PROCEEDINGS OF THE 2008 CENTRAL PLAINS IRRIGATION CONFERENCE

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MANURE SAMPLING AND SPREADER CALIBRATION: TESTING OUR RECOMMENDATIONS

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INTRODUCTION

The purpose of this work was to evaluate whether the innate variability of manures and the difficulty in achieving a uniform spread negate the recommendations often made by land-grant universities to sample manure and calibrate manure spreaders.

MATERIALS AND METHODS

Manure Sampling Study

The objectives of this study (Davis et al., 2002) were 1) to measure the variability within stockpiles of various animal manures and determine the number of sub-samples needed to characterize the nutrient content within a 10% probable error and 2) to compare Colorado manure analyses to the table values we have been using in our publications, which come from Midwestern data.

Ten sub-samples (approximately 0.5 qt each) from each of five manure stockpiles (beef, dairy, horse, sheep, and chicken) were collected. Each stockpile was sampled from a different farm. Two samples were taken from the top and two from each side of each stockpile (north, south, east, and west). For each pair of samples, one was taken shallowly (1 ft), and one was taken more deeply (3 ft). For the side samples, one of each sample pair was taken from the middle and one from near the bottom of the stockpile. Each sub-sample was analyzed separately for dry matter (D.M.), total nitrogen (N), ammonium (NH_4-N), nitrate (NO_3-N), phosphorus (P), and potassium (K) to determine the variability within the pile. Collected data and the following equation were used to determine the number of sub-samples needed.

$$n = t^2CV^2/p^2$$

where t=Student's t value (for a 95% confidence interval, n=10 and degrees of freedom=9, t=2.26), CV=coefficient of variation expressed as a decimal, and p=probable error expressed as a decimal (0.10 for 10% error).

Beef, dairy, horse, sheep, and chicken manures were sampled in order to compare Colorado manure analyses to Midwestern table values. Six to ten different livestock operations were sampled for each manure type. Each sample was a composite of six 0.5 qt sub-samples taken from different locations and depths within the stockpile. The D.M., total N, NH_4, P_2O_5, and K_2O values measured in these samples and manure sample means from each farm tested in the within-stockpile variability experiment described above were combined into a database. Results were compared to values previously used in Colorado extension publications which came from Midwestern manure samples.

Spreader Calibration Study

The objectives of this study (Davis and Meyer, 1998) were 1) to compare the Tarp Method and the Swath Width and Distance Method for manure spreader calibration, 2) to measure the variability among tarps in the Tarp Method and to calculate how many tarps would be required to achieve 10% probable error, 3) to evaluate the uniformity of the spread patterns and measure the swath widths of the manure spreaders, and 4) to compare the measured application rates from both the Tarp Method and the Swath Width and Distance Method with the stated goals of the operators.

We worked with ten different operators of manure spreaders. All of the spreaders were truck-mounted. We used eight tarps, three 10 x 12 ft tarps lined up in a row in the direction of travel for the Tarp Method and five 5 x 10 ft tarps lined up side-by-side perpendicular to the direction of travel (with the 10 ft direction going in the direction of travel). The tarps were each weighed with a hanging scale prior to laying them out. After laying the tarps out, we measured the weight of the full manure spreader using a set of four wheel-load scales or a drive-on scale at the feedlot source. Then, the operator drove over the tarps while spreading manure. Each tarp was weighed with the manure on it using a hanging scale, and the tarp weight was subtracted from the manure plus tarp weight to calculate the net weight (weight of manure only). The empty manure spreader was also weighed, and the manure weight was calculated by subtracting the empty spreader weight from the full spreader weight. The average capacity of the trucks was 15.4 tons of manure, but the capacity ranged from 12.3 to 20.6 tons.

For the Tarp Method, the net weight in lbs was divided by the area of the tarp (120 sq ft), multiplied by 43,560 sq ft/acre and divided by 2000 lbs/ton to calculate the application rate in tons/acre. The coefficient of variation was calculated for the three tarps, and the number of tarps required to achieve 10% probable error was calculated using the equation shown above.

The lb per tarp measurements were graphed as a function of tarp location as part of the Swath Width and Distance Method. Using the graph, we did a field estimate of swath width by predicting the location where the application rate would be 50% of the maximum. Swath width was subsequently calculated based on determination of the slope of the line from the middle tarp to the inner tarps, and then calculating the distance from the center which would receive 50% of the maximum application rate. We used a measuring wheel to measure the distance that manure was spread on from each truck load. The average travel distance per load was 0.45 miles, with a range of 0.31 to 0.56 miles. Then we calculated application rate by dividing the weight of the manure in tons by the receiving area in square feet (swath width times distance) and then converting to tons/acre by multiplying by 43,560 sq ft per acre. We defined an off-center spread pattern as one where the difference between the inner tarps was greater than 50% of the lower weight, and calculated which manure spreaders resulted in off-center spread patterns.

The Tarp Method, Swath Width and Distance Method, and operator goals were compared using analysis of variance and the Least Significant Differences Mean Separation Test at $p \leq 0.05$. The average spread pattern and comparison of field estimated and calculated swath width were evaluated similarly.

RESULTS AND DISCUSSION

Manure Sampling Study

The variability of samples within a manure stockpile differed for the various constituents. Ammonium and nitrate had the greatest coefficients of variation due to their relatively low concentrations. The greater the coefficients of variation, the greater the number of sub-samples required for useful analysis. For example, to achieve probable error within 10% for a beef manure stockpile, one would need 17 sub-samples to characterize total N, 20 sub-samples for P, 32 for K, 121 for NH_4-N, and 692 sub-samples for NO_3-N.

For solid manures, it seems possible to estimate the total N, P, and K in a stockpile within 10% probable error with a moderately intensive sampling plan (collecting 21-27 sub-samples and combining them to form one composite sample). However, to characterize the NH_4-N and NO_3-N levels in order to predict N availability to crops, the required sub-sample number becomes impractical (>100).

In addition to CVs, another measure of similarity is the confidence interval (C.I.), which is a measure of the probability that a sample will fall within an upper and lower limit. For the one case in which we had over 100 samples (solid beef manure), the 90% C.I.s were quite narrow. For example, the mean total N content was 23 lb/ton, with a C.I. of 21-24 lb/ton. We can interpret this to mean that nine out of ten beef manure stockpiles will have a N content between 21 and 24 lb/ton.

Based on our information, we recommend a minimum of 25 farms for manure database creation in the Mountain West in order to achieve 90% C.I. ranges of 10% D.M. and 10 lb/ton for the nutrients. Including 72 farms in each database (for each manure type) would reduce the ranges in the 90% C.I.s to 5% D.M. and 5 lb/ton for each of the nutrients.

The solid manures sampled from Colorado operations differed in comparison with those we previously used in our extension publications, which originated from sources in the Midwest. The dry matter contents of the Colorado manures were consistently higher than those reported from the Midwest. On a wet weight or “as is” basis, the Colorado manures had higher total N contents in four out of five cases. Ammonium was lower in all of the Colorado manures on a wet weight basis. Colorado P_2O_5 and K_2O contents were higher than Midwestern data for all manure types, when evaluated on a wet weight basis.

The semi-arid and windy climate of Colorado probably leads to greater evaporation of water and volatilization of NH_3^o from manure stockpiles, resulting in the higher dry matter values and lower contents of NH_4-N in all of the manures. Phosphate and K_2O contents are probably greater in Colorado manures because of the concentration effect from the greater loss of water. This concentration effect also occurs with organic N, causing the increase in total N content in most of the manures.

Spreader Calibration Study

The Swath Width and Distance Method resulted in significantly higher measured application rates than the Tarp method. When a spreader truck was driven over the tarps, the tarp width was effectively reduced due to being pulled in by the weight of the truck. The data was corrected for this shrinkage, and the Tarp Method still resulted in lower measured values.

The coefficient of variation (CV) for the weights on the three tarps used in the Tarp method ranged from 17-56%, with an average CV of 30%. We used relatively large tarps for the Tarp method, because the larger the tarp, the lower we expect the CV to be. Only two of the ten test cases had CVs > 40%.

We calculated that three tarps result in 39% probable error, and five tarps result in 30% probable error. In other words, if the goal of the operator is to spread 20 tons manure/acre, three tarps would result in measured values from 12-28 tons/acre, and five tarps would result in measured values of 14-26 tons/acre. Since using five or less tarps results in so much error, we do not have sufficient confidence in the Tarp Method. We determined that 46 tarps would be required to achieve 10% error in measured application rate by the Tarp method.

On average, the spread patterns were centered. However, seven out of ten spreaders had patterns which were off-center. One of these seven cases could potentially be attributed to strong winds. Another one of the spreaders had one side with 7.5 times the amount of manure on it than the other side. Some of the trucks did not seem to be loaded evenly, but trucks were loaded according to common procedure; therefore, the unevenness of the spreading could be partially attributed to asymmetrical loading and partially attributed to the need for adjustment and improvement of manure spreaders.

Calculated swath widths ranged from 7.5 ft to 16.1 ft, with an average of 11.1 ft. With swath widths less than 10 ft, using 10 ft x 10 ft tarps would be inadequate for swath width determination. The calculated swath widths were not significantly different from those estimated in the field.

On average, neither the Tarp method nor the Swath Width and Distance method were significantly different from the application rate goal of the operator. Three of the operators stated their goals in ranges of 5 tons/acre, and, in these cases, we used the middle of the range for the comparison. Nonetheless, the operators are generally achieving their stated application rates, with $p \leq 0.05$.

Both of the methods tested here were too variable to be useful. Of course, manure spreading is innately variable, and evaluating a large area from small tarps whether for swath width determination or actual application rate calculation only works if the spreading is uniform. Although we did not evaluate the Loads per Field Method (in which the operator counts the number of loads delivered to a field of known area and multiplies by the average weight of a load), since this method encompasses the entire spreading area and does not involve the use of small tarps, we would expect the variability to be less with this method. Rather than emphasizing spreader calibration, we should focus on improving manure spreader design to be more uniform and checking spread patterns and overlap distances in order to improve uniformity of applications.

CONCLUSIONS

Manure varies within and among livestock operations due to different feeding and management practices. Table values can replace site-specific sampling if enough ($\geq$72), local sample numbers were used to develop those table values. Otherwise, if you are uncertain of the source of the table values, site-specific manure sampling remains valuable. Be sure to take a minimum of six sub-samples per stockpile (20-25 would be better but may not be a reasonable expectation) in order to have some level of confidence in the analysis.

Manure spreading is also a variable process. The Tarp Method for spreader calibration does not adequately capture that variability. The Swath Width and Distance Method is usefully for determining necessary overlap distance to reduce application variability. It is important to weigh manure loads, load spreaders evenly, overlap properly, and count loads applied per field to get a decent estimate of application rate.

Although agronomic manure application rate can be done very precisely, the innate variability of manure and manure spreading require us to be reasonable in our expectations. Annual soil sampling provides a critical feedback loop to adjust manure utilization practices from year-to-year.

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SALT THRESHOLDS FOR LIQUID MANURE APPLICATIONS THROUGH A CENTER PIVOT

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INTRODUCTION

Application of liquid manure to growing crops is often a convenient and agronomically acceptable means of land application (Kranz, et al. 2007). Center pivots have been adapted to apply a broad range of fertilizers and pesticides. Development of large animal production facilities has added manure application to the list of materials that can be applied via center pivots if appropriate equipment is selected for pumping and distributing the liquid and solids contained in storage facilities. Al-Kaisi, et al. (2002) reported on the impact of using a center pivot to apply dilute swine lagoon water to cropland in Colorado. However, some producers have learned the hard way that more concentrated manure contains some good and some bad materials. Crop damage can occur as a result of application of concentrated manure presumably because of high salt concentrations.

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

Electrical conductivity (EC) level is an indication of the salt concentration in the manure sample. Crop damage due to sprinkler application of liquid manure with high (EC) levels occurs because of the direct contact of the salt with plant leaves and potentially the roots. Early research reporting the salinity thresholds for induced foliar injury concluded that since damage was caused by salt absorption into plant tissues, foliar application should be avoided in hot, dry, windy conditions that produce high potential evapotranspiration (PET). It was noted that species varied in the rate of foliar absorption of salts, such as: sorghum < cotton = sunflower < alfalfa = sugar beet < barley < potato. However, the susceptibility to injury was not related to salt absorption, as injury varied as: sugar beet < cotton < barley = sorghum < alfalfa < potato (Maas, et al., 1985; Maas, 1982). They found that leaf absorption of salts may be affected by leaf age, with generally less permeability in older leaves, and by angle and position of the leaf, which may affect the time and amount of leaf salt exposure. However, in other research, Mass et al., (1982) found that corn yield was not affected at soil water EC levels less than 5.5 dS m^{-1} for conditions in California. Producers need to know what the safe salinity levels are and the effect of timing of application on potential plant damage for corn and soybeans.

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

METHODS

Salt and ammonia concentration data from over 2700 manure samples were obtained from a private laboratory to determine the range in concentrations that should be evaluated in the field research. Figure 1 is a summary of the samples analyzed where the median EC level was 6.7 dS m^{-1} with a range from 0.1 to 70 dS m^{-1}. The median ammonia concentration was 497 ppm NH_4-N with a range from 0.03 to 12,646 ppm NH_4-N. Work with several swine production facilities indicated that lagoon style facilities could have EC's around 12 and below ground pits could have EC's around 20-25.

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

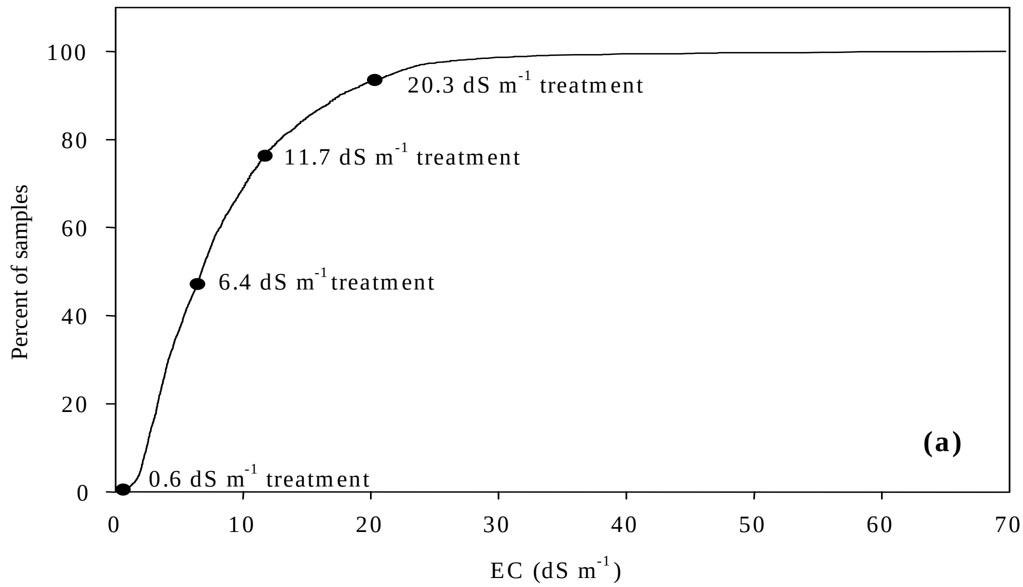

Figure 1. Cumulative distribution of electrical conductivity of liquid manure submitted for analysis to a commercial laboratory in Nebraska. The concentrations used in this study are also presented.

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

The screened manure was diluted with fresh water to create four levels of EC in the liquid manure. The original manure had an EC level of 20.3 dS m^{-1}. Fresh water was added to dilute the manure down to 6.4 and 11.7 dS m^{-1}. Fresh water with an EC of 0.6 dS m^{-1} was used as a control treatment. A portable applicator was developed and attached to the boom of a Hi-Boy sprayer (Figure 2). The applicator consisted of 21 nozzles arranged in a 3-nozzle wide by 7-nozzle long

grid with a spacing of 3 feet between nozzles in each direction. The liquid manure application treatments consisted of a single application of four soluble salt concentrations applied at one of two selected growth stages of corn and soybean. The first application was applied on July 2when corn was at the V7 growth stage and soybean was in the V3 stage (Ritchie, et al., 1996; Ritchie and Hanway, 1984). Air temperatures during application were in the upper 80's. The second application was applied on July
24 when corn was at the V14 stage and soybean was at the R1 stage. Air temperatures during application were again in the upper 80's. Approximately 0.5 inches of liquid manure was applied over a 10-minute period to corn and soybeans at each EC level.

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

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

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

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

RESULTS

Soybean

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

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

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

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

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

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

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

Figure 3. Plant damage to soybean caused by a single application of liquid swine manure with a EC of 20.3 at the R1 growth stage.

Corn

Corn growth was less affected than soybean, and damage was detected only with the V8 application at the 20.3 dS m^{-1} concentration (Figure 4 & Table 3). The V14 application caused even less damage, likely due to salt tolerance of the fully developed cuticle on the corn leaves. The V8 application of 20.3 dS m^{-1} concentration caused some stunting of plants but no plant death. Overall, the manure increased the corn yields when applied at V14 (178 bu/ac) compared to V8 (165 bu/ac).

Figure 4. Plant damage to corn at the V8 stage following application of liquid swine manure with an EC of 20.3 in 2003.

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

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

[1] Statistical significance of ANOVA main effects are given by the probability of the F-test (α = 0.05); Significant differences are indicated by *.
[2] T × R is the Timing × Rate statistical interaction.
[3] V8 and V14 are leaf stages at the time of application.

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

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

SUMMARY

Producers can use inexpensive EC meters to estimate the potential for damage with liquid manure application. Application of liquid manure to corn and soybean through a sprinkler system is feasible with proper management and equipment selection. These results support the hypothesis that growth stage and liquid manure soluble salt concentration (EC levels) influence plant damage. Based on the conditions of this study, liquid manure with EC levels greater than 6.4 dS m^{-1} should not be applied to soybean during early vegetative growth. Liquid manure with EC levels less than 11.7 dS m^{-1} can be applied to corn and to soybean after flowering. If the soybean plants are not defoliated as a result of liquid manure application, yield is not likely to be reduced. Crop tolerance to soluble salt application is greater during the reproductive growth stages of the season than during the early vegetative stages. Applications of liquid manures to other crops and earlier in the growing season should be conducted to make sure phytotoxicity is not greater earlier in the season or for other commonly irrigated crops such as wheat and alfalfa.

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USING AN INTEGRATED APPROACH TO UTILIZING CENTER PIVOTS FOR LIVESTOCK WASTE MANAGEMENT

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Summary:

The title says it all – using an integrated approach to utilizing center pivots for livestock waste management. What does integrated mean? It means considering the entire system from waste source to the application in the field. To achieve this, the discussion will focus not on center pivots, or separators, or pumps, or lagoon design or any one element of a livestock waste management system, but all of them together – integrated into one package so all parts work together and no one part is a constraint. Consideration will be given to planning for a new or updated system and what to do with an existing system.

Introduction:

Land application of wastewater with mechanical move irrigation equipment – both center pivot and linear – has been successfully used for many years. Since the early 1980's the equipment and techniques for irrigating with fresh water have changed dramatically. Many of these changes have been incorporated into mechanized equipment used for land application. While these changes have brought significant improvements, we must take into account other issues and particularly public perception of land application systems.

Today, too often phone calls are received by consultants, dealers and manufacturers from a farmer that goes something like this - "My pivot is plugged and I need it fixed." So how does one start when responding? Is the problem the sprinkler package, the pivot or something else? Where does one begin to look for a solution to the farmer's problem? And better yet how does one ensure this does not happen again? Today it is very common that the wastewater producer does not farm or own sufficient farmland. They rely on working with the irrigator who has little or no experience with confined livestock so collecting information from the irrigator may be a challenge. And if the wastewater producer does own the irrigation equipment they still may treat it as a separate enterprise and commonly will have separate management focused on crop production and meeting the grain and forage needs of the animal unit.

Discussion:

Whether looking at a new installation or trying to resolve an existing situation like the phone call, it is imperative that one considers the complete system and not just one specific component. There are a number of ways to look at a system. One example of how the system may be broken down into components is as follows:

- Waste source – hog, beef, dairy, other
- Collection – how is the waste collected
- Storage – how is the waste stored
- Pumping – how is the waste pumped and distributed
- Land application unit – for our discussion we will use the center pivot and its sprinkler package.

Briefly before we go into a more detailed discussion, let's consider what each party (producer and irrigator) wants out of the system:

- The wastewater producer wants:
    - Fast delivery of large volumes
        - Particularly important to beef feedlots after a rainfall event to ensure they have the capacity to contain another event
    - The possibility to eliminate large volumes early in the crop growing season and at the end of the season
        - Storage may be full after the winter and may need to be lowered as much as possible prior to winter
    - To 'dispose' of chunks and trash
    - No problems
    - The nutrient management plan to work as planned

- The irrigator wants:
    - Waste water only when crop needs it
    - A sprinkler package with good uniformity
    - No problems – eliminating sprinkler plugging is at the top of the list

Back to the situation of the phone call and how to proceed. Whether you are a farmer, consultant, dealer or manufacturer, there are suggested steps to follow to determine how well the system is integrated and how to proceed.

Typically the irrigator is asked to describe the system. Often there are long periods of silence as he does not know:

- The waste source – not critical but helps to know what to expect
    - He knows the species of livestock, but:
        - If hogs –
            - Farrowing, feeder or finisher

              Important as farrowing units usually have plenty of water and is a dilute stream while feeder and finishers need to have a higher level of solids

- If dairy -
  - Type of bedding if any

    Important for bedding is if sand is used is it collected and recycled or how will it be handled

  - Type of collection system in the confinement unit

    Importance of collection is if flushing should have plenty of water for dilution and if scraping may have challenge of high solids content

- Collection (This is generally the area where the irrigator knows the least)
  - How the waste stream is moved to storage
    - Pipeline or open channel
    - Pumped

    Important to understand if trash can get into the stream
  - Is separation used
    - Sand recovery for use as bedding
    - Removal of solids

    Important to help understand what solids potentially could be expected at the center pivot. If lots of solids are coming to the pivot and a separator is being used would indicate a problem in this area

- Storage
  - He knows there is storage, but not sure of:
    - Numbers of units
    - Which unit his waste stream comes from

    Important as if multiple cells should be pumping from the last cell which should have the least solids.

- Pumping
  - He knows there is a pump, but:
    - Does not know the waste producer's plan to send to the field?
      - Percent of solids
      - Size of solids
      - Volume
      - Frequency

    - If a single cell is the pump close to where the waste stream comes into the storage?

    Important – moving away from where the waster stream comes into the lagoon can help minimize solids
    - Type of pump – commonly the irrigator will say he thinks it is a solids handling pump – not knowing that this means the

pump will deliver big chunks. This is *good* for the waste producer but *bad* for the irrigator.

- Position of the inlet to the pump in the lagoon – one of the big issues
  - Is it a floating inlet
  - On the bottom
  - Somewhere in between

  Important as where the inlet is positioned generally relates to the waste producers expectations as to the solids they plan to pump.

- Land application unit
  - He knows the center pivot, but may not be well aware of how it applies wastewater
  - Says he has pressure regulators
  - Uses spray nozzles

  Important to guide the change to the sprinkler package to minimize the problems

At this stage the consultant, dealer, or manufacturer needs to really dig into what is happening. There are some questions that must be answered.

The most important questions to get answered are (working back upstream):

1) What is the sprinkler package and where is it plugging?
   a. If the irrigator has pressure regulators this needs to be evaluated to determine if regulators are really needed or if an alternative such as flow control nozzles would be a solution. Or if the pump intake is moved would that minimize the amount of solids in the liquid stream so regulators could be used?
   b. If the nozzles are plugging in the first spans of the center pivot consider a wider spacing even if the uniformity may not be optimum. Remember the uniformity of plugged nozzles is poor!
   c. If the plugging is occurring on the pad consider a different pad configuration that provides less opportunities for trash to 'catch'.

2) What type of pump is being used?
   a. A solids handling pump is going to send large chunks to the center pivot. Consider the location of the inlet to minimize chunks getting into the pump

3) Intake to the pump location
   a. Position so it is not on the bottom or top of the storage in a zone that is as free of trash and solids as possible unless the overall plan is to pump high amounts of solids.

4) What are the waste producer's expectations of what is sent to the field?

a. Percent of solids
b. Size of solids
c. Volume
d. Frequency

e. There may be a complete mis-match of ideas as to what is going to happen. On an existing system the costs to fix can be substantial.

f. If the irrigator and wastewater producing cannot agree the producer will need to find another area to use and amend the nutrient management plan.

When one is starting a new wastewater system it is necessary to integrate (combined in a logical way) all of the following items to meet the overall system needs. Hopefully the wastewater producer and the irrigator can work together in a partnering that is mutually beneficial to both. If these items are not integrated, it could jeopardize one partner or the other or only meet one partner's needs.

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

Design – Waste producer may want rapid disposal of large volumes any time during the season while the irrigator wants even volume over the season and no plugging. Both want no problems. The design is critical to identify and outline the solutions to try to satisfy both parties.

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

Operation – If the design was balanced to meet both parties' needs, there should not be operational issues. If however the design is oriented to meet only one, then someone is going to be unhappy.

Conclusions:

For a land application project to be successful, all parts of the project need to be integrated together – planning, design, collection, storage, pumping and the land application equipment. Mechanical move irrigation equipment can be beneficial to the reuse of wastewater if it is integrated with the entire project.

Both the wastewater producer and the irrigator need to understand the needs and expectations of the other.

When problems arise within a system, one needs to look at the entire stream from where it is produced to the land application equipment to determine the best course of action. Often several different parts of the system will need to be reviewed and changes considered to meet both the irrigator and livestock producer's expectations.

References:

Personal communication with a number of waste water projects.

Strategies for Reducing Consumptive Use of Alfalfa

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Introduction

There is increasing competition for a limited water supply throughout much of the western U.S. Urban and municipal water users, declining groundwater levels, and drought are factors that are leading to reduced irrigation water quantities for large areas of agricultural land. As an example, Colorado's population is expected to grow about sixty-five percent in the next twenty-five years (Colorado Water Conservation Board, 2004). Most of this growth will occur in the corridor from Fort Collins to Colorado Springs, CO. As Colorado's population grows, water is expected to shift from agriculture to municipal and industrial uses. Estimates are as high as 400,000 acres of irrigated farmland that will dry up to meet changes in water supply and demand (Colorado Water Conservation Board, 2004). Changes in water allocation have important implications for the economic and environmental sustainability of agriculturally based economies. There is growing interested in the potential of limited irrigation in cropping systems as a means of addressing changing water supply and demand issues while maintaining profitable irrigated agricultural systems. Limited irrigation consists of applying water at rates lower than full ET demand by the crop. Such a practice requires managing crop water stress and depends on the ability to irrigate during critical crop growth stages. This paper outlines strategies for reducing consumptive water use of alfalfa through limited irrigation practices.

Background

There has been much work done in the past to determine the relationship between consumptive water use and alfalfa yield (Daigger, *et al*, 1970; Bauder *et al*, 1978; Retta and Hanks, 1980; Sammis, 1981; Guitjens, 1982; Carter and Sheaffer, 1983; Undersander, 1987; and Smeal *et al*, 1991) . Studies of alfalfa water use conducted across a range of climates and geographic areas in the U.S. illustrate a linear relationship of yield to ET with the slope of this line indicating alfalfa yield per unit of consumed water (Figure 1). The slope of this relationship is 0.18 tons/ac/in can also be interpreted that it requires an average of 5.6 in of ET per ton of alfalfa hay produced. This result corresponds well with a rule of thumb among Colorado irrigators that it takes 6" of water to produce a ton of hay. The data in Figure 1 illustrates that there is a lot of variability in the yield and ET relationship, resulting from the many factors that can affect alfalfa water use efficiency. One study (Undersander, 1987) compared the yield and ET relationships for individual hay cuttings across a growing season and found that the relationship changes depending on the cutting. In that study, the first and fourth cuttings had higher WUE than the middle two cutting. This makes sense because alfalfa is a C3 plant that is adapted to the cooler temperatures in the spring and fall cuttings, while loosing efficiency during the hotter summer cuttings. Thus, we hypothesized in our study that we would get the highest water use efficiency by focusing irrigation water to the early or late season growth.

Alfalfa is a good candidate crop for limited irrigation for several reasons. First, under full irrigation, alfalfa consumes large quantities of water during the growing season, leaving a large potential for water savings under limited irrigation practices. Second, alfalfa has drought tolerance mechanisms that make it biologically suited to deficit irrigation. Alfalfa is a deep rooted perennial crop with the ability to go into dormancy during drought. During dormancy, alfalfa limits above ground growth while storing energy for rapid growth from buds when water becomes available. This characteristic gives the irrigation manager flexibility to apply water during times when it is available and withhold water when it is in short supply. A third reason that alfalfa is suited for limited irrigation is the potential for managing irrigation in a way that promotes higher quality hay, partially offsetting yield reductions with potentially higher price for quality hay.

Objectives

The study objectives were to:

1. Quantify alfalfa growth responses and consumed water (ET) under full and limited irrigation regimes.
2. Evaluate alfalfa forage and stand quality under full and limited irrigation regimes.

Methods

The study was located at the Northern Colorado Water Conservancy District (NCWCD) headquarters in Berthoud, CO. Average rainfall at this site is 13-15 inches and the soil type is a clay loam. The elevation is about 5,000 feet above sea level. The water table is located about 20 ft. which was monitored using on-site observation wells. The study area is about 2.5 acres divided into twelve plots each measuring 290 ft. long by 51 ft. wide with a 15 ft. buffer separating each replicate. There were three replicates of four irrigation treatments and the treatments were randomized within each replicate. The plots were irrigated with a state-of-the-art linear sprinkler that had drop valves with solenoids controlled by GPS to automatically turn on and shut off sections of the sprinkler as it passed over the different plots. The irrigation water was ditch water supplied from a holding pond on the site. Dairyland Magna Graze alfalfa from AgLand was planted in August of 2004 and overseeded in 2005 to improve stand density.

Irrigation treatments began in 2006. The four irrigation treatments applied to the alfalfa crop were as follows:

> Full Irrigation (FI) – No water stress. Crop was irrigated to fully meet crop ET demands.
>
> Stop Irrigation After 2^{nd} Cutting (S2) – Crop was irrigated to meet ET demands through the 2^{nd} cutting then received no irrigation for the rest of the season.
>
> Spring and Fall Irrigation (SF) – Crop was irrigated to meet ET demands through the 1^{st} cutting, was terminated, and was resumed after 3^{rd} cutting to meet ET demands during the 4^{th} cutting.
>
> Stop Irrigation After 1^{st} Cutting (S1) – Crop was irrigated to meet ET demands through the 1^{st} cutting then received no more irrigation for the rest of the season.

Yields samples were collected by weighing a 20 ft. section of windrow. Sub-samples from the large sample were taken to determine percent dry matter as well as for forage quality analysis. Dry matter was determined by drying the sample to 0% moisture in an oven at 105°C until no weight change was detected. Once dry matter was determined, that percentage was applied to the total fresh weight and then extrapolated to a full acre. Forage subsamples were ground and analyzed for protein content and fiber digestibility by standard methods and quality analysis was used to compute relative feed value.

ET was determined using a water balance method. This method balances all of the water inputs and losses according to the following formula:

$$ET = \Delta\Theta + I(Irr.Eff.) + P - R - D$$

Where:

ΔΘ is the change in soil moisture during a period of time (ie: cutting).
I is the amount of irrigation applied.
(Irr. Eff.) is an irrigation efficiency factor (95%).
P is the amount of precipitation.
R is run-off (assumed to be zero)
D is the deep percolation (also assumed to be zero)

The ΔΘ value was determined at greenup and after each harvest period by taking soil samples down to 8 feet in 1 foot increments. The samples were weighed wet, then oven-dried at 105°C until no weight change was detected, then weighed dry to determine the moisture in each foot. The moistures for each foot were summed to get an 8 foot profile total. Run-off was assumed to be zero because the irrigations were small (~0.75 in) and the plots were fairly flat. Deep percolation was also assumed to be zero because of the small irrigations, the heavy soil type being able to hold large amounts of moisture, and the deep root system of alfalfa. Stand density was assessed in April 2007 by counting the crowns/ft^2 by randomly sampling in each plot four times to get and average stand density.

Results and Discussion

Alfalfa yields were responsive to irrigation level, decreasing with reductions in irrigation amount. The average total season yields for 2006 were 8.2, 6.4, 5.9, and 3.6 tons ac^{-1} for the FI, S2, SF, and S1 irrigation treatments, respectively (Figure 2). It should be noted that the individual average fourth cutting yields for the FI and SF treatments were almost the same even after two months of water stress in the SF treatment indicating the ability of alfalfa to recover after severe water stress within the growing season. The average total season yields for 2007 were 8.5, 7.9, 7.7, and 6.9 tons ac^{-1} for the FI, S2, SF, and S1 treatments, respectively (Figure 2). It should be noted that the average first cutting yields for 2007 were virtually the same for all four treatments, even after one growing season of water stress for the limited irrigation treatments illustrating again the ability of alfalfa to recover from severe water stress across growing seasons. Also, the average fourth cutting yields for the FI and SF treatments were again similar. Individual cutting yields can also be compared for both years in Figures 3 and 4. Over the two years of the study, with 2006 being a dry year and 2007 being a more average year in terms of precipitation, the average yields were 8.4, 7.2, 6.8, and 5.3 tons ac^{-1} for the FI, S2, SF, and S1 treatments respectively.

The average total season ET values for 2006 were 26.6, 15.6, 15.1, and 10.0 inches for the FI, S2, SF, and S1 treatments, respectively (Figure 3) with only 3.7 inches coming from precipitation. Irrigation amounts were 24.0, 12.0, 11.5, and 3.6 inches for the FI, S2, SF, and S1 treatments, respectively. Also, on average, 1.1 inches of soil moisture was stored in the profile in the FI treatment, 0.1 inches were stored in both the S2 and SF treatments, and 2.7 inches of moisture were extracted from the soil profile in the S1 treatment. These results illustrate that alfalfa will utilize moisture from the soil profile to a greater degree under limited irrigation. This moisture depletion has been accounted for in the ET reported in this study. In 2007 the average total season ET values were 34.4, 23.4, 24.7, and 17.9 inches for the FI, S2, SF, and S1 treatments, respectively (Figure 3) with 11.9 inches contributed by precipitation. Irrigation amounts were 21.3, 9.5, 10.4, and 2.7 inches for the FI, S2, SF, and S1 treatments, respectively. On average, 1.2 (FI), 2.0 (S2), 2.4 (SF), and 3.3 (S1) inches of soil moisture were extracted from the soil profile. The average ET values for both years were 30.5, 19.5, 19.9, and 14.0 inches for the FI, S2, SF, and S1 treatments, respectively. When looking at the change in soil moisture it seems strange that during 2006, the drier year, that moisture was actually stored in some treatments. This may be caused by the alfalfa going into dormancy longer in 2006 than in 2007 and using less water in general and therefore storing some in the soil. The exception is the S1 treatment in 2006 where soil moisture was still used. This may have happened because the alfalfa was in dormancy so long and so little water was applied through irrigation and precipitation that it eventually had to use some from the soil. In contrast, soil moisture was used from profile across all treatments in 2007, perhaps because the alfalfa was more actively growing and was supported by timely precipitation keeping it from going completely dormant.

Water use efficiency (WUE) is reported here as a measure of the amount of hay produced per unit of water consumed (Figure 4). The WUE values for 2006 were 0.31 (FI), 0.41 (S2), 0.39 (SF), and 0.39 (S1) tons ac^{-1} in^{-1}. This data shows that alfalfa under the limited irrigation system uses water more efficiently than under furrow irrigation. A similar trend was observed in 2007, where WUE was 0.26 (FI), 0.33 (S2), 0.31 (SF), and 0.39 (S1) tons ac^{-1} in^{-1} (Figure 4). While these WUE values for individual treatment seem high compared to the literature, when all yield and ET data on a seasonal basis are regressed, the slope of that relationship is 0.234 and 0.116 tons ac^{-1} in^{-1} for 2006 and 2007 with an average slope of 0.185 tons ac^{-1} in^{-1} for both years, which matches very well with the average relationship found in the literature (Figure 1).

The stand density assessment yielded some interesting and, at first, counter-intuitive results. Random sampling found that there were a higher number of crowns per square foot in the S1 and S2 treatments than in the FI and SF treatments (Figure 5). One of the main factors that reduces alfalfa plant density is disease. Perhaps, because the limited irrigation treatments have a drier microclimate in the canopy there is less disease pressure acting on the plants and therefore, preserving the stand. The late season irrigation applications must also have an effect to decrease the crown density in the SF treatment, but it is not understood yet.

Summary and Conclusions

The findings of this study have potentially important implications for alfalfa producers with limited irrigation water supply. Over the two years of the study, an average 11.0, 10.6 and 16.5 ac-in of ET water were saved in the S2, SF, and S1 treatments, respectively, relative to fully irrigated alfalfa. These ET reductions resulted in yield reductions of 1.2, 1.6, 3.1 tons ac^{-1} in the S2, SF, and S1 treatments, respectively. However, as ET declined, WUE increased, indicating more efficient use of water by the crop. For alfalfa producers faced with decreasing irrigation water supplies, this is encouraging. Economically speaking, as production decreases, so should most input costs resulting in only a slightly reduced return per acre. On the other hand, if irrigation water is not limiting but limited irrigation strategies are still employed to conserve water for lease to municipalities to supplement farm income, the enterprise would increase in profitability depending on the market price of water. Currently, water rights cannot be partially leased but there is current debate in the state of Colorado that could lead to allowing such transactions in the future.

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Tables and Figures

Table 1. Average seasonal consumptive water savings of limited irrigation alfalfa relative to fully irrigated alfalfa and the corresponding yield reduction. Results are the average values for 2006 and 2007.

Treatment	**Seasonal Consumptive Water Savings (ET ac-in)**	**Seasonal Yield Reduction (tons/ac)**
Full Irrigation	0	0
Stop Irr. After 2nd	11.0	1.2
Spring and Fall Irr.	10.6	1.6
Stop Irr. After 1st	16.5	3.1

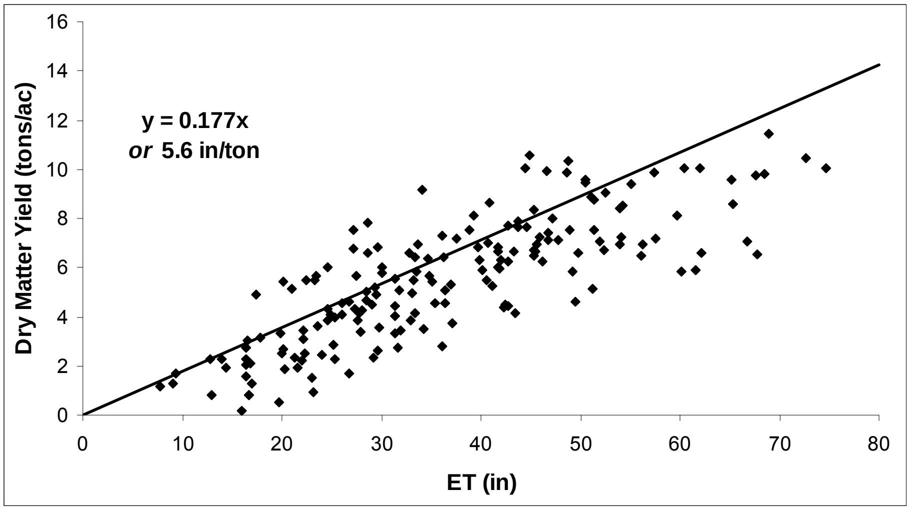

Figure 1. Alfalfa yield response to evapotranspiration (ET) as summarized from published studies (Daigger et al, 1970; Bauder et al, 1978; Retta and Hanks, 1980; Sammis, 1981; Guitjens, 1982; Carter and Sheaffer, 1983; Undersander, 1987; and Smeal et al, 1991). To avoid skewing the fit line towards one study, points were weighted so that indidual study sites are equal in importance, regardless of the number of data points from that site.

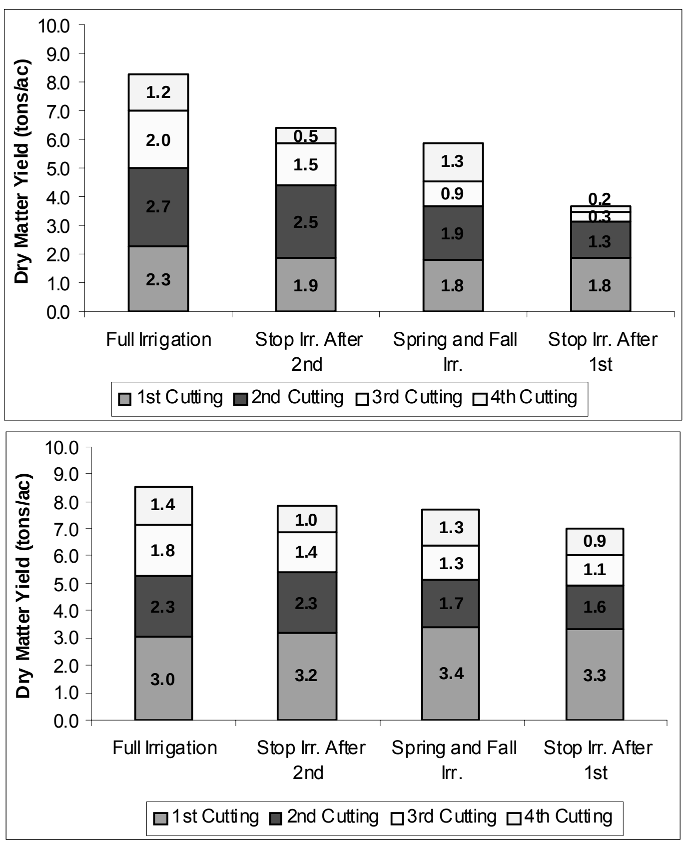

Figure 2. Alfalfa yields as affected by irrigation treatments for 2006 (upper) and 2007 (lower) seasons at Berthoud, Colorado.

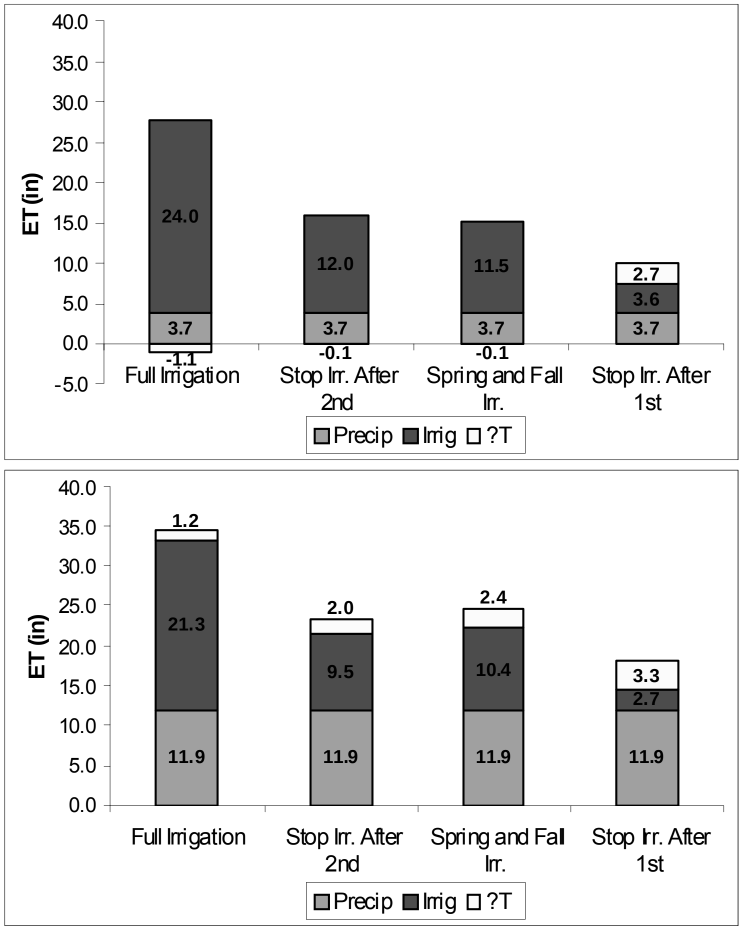

Figure 3. Consumptive water use (ET) from alfalfa as affected by irrigation treatments for 2006 (upper) and 2007 (lower) seasons at Berthoud, Colorado. ET is reported by contribution from precipitation, irrigation, and the use or storage of moisture in the soil profile.

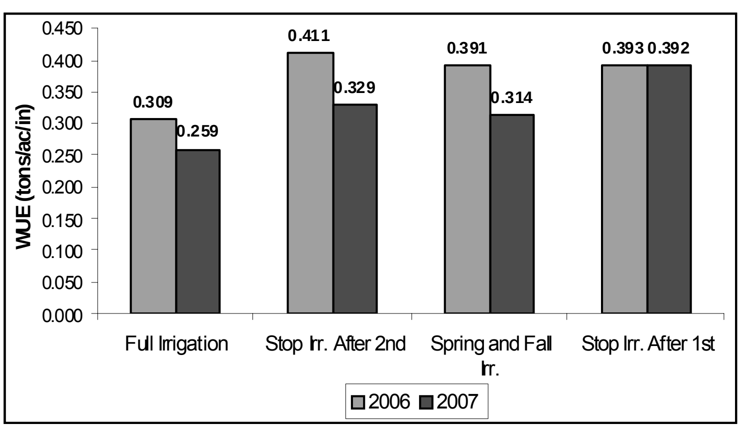

Figure 4. Water use efficiency (WUE) for alfalfa as affected by irrigation treatments for 2006 and 2007 seasons at Berthoud, Colorado.

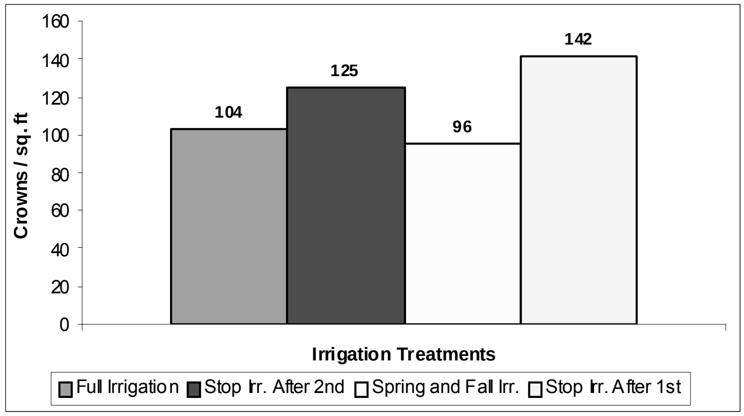

Figure 5. Alfalfa crown density measured in the spring of 2007 to determine the effect of 2006 irrigation treatments on stand at Berthoud, Colorado.

OILSEED PRODUCTIVITY UNDER VARYING WATER AVAILABILITY

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INTRODUCTION

Meeting the growing demands for fuel in the United States will require a variety of alternative energy strategies and technologies. One of the emerging sources of alternative energy is biofuels, and one of those biofuels is biodiesel. Biodiesel can be produced from oil extracted from a number of oilseed crops, including canola (*Brassica napus* L.), mustard (*Brassica juncea* L.), camelina (*Camelina sativa* L.), sunflower (*Helianthus annuus* L.), safflower (*Carthamus tinctorius* L.), and soybean (*Glycine max* L.). This paper discusses basic agronomic differences between these crops, their responses to varying water supply, and expected dryland and irrigated yields for northeastern Colorado.

BASIC CROP DESCRIPTIONS

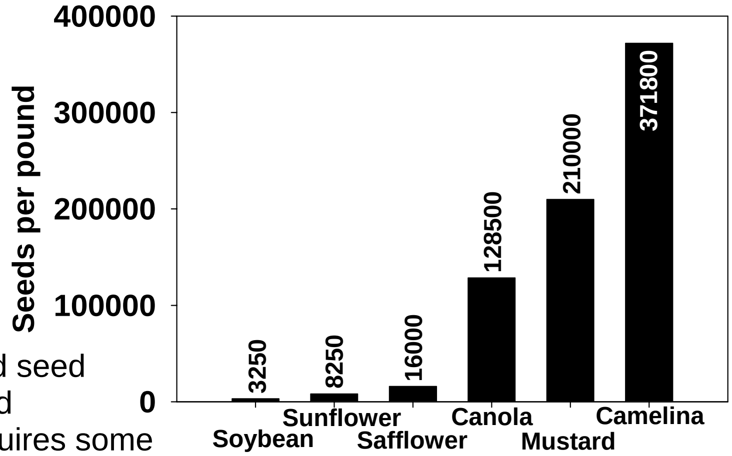
Canola, mustard, and camelina are Brassica crops, among the oldest cultivated plants known to humans (Raymer, 2002). The term “canola” is a registered trademark of the Canadian Canola Association and refers to cultivars of oilseed rape that produce edible seed oils with less than 2% erucic acid (22:1) and meals with less than 30 mmol of aliphatic glucosinolates per gram (Raymer, 2002). In northeastern Colorado all three are generally planted in the early April and harvested in late July. Seed oil contents for these species generally run between 37 and 45%.

Sunflower and safflower are both deep-rooted species. Sunflower is native to the Americas while safflower is believed to have originated in southern Asia. Oil content generally runs from 40 to 47% for both species. Sunflower is generally planted in late May and matures by the end of September, while safflower is planted at the beginning of May and harvested at the end of August.

Soybean is a legume native to east Asia. It is generally planted in mid-May and harvested at the end of September. Oil content generally runs 18 to 20%.

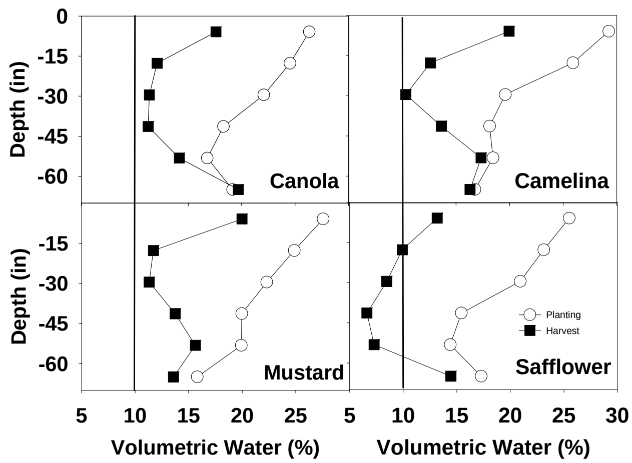
SEED SIZE

There is wide variation in the seed size of the six oilseed crops. The figure shows that the number of seeds per pound ranges from 3250 seeds per pound for soybean to 371,800 seeds per pound for camelina. The small seed size for canola, mustard, and camelina generally requires that a good seed bed be formed to ensure good germination. That usually requires some tillage operations and a rolling operation to pack and firm the seed bed. Accurate depth control on the seeding drill is also essential for proper placement of these small seeds. On the other hand, the larger seeds of sunflower and soybean, while easier to plant, require more water for imbibition and germination to occur.



SOIL WATER EXTRACTION

In the figure at the right the open circles are soil water content at planting, and the filled squares are water content at harvest. The space between the two lines is an indication of the amount of soil water extracted. Canola, mustard, and camelina extract soil water mostly from the top four feet of the soil profile. More water is extracted by safflower (and sunflower, not shown) in the fifth foot. Safflower and sunflower can extract soil water to lower water contents (less than 10% volumetric water content) than canola, mustard, and camelina. Other data (not shown) indicates that safflower and sunflower can extract soil water to less than 10% water content in the sixth foot as well.



This more aggressive soil water extraction by safflower and sunflower compared with the other oilseed species means that subsequent crop yields will be adversely affected by safflower and sunflower as the previous crops in a cropping system, and that dryland farmers will likely need to incorporate a year of fallow into the system before another crop is planted. Irrigated producers will need to perform some off-season irrigations to restore soil water contents to near field capacity in the lower half of the soil profile prior to planting the next crop.

PRODUCTION FUNCTIONS

The seed yield response of five of the six oilseed crops to water use is shown in the figure to the right and the regression equations for the production functions are given in Table 1. The regression slopes (determined at Akron, CO) range from 110.5 lb/a per inch of water use for camelina to 175.2 lb/a per inch of water use for canola. Soybean shows the highest seed yield for any given amount of water use. The production functions estimate that canola, camelina, safflower, and sunflower will all yield about the same for water use in the 15 to 20 inch range (approximately 1470 to 2170 lb/a).

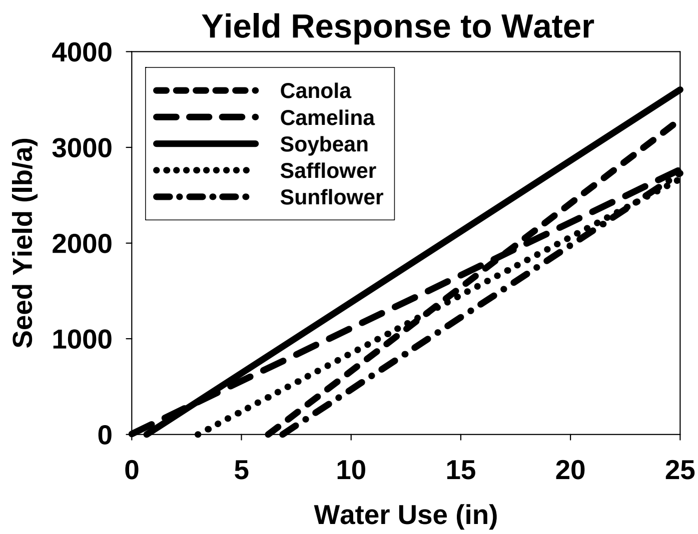


Table 1. Linear regression production functions for five oilseed crops grown at Akron, Colorado.

Crop	Production function (seed yield [lb/a] vs. water use [inches])
Canola	lb/acre = 175.2*(in – 6.2)
Camelina	lb/acre = 110.5*(in – 0.0)
Soybean	lb/acre = 148.1*(in – 0.7)
Safflower	lb/acre = 121.4*(in – 3.0)
Sunflower	lb/acre = 150.6*(in – 6.9)

ESTIMATING YIELDS UNDER A RANGE OF WATER AVAILABILITY

Table 2 shows seed yields predicted using the production functions given in Table 1 (assuming average growing season precipitation and six inches of soil water extraction) at three Great Plains locations. The production functions indicate that soybean would produce the largest yields at all of the locations under all of the water availability conditions. However, soybean yields would likely be lower than shown due to seed loss from not being able to effectively harvest the lowest node of pods (podding to close to soil surface) and seed shatter as pods spontaneously open due to very low afternoon humidity and high winds at harvest time in the Great Plains . Also it should be remembered that the oil content of soybean seed is lower than that of the other oilseed crops. For the other four crops grown at Briggsdale, camelina would yield highest under rainfed conditions and with three inches of irrigation, but canola would yield highest with six inches of irrigation (2093 lb/a). At all three locations and all three water availability conditions sunflower yields the least of all of the oilseed crops.

Table 2. Estimated seed yields of sunflower, safflower, camelina, canola, and soybean at three Great Plains locations assuming six inches of soil water use and average precipitation, average precipitation plus three inches of irrigation, and average precipitation plus six inches of irrigation.

Location	**Crop**	**Rainfed**	**3” Irrigation**	**6” Irrigation**
		lb/a		
Briggsdale, CO	Sunflower	863	1315	1767
	Safflower	1306	1670	2034
	Camelina	1350	1681	2013
	Canola	1042	1568	2093
	Soybean	2087	2531	2975
Wray, CO	Sunflower	1056	1508	1959
	Safflower	1570	1935	2299
	Camelina	1604	1935	2267
	Canola	1445	1971	2496
	Soybean	2365	2809	3254
McCook, NE	Sunflower	1285	1737	2188
	Safflower	1802	2166	2531
	Camelina	1805	2136	2468
	Canola	1764	2290	2815
	Soybean	2636	3080	3525

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RESPONSE OF CORN TO DEFICIT IRRIGATION AND CROP ROTATIONS

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Introduction

Dwindling water supplies for irrigation are prompting alternative management choices by irrigators. Deficit irrigation, where less water is applied than full crop demand, may be a viable approach. Application of deficit irrigation management to corn was examined in this research. A field study was designed to test crop management that (1) took advantage of delayed irrigation during crop vegetative growth, (2) reduced irrigation when water applications were unable to supply the full potential of crop yields, and (3) used no-till practices to reduce soil water evaporation and achieve other soil and water conservation benefits. Multi-year crop performance results were needed to determine the yield risks for adopting deficit irrigation practices. The specific objectives of this study were to: (1) find relationships of irrigation and crop yield, (2) determine crop evapotranspiration (ETc), (3) measure soil water gains non-growing season and soil water use during the growing season, (4) predict the probabilities for achieving grain yields.

METHODS

Crop rotation research with full irrigation, deficit irrigation, and dryland management was conducted at the West Central Research and Extension Center of the University of Nebraska-Lincoln at North Platte, Nebraska located at 41.1° N, 100.8° W and 2800 feet above sea level (Schneekloth et al. 1991; Hergert et al., 1993). The semiarid climate in North Platte is characterized by frequent and rapid changes in weather conditions throughout the year. The average annual precipitation is approximately 19 inches, which is 36% of annual reference ET (ETr) using alfalfa as the reference crop (Kincaid and Heermann, 1984). The soil texture was predominantly Cozad silt loam (fluventic Haplustoll) with pH of 7.5. Plant-available soil water holding capacity was 0.17 $ft^3\ ft^{-3}$ for volumetric soil water contents from 32% for field capacity to 15% for permanent wilting. The land slope was less than 1%.

The crop rotations were continuous corn (CC) and wheat-corn-soybean (WCS). Both rotations were managed with no-till practices and non-limiting fertility and pest management. Corn was planted directly into the previous crop's residue with a no-till planter equipped to apply starter fertilizer. The rest of the nitrogen was applied near the four to six leaf growth stage. Pre-emergence and post-emergence herbicides were applied as needed.

Irrigation to meet full crop ET (ETc) was scheduled from measurements of soil water deficits in each crop rotation treatment. An annual water allocation was restricted to 6 inches for the deficit irrigation treatments unless there was sufficient soil water to achieve full ETc. Deficit irrigation was scheduled to favor applications during critical growth stages for crop development. For corn, irrigation was reduced or withheld during the vegetative period and concentrated on reproduction and grain fill.

Soil water was measured weekly to a depth of 6 ft. in 1 ft. increments with the neutron attenuation method (Evett and Steiner, 1995). Precipitation, net irrigation, and changes in soil water from one measurement to the next were used to calculate weekly ETc. Drainage was assumed to be minimal within the one-week sampling interval of soil water and was not included in the soil water balance. Water runoff and run-on to the plots were observed to be zero. ETr, referenced to alfalfa, was estimated with a Penman combination model, which used maximum and minimum daily air temperatures, relative humidity, solar radiation, and daily wind run as inputs.

RESULTS AND DISCUSSION

PRECIPITATION & IRRIGATION

Cropping season precipitation (table 1) was the sum of all precipitation that occurred from October in the year preceding corn planting through September of the growing season. Cropping season precipitation as a percentage of long-term average annual precipitation provided a characterization of wetter or drier years. The criterion for wetter and drier years was ±95% of the average cropping season precipitation, which divided the years into two equal groups. Years 1985, 1989, 1990, 1991, 1994, 1997, and 1998 were considered drier than the long-term average. Years 1986, 1987, 1988, 1992, 1993, 1995, and 1996 were considered wetter. Precipitation during the growing season also was a factor for crop yields. Drier years had less than 12 inches of rain during May through September, while the precipitation in the wetter years for the same time period was 12 to 24 inches. Another indicator of crop performance was rainfall for April, May, and June because this water accumulated closest to crop water needs was more effective than earlier precipitation. For example, 1995 was classified as wetter overall; however, adequate early growing season rainfall was followed by very dry months of July and August, which coincided with periods of high ET demand.

Table 1. Cropping season precipitation (inches) for Oct. 1-Sep. 30.

Drier Years	1985	1989	1990	1991	1994	1997	1998
Precipitation	17.7	13.8	10.8	14.9	16.7	11.2	17.3
% of Avg.	89	69	54	74	84	56	86
Wetter Years	1986	1987	1988	1992	1993	1995	1996
Precipitation	21.2	20.8	25.7	21.1	20.6	19.4	25.0
% of Avg.	106	104	129	105	103	97	125

Average annual irrigation (table 2) was less than anticipated. The first water applications on the deficit irrigation plots often were later than those on the full irrigation plots. Timely precipitation events during June were more effective for the deficit irrigation when irrigation was delayed.

Table 2. Average annual irrigation (in) applied to corn at North Platte, Nebraska, during 1985-1999.

	-Deficit Irrigation--		--Full Irrigation--	
	CC	WCS	CC	WCS
Irrigation	4.7	4.6	10.1	9.9
% of Full	47	47	---	---
Annual Precip.	18.5	18.5	18.5	18.5
c. Precip. + Irr.	23.2	23.1	28.6	28.4

Cropping season precipitation plus irrigation for the full and deficit irrigation treatments correlated with ETr (data not shown). Irrigation plus precipitation was from 23.2 to 28.4 inches during the fourteen years of record, which was 80% to 125% of the mean. Atmospheric demand for evaporation was predicted by ETr, which ranged from 0.16 to 0.30 inch day^{-1} and from 61% to 121% of the mean.

GRAIN YIELD

Average corn grain yields were 70% to 127% of the mean for 1985-1999 (tables 3). More or less, corn production followed the pattern of wetter and drier years, except for 1995, which had the least precipitation in July and August. Corn yields were statistically different among water treatments and increased with additional irrigation. Corn yields from the WCS rotation were significantly more (10 bu ac^{-1}) than CC during 1985-1999, which could be attributed to more off-season gains in stored soil water and in-season use of stored soil water in the WCS rotation..

Table 3. Results for corn in the continuous corn (CC) and wheat-corn-soybean (WCS) rotations at North Platte, Nebraska, during 1986-1998.

	Yield[b]	IWUE[c]	CS[d] Precip	Net Irr.	SW Gain[e]	SW Use[f]	ETc/day[g]	ETr/day[g]	
	bu/ac	bu/ac-in	in	in	in	in	in/day	in/day	Etc/ETr
(a) Irrigation as an independent variable over years and rotations									
Dryland	116 c	--	16.6	0.0	8.1 a	7.6 a	0.19 c	0.25	0.77
Deficit	158 b	8.9 a	16.6	4.7	6.0 b	5.7 b	0.22 b	0.25	0.88
Full	175 a	5.9 b	16.6	9.8	4.4 c	3.2 c	0.27 a	0.25	1.06
$LSD_{0.05}$	6	1.1	--	--	0.8	0.7	0.01	--	0.04
(b) Rotation as an independent variable over years and water treatments									
CC	137 b	---	16.6	7.2	4.5 b	4.9 b	0.22 b	0.25	0.88
WCS	147 a	---	16.6	7.2	7.8 a	6.1 a	0.23 a	0.25	0.93
$LSD_{0.05}$	5	---	--	--	0.7	0.6	0.01	--	0.03

[a] Means followed by the same letters in the same column and independent variable are not significantly different.

[c] IWUE = irrigation water use efficiency (irrigated yield - dryland yield)/(irrigation amount).

[d] Cropping season precipitation from Oct. 1 of previous year to Sept. 30 of current year.

[e] Off-season soil water accumulation from previous fall through the current spring.

[f] Growing season stored soil water use.

[g] ETc and ETr = crop and reference ET during soil water measurement period.

More soil water was accumulated and consumed in the WCS rotation because more time was available to accumulate soil water after winter wheat harvest than after the corn harvest

Irrigation water use efficiency (IWUE = [irrigated yield - dryland yield] / [irrigation amount]) was calculated for the deficit and full irrigation treatments. IWUE was consistently more for deficit irrigation than full irrigation because the first increment of irrigation was used more efficiently than additional irrigation. Full irrigation had more possibility for more soil water evaporation from more frequent surface wetting.

Soil Water

Growing season use of soil water (tables 3) tended to correlate with off-season gains in soil water. Available soil water holding capacity in the deep silt loam soil at the research site contributed to the ability to store water. Gains and use of soil water increased with less irrigation because roots grew deeper, creating more soil water storage volume to hold off-season precipitation. Dryland corn extracted water from as much as 7 feet deep into the soil, while fully irrigated corn extracted most of its water from the top 3 feet of soil (data not shown). When the CC and WCS rotations were compared, soil water gain and use were significantly different from each other. More time was available for soil water accumulation in the WCS rotation because corn followed winter wheat rather than corn in the CC rotation. Stored soil water use was 15%, 27%, and 52% of ETc for full irrigation, deficit irrigation, and dryland, respectively. Less stored soil water contributed to ETc as more irrigation was added. Stored soil water was 27% to 32% of ETc across the three crop rotations.

ETc and ETc/ETr (tables 3) increased significantly for each water treatment from dryland to full irrigation. However, ETc and ETc/ETr remained nearly constant across crop rotations. Additional irrigation was used to increase ETc, and more off-season soil water accumulation from dryland management also contributed to more ETc.

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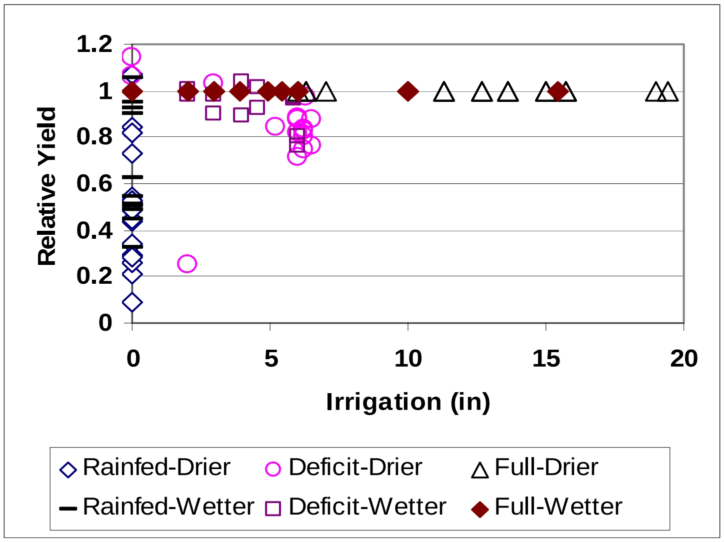

Figure 1. Crop yields as a fraction of fully irrigated yields for the drier years of 1985, '89, '90, '91, '94, '97, and '98 and the wetter years of 1986, '87, '88, '92, '93, '95, and '99.

RELATIVE GRAIN YIELD

Deficit irrigation and dryland corn yields were scaled as a fraction of fully irrigated yields from the same year (fig. 1). Data from all crop rotations were used in this analysis. The range of relative yields from dryland management (*y*-axis of fig. 1) was 0.10 to 1.15 in the drier years and 0.20 to 1.05 in the wetter years, which indicated somewhat more variation in yields from the drier years. The deficit irrigation applications generally were more during the drier years than the wetter years. Deficit irrigation increased relative yields compared with dryland yields and decreased the risk for yield results because added irrigation reduced the range of relative yields to 0.2 to 1.2 for the wetter years and 0.75 to 1.15 for the drier years. The range of full irrigation applications demonstrated that irrigation scheduling was necessary to capitalize on water conservation during the wetter years and match ETc during drier years.

YIELD PROBABILITY

Corn yields were ranked from maximum to minimum by water treatments for all years and crop rotations. The ranked data were divided into seven groups of probability values by years (fig. 2). Annual rainfall was 640, 610, 560, 510, 460, 430, and 410 mm for the 14%, 28%, 42%, 56%, 70%, 84%, and 98% probability levels, respectively (NOAA, 2007). Corn yields for each grouping of vertical bars would be expected to exceed that amount *X* years out of 100 years. For the least probability or wettest years (14 out of 100 years), all water treatments had similar yields. As probability increased from wet to dry years, irrigated corn yields decreased, but the dryland yields decreased more dramatically.

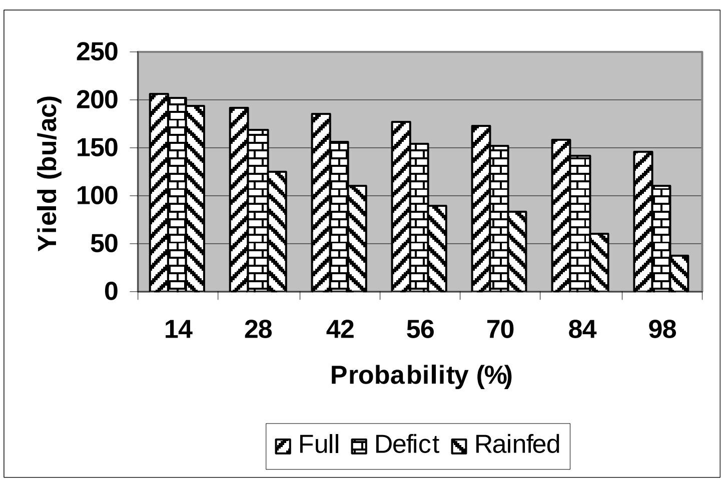

Figure 2. Percentage of time that crop yields exceed a given amount. Results based on yield history for the years 1985-1999.

SUMMARY

Corn was grown in a no-till cropping system using best management practices to apply water to deficit and full irrigation treatments. Deficit irrigation was initiated late in the vegetative growth stage or early in the reproductive stage, while full irrigation was applied to meet ETc during the growing season. The deficit irrigation treatment received no more than 6 inches of water, which was timed to favor supplying water during the reproductive and grain fill growth stages. Continuous corn (CC), and wheat-corn-soybean (WCS) crop rotations were grown in the dryland, deficit irrigation, and full irrigation treatments. Corn yields were statistically different among dryland, deficit irrigation, and full irrigation treatments and increased with added irrigation. Corn yields were statistically more in the WCS rotation than the CC rotation across water treatments. ETc was significantly different among water treatments, increasing with additional irrigation, but there was a small crop rotation effect on ETc. Irrigation water use efficiency (IWUE), defined as the additional crop yield over dryland production divided by irrigation, was significantly more from deficit irrigation than full irrigation.

From soil water parameter measurements, corn in the WCS was able to use more stored soil water than the CC rotation, which led to less dependence on irrigation. The dryland treatment accumulated significantly more soil water during the non-growing season than the deficit or fully irrigated treatments because the dryland corn was forced to extract more soil water deeper into the soil profile, leaving more room for water storage.

Dryland yields, as a fraction of fully irrigated yields (relative yield), varied more than deficit irrigation yields, which decreased the income risk for deficit irrigation compared with dryland. Over the years of the study, a wide range in water applications to the full irrigation treatment demonstrated the need to schedule irrigations to match crop water needs; otherwise, over and under irrigation could occur. When crop yields from all years and rotations were ranked from maximum to minimum values within each water treatment, yield results were predicted on the basis of probabilities. During the wettest years with low probability of occurrence, dryland, deficit irrigation, and full irrigation yields were nearly the same. As probabilities to achieve yields increased, indicating drier and drier years, dryland yields were 25% of fully irrigated yields, and deficit irrigation yields were 75% of fully irrigated yields at 98% probability of occurrence.

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LIMITED IRRIGATION RESEARCH AND DEMONSTRATION IN COLORADO

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The combination of climate variability, drought, groundwater depletion, and increasing urban competition for water has created water shortages for irrigated agriculture in Colorado and is driving the need to increase water use efficiency. A statewide water supply survey predicts that 428,000 irrigated farm acres will be converted to dryland cropping or pasture within the next 15 years, mostly due to transfer of water from agricultural uses to meet the water needs associated with population growth (Colorado Water Conservation Board, 2004). A shift from irrigated to dryland cropping would significantly impact the economic viability of agricultural producers and have far reaching indirect effects on businesses and communities that support irrigated agriculture.

Water conservation options other than complete land fallowing are desirable because of the potential economic and environmental concerns associated with conversion to dryland. One approach to reducing consumptive use of irrigation water is adoption of limited irrigation cropping systems. With limited irrigation, less water is applied than is required to meet the full evapotranspiration demand of the crop. Crops managed with limited irrigation experience water stress and have reduced yields compared to full irrigation, but management is employed to maximize the efficient use of the limited irrigation water applied. These systems are a hybrid of full irrigation and dryland cropping systems and are currently of great interest to Colorado farmers. Successful limited irrigation systems are based on the concepts of: 1) managing crop water stress, 2) timing irrigation to correspond to critical growth stages for specific crops, 3) maximizing water use efficiency by improving precipitation capture and irrigation efficiency, and 4) matching crop rotations with local patterns of precipitation and evaporative demand. Research in the Great Plains illustrates that limited irrigation cropping systems are significantly more profitable alternatives than dryland (Schneekloth, 1991 and 1995).

METHODS

Two demonstration sites were developed in 2006. Site 1 is located near LaSalle, Colorado on a sandy loam soil. This field is furrow irrigated and the crop rotation is continuous corn. Irrigation management strategies include full irrigation management and limited irrigation management. Limited irrigation management tries to limit water during the vegetative growth stage and irrigate during the reproductive growth stage. Cultural practices such as populations were also studied at this site. Impacts on reducing plant populations with limited and full irrigation management were observed.

A second site was located near Burlington, Colorado on a silt loam soil. This field is center pivot irrigated. Alternative water management strategies were studied at this site within a 4-year crop rotