec.
3. Warren, J. 2015. Planting Strategies for Wheat Under SDI. Presented at the Oklahoma Irrigation Conference. Fort Cobb, OK. 18 Aug.
4. Warren, J. 2015. Economics of Irrigated Corn vs. Grain Sorghum. Presented at the Winter Crops Clinic. Goodwell, OK. 10 Apr.

Presentations (Sustainability Project):

1. Governors Water Conference (Norman) 2015 – Presentation and Poster
2. Water In-Service (OSU) 2015 – Presentation
3. Crop Clinic (OAES, OCES - Goodwell) 2015 – Presentation
4. Winter Crop Clinic (OSU) 2016 – Presentation
5. Irrigation Conference (OAES, OCES – Fort Cobb) 2015 – Presentation
6. Irrigation Conference (OAES, OCES – Woodward) 2016 - Presentation

Synergistic External Funding Awards:

1. Taghvaeian, S., T. Ochsner, D. Rogers, C.C. Hillyer, J.P. Bordovsky, T. Marek, J. Warren, R. Boman, R. Taylor, D. Porter, S. Frazier, and J. Aguilar. 2015. Promoting Sensor-based Technology to Improve Land and Water Resources Conservation. Submitted to NRCS-CIG for $772,029. Funded.
2. Schipanski, M., R. Waskom, P. Gowda, G. Kelly, C. Ray, M. Marsalis, K. Wagner, C. West, C. Rice, B. Guerrero, B. Auvermann, and J.G. Warren. 2016. Sustaining Agriculture through Adaptive Management Resilient to a Declining Ogallala Aquifer and Changing Climate. Submited to USDA-AFRI for $10,000,000. Funded for $9,900,000.

Publications under Development:

Two extension factsheets focusing on salinity issues in southwest Oklahoma are under preparation and will be ready for publication by December 2016.

Three journal manuscripts are under preparation and will be submitted within the next four months.

An extension factsheet presenting the findings of the energy audit is currently in preparation.

Project Summary:

The following report contains the results of three projects related to irrigation systems management in Oklahoma which were combined to facilitate the creation or an irrigation team at Oklahoma State University. First of all, the combination of these projects has resulted in the development of a strong team of faculty focused on irrigation issues which includes Dr. Frazier, Dr. Taghvaeian, and Dr. Warren as PI's on these projects as well as Dr. Stoecker who is not include as an investigator on these projects but does collaborate to provide economic analysis. I mention the development of this team first because it has likely been the most valuable outcome of the funds provided by the DASNR water grant. As listed above this collaboration has resulted in a variety of presentations and collaborative development of publications related to irrigation management. It has also made us competitive in acquiring external funding to support our future efforts.

The assessment of salt accumulation and movement under subsurface drip irrigation in SW Oklahoma has resulted in the development of a HYDRUS-2D model used to simulate salt movement from subsurface drip irrigation. This effort showed that salt will preferentially accumulate in the root zone between the tape and crop row. Soil samples were collected from fields in SW Oklahoma which had been previously sampled in 2007. This field data showed that the salinity had decline during this time period. This decline was primarily attributed to the excessive rainfall (twice the average) experienced prior to the recent sampling.

Evaluation or driver accuracy for planting of corn and sorghum showed that yields were unaffected by driver accuracy regardless of irrigation rate. The stress indexes calculated using canopy temperature were sensitive to crop water stress in 2015 and show promise for use for irrigation scheduling in the Oklahoma Panhandle. Furthermore, soil moisture potential below the crop row was highly correlated to yield, suggesting that efforts to monitor soil moisture for subsurface drip irrigation management should focus on soil moisture potential directly below the crop row. Efforts to evaluate alternative row configurations for wheat found that planting solid stands of wheat optimized yield in drip irrigation and that removing rows from the dry area between the drip tape resulted in significantly reduced yields.

The sustainability analysis evaluating energy use of irrigation wells resulted in data collection from 10 wells. The analysis showed that well efficiency ranged from 10-70% of standard achievable efficiency. Improvements in the observed efficiency could reduce operating cost as much as $2,972 per pivot per year. In addition, a life cycle analysis comparing the measured efficiency of the 10 wells evaluated to that of standard efficiencies and found that greenhouse gas emissions could be reduced by 48,786 kg CO_{2eq} yr^{-1} if the efficiency of the 10 wells is increased to standard efficiency. Irrigation water application uniformity was evaluated on 5 center pivots. This analysis found that application efficiency ranged from 100 to 85% of water pumped from the aquifer but that the distribution uniformity ranged from 85 to 14%.

Studying Salt Movement and Accumulation under Subsurface Drip Irrigation Systems

Final Research Report

Saleh Taghvaeian; BAE

Problem and Research Objectives:

Salt buildup in agricultural soils is a growing problem in many areas in the world, such as Southwest Oklahoma. A major contributor to the salinity issue is the growing competition over freshwater resources, which forces agricultural producers to seek non-traditional water resources such as saline groundwater, partially-treated wastewater, and produced water from oil and gas exploration. A common characteristic of these sources is their low quality usually caused by high levels of salts. Another contributor is the projected increase in frequency and severity of extreme weather events, which will have a direct impact on quantity and quality of available agricultural water resources. An example is the most recent drought in southwest Oklahoma (2011-2014), which resulted in historically low water levels in Lake Altus with devastating impacts on the environment (total fish kill) and economy (cotton production and processing).

Another factor that complicates the impact of using low-quality water is that many growers in southwest Oklahoma are adopting strategies to apply water more efficiently. One of the common approaches is switching from current irrigation systems (furrow and sprinkler) to subsurface drip irrigation (SDI). Despite all the benefits of SDI systems such as efficient application of water and nutrients in the root zone, they may exacerbate potential salinity issues. This is because SDI systems are located beneath the soil surface, distributing water in small amounts and all directions. This can potentially lead to accumulation of salts in the top soil, especially if rainfall is not enough to leach the salts below the root zone.

The goal of this project was to study the current situation and future trends of salt accumulation in top soil in southwest Oklahoma. More specific objectives were:

1. To simulate the effects of irrigation management practices under SDI on root-zone salt accumulation using a computer model
2. To evaluate salt accumulation changes in irrigated fields in southwest OK by conducting deep and shallow soil sampling

The first objective provides information on the effect of different irrigation practices on the pattern and accumulation of salts in the soil profile. The second objective provides an insight to the current condition of soil salinity and change in salt accumulation in southwest Oklahoma over the past eight years.

Methodology:

Simulating salt accumulation

To achieve the first objective HYDRUS 2D/3D model was purchased and used for simulating salt movement within the root zone of cotton, which is the predominant crop in southwest Oklahoma. The HYDRUS 2D/3D software package has two main components: a graphical user interface and a computational finite element model for simulating water, heat, and solutes movements under variable water content. Water fluxes are simulated through solving the Richards equation, while solute fluxes are modeled based on the Convection-Dispersion Equation.

To simulate the impact of management practices on root-zone salt buildup six scenarios were considered by combining two levels of irrigation amounts as percentages of crop evapotranspiration (ET_c) and three levels of irrigation water salinity represented by the electrical conductivity of irrigation water (EC_{iw}). Table 1 lists the six modeling scenarios.

Table 1. Experimental scenarios

Scenario	Description	Irrigation (% of ET_c)	EC_{iw} (dS m^{-1})
Full-EC0.5	Full-irrigation, non-saline	100%	0.5
Full-EC4.0	Full-irrigation, moderately saline	100%	4.0
Full-EC9.0	Full-irrigation, highly saline	100%	9.0
Deficit-EC0.5	Deficit-irrigation, non-saline	80%	0.5
Deficit-EC4.0	Deficit-irrigation, non-saline water	80%	4.0
Deficit-EC9.0	Deficit-irrigation, highly saline water	80%	9.0

The simulation domain was assigned based on a typical SDI system in the Lugert-Altus Irrigation District in southwest Oklahoma (Figure 1). To simulate the future soil salinity buildup in HYDRUS-2D, future weather parameters were needed. These future weather data (2016-2035) were simulated using the WeaGETS weather generator. WeaGETS is a stochastic weather generator which can generate daily weather parameters using historical precipitation and minimum/maximum air temperature. The historical weather data were obtained from the Altus Mesonet station for the period of 1995-2013.

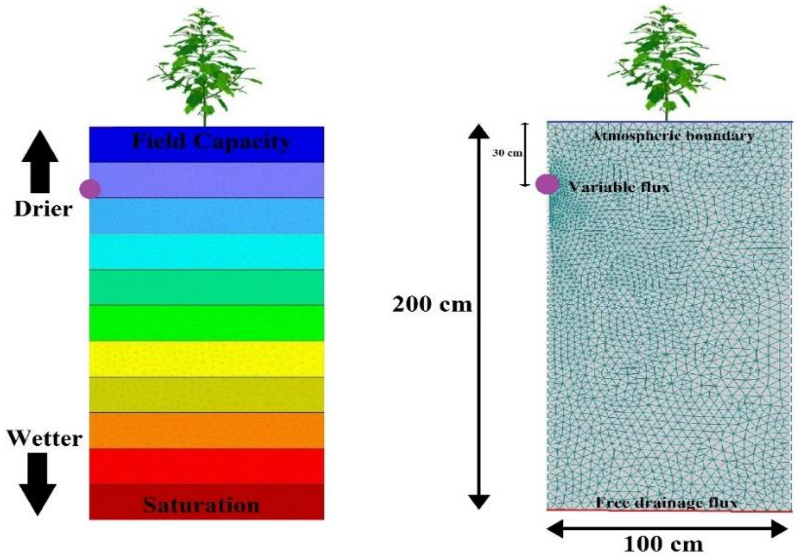

Figure 1. Physical layout, initial, and boundary conditions of the simulated

Cotton was used in the model as it is the predominant crop in southwest Oklahoma. Planting was assumed to be on day of year (DOY) 130 and harvest on DOY 290. Silty clay loam was used as the soil type with hydraulic properties estimated by the Rosetta model. Dual crop coefficient approach was implemented to partition ETc into evaporation and transpiration components. Irrigation depths were identified by running a daily water balance, using maximum allowable depletion of 10% for irrigation timing.

Sampling soil salinity

The second objective of the project was accomplished by sampling soil salinity at twenty points across seven fields in southwest Oklahoma, representing variable soil salinity levels. These fields were first sampled in October 2007. In February 2016 we took new soil samples from the same locations, using their GPS coordinates. A soil sampling probe was used to take soil cores (Figures 2 and 3). Each core was divided into several sub-cores with the top two ones being 6 inches in length and the remaining sub-cores 12 inches.

Figure 2. Soil coring device used in one of the study fields

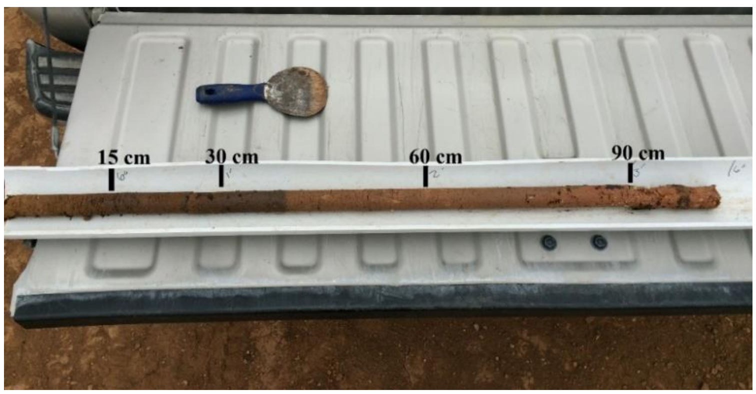

Figure 3. soil core and sub-cores lengths

Each sub-core was put in a separate bar-coded bag and sent to the OSU Soil, Water and Forage Analytical Laboratory (SWFAL), where they were analyzed for the Salinity Management Test (1:1 soil to water extraction). In this test, equal parts of water and soil are mixed together using 100 milliliters of deionized water and 100 grams of oven-dried and ground soil. The results were used in studying changes in soil salinity profile between the two sampling dates in October 2007 and February 2016.

Principal Findings and Significance:

Simulating salt accumulation

The output of HYDRUS 2D/3D model showed differences in water fluxes among simulated scenarios. This difference was mainly between irrigation treatments and not water quality treatments. Figure 4 demonstrates the partitioning of applied water (irrigation and precipitation) to different water balance components. The results are presented as the percentage of total applied water to allow for a better comparison between scenarios. As expected, all deficit irrigation scenarios resulted in a smaller portion of drainage water and a larger share of transpiration.

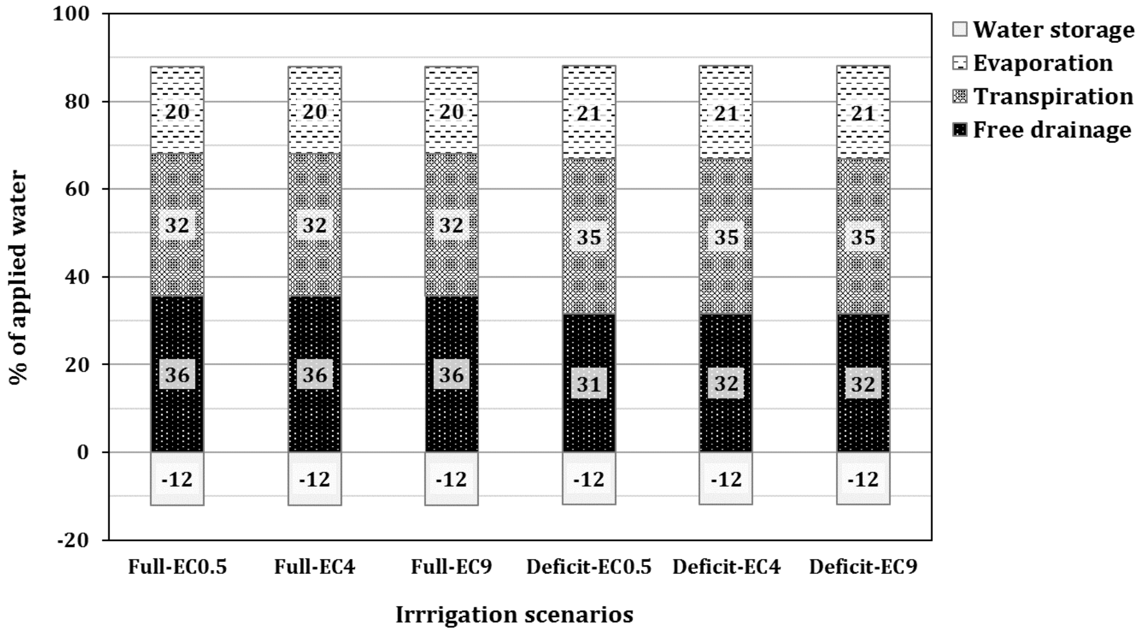

Figure 4. Partitioning of total applied water to different water balance components

The average salt concentration over the domain area (cotton root zone) had significant fluctuations over the 20 years of simulation. The initial soil EC was assumed to be 7.0 dS m^{-1}. A few months after the beginning of simulation period on January 1, 2016 average EC under non-saline treatments (Full-EC0.5 and Deficit-EC0.5) started declining rapidly and reached values less than 5.0 dS m^{-1} by December 2016. The rapid decline continued for about three more years until it reached about 0.5 dS m^{-1} (EC of irrigation water) and remained at this level for the rest of the study period. The year-to-year variation in EC was not considerable regardless of the amount of precipitation received. This finding has significant importance for agricultural growers in southwest Oklahoma as it shows that most soils with high salinity can be leached within a few years under generated weather conditions if high-quality irrigation water is applied and the soil profile is well-drained (naturally or artificially).

For moderately saline treatments (Full-EC4.0 and Deficit-EC4.0) salt concentration had a fairly rapid decline to levels near 4.0 dS m^{-1} (EC of irrigation water) by the end of the second year. For the remaining period EC fluctuated between 3.0 and 4.0 dS m^{-1} depending on precipitation amounts in each growing season, but never exceeded 4.0 dS m^{-1}. This 1.0 dS m^{-1} fluctuation in root zone salinity highlights the importance of precipitation in leaching salts when the irrigation water has higher levels of salt concentration. The results also reveal that some level of leaching salts and reclaiming soils can be achieved through irrigation as long as the salinity of irrigation water is less than the soil salinity.

For highly saline treatments (Full-EC9.0 and Deficit-EC9.0) salt concentration had a rapid increase to levels above 8.5 dS m^{-1} by the end of the first year. For the remaining period EC fluctuated between 6.5 and 9.0 dS m^{-1}. Root zone EC was closer to the initial levels during wet years, but increasing to 9.0 dS m^{-1} (irrigation water salinity) in dry years. The difference between full and deficit irrigation scenarios was larger for highly saline treatments, with full irrigation showing larger salt buildup. Figure 5 shows daily fluctuations in root zone salt concentration during the 20 years of simulation.

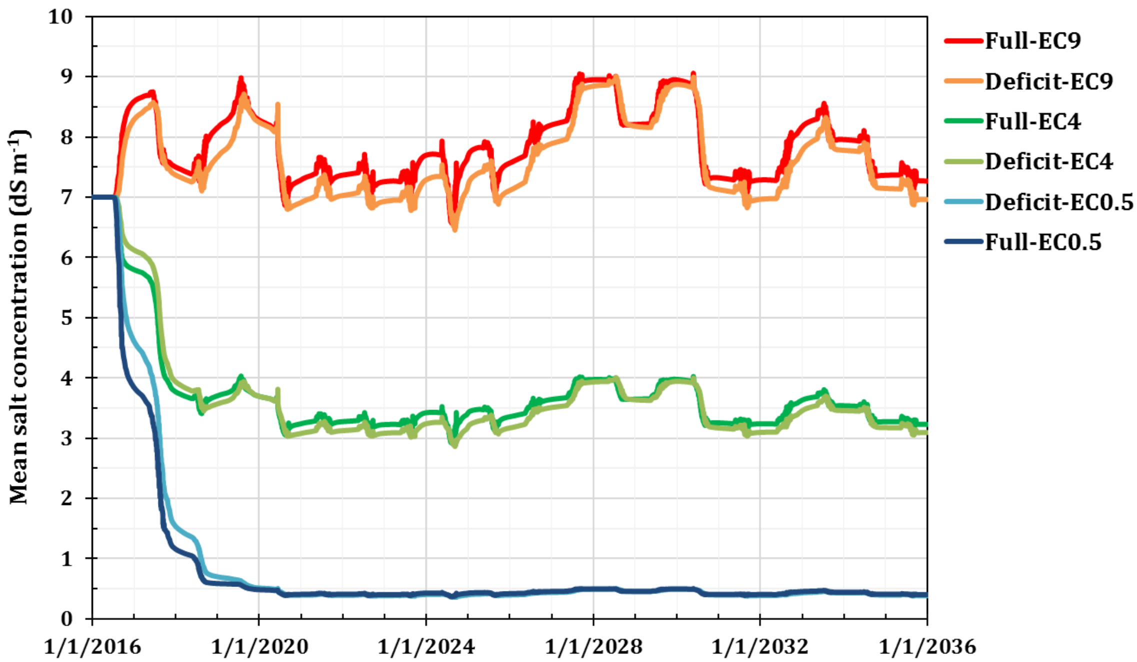

Figure 5. Daily fluctuations in root zone salinity over 20 years of simulation

Simulating the average salt concentration in the root zone is crucial in identifying potential yield loss and in evaluating the effectiveness of different irrigation management practices. However, under SDI systems root distribution is not uniform across the root zone. Hence, it is more important to simulate the spatial pattern of salt buildup within the root zone to better investigate possible impacts of salinity on crop production. HYDRUS 2D/3D allows for a detail spatial simulation of solute movement and accumulation in soil at any time step. As an example, Figure 6 provides salt distribution patterns for the last day of the study (12/31/2035) under each simulation scenario when irrigation water is applied through SDI system.

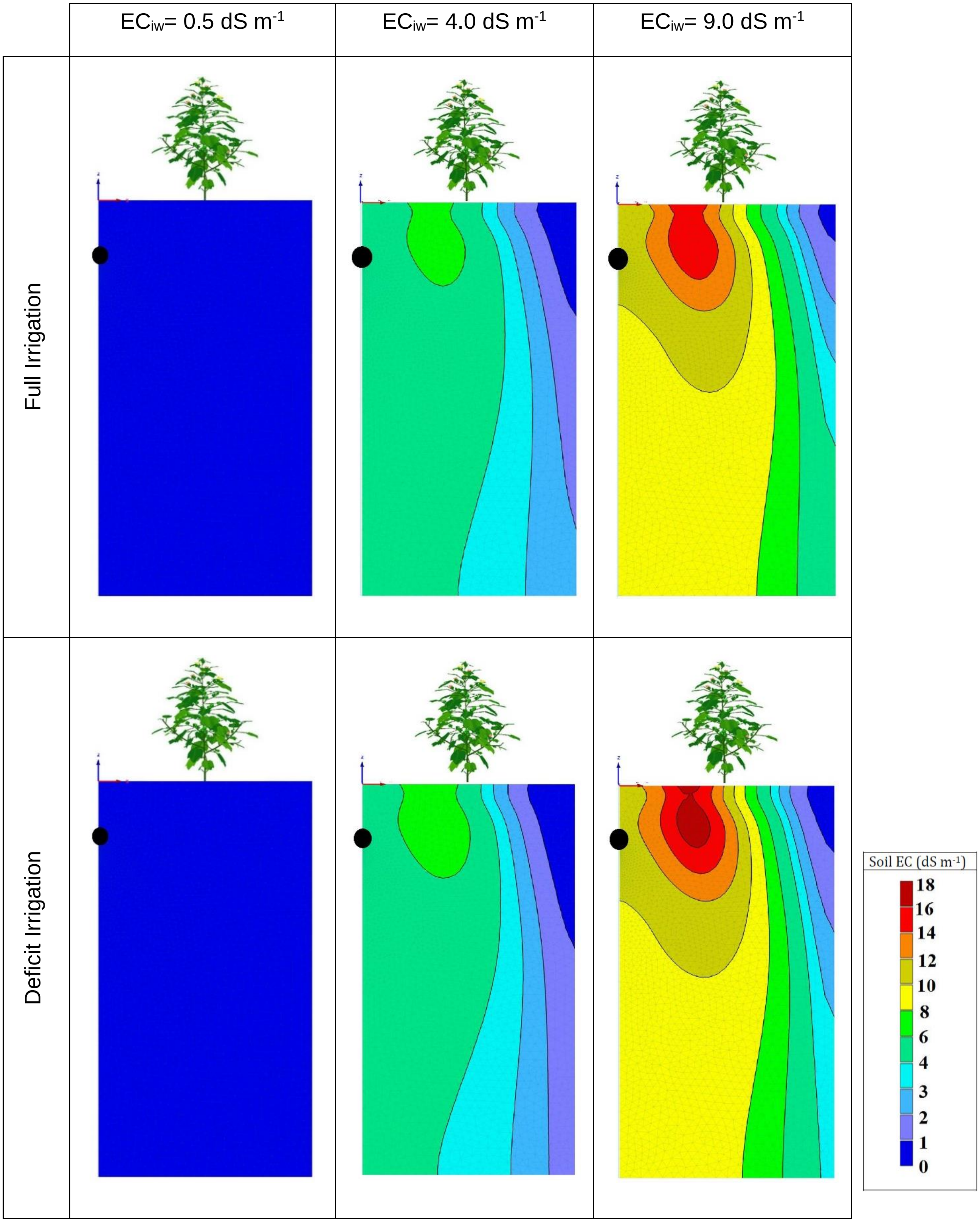

Figure 6. Simulated salt accumulation in the cotton root zone by the end of 2035. The black circle shows the location of drip line (cross section)

As depicted in Figure 6, soil EC in parts of the root zone reached levels significantly larger than the average estimates. For moderately saline treatments (Full-EC4.0 and Deficit-EC4.0) the average soil EC was slightly more than 3.0 dS m^{-1} at the end of the study, while an EC of over 6.0 dS m^{-1} was simulated in the upper left corner of the modeled root zone. For highly saline treatments (Full-EC9.0 and Deficit-EC9.0) average soil EC was 7.0 dS m^{-1} and slightly above for deficit and full irrigation treatments, respectively, while localized EC reached above 16.0 and 14.0 dS m^{-1} for the same treatments. On the other hand, the top right corner of the root zone (near soil surface in the middle of two adjacent crop rows) had negligible salt accumulation.

The simulated patterns of salt buildup have significant implications for SDI systems. This is due to the fact that the root growth is skewed under SDI since water is discharged from a line source usually installed on only one side of the crop row and at relatively shallow depths. As roots move toward the source of water the majority of root density is observed at the same location where the highest level of EC is predicted by HYDRUS 2D/3D model. Thus a better representative of root zone salinity would be a weighted average EC, with weights determined based on root density.

Sampling soil salinity

Out of twenty sampling locations only two (10%) had a low EC (less than 3.0 dS m^{-1}) across the entire sampled profile in 2007. The remaining points showed an increase in EC below the top one foot of the soil. For some of these points EC declined after this initial increase and for the rest it kept increasing with depth. The highest EC of all sub-cores was about 26.0 dS m^{-1}. The results from 2016 sampling showed that 12 locations had a lower level of salinity compared to 2007, either at all depths or at top soil layers. This is an indicator of salts being leached to lower layers in the soil profile for 60% of locations. Four locations (20%) had slightly higher EC and the remaining 20% had the same level of EC in 2016 (Figure 7).

The average and maximum soil EC of all sub-cores were 7.6 and 23.5 dS m^{-1}. Cotton is more tolerant to salinity than many other agricultural and horticultural crops, but its yield is expected to start declining at the EC threshold of 7.7 dS m^{-1} at the rate of about 5% per every unit increase in EC. So about 50% yield reduction is expected at EC of about 17.7 dS m^{-1}. Sodium was the major ion responsible for elevated salinity levels in soil samples, followed by calcium and magnesium.

It appears that the leaching observed in majority of locations was a result of significant rainfall in Spring 2015, with a total seasonal amount that was more than two times larger than the historic spring rainfall in the region. To further investigate the impact of rainfall on leaching salts additional samples were taken from several fields in the region and were compared with shallow soil samples collected in March 2015. Out of eight sampled fields four showed a significant decline in EC and three had no change.

A comparison between the sampling locations within the same field revealed that the location of sampling with respect to irrigation head ditch had an impact on spatio-temporal variations in soil salinity. The locations closer to the head ditch had usually higher EC. This is perhaps due to the fact that these locations were subject to larger irrigation amounts and frequencies, especially since the irrigation distribution uniformity is usually low under the dominant flood irrigation systems of the region. Hence upstream points receive far more irrigation water than downstream ones. Proximity to natural drains was also an influencing factor, with locations closer to natural drains (e.g. dry creeks) showing a lower EC.

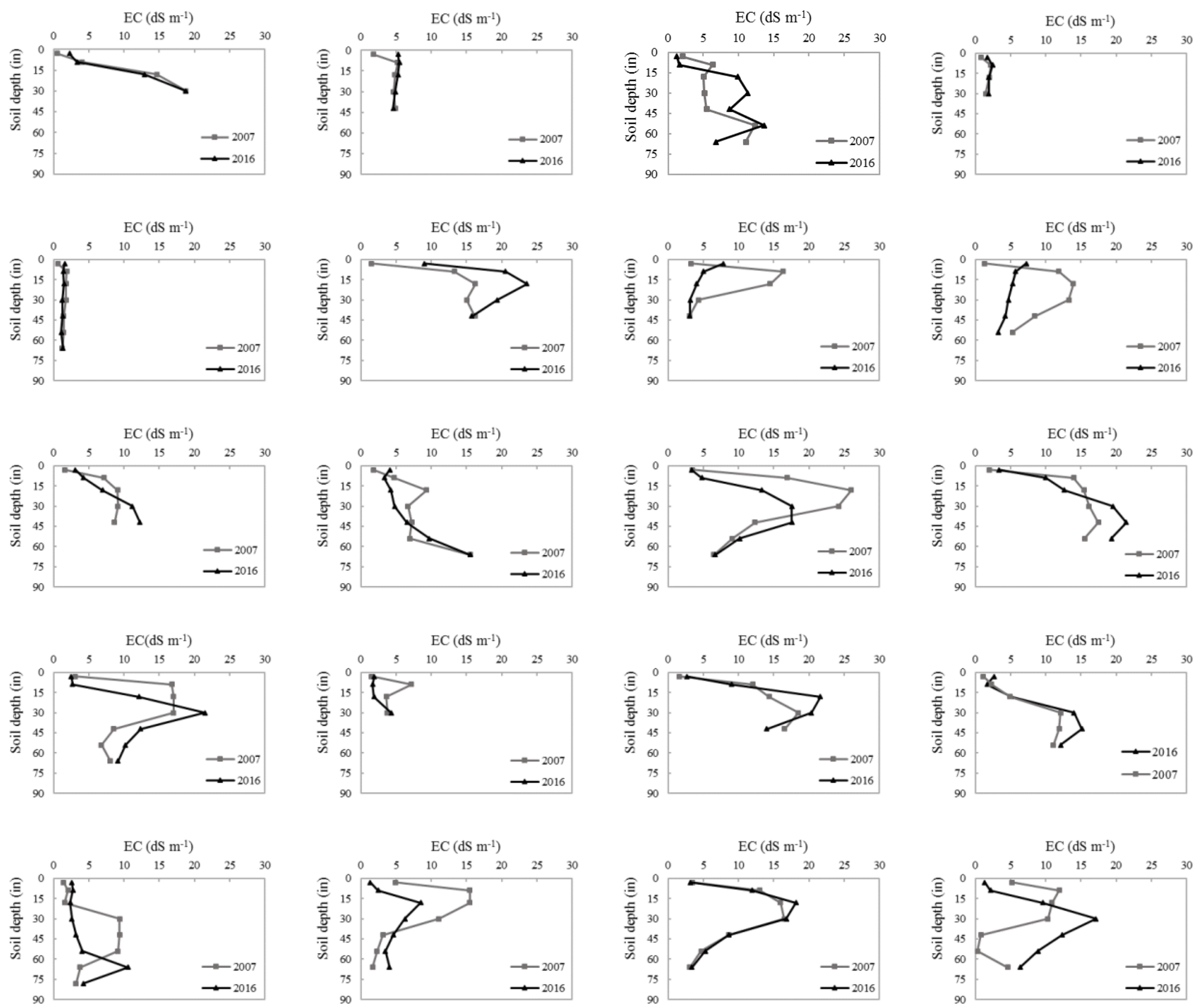

Figure 7. Soil EC profiles for 20 sampling locations in southwest Oklahoma

The average EC and Exchangeable Sodium Percentage (ESP) of the twenty soil cores were used to classify them into four major classes of normal, saline, sodic, and saline-sodic (Figure 8). Ten percent of soil cores were under normal classification in 2007. This number increased to 15% in 2016. No soil core was classified as sodic in 2007 and 2016. Saline samples dropped from 70% in 2007 to 65% in 2016 and the percentage of saline-sodic samples remained the same between 2007 and 2016.

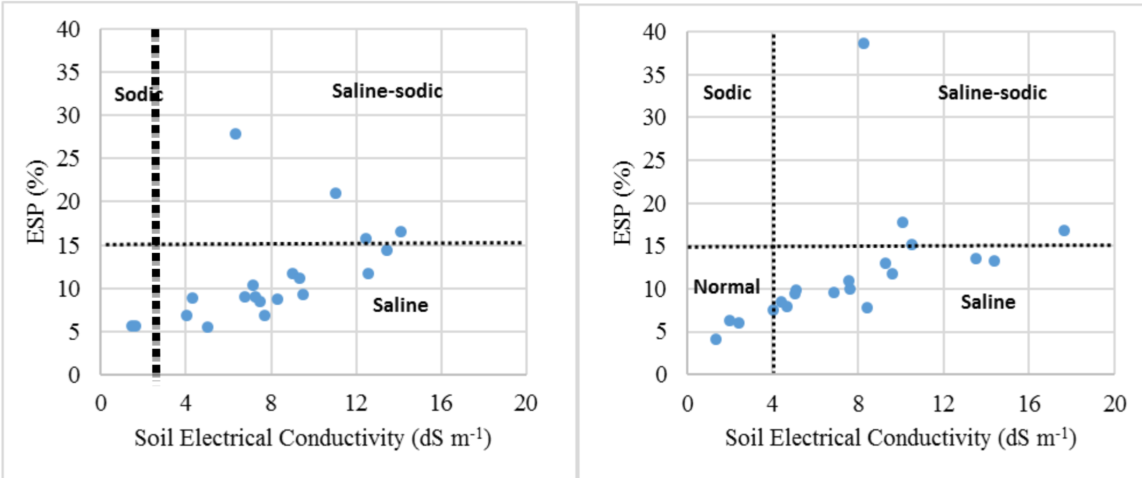

Figure 8. Soil classification based on EC and ESP in 2007 (left) and 2016 (right)

Title: Developing Management Strategies for Subsurface Drip Irrigation in the Oklahoma Panhandle

Jason Warren, Saleh Taghvaeian, Cameron Murley, Dalton Sims and Randy Taylor;
Oklahoma State University

Summary:

Evaluation or driver accuracy for planting of corn and sorghum showed that only at 50% of full irrigation will driver accuracy have a significant impact on corn yield. At this limited irrigation rate driver accuracy must be within 6 inches to ensure no negative impact on corn yield. In contrast, Grain sorghum yields were unaffected by driver accuracy regardless of irrigation rate. The stress indexes calculated using canopy temperature were sensitive to crop water stress in 2015 and show promise for use for irrigation scheduling in the Oklahoma Panhandle. Furthermore, soil moisture potential below the crop row was highly correlated to yield, suggesting that efforts to monitor soil moisture for subsurface drip irrigation management should focus on soil moisture potential directly below the crop row.

Introduction

Various sources can be cited to demonstrate the fact that water availability in the Ogallala Aquifer is declining. For example, the USGS found that water levels had decline by as much as 100 ft under Texas County, OK between the 1940s and 1990s. The report went on to suggest that if withdrawal continued at the same rate as in 1996 that the water level would decrease by an additional 6-7.5 m under Texas County, OK by 2020 (Luckey, et al. 2000). This declining water table is decreasing pumping capacity for agricultural producers in the Panhandle region. The adoption of new irrigation water management strategies are needed to improve water use efficiency in the region to offset this decline. Also, adoption of improved efficiency systems will be imperative if government restrictions on pumping are imposed in the future.

Previous research efforts in the High Plains Regions have shown that subsurface drip irrigation (SDI) provides superior water use efficiency compared to center pivot irrigation systems. In fact, Lamm and Trooien (2003) summarized 10 years of research in Kansas and concluded that irrigation water use for corn can be reduced by 35-55% using subsurface drip irrigation compared to commonly used irrigation systems in the region. Therefore research is not need to demonstrate the improved efficiency. However, research is needed to evaluate how variations in crop management will impact the performance of SDI in the region.

For the last two years we have been utilizing the subsurface drip irrigation system located at the Panhandle Research and Extension center to evaluate the yield response of corn compared to sorghum under limited irrigation water availability. This effort has provided opportunity for us to engage producers regarding the use of drip irrigation, which allows us to learn why producers are apprehensive in adopting this technology.   In addition to its increased cost, producers are currently not certain that the technology will fit their production system. Specifically, information is needed on how crop row placement will impact crop performance under drip with respect to stand establishment and yield.

In order to minimize costs of SDI systems the drip tape buried at intervals such that one row of drip tape will irrigate two crop rows. Research on cotton row placement has previously been conducted in the Southern High Plains near Halfway, Texas. This research found that for cotton planted on 76 cm row spacing, yield was significantly reduced when the offset between the drip tape and crop rows was 38 cm. This yield reduction occurred at the “high” irrigation rate (approximately equal to daily evapotranspiration).   At the “low” irrigation rate (approximately half of daily evapotranspiration) yield was reduced by 2% but this was not a significant reduction. The researchers evaluated yield in each row and found that at low irrigation the yield for the cotton row nearest the tape was equivalent to yields in the “high” irrigation treatments and that this compensated for the yield loss in the cotton row place 114 cm from the tape, making the average similar to the yield when rows were equidistance from the tape (each was 38 cm from the tape. In contrast, at “high” irrigation the cotton row placed 114 cm from the tape simply reduced the average of the two rows because the yield was not increased in the cotton row directly over the tape (Bordovsky et al. 2010). A similar analysis of the effect of crop row placement has not been conducted on corn or sorghum in the Southern Plains. Because the buried drip tape cannot seen from the surface, the potential for row placement error during planting is high. The use of high precision GPS systems can reduce this error, but research is needed to determine the accuracy required. Also, producers prefer to alternate row locations to improve ease of planting. This reduces the need to move root crowns out of the planting row. Producers need to know if this practice of alternating row locations from one year to the next will adversely impact crop performance. Sorghum and especially corn are more sensitive the water availability than is cotton. It is therefore expected that these crops will be more sensitive to row placement.

Objectives:

1) Evaluation of Driver Accuracy:

The objective is to evaluate how crop row placement will influence corn and grain sorghum yield response at irrigation regimes of 50, 75, and 100% of full ET replacement.

2) Row configuration for subsurface drip irrigated Wheat

The objective is to evaluate solid stands of wheat compared to planting 6 or 7 rows over the drip tape with 2 or 1 skip rows in the dry area at 50, 75 and 100% of full ET replacement

3) Canopy temperature to assess water stress in corn and sorghum

The objective was to evaluate canopy temperature measurements as a method to assess water stress in corn and sorghum. This will provide preliminary data needed to evaluate water stress thresholds and ultimately irrigation scheduling protocols.

Methodology:

Objective 1) Diver Accuracy:

This research utilized the SDI system at the Oklahoma Panhandle Research and Extension Center near Goodwell, OK. This series of studies uses 9 irrigation zones, each are 192 m long and 18 m wide. Grain sorghum, corn, and wheat are rotated annually such that each crop is planted on 3 zones. The corn is planted into sorghum stubble, the sorghum is planted into wheat stubble and the wheat is planted directly behind corn harvest. This was done to allow for more successful no-till management to minimize pest pressures. The study presented here is focused on evaluating driver accuracy for corn and grain sorghum and the wheat simply serves as a rotation crop.

Within each zone subsurface drip irrigation tape is located 30 cm below the surface and spaced 153 cm apart such that each tape will supply water to two crop rows when planted 76 cm apart. The tape contains emitters 60 cm apart along the length of the tape, designed to supply 0.68 liters per hour at 68 KPa allowing for 41.6 liters per minute (LPM) being supplied to each zone.

Pressure was adjusted to 89.6 KPa at the inlet of each zone such that instantaneous flow rates of 53 LPM were achieved on each zone. The instantaneous flow was evaluated periodically with manual observations of the flow meters (model # 36M251T, NetifimUSA, Fresno, CA). The flow meters were installed at the inlet of each zone and included totalizers which were used to determine the total water applied during the season.

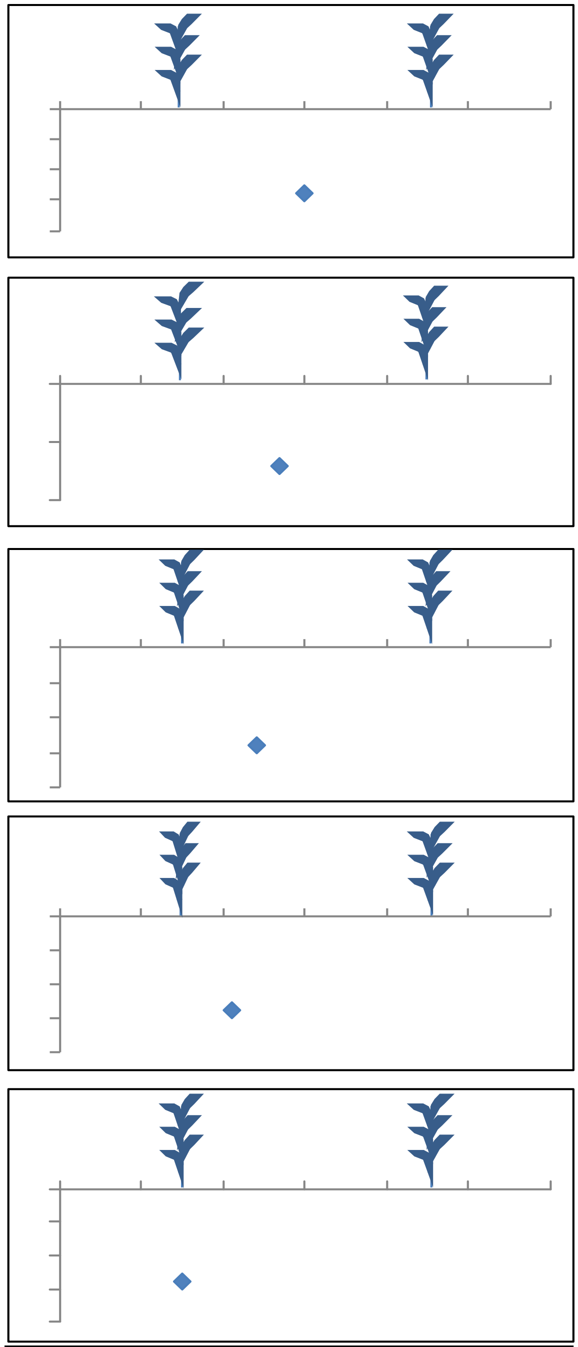

Figure 1: row placement over Drip tape

Experimental Design

The drip tape was installed using real time kinematic global positioning (RTK GPS) Guidance. Therefore, all planting was conducted using this technology to place rows in desired locations relative to drip tape. Within each zone an experiment was established to evaluate the impact of driver accuracy on corn and Grain Sorghum yields under three different irrigation regimes. The experimental design for each experiment was a randomized complete block design with 4 replicates and 5 treatments. The treatments consisted of crop rows being planted at 0, 8, 15, 23, and 38 cm offsets from the drip tape (Figure 1). These offset treatments were applied at planting using real time kinematic global positioning (RTK GPS) Guidance. Each plot was 4.57 m (6 rows) wide and 9.15 m long.

Crop Management

On May 5th, 2014 and April 21st, 2015 corn hybrid Pioneer 1768AMX and on April 15, 2016 corn hybrid Pioneer 1625 was planted in 3 zones and on June 6th, 2014; June 1st, 2015; and June 8, 2016 sorghum Hybrid Pioneer 84G62 was planted in 3 zones. One zone for each crop was designated to receive irrigation at a rate equal to estimated evapotranspiration. In 2014 and 2015 evapotranspiration was estimated by the Aquaplanner (www.Aquaplanner.net) irrigation scheduling program. In 2016 the Mesonet irrigation scheduling tool was used in combination with adjustments made based on work conducted by Gatlin (2014). The remaining zones were designated to receive irrigation equal to 75 and 50% of this fully irrigated rate. All corn plots received 8 cm of pre-plant irrigation in 2014 and 2015; and 5 cm in 2016. Post planting irrigation was initiated on 5 June, 2014; 4 June, 2015; and 12 May, 2016. The last irrigation events were applied to corn on 26 August, 2014; 25 August, 2015; and 24 August, 2016. Irrigation of the sorghum was initiated on 19 June 2014; 26 June, 2015; and 5 July, 2016. The last irrigation events were applied to the grain sorghum on 11 September, 2014; 28 September, 2015; and 9 September, 2016. Irrigation was applied daily when the soil water deficit was greater than 0.5 cm since the last irrigation event. When rainfall was anticipated irrigation was delayed to allow for optimum rainfall capture.

Fertilization

In 2014, the corn and sorghum received 3.3 L ha^{-1} of 10-34-0 fertilizer applied in row at planting with no in-season nitrogen applications because soil test NO_3-N plus NH_4-N in the surface 30 cm of soil was 200 kg ha^{-1}. In 2015 and 2016, both crops again received starter fertilizer (3.3 L ha^{-1} of 10-34-0) in addition to in-season N fertigation. The corn received 34 kg N ha^{-1} as 32-0-0 liquid fertilizer injected into the irrigation system weekly for 8 weeks starting on 15 June resulting in a seasonal application of 269 kg N ha^{-1}. The sorghum received 34 kg N ha^{-1} as 32-0-0 liquid fertilizer injected into the irrigation system weekly for 6 weeks starting on 8 July resulting in a seasonal application of 202 kg N ha^{-1}. In 2016, the weekly fertigation of the corn was initiated on 10 June and was applied for 8 weeks; and the grain sorghum fertigation was initiated on 30 June and applied for 6 weeks.

Herbicides and Insecticide Applications

Corn and sorghum ground both received an early pre plant herbicide application of 1qt. Roundup® Weathermax, 1 Quart Aatrex® Atrazine 4L, 1 pint of Rifle® Dicamba, and 2oz of granular Valor® in early April for all 3 data years. At planting, corn and sorghum received a post plant pre emergence herbicide application of 1qt Roundup® Weathermax, 1qt. Aatrex® Atrazine 4L, and 2oz Sharpen®. Post emergence application of 6.4 oz. of Starane® was administered to control any remaining broadleaves in early may for corn and late June for grain sorghum with Huskie® and nonionic surfactant added in. Corn was treated pre tassel, with 3 pints Comite® II miticide at V8 all three seasons. In 2016 grain Sorghum was treated for Sugar cane aphids on August 24th with Silvanto® and LI700 and then followed up with an application of Transform® and Warrior® on September 23rd.

Harvest

Corn grain yield was collected at maturity on 8 October, 2014; 1 October, 2015; and 5 October, 2016. Sorghum yields were collected at maturity on 15 October, 2014; 14 October, 2015; and 29 October, 2016. All grain was harvested using a Kincaid 8-xp small plot combine to harvest the center 2 rows from each plot. In 2015 and 2016 the rows were harvested as individual rows such that the distribution of yield between rows could be utilized.

Objective 2) Wheat Row Configurations:

The wheat was planted into the same zones with corn stubble from objective 1. Specifically, the wheat was planted with a small plot no-till drill at the opposite end of the zone where bulk corn had been planted with no offsets. Within each of the 3 wheat zone a factorial treatment structure was imposed in a randomized complete block treatment structure. The treatment factors were variety and row orientation. Billings and Iba will be used in this study. Each have good yield histories under irrigation at the Goodwell research station, however Billings does not do as well under low water availability and does not tiller as well as Iba. These varieties were planted on Oct. 22nd in 19 cm rows. The row configurations presented in figure 2 were created by terminating the "skip rows with Glyphosate after emergence.

Irrigation was initiated on March 10, 2015 with a final irrigation event occurring on May 4. Irrigation was terminated because sufficient rainfall occurred to maintain soil moisture according to the aquaplanner.net program as well as the mesonet irrigation scheduling tool.

Nitrogen deficiencies were observed in wheat rows between prior year's corn crop rows. Fertigation was subsequently initiated on March 30th and applied weekly for 6 weeks at a rate of 34lbs per week to provide a total of 202 kg N ha^{-1}.

Wheat was harvested for yield at maturity on June 25, 2015. At harvest 8 rows were harvested from the middle of the solid stand treatments and the 7 and 6 rows were harvested from above the drip tape in the remaining treatments.

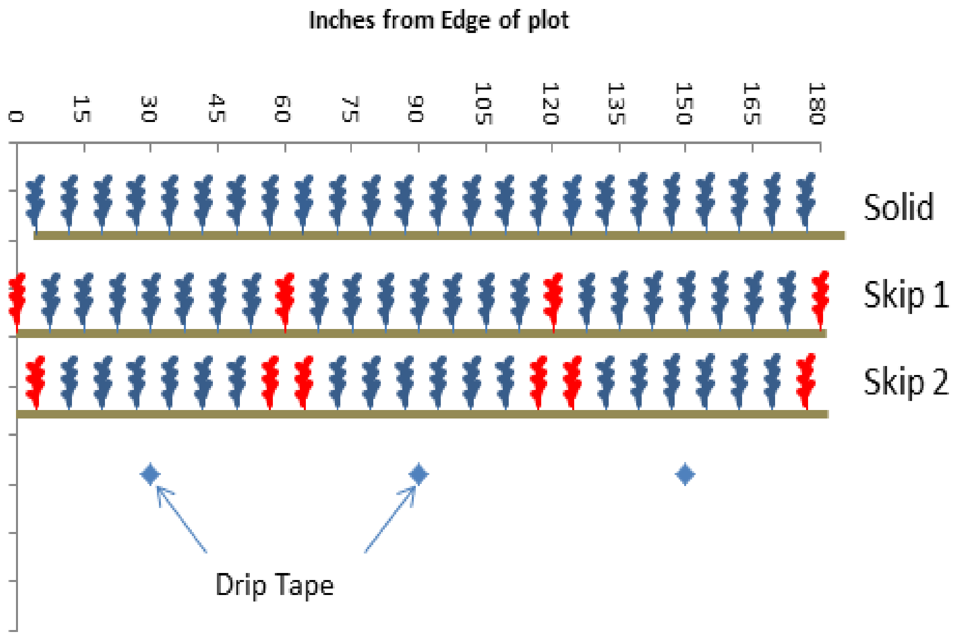

Figure 2: Row orientation for wheat when planted as a solid stand, as 7 or 6 rows over the tape

<u>Objective 3) Canopy Temperature:</u>

After emergences Apogee SI-111 Infra-Red Thermometers (IRTs) were installed and maintained one meter above the top of the canopy at a downward angle of 30° below horizon toward northeast to measure canopy temperature (Tc). Soil moisture was measured over 12-16 inch depth, using the Campbell Scientific CS-655 sensors. Data measurement and storage was performed by a CR1000 data-logger. A nearby Mesonet weather station provided required weather parameters on an hourly basis.

Three stress indexes were calculated using the canopy temperature data. The time-temperature threshold (TTT) was calculated as the total time when the canopy temperature was above the biologically identified threshold. In this study a temperature of 28 °C was used. The second stress index used was the degrees above non-stressed (DANS) threshold. This was calculated as the stressed canopy temperature minus the non-stressed canopy temperature. The Third threshold calculated was the canopy temperature ration which was calculated as the non-stressed canopy temperature divided by the stressed canopy temperature. The canopy temperature for the 100% irrigation treatment was used for the non-stressed canopy temperature and the 75 and 50% irrigation treatments were used as the stressed canopy temperatures in these threshold calculations.

Results and Discussion

Irrigation Applied

Table 1 shows the in-season and pre-season irrigation applied to each zone for the corn and sorghum crops grown in 2014 and 2015 as well as the in-season rainfall totals. The irrigation reported in this table is as measured by flow meters at the inlet of each zone. The irrigation applied to corn plots in 2014 is well below the target application of 20 inches because of overestimated flow rates early in the season. In addition, visual observations that the soil surface was consistently moist during the reproductive growth stages suggested that irrigation was sufficient to allow optimum growth. For the remaining crop years the applied irrigation reported in Table 1 as measured by the flow meters is within 10% of the target irrigation rates estimated by Aquaplanner.

Table 1: Irrigation applied to the 100, 75 and 50% irrigation zones for corn, sorghum, and wheat in 2014-16 as well as the pre-plant irrigation applied to all zones and the in-season rainfall.

Water Supply	-------Corn-------			-----Sorghum-----			--Wheat--	
	2014	2015	2016	2014	2015	2016	2015	2016
	---------------------------------cm-------------------------------							
100% In-season	42	51	53	38	33	33	34	27
75% In-season	34	39	41	30	25	25	24	21
50% In-season	24	28	25	19	18	18	16	14
Pre-season irrigation	8	8	5	0	0	0	0	0
In-season Rainfall	32	47	26	27	30	14	44	44

Corn Grain Yield

Table 2 shows that there was no significant impact of offset treatment on corn grain yield. Irrigation regime and year were found to be significant but there was also a significant year by irrigation interaction that is shown in figure 3. In 2014, yield increased with increasing irrigation. In contrast, in 2015 and 2016 there was little or no difference between the 100 and 75%. Table 3 shows that in 2015 rainfall totals nearly doubled when compared to the fifteen-year average. Much of this rainfall occurred early in the season and was assumed to be lost to drainage or runoff. The water budget used to irrigate was based on a soil water balance for the 100% irrigated and therefore estimated drainage and runoff was higher for this treatment compared to the 75 % regime which was more often in a position to capture rainfall because of drier soil conditions. This increased the efficiency of this treatment in the 2015 crop year. In contrast, Table 3 shows in 2016 much of the rainfall received also occurred in the early months of the season but was significantly less when compared to the 2015 early season rainfall totals, therefore irrigation was initiated earlier in 2016. This resulted in excellent growing conditions for both 100 and 75% irrigated treatments. As a result of limited visual differences between the two irrigation regimes, irrigation rates were limited to 0.9, 0.67, and 0.45 cm per day for the 100, 75, and 50% irrigation treatment in 2016. This was done in an effort to prevent the occurrence of over irrigation of the 75% treatment that occurred in 2015 from occurring again. However, in 2016 lower than normal rainfall occurred during and after flowering. This combined with the estimated ET rates of fully irrigated corn being in excess of 0.9 cm per day caused the 100% irrigation regime to experience more water stress during this critical time when compared to the75% regime which had a visibly more limited canopy and therefore, proportionally lower ET demand. Payero et al. (2006) found that seasonal Et values are linear with irrigation and rainfall in such that more water yields larger biomass and larger biomass yields higher ET rates. Traore et al. (2000) found that the harvest index of corn is affected by water stress when the stress occurred at flowering and that yields are significantly reduced. These findings support the data for the 2016 yield response where the 100% treatment was fully irrigated early on but in an effort to prevent over irrigation of the 75% we did not fully irrigate during reproductive stage and therefore yield was limited in the 100%. In contrast, the 75% was sufficiently stressed early in the season and the canopy size restrictions reduced ET, and water stress on the smaller plants allowing it to apply energy into making grain and producing yields comparable to the 100% irrigation.

Table 2: Type III tests of fixed effects of treatment (Trt), irrigation (Irr), and year for corn grain yield

Effect	Num DF	Den DF	F Value	Pr > F
Trt	4	44.68	1.37	0.259
Irr	2	50.15	255.04	<.0001
Trt*Trr	8	57.84	1.05	0.4119
Year	2	50.47	338.93	<.0001
Year*Trt	8	57.73	1.21	0.311
Year*Irr	4	40.91	12.98	<.0001
Year*Trt*Irr	16	54.97	0.86	0.6129

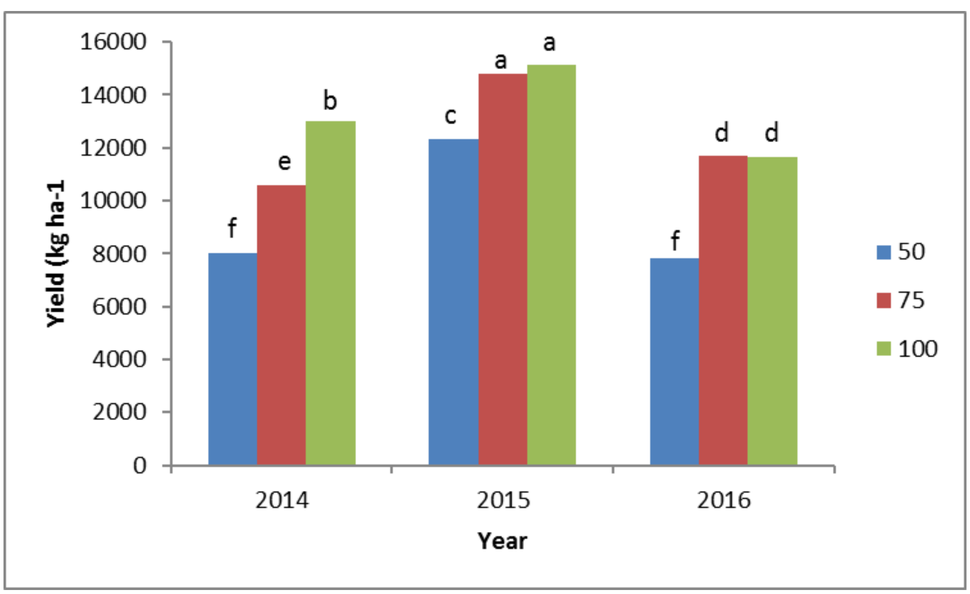

Figure 3: corn grain yield averaged across treatments for each irrigation rate and year. Yields with the same letter are not significantly different at the 0.05 probability level.

Table 3: Monthly Rainfall Totals for April- October with 15-year Average

Month	2014	2015	2016	15 year avg.
	-------------------cm--------------------			
April	1.19	4.75	9.6	2.3
May	8.68	16.18	3.55	4.72
June	9.47	4.64	6.02	5.76
July	7.36	10.43	4.21	5.28
August	2.46	8.17	8.3	6.4
September	4.14	3.35	.15	3.25
October	3.5	13.05	1.52	4.13
Totals	36.8	60.6	33.35	31.84

Table 4 shows the yields resulting from the offset treatments averaged across years for the three irrigation rates. As mentioned above, there are no significant differences resulting from offsets within any irrigation regime. However, it is noteworthy that at the 50% irrigation rate yields were 10% lower at the 38 cm offset as compared to 0 cm offset. Furthermore, it is noteworthy that the offset treatments did influence the distribution of yield between the two rows harvested (Table 5). Specifically, at 0cm offsets 50% of the yield was harvested in the north row. However, as this row moved closer to the tape, the percentage of yield it produced increased to 59% in 2016. This is similar to the observations made by Bordovsky et al. (2010) when irrigating cotton with rows offset from equidistance from the tape. Specifically, they found at limited irrigation, rows that moved closer to the tape showed an increase in yield while the rows moving further away produced a declining yield. However, unlike the data collected by Bordovsky et al. (2010) the corn and grain sorghum yields were unaffected by driver accuracy at full irrigation.

Table 4: Corn grain yields averaged across years from different offsets within each irrigation regime

Offset	50%	75%	100%
cm	--------------------kg ha^{-1}--------------		
0	9865	12291	13280
8	9972	13087	13151
15	9701	12474	13026
23	8985	12394	13228
38	8901	12302	13420

†means followed by the same letter or no letter are not significantly different at the 0.05 probability level

Table 5: Percentage of corn yield produced by the north row.

Offset	2015	2016
cm	--------%---------	
0	51	50a†
8	50	50a
15	51	53a
23	51	53a
38	53	59b

†means followed by the same letter or no letter are not significantly different at the 0.05 probability level

Grain Sorghum Yield

Analysis of variance for the grain sorghum yields resulted in the same outcome as was observed in the corn with no treatment affect and a significant year by irrigation interaction (Table 6). Figure 4 shows that in 2014, the 75% and 100% irrigation regime were higher than the 50%, but that in 2015 and 2016 there was no differences among the irrigation regimes. The lack of yield differences among irrigation regimes in 2015 are apparently in part due to over estimation of ET for grain sorghum as well as over estimation of runoff and drainage as was discussed previously with the corn yield data. Furthermore, there is very limited data available in the literature to validate the ET estimates used by Aquaplanner and the Mesonet software. Similar research conducted at the OPREC research station also showed that grain sorghum produced under limited water conditions was able to extract soil moisture to depths greater than expected prior to the establishment of this study which presented additional challenges (Gatlin et al 2014). Specifically, early season water stress in the limited irrigation regimes (50% and 75%), allowed for more effective rooting and subsoil water extraction. This combined with timely rainfall allowed for comparable yields to the fully irrigated regime, which apparently received excess irrigation due to over estimation of ET. In 2016, these challenges were exacerbated by the fact that grain sorghum in the 100% irrigation regime was later maturing which caused it to be more susceptible to bird damage and sugar cane aphid pressure, explaining why yields were numerically lower than the limited irrigation regimes.

Table 7 shows than not only were there no significant differences between treatments there was very limited numeric difference. Similar to the corn yield distribution between rows, the yield in the northern grain sorghum row increased when it was moved closer to the tape (Table 8).

Table 6: Type III tests of fixed effects of treatment (Trt), irrigation (Irr), and year for grain sorghum yield

Effect	Num DF	Den DF	F Value	Pr > F
Trt	4	51.81	1.07	0.3824
Irr	2	48.89	13.25	<.0001
Trt*Trr	8	57.59	0.71	0.6809
Year	2	64.2	83.6	<.0001
Year*Trt	8	54.89	0.46	0.8819
Year*Irr	4	37.67	9.64	<.0001
Year*Trt*Irr	16	50.79	0.44	0.962

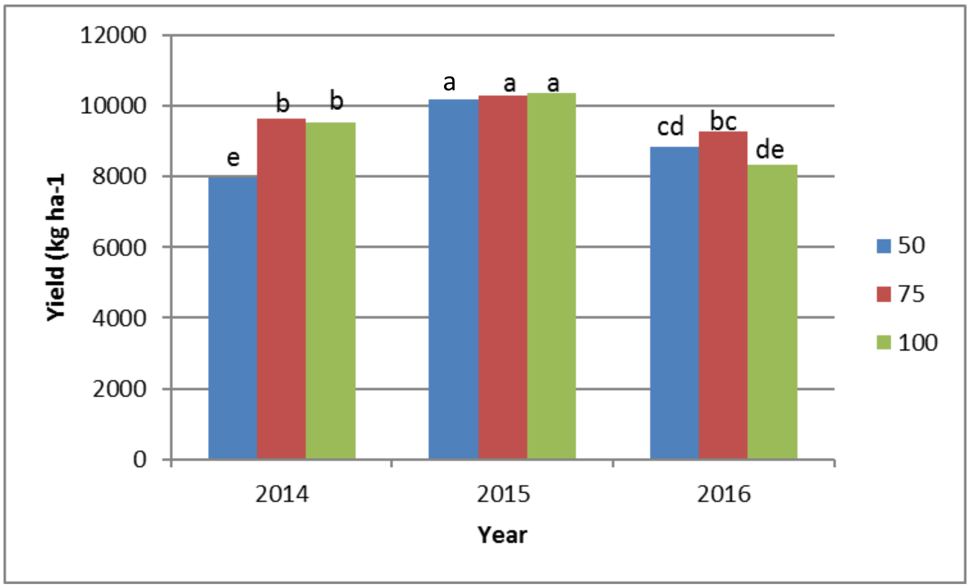

Figure 4: Grain sorghum yield averaged across treatments for each irrigation rate and year. Yields with the same letter are not significantly different at the 0.05 probability level.

Table 7: Sorghum yields averaged across years from different offsets within each irrigation regime

Offset	50%	75%	100%
Inches	--------------------Bu acre^{-1}--------------		
0	8889	9608	9593
8	9126	10003	9444
15	8980	9897	9620
23	9371	9692	9171
38	9055	9498	9175

†means followed by the same letter or no letter are not significantly different at the 0.05 probability level

Table 8: Percentage of grain sorghum yield produced by the north row.

Offset	Yield in N Row
cm	%
0	51a†
8	53ab
15	53a
23	54a
38	54a

†means followed by the same letter or no letter are not significantly different at the 0.05 probability level

Wheat Yields:

When wheat yields were pooled across variety and irrigation treatment a significant different was found between row configurations (Table 9). Specifically, the wheat planted in a solid stand resulted in a significantly higher yield than the 2 skip row treatments with the treatments with 2 rows removed from the dry area between drip tapes having the lowest yield.

Table 9: Wheat yields resulting from planting treatments presented in figure 2 when averaged across irrigation treatments and varieties

planting treatment	yield (kg/ha)
solid	4599a
skip 1 row	3994b
Skip 2 rows	3639c

Relationships between soil moisture and Yield

Figure 5 shows the relationship between 60 day average volumetric soil water content measured at a depth of 12-16 inches in the south rows of corn and sorghum in treatments with offsets of 0, 6 and 15 inches (sensors and crop rows were 15, 21 or 30 inches away from drip tape). This data demonstrates that corn grain yields are more sensitive to surface soil moisture than grain sorghum. This is somewhat contradictory to the observation that sorghum yields were more sensitive to row distance from drip tape. However, the strong correlations between VWC and corn yield in figure 5 can be explained by the substantial differences in corn yield between irrigation regimes. Specifically, the average corn yields were 129, 168 and 207, for the 50, 75, and 100% irrigation regimes, respectively. In contrast, the sorghum yields were 127, 153, and 152 bushels/acre, for the 50, 75, and 100% irrigation regimes, respectively. Although single row sorghum yields within an irrigation regime were sensitive to distance to the drip tape (Figure 4), the relationship in figure 5 is stronger for corn because of greater differences in corn yield between the three irrigation regimes.

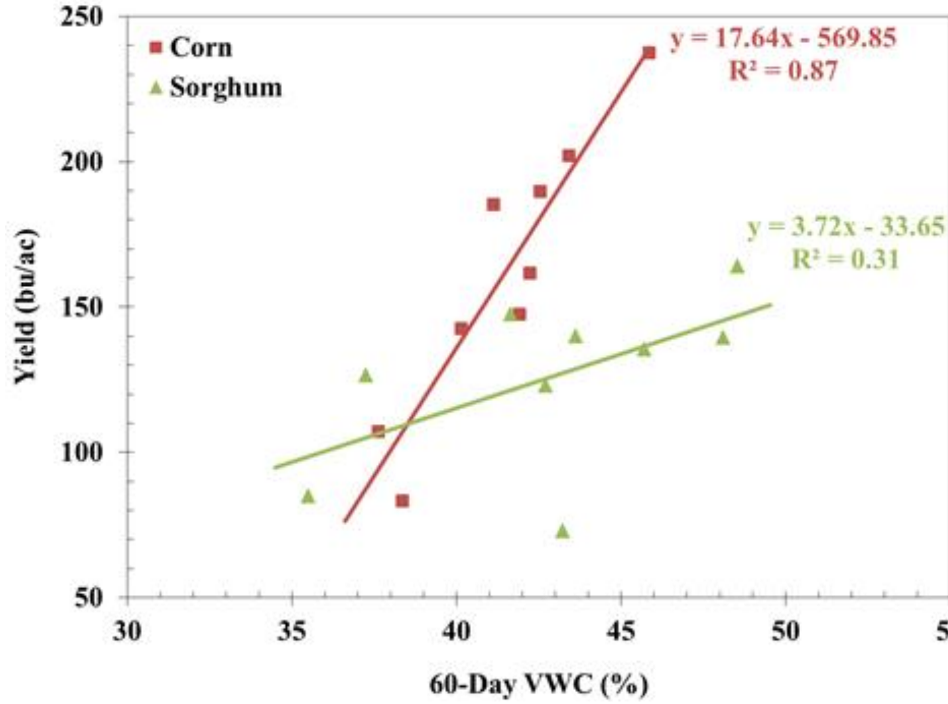

Figure 5: the relationship between yield observed in the south rows and the volumetric water content (VWC) measure within the south rows at 6 inches below the soil surface. The VWC data were averaged over a 2-month period which was Jul 9 to Sep 7 for corn and Jul 18 to Sep 15 for sorghum.

Stress indexes using Canopy Temperature

Time-Temperature Threshold (TTT)

Excluding the days when TTT was zero, the 2-month daily average TTT was 426, 419, and 447 minutes for 100%, 75%, and 50% irrigated corn, respectively (Figure 6). These values are similar to the 443 and 461 minutes estimates for 100% and 67% total ET replacement irrigation levels reported by Wanjura and Upchurch (2000). The maximum corn TTT was 660 minutes (11 hours), estimated on July 26th at both deficit irrigation levels.

Other studies have reported smaller TTT values for similar irrigation levels of corn. But this is mainly due to the fact that these studies used a larger solar radiation threshold in filtering TTT values, thus integrating the results over a shorter period of the day (mostly afternoons). For sorghum, the average TTT was 324, 336, and 428 minutes for 100%, 75%, and 50% irrigation levels, respectively (Figure 7). The larger inter-treatment TTT difference for sorghum compared to corn could be attributed to larger water application and soil moisture difference for the sorghum. It may also indicate that this threshold is more sensitive for sorghum. The maximum TTT was 660 minutes at 50% irrigation level, measured on Sep. 3rd, 2014, when air temperature reached 37.2 °C (RH was 19%).

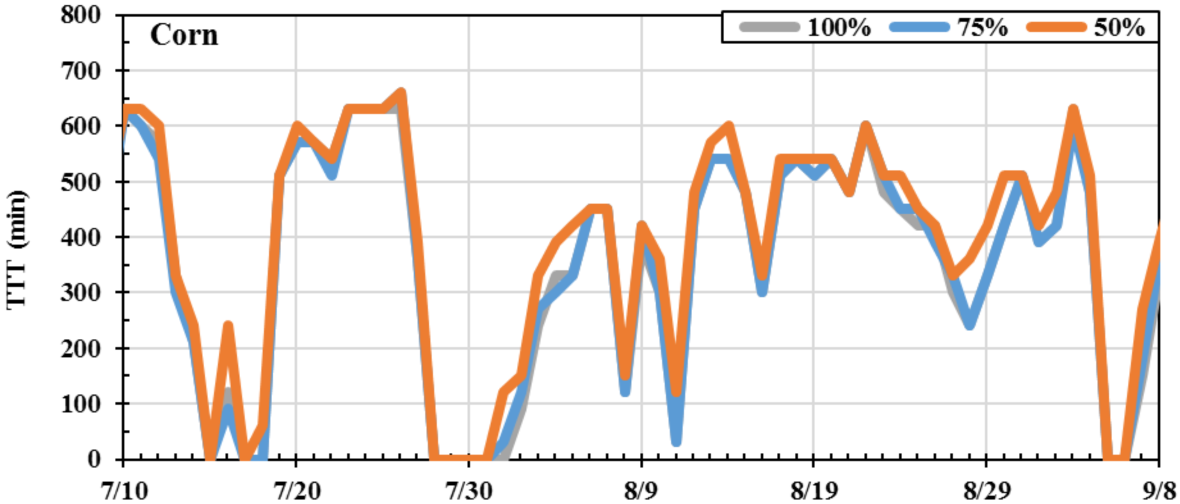

Figure 6: The time-temperature threshold for corn in the 100, 75, and 50% irrigation regimes.

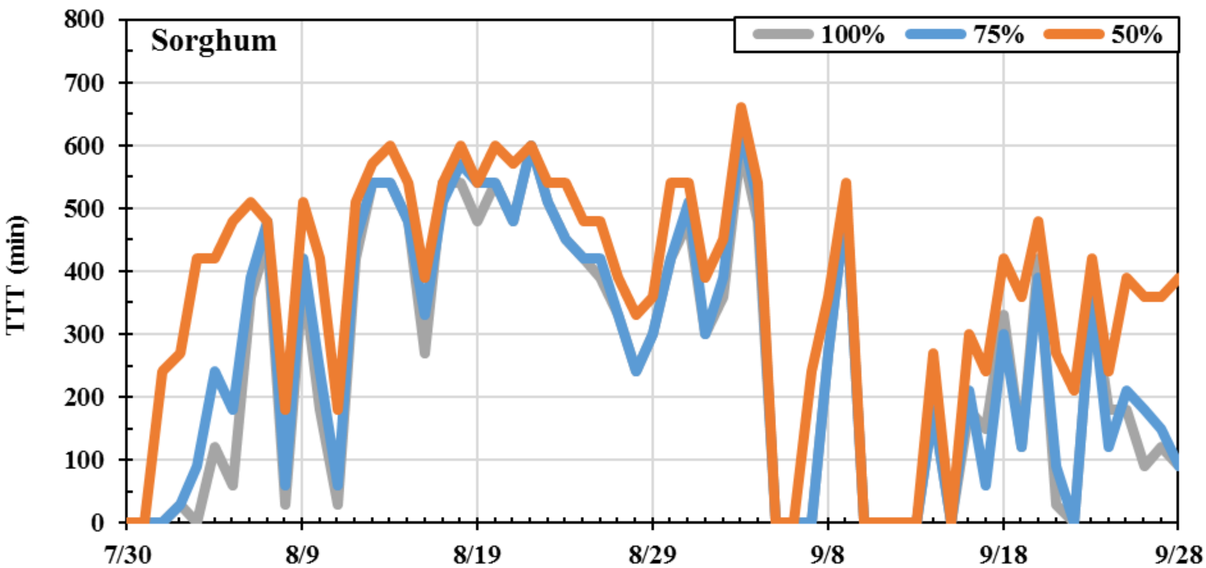

Figure 7: The time-temperature threshold for sorghum in the 100, 75, and 50% irrigation regimes.

Degrees Above Non-Stressed (DANS)

The 60-day average DANS was -0.1 and 1.4 °C for 75% and 50% irrigated corn, respectively. The average values were larger at 0.2 and 2.4 °C for the same irrigation levels of sorghum. The maximum DANS was 3.9 and 4.8 °C for corn and sorghum.

Figures 8 and 9 represent daily variations in DANS for the canopy temperature measurements made during 1300-1400 hr. To assist with interpreting DANS dynamics (solid lines), the relative Volumetric Water Content (VWC) is also graphed in dashed lines for each irrigation treatment.

In case of corn, DANS had a rapid decline on Aug 27th, when 23 mm of rainfall was recorded by the adjacent weather station. This event was followed by another 36 mm of rain that fell during the next two days.

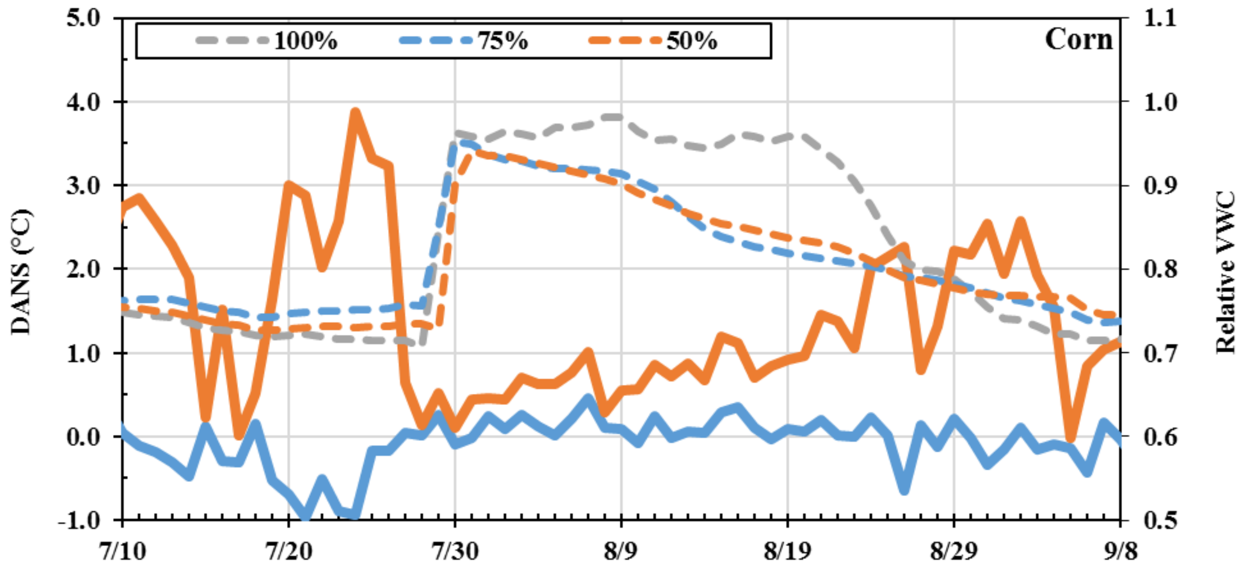

Figure 8: Daily variations in DANS for the corn canopy temperature measurements made during 1300-1400 hr

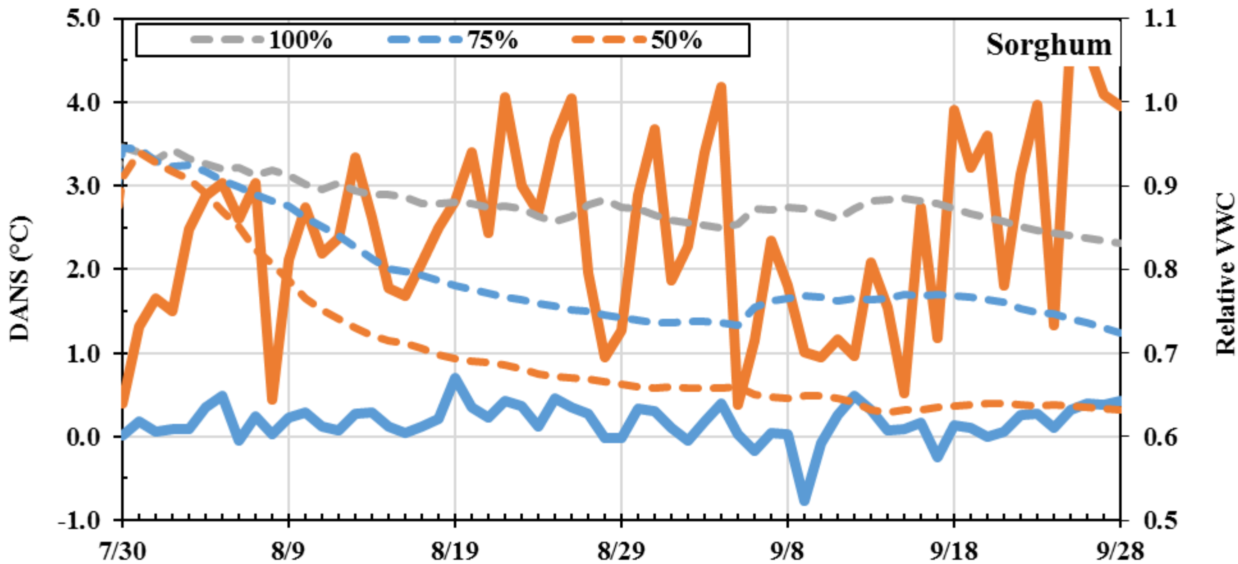

Figure 9: Daily variations in DANS for the Sorghum canopy temperature measurements made during 1300-1400 hr

Canopy Temperature ratio

The canopy temperature ratio had a small range of 0.99-1.03 for 75% irrigated corn, with an average of unity (Figure 10). The range was larger for 50% irrigated corn at 0.90-1.00, (average 0.96). For sorghum, the range was 0.95-1.02 and 0.85-0.98 for 75% and 50% irrigations, respectively (Figure 11). The average Tc ratio was 0.99 and 0.92 for the same two irrigation treatments.

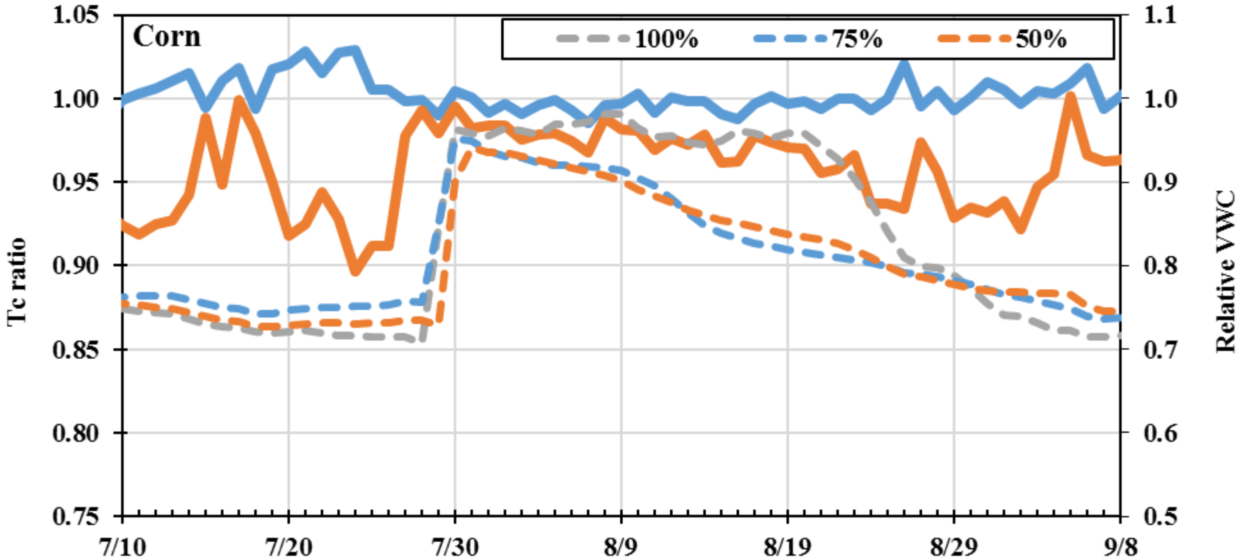

Figure 10: Daily variations in the temperature ratio for the corn canopy temperatures

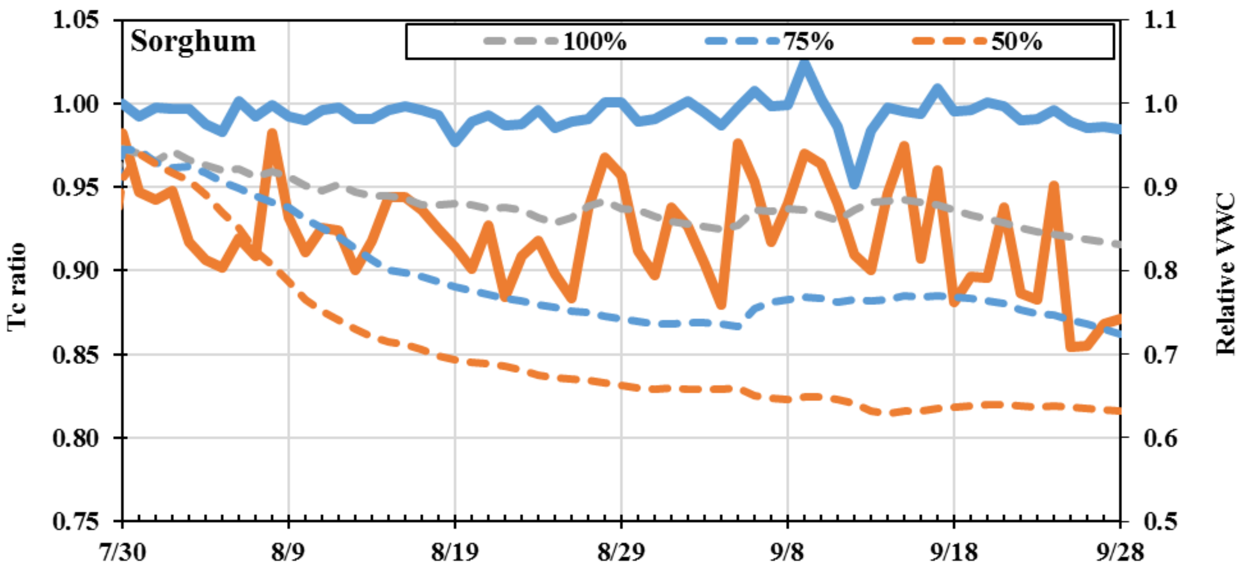

Figure 11: Daily variations in the temperature ratio for the grain sorghum canopy temperatures

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Project Title: Ogallala Aquifer Irrigation Sustainability Study

Investigator(s): Dr. Robert Scott Frazier (PI), Associate Professor, Oklahoma State University Department of Biosystems and Agricultural Engineering (BAE), 212 Ag Hall, Stillwater, OK 74078. Dr. Saleh Taghvaeian (BAE), Dr. Jason Warren (PSS), Mr. Cameron Murley (FRSU, Panhandle Research and Extension Center-Goodwell)

Goal: To determine the overall efficiency and effectiveness of energy and water usage from the Ogallala underground aquifer to application to the soil for irrigation in the Panhandle and Western Oklahoma in order to minimize aquifer degradation. The project also examines important irrigation areas such as irrigation operations costs along with recommendations.

Problem and Research Objectives:

Agricultural production in the arid Oklahoma Panhandle relies on the availability of water in the Ogallala (High Plains) aquifer. Since about 1950 and the advent of pressurized irrigation systems, this water supply has been depleted at an alarming rate. In some areas the water table has dropped over 150 feet (USGS 2008). Preliminary discussions with area extension personnel indicate many panhandle irrigation systems are very inefficient and being shut down due to poor performance. Current total aquifer discharge rates are about twice the charge rates. If the discharge rates were lowered by decreasing the inefficient use of water, the Ogallala resource could be extended. Given that this precious resource is threatened, we should make all attempts to assure that irrigation in this geographic area is as effective and efficient (sustainable) as possible.

According to USDA-NASS Farm and Ranch Irrigation Survey (2008), irrigated agriculture in Oklahoma rely heavily on groundwater resources, extracted using 3,727 irrigation wells. Pumping groundwater resources requires large amounts of energy, which impose significant costs to irrigated farmers. In 2008, for example, Oklahoma producers spent over 32 million dollars in energy expense for pumping irrigation water. The energy expense of operating an irrigation system is inversely related to the efficiency of its pumping plant and can easily exceed 50% of the selling price of the crop in some instances MSSOY (2014). Hence, significant savings can be made by identifying existing inefficiencies and providing recommendations on how to minimize them. This is especially the case since pumping plant efficiency is often far from what is claimed by equipment manufacturers due to major differences between actual groundwater levels and field conditions and those under which manufacturers estimate pump efficiency. In California, for example, Burt (2011) conducted tests on 12,876 electric pumps and found an average efficiency of 56%, far from 80-95% claimed by electric pump manufacturers. In state of Oklahoma electric pumps provide water to 27% of all irrigated acres. Half of Oklahoma irrigated lands receive water from pumping plants that run on natural gas, with a claimed total system efficiency of only 23% (Kenny 2013). A comprehensive efficiency evaluation project conducted in 25 counties in Texas found that actual efficiencies varied from 7.5% to 17.9% for natural gas pumping plants, with an average value of 13.1% (Fipps & Neal 1995). These dismal numbers point to significant opportunities for improvement.

Given the large amount of energy expenses paid by Oklahoma producers, improving pumping plant efficiency by even small percentages can free a significant amount of financial resources that can be used toward other purposes such as the implementation of smart technologies (sensors, computer models, etc.) to improve agricultural water management. In times when severe droughts and declining Ogallala water levels threatens the sustainability of agricultural production in Oklahoma Panhandle, evaluating and improving pumping plant efficiency is a high-priority necessity, not just a research project.

In addition to the low efficiency of getting the water out of the ground and out to the application nozzles, there is considerable waste in getting the water to the plant root system. About 84% of all irrigated lands in Oklahoma are under sprinkler irrigation systems. This percentage is higher in the Panhandle region, where groundwater is the main source of irrigation water. Out of several different types of sprinkler systems, center pivot systems (circles) are the leading type in Oklahoma, accounting for 95% of all sprinkler-irrigated farmlands. From their invention in early 1950s, center pivot systems have come a long way in terms of technological advances to minimize water losses and improve water application/conveyance efficiencies. Early center pivots had impact sprinklers that were placed on the top of the main line, shooting water into the air across the field at a high pressure (60 psi and above). As a result, a large portion of applied water was lost to wind drift and droplet evaporation. Previous studies have showed that this lost portion could easily reach one-third of applied water on hot, windy days (Keller & Bliesner 1990). The loss of water would be larger as atmospheric conditions become extremely dry and windy. Lyle & Bordovsky (1981) reported a loss of 94% of applied water on a day with average wind speed of 22 mph in the Southern High Plains of Texas. Newer center pivots have spray applicators that are placed at lower elevations and operate on a lower pressure (30 psi or less), thus being less impacted by weather conditions. However, wind drift and droplet evaporation losses from these new models could still reach 10% or more of total applied water (Keller & Bliesner 1990). In addition, leaks from joints and fittings could significantly add to water losses.

Our study aimed to address these issues while providing useful solutions to stakeholders. The project goal was to determine the overall efficiency and effectiveness of energy and water usage from the Ogallala underground aquifer to application to the soil for irrigation in the Panhandle and Western Oklahoma in order to minimize aquifer degradation. The project also examined important irrigation areas such as irrigation operations costs along with specific recommendations for participating producers and general recommendations for extension programs.

Methodology:

This project was conducted on a sample of ten different center pivot locations reflecting the diversity of existing systems. In order to measure overall efficiency, the irrigation system was divided into three subsystems: the engine/motor, the pumping station (transferring water from the aquifer to the center pivot) and the center pivot (transferring water from the pivot point to crop root zone). Each subsystem was tested separately and together.

The efficiency of the system engine/motor was directly measured via electrical or fuel inputs via wattmeter and fuel flow loggers. Simultaneously the output shaft power was monitored with a load cell dynamometer and recorded (Eaton Mod 7530 and transducer). The energy input versus the shaft power output gave the efficiency of the driver (motor/engine). The pump efficiency was measured via flow, head and power input measurements. Finally, the water delivery subsystem (pivot) was tested and observed. Water losses from the pivot point (pump outlet) to the soil at plant level were measured under variable climatic conditions (wind speed, relative humidity, etc.). The head measurement also gave the aquifer water table level at the time. The output horsepower from the engine or motor also served as the input horsepower to the pump and was used to evaluate the combined pump and well efficiency. The required horsepower for a pump during any given pumping condition was calculated using the water horsepower equation based on water flow, pumping depth, water pressure and well column friction.

The overall efficiency of a pumping plant is the ratio of the water horsepower to the potential energy. This can be calculated by multiplying the engine efficiency and the pump/well efficiency or it can be figured directly. The overall efficiency typically is calculated in cases where a torque cell is not available or not able to be installed.

These studies gave the overall energy and water delivery efficiency of the entire center pivot pump system. In addition, the life cycle assessment of the system reported greenhouse gases (GHG) and other emissions. Additionally, water usage, local water supply and ecosystem impacts and other life cycle impacts were measured and reported. Areas for suggested improvement were also identified and quantified. Although this study targeted the users of the Ogallala aquifer, the results provide useful information for other parts of the state, since center pivots in the Panhandle region are similar to those in operation in other areas.

Principal Findings and Significance:
The tests were conducted on ten selected center pivot sites (Table 1) in the Oklahoma Panhandle (Ogallala Aquifer region).

Table 1. Selected Ogallala Irrigation Center Pivot Test Sites

Site No.	Site	Power	County	Depth to water
1	NG 1	Natural gas	Texas	222.4 ft
2	NG 2	Natural gas	Texas	278.0 ft
3	ELECT 1	Electricity	Beaver	15.4 ft
4	ELECT 2	Electricity	Beaver	10.8 ft
5	ELECT 3	Electricity	Beaver	10.4 ft
6	ELECT 4	Electricity	Beaver	27.4 ft
7	ELECT 5	Electricity	Beaver	17.5 ft
8	ELECT 6	Electricity	Beaver	20.2 ft
9	ELECT 7	Electricity	Beaver	10.4 ft
10	ELECT 8	Electricity	Beaver	27.4 ft

Irrigation Uniformity and Water Conveyance Efficiency

This irrigation efficiency study was unique in that it measured both irrigation energy and water efficiency. The study measured both the amount of pumped water delivered via the spray nozzles and the relative uniformity of this application. Irrigation uniformity was evaluated based on the readings from catch cans placed under the irrigation boom/nozzles. Two commonly-used indicators besides water delivery efficiency are

Christiansen's Uniformity (UC) and Distribution Uniformity (DU) and these were reported in this project.

Catch cans were placed across the irrigated area on 10 or 20 ft spacing to collect applied water and estimate distribution uniformity.

$$UC = 1 - \frac{Average\ absolute\ deviation\ from\ mean\ catch\ can\ readings}{Mean\ catch\ can\ readings}$$

$$DU = \frac{Average\ of\ the\ lowest\ quarter\ of\ catch\ can\ readings}{Mean\ catch\ can\ readings}$$

$$Efficiency = \frac{Volume\ of\ water\ that\ reached\ soil\ surface}{Volume\ of\ water\ discharged\ at\ pump\ outlet}$$

Irrigation uniformity indicators and irrigation water conveyance efficiency are demonstrated below for a system with poor uniformity (Figure 1) and a better uniformity system (Figure 2). Note that the water conveyance efficiency is not that bad in the former but the uniformity is not good.

Site: NG 2; Pivot radius: 1260 ft
UC: 31% DU: 14% Efficiency: 83%

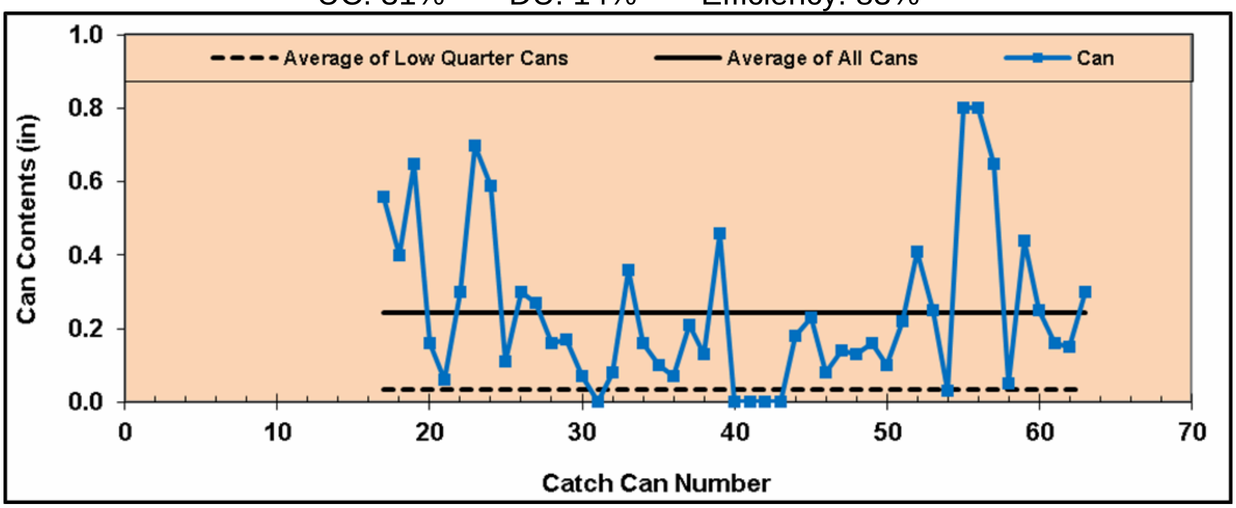

Figure 1: Example of poor uniformity in tested Ogallala irrigation system

Site: ELECT 5; Pivot radius: 640 ft
UC: 76% DU: 69% Efficiency: 93%

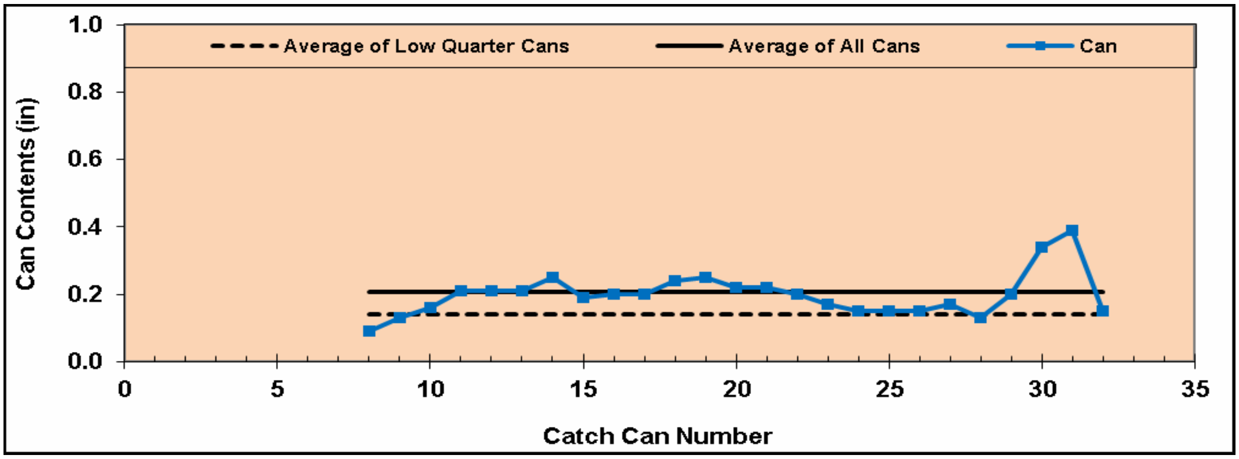

Figure 2: Example of acceptable uniformity in tested Ogallala irrigation system

Energy Efficiency

Ten wells were tested including two natural gas and eight electric systems. The overall efficiency of the natural gas systems tested was much lower than the electric systems. Part of this is due to the nature of electrical versus fuel efficiency reporting. If we include the electric generation plants the reported efficiency for electrical systems would drop considerably. This project used comparison criteria that take this into account.

Nearly all of the inefficiency of the internal combustion engines was due to the aging equipment since the pump efficiencies for all systems were surprisingly similar. Using the Nebraska Pumping Plant Performance Criteria (NPPPC) [UGA, 2016] we could compare the measured energy efficiency to an accepted standard (See Table 2). The standard efficiency assumes a well-designed and maintained pumping plant.

Table 2: Fuel and Electrical Pumping Performance Per Nebraska Pumping Plant Performance Criteria (NPPPC) Ref (UGA)

Energy Source	Average Energy Content		Nebraska Pumping Plant Performance Criteria		Engine or Motor Efficiency %	Pumping Plant Conversion %
	BTU	Horsepower hour	Engine or Motor Performance hp-hr/unit	Pumping Plant Performance whp-hr/unit †		
1 gallon of diesel fuel	138,690	54.5	16.7	12.5	31	23
1 gallon of gasoline	125,000	49.1	11.5	8.66	23	18
1 gallon of liquefied petroleum gas (LPG)	95,475	37.5	9.20	6.89	25	18
1 thousand cubic foot of natural gas		401	82.2	61.7	21	15
1 therm of natural gas	100,000	39.3	8.06	6.05	21	15
1 gallon of ethanol ±	84,400	33.2	7.80	5.85	X	X
1 gallon of gasohol (10% ethanol, 90%	0.70 to 0.80					
1 kilowatt-hour of electrical energy	3,412	1.34	1.18	0.885	88	66

Table 1: Energy Content of Fuels for Powering Irrigation Engines
Conversions: 1 horsepower = 0.746 kilowatts, 1 kilowatt-hour = 3412 BTU, 1 horsepower-hour = 2,544 BTU
† Assumes an overall efficiency of 75% for the pump and drive.
± Nebraska Pumping Plant Criteria for fuels containing ethanol were estimated based on the BTU content of ethanol and the performance of gasoline engines. Source: Martin, et al. 23rd Annual Central Plains Irrigation Conference, 2011

The following charts (Figs 3-5) demonstrate the calculated pump efficiency (%), the overall plant efficiency (%), the percent overall efficiency compared to NPPPC, and the potential reduction (%) for all tested systems. The "potential reduction" in Figure 6 is the estimated amount of energy savings possible if the inefficient system were operating at the NPPPC (criteria) efficiency.

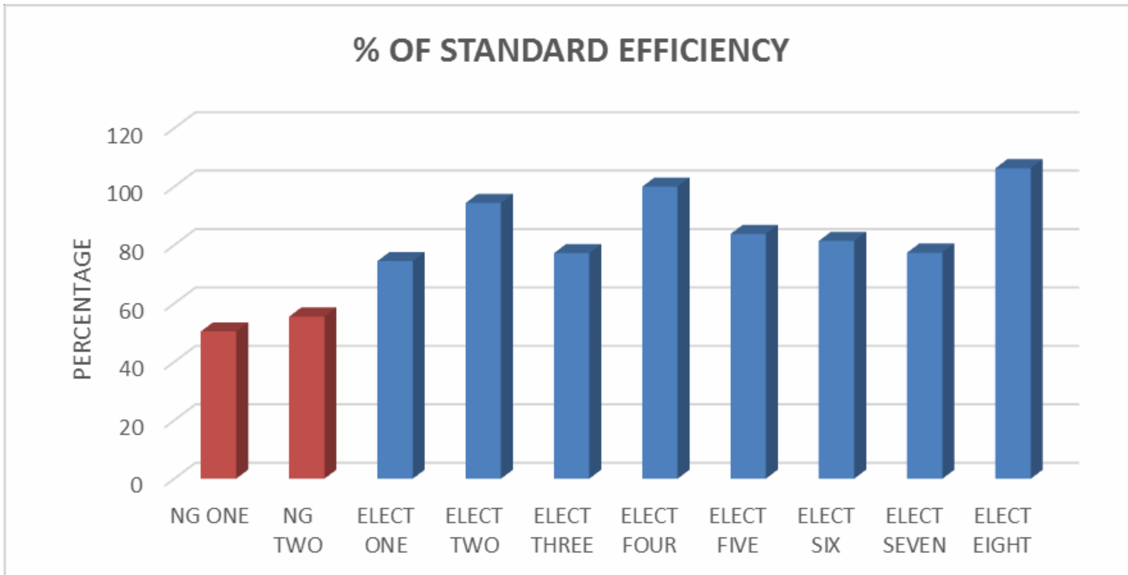

Figure 3. Percent of standard efficiency of only the pump unit

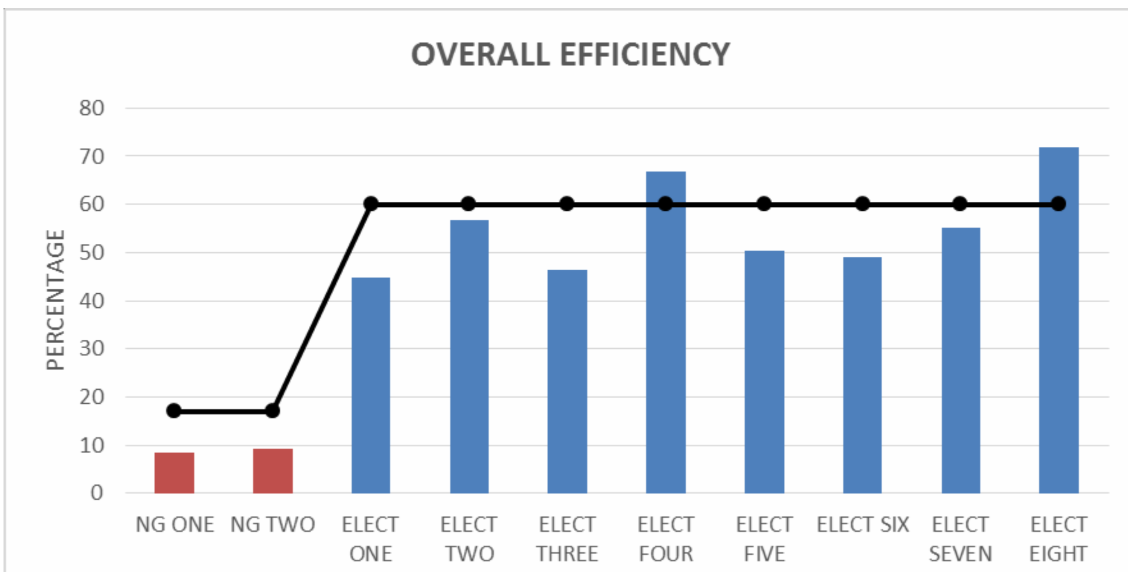

Figure 4. Overall efficiency of the plant and pump compared to NPPPC acceptable efficiency (black line)

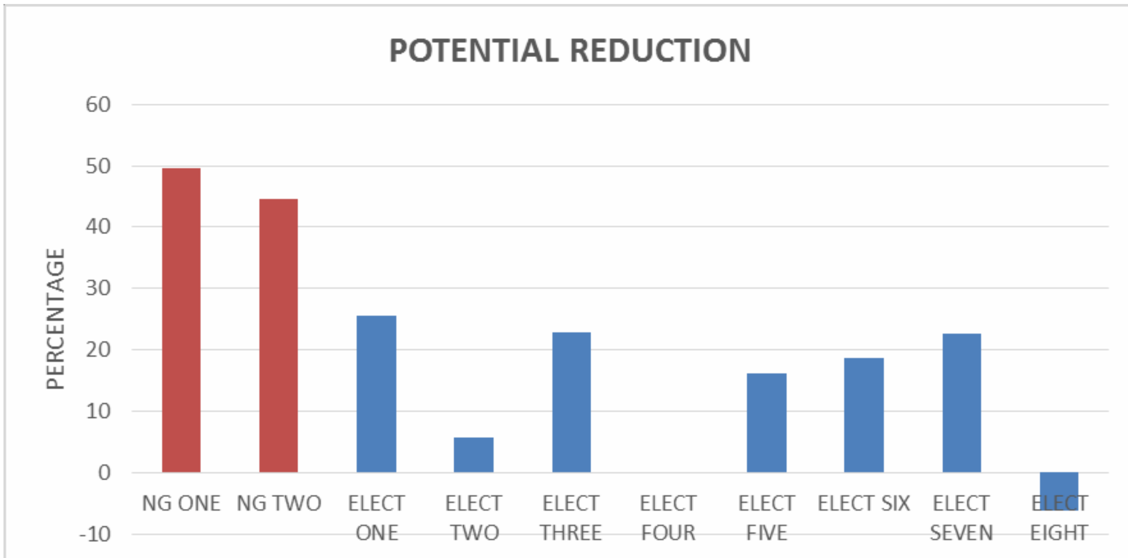

Figure 5. Percentage reduction in energy and cost from bringing systems to NCCCP efficiency recommendations

<u>Economics of Improving Irrigation Efficiency</u>

If the producer were able to improve the efficiency of the energy use (NG and Electricity) to the recommended NPPPC standards, the cost to irrigate would be lowered in all tested cases except one. Table 3. below shows the projected savings in dollars per 1,000 hours run time (season) for the ten systems examined. Further cost reduction may be possible by improving the water conveyance efficiency discussed below.

Table 3: Economics of Current Operations and Cost Reduction Possibilities from Improvements

Producer	Fuel Consumption (ft^3/hr)	Input HP	Potential energy reduction	Seasonal run time (hours)	Total seasonal power savings (ft^3/yr)	Total seasonal power savings (MMBtu/yr)	Total seasonal power savings (mJ/yr)	Total seasonal cost savings @ $5/MMBtu
1	1181.3	464.2	0.496	1000	585924.8	585.9	618185.8	$2,930
2	1335.7	524.9	0.445	1000	594386.5	594.4	627113.4	$2,972

Producer	Input Power (kW/hr)	Input HP	Potential energy reduction	Seasonal run time (hours)	Total seasonal energy savings (kWh/yr)	Total seasonal cost savings @ $0.11/kWh
3	10.25	13.74	0.16	1000	1640	$180
4	22.5	30.2	0.19	1000	4275	$470
5	27.2	36.5	0.26	1000	7072	$778
6	27.5	36.8	0.06	1000	1650	$182
7	35.4	47.4	0.23	1000	8142	$896
8	38.9	52.1	-0.11	1000	NA	NA

Water Distribution Efficiency and Effectiveness

The ‘water application at distances from the pivot’ figures graphically show how well, or uniform, the water is being delivered to the ground (Figures 6, 7, 8, 9, and 10). The statistical uniformity is shown by using the accepted Distribution and Christiansen Uniformity coefficients (DU, CU). In general, the DU (and CU to a lesser extent) shows us how uniform the center pivot applies water to ground level as the boom passes along the ground with the nozzles spraying (see Tables 4, 6, 8, 10, 12).

These are several points of interest in the results of these water distribution studies: Is the average amount supplied to the ground of the correct quantity? And, how uniform is this water application? Examination of Figure 9 and Tables 8 & 9 shows a widely varying application of water from one end of the spray boom to the other. In some cases there is no water reaching the ground (clogged nozzles) and on other sections an excess of water. This leads to poor consistency in crop production. This may also cause producers to increase the flow and pressure to make up for the variability in the application. This, of course, is the worst thing to do from an aquifer conservation and energy minimization point of view – however, we see some evidence of this in the higher than needed pressures and flow rates employed by some producers.

The water conveyance efficiency (Tables 5, 7, 9, 11, 13) shows the calculated amount of water (total) being delivered to the ground. A value of 100% indicates that all of the water leaving the pump is being delivered to the ground (plant base). Values less than 100% are typically due to leaks in the distribution piping.

An example of the combined energy/water study is examining the possible inter-dependence between energy and water use. In the case of Natural Gas site #2, the energy efficiency of the plant is a rather low at about 45% of nominal efficiency (old detuned engine). Yet, the water conveyance efficiency is very good at 100% and the DU is acceptable at 85%. In this case the water delivery system appears to be adequate. However, for the *water applied* – the energy use is excessive. Improvements on this site should obviously first focus on the power-plant (NG engine).

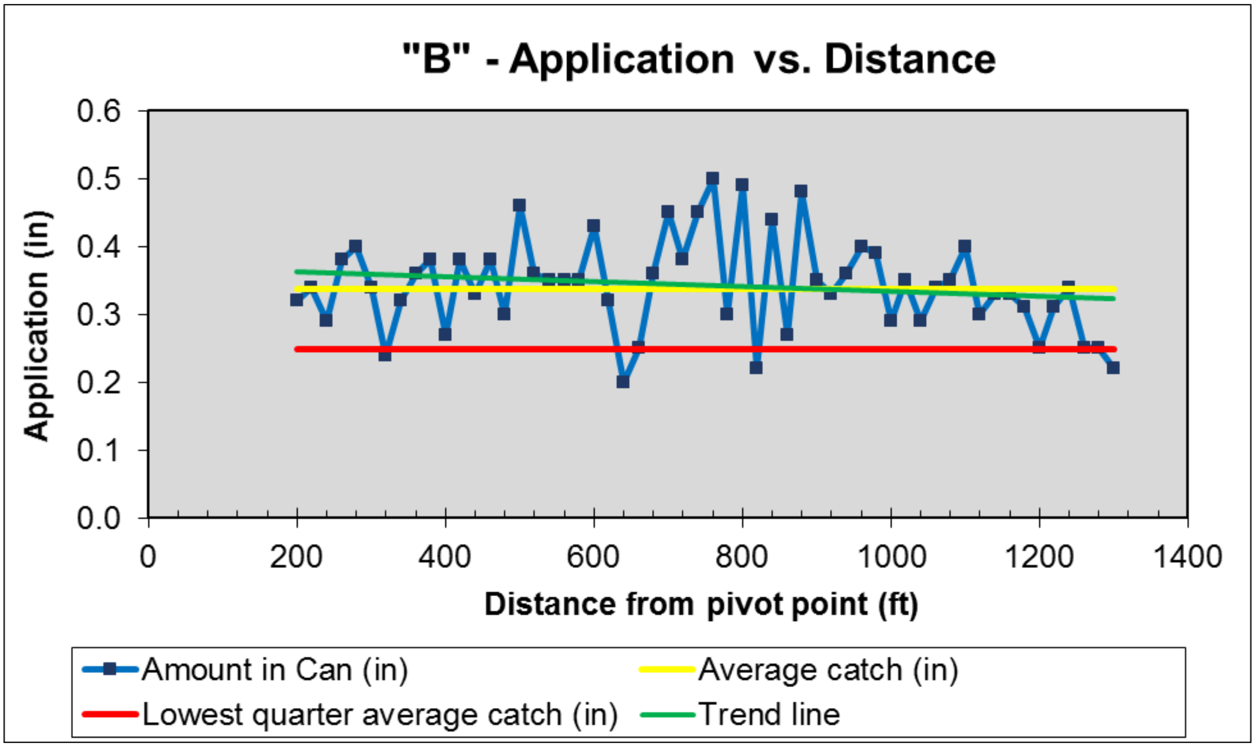

Figure 6: Water application amount at distances from pivot

Table 4: Uniformity Coefficients

Sum of lowest quarter weighted catches	90
Sum of lowest quarter used can numbers	362
Lowest quarter average catch (in)	0.25
Distribution Uniformity - DU_{lq}	**73%**
Sum of absolute value of diff from avg catch	115.00
Christiansen Uniformity - CU	**84%**

Table 5

Pivot Settings and Water Conveyance Efficiency

Pivot Wetted Radius (ft)	1290
Inflow Rate (gpm)	817
% Setting During Eval.	75
Fraction of Full Circle %	100
Conveyance Efficiency	**99.7%**

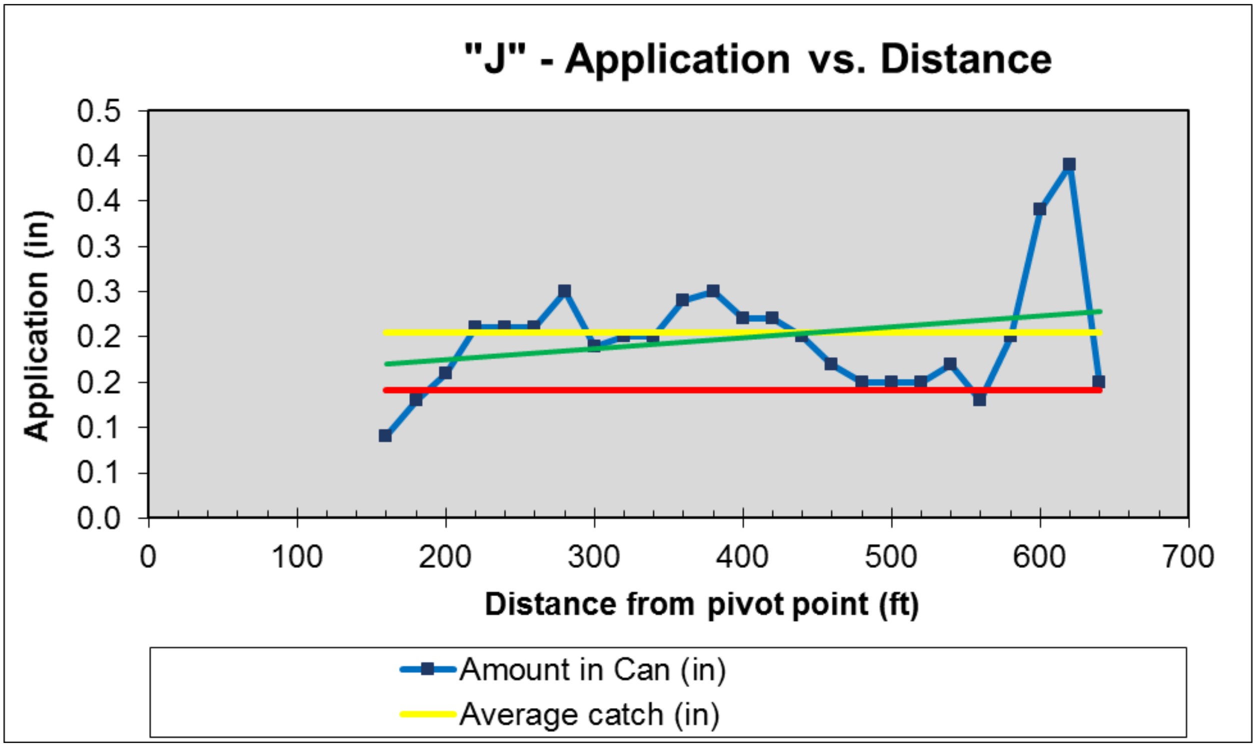

Figure 7: Water application amount at distances from pivot

Table 6: **Uniformity Coefficients**

Sum of lowest quarter weighted catches	14
Sum of lowest quarter used can numbers	98
Lowest quarter average catch (in)	0.14
Distribution Uniformity - DU_{lq}	**69%**
Sum of absolute value of diff from avg	25.19
Christiansen Uniformity - CU	**75%**

Table 7:

Pivot Settings and Water Conveyance Efficiency

Pivot Wetted Radius (ft)	640
Inflow Rate (gpm)	300
% Setting During Eval.	20
Fraction of Full Circle %	100
Conveyance Efficiency	**92.9%**

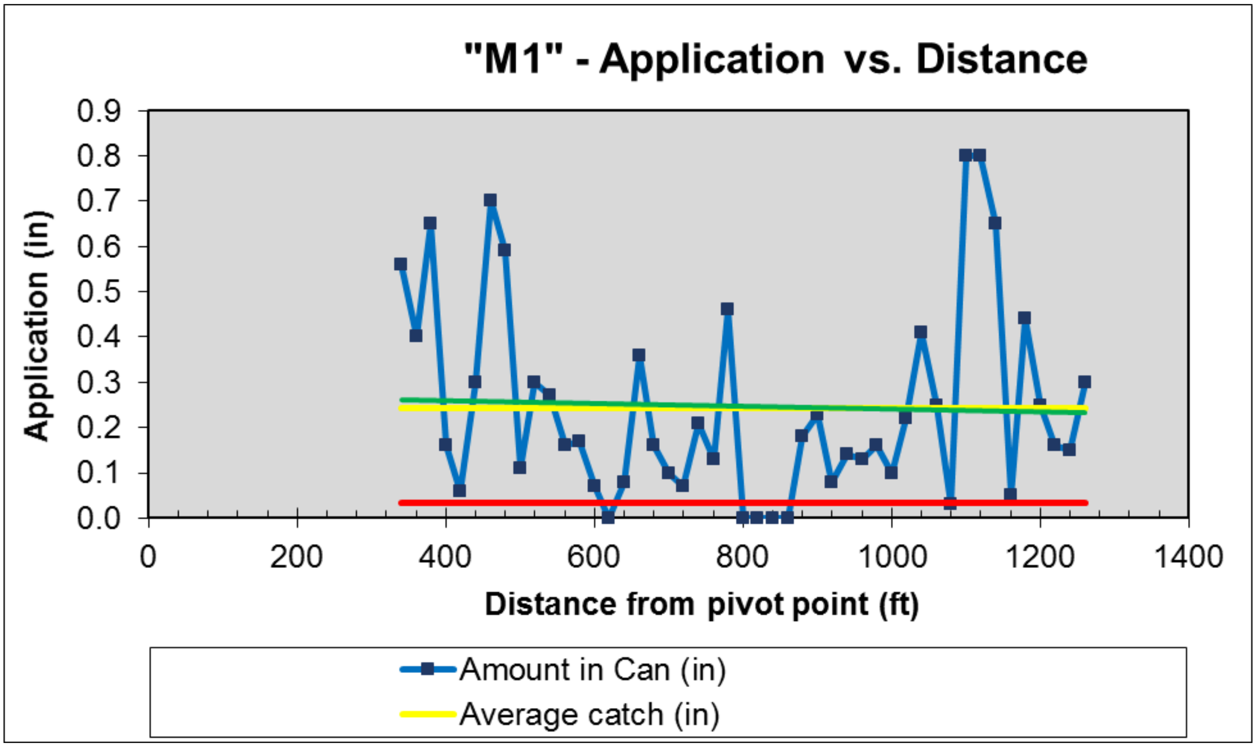

Figure 8: Water application amount at distances from pivot

Table 8: **Uniformity Coefficients**

Sum of lowest quarter weighted catches	13
Sum of lowest quarter used can numbers	380
Lowest quarter average catch (in)	0.03
Distribution Uniformity - DU_{lq}	**14%**
Sum of absolute value of diff from avg	318.98
Christiansen Uniformity - CU	**31%**

Table 9:

Pivot Settings and Water Conveyance Efficiency

Pivot Wetted Radius (ft)	1295
Inflow Rate (gpm)	584
% Setting During Eval.	60
Fraction of Full Circle %	100
Conveyance Efficiency	**88.6%**

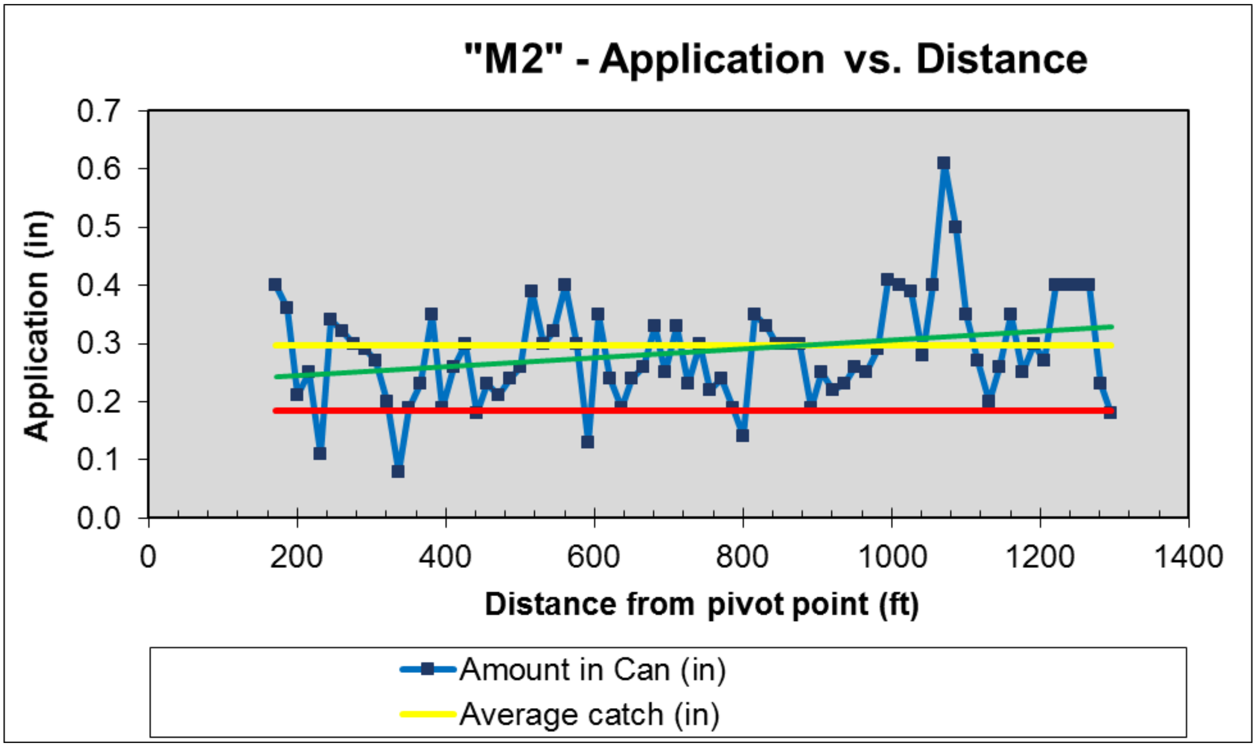

Figure 9: Water application amount at distances from pivot

Table 10: **Uniformity Coefficients**

Sum of lowest quarter weighted catches	95
Sum of lowest quarter used can numbers	518
Lowest quarter average catch (in)	0.18
Distribution Uniformity - DU_{lq}	**62%**
Sum of absolute value of diff from avg	262.81
Christiansen Uniformity - CU	**76%**

Table 11:
Pivot Settings and Water Conveyance Efficiency

Pivot Wetted Radius (ft)	1302
Inflow Rate (gpm)	800
% Setting During Eval.	90
Fraction of Full Circle %	100
Conveyance Efficiency	**88.8%**

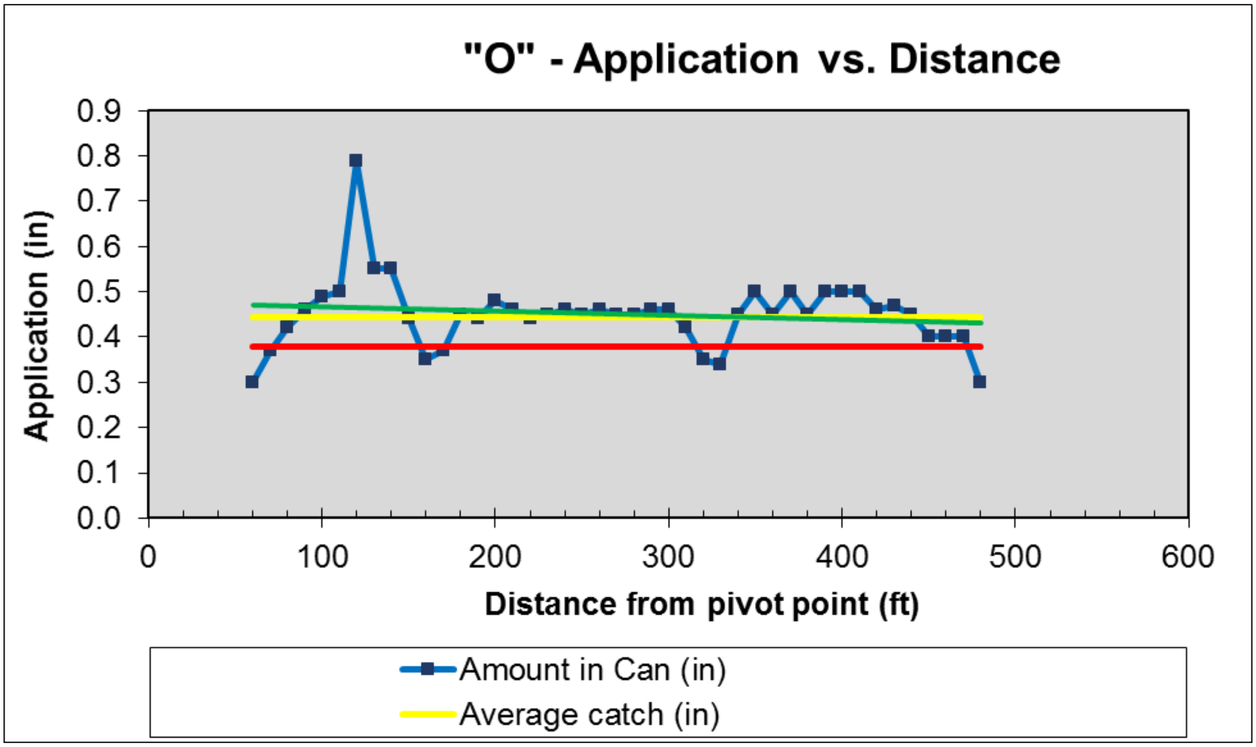

Figure 10: Water application amount at distances from pivot

Table 12: **Uniformity Coefficients**

Sum of lowest quarter weighted catches	89
Sum of lowest quarter used can numbers	234
Lowest quarter average catch (in)	0.38
Distribution Uniformity - DU_{lq}	**85%**
Sum of absolute value of diff from avg	49.78

Table 13:

Pivot Settings and Water Conveyance Efficiency

Pivot Wetted Radius (ft)	480
Inflow Rate (gpm)	580
% Setting During Eval.	37
Fraction of Full Circle %	100
Conveyance Efficiency	**100.0%**

Life Cycle Assessment (LCA) of Efficiency Improvements

The LCA analysis for this study examined the environmental impacts that could be avoided by improving the ten systems (power plants only for this section) to NPPPC recommended efficiency levels. Further improvements would be possible by optimizing the water operations management but are not examined in this study.

The LCA study used the GREET v1.3.0.12704 (Argonne National Lab) software (greet@anl.gov) and examined the electrical (kWh) and fuel (Natural Gas) that could be avoided by getting the irrigation system power plants to NPPPC standards. The natural gas analysis was from a file “NG from Shale and Regular Recovery”. The LCA of utility electricity was from the GREET file “Distributed – U.S. Central and Southern Plains”. The LCA analysis is a “well to product or wheel” type study where the impacts from extraction (coal/electricity, petroleum), through refining, generation, transmission and end use (transportation) are included. Therefore, some of the impacts may not be in the immediate vicinity of the irrigation site but certainly are in the overall ecosystem.

While the GREET model is a transportation-centric model, it can be used to simulate stationary engines/motors. In the case of natural gas, we included the end-use (stationary pump engine), which for GREET, is a natural gas powered vehicle. We felt this was a reasonable approximation as the irrigation engines are essentially automotive-based units. We used the efficiency calculations from the center pivot energy tests to drive the LCA outputs.

It may appear curious that there is uranium ore in the natural gas production outputs. Utility electric power is used in various stages of the Natural Gas production. The grid, on average, has some percentage of nuclear- produced power that varies according to geographic region. The electricity mix used in this LCA study was from the Southwest Power Pool which is the group of utilities for the region studied.

What follows are the (predicted) avoided environmental (LCA) “impacts” projected by improving tested center pivots to NPPPC standards (natural gas and electric) (Table 14-16 and Figures 11-13):

Table 14: Avoided IC natural gas fuel production and use emissions

		Units	Avoided NG fuel production emissions	Avoided NG end-use emissions	Total Avoided Emissions
Emission Type	VOC	kg/year	7.6	38.04	45.64
	CO	kg/year	14.38	759.63	774.01
	NOx	kg/year	19.8	33.92	53.72
	PM10	kg/year	0.56	1.53	2.09
	PM2.5	kg/year	0.49	1.36	1.85
	SOx	kg/year	13.38	0.00	13.38
	GHGs	kg/year	9,517.18	71,405.46	80,922.64

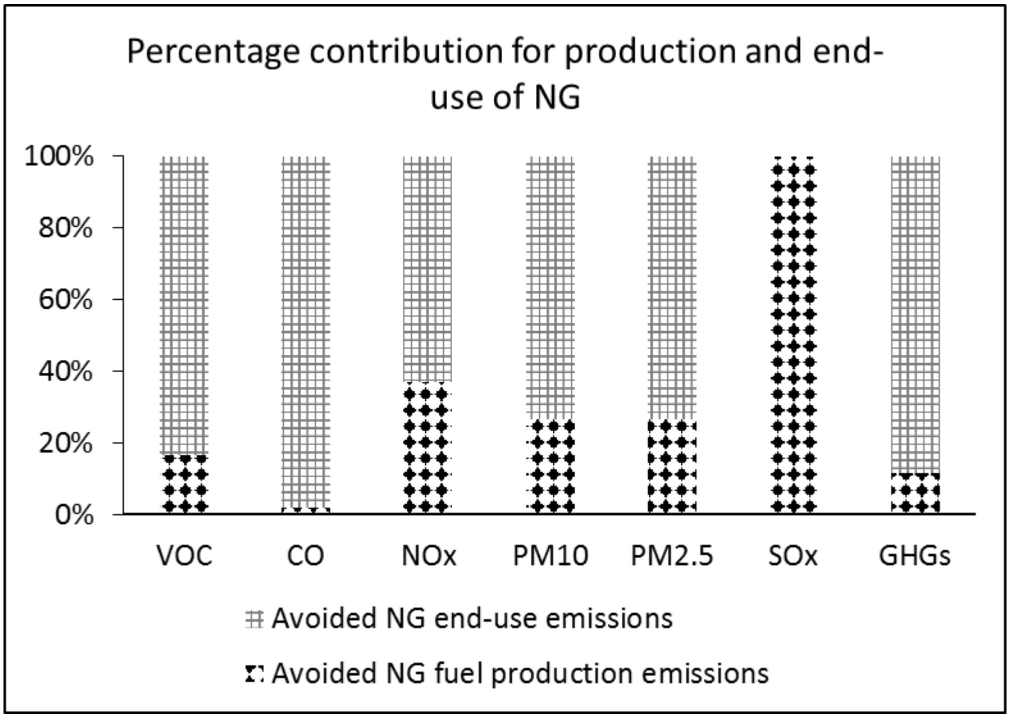

Figure 11. Comparison of natural gas emissions for gas production versus end-use (engine)

Table 15: Avoided natural gas fuel production resources consumed

Well to Product - Resources Saved by NPPPC

Resources	mmbtu		327.5	
Natural Gas	mmbtu		325.0	
Crude Oil	btu		1,114,213.1	
Coal Average	btu		987,824.5	
Nuclear Energy	btu		160,807.6	
Bitumen	btu		110,101.8	
Hydroelectric Power	btu		67,604.0	
Wind Power	btu		24,575.5	
Forest Residue	btu		10,867.6	
Renewable (Solar,	btu		4,103.6	
GeoThermal Power	btu		3,952.7	
Pet Coke	btu		1,870.6	
Solar	btu		31.1	
Water	gal		**1,712.6**	
Uranium Ore	mg		1,607.1	
Groups			0.0	
Fossil Fuel	mmbtu		327.2	
Natural Gas Fuel	mmbtu		325.0	
Petroleum Fuel	btu		1,226,185.5	
Coal Fuel	btu		987,824.5	
Non Fossil Fuel	btu		271,942.7	
Nuclear	btu		160,807.6	
Renewable	btu		111,134.8	
Biomass	btu		10,867.6	

Table 16: Avoided utility electrical production emissions (Stationary Motor at Irrigation Pump) – local LCA emissions negligible for electric motor

Well to Product- Resources

** Includes all efficiencies

			Saved by NPPPC**	
Resources	2.667	mmbtu	238.4	mmbtu
Coal Average	1.567	mmbtu	140.1	mmbtu
Natural Gas	913530.4	btu	81,669,620.3	btu
Nuclear Energy	108896.6	btu	9,735,357.1	btu
Crude Oil	26092.97	btu	2,332,711.3	btu
Wind Power	26086.08	btu	2,332,095.7	btu
Forest Residue	10846.54	btu	969,680.8	btu
Renewable (Solar	4353.078	btu	389,165.2	btu
GeoThermal Power	4193.039	btu	374,857.7	btu
Hydroelectric Power	3525.195	btu	315,152.4	btu
Bitumen	2578.387	btu	230,507.8	btu
Pet Coke	43.807	btu	3,916.3	btu
Solar	33.075	btu	2,956.9	btu
Water	403.011	gal	36,029.2	gal
Uranium Ore	1.088	g	97.3	g
Groups				
Fossil Fuel	2.509	mmbtu	224.3	mmbtu
Coal Fuel	1.567	mmbtu	140.1	mmbtu
Natural Gas Fuel	913530.4	btu	81,669,620.3	btu
Non Fossil Fuel	157933.6	btu	14,119,265.8	btu
Nuclear	108896.6	btu	9,735,357.1	btu
Renewable	49037.01	btu	4,383,908.7	btu
Petroleum Fuel	28715.16	btu	2,567,135.5	btu
Biomass	10846.54	btu	969,680.8	btu

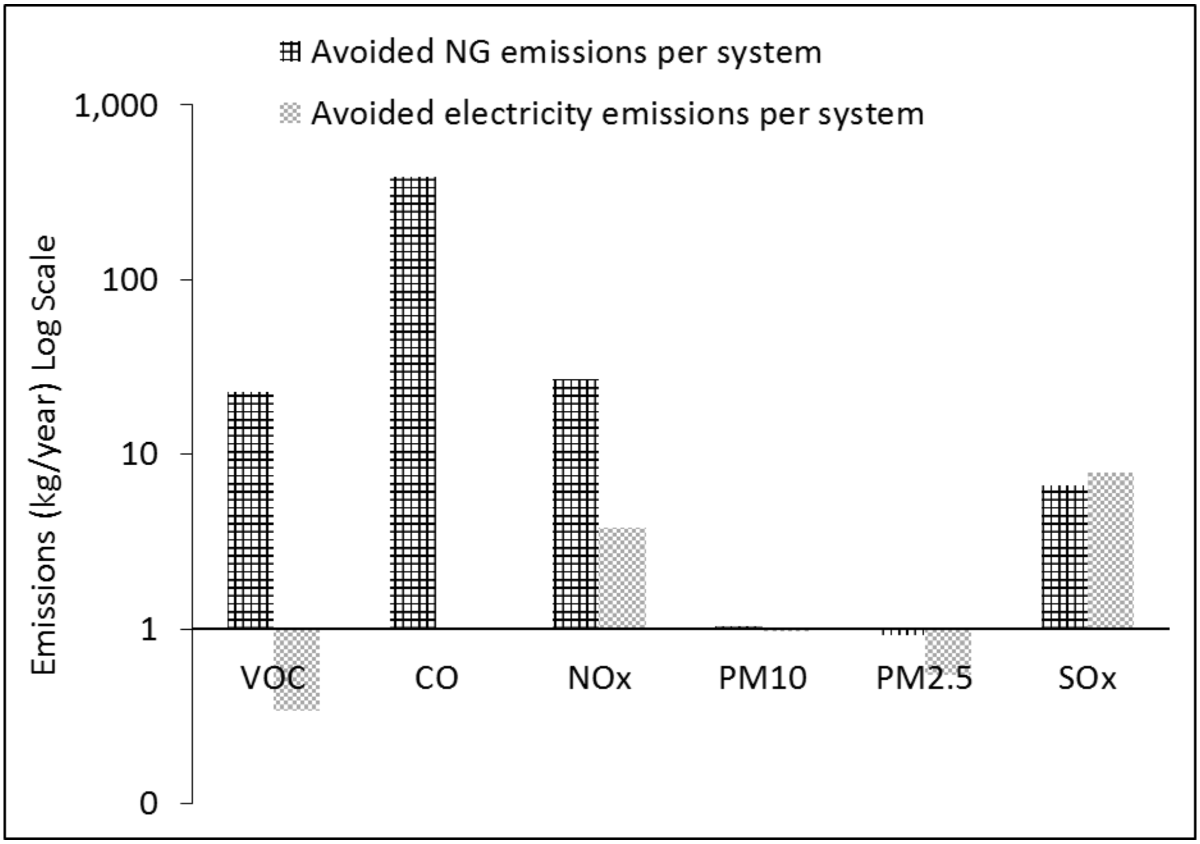

Figure 12. Log scale of primary pollutants for average individual system (electric and gas) tested – not including greenhouse gases

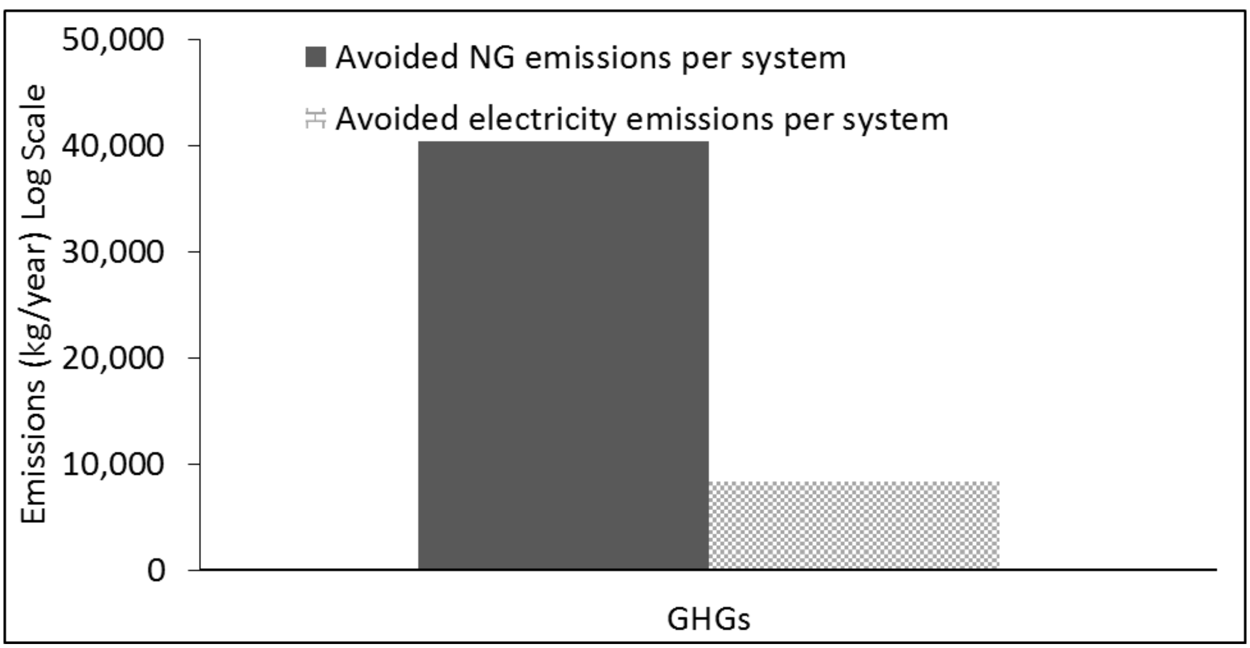

Figure 13. Greenhouse gas emissions for natural gas engine (red) versus electric motor (green) irrigation system (average for study)

Combined avoided LCA outputs for All Tested Irrigation Systems:

- Total greenhouse gases (GHG) Saved (NPPPC Stds) = **48,786 Kg/year (107,329 Lb/year)**

- Total Energy- Process Water Saved = **37,751 Gallons/year (Not Irrigation Water)**

Ultrasonic Flow Meter Testing

Early in the project the team discovered that the NRCS (loaned) GE PT-878 portable flow meter was giving very erratic and odd results for water flow in metal pipes. The PT-878 was taken to the Payne County ARS Hydraulics lab where calibrated water flow in 12" metal pipes could be observed and tested. Again, the PT-878 delivered unusual readings (sometimes negative). This led the OSU team to purchase a Fuji Portaflow C® ultrasonic flow meter for the main irrigation efficiency project. The Fuji has proven to be accurate and reliable under a wide variety of conditions.

The inconsistent PT-878 readings caused the NRCS offices to conduct a mass test of their PT-878 meters at the ARS lab. OSU grant personnel assisted with tests and observed the outcomes. Essentially, the tests revealed that almost all the 15 meters were in need of rework and calibration.

A fact-sheet regarding the tests and operational details surrounding the portable meters is under construction.

Conclusions

The tests conducted revealed several issues facing panhandle irrigation systems. For the internal combustion (IC) engines, mechanical degradation over time is a major contributor to the lowering of energy efficiency and can be seen directly in increased fuel consumption and costs for the same amount of water pumping. We are unsure whether producers monitor the decrease in fuel efficiency or simply run these engines until they fail or require attention. A systematic maintenance program is needed for the IC engines doing irrigation pumping duty.

The electric motor pumping systems seem to be fairing much better over time. Electric motors with essentially only one moving part make it easy to understand why this might be the case. Almost all of the efficiency issues found on electrical systems pointed to the pumps as the probable cause (some faulty wiring was also found). Old, worn, and clogged pumps can drag down efficiency very quickly. However, removing buried turbine pumps for inspection can be very expensive. For this reason we advised producers to obtain a second independent test to verify ours before pulling the pumps.

The producers, almost to a person, were fascinated by what their current water level was and how far the drawdown would be when operating the system. Most had never measured the water levels.

The water tests showed both issues with water losses in the distribution system (pipes) and in the nozzle applicators. In some cases the most energy efficient pivot systems had the worst water delivery “effectiveness”. This, of course, can affect the energy usage but we did not examine water application management in this project.

Recommendations for Improving Systems:

The old adage: You can’t improve what you can’t measure – applies here. We were somewhat surprised that producers did not know their actual water levels (other than guessing). This is the easiest and least expensive of the various tests we performed. It does require an access hole from the top-side inside the casing to the water level. Some pumps were missing this access hole but a large hand held drill and a ½” high speed steel bit would provide the hole in many cases. Then a water level meter is used to measure the water level. The water level will vary over the day and season (something we could not observe very well). If the water level has dropped significantly since the pump was installed, it is guaranteed that the pump efficiency is now lower as the total dynamic head (depth etc.) is such an important design criteria.
The same measurement idea applies to the motors and engines. Continuous, or at least occasional, monitoring of the fuel and electrical power flow to the pump would show operating inefficiencies. Once the overall pumping plant efficiency drops to some level below the NPPPC standards (e.g., 75% of NPPPC for electric or fuel), a tune-up, rebuild, or detailed system audit is in order.

Our job is to sensitize the producers and others to these issues through face-to-face meetings and other extension mechanisms. To that end we have arranged with Ag-Communications to prepare a series of video shoots on the issues we discovered in this project. We also report these findings and extrapolate the possible savings over wider areas of the state in order to show the large scale potential of such efforts.

Future Work:

We have already secured the funds for the continuation and extension of this work via an USGS104b grant through the OSU Water Center in 2016-2017. This grant extends the scope of this DASNR seed-grant to more systems and a wider state area (western Oklahoma) for investigation. We will also have the expanded extension-based products such as video spots for public dissemination. We are also seeking partnerships with commercial entities and are in negotiations with a large public electric utility to partner on further such projects.

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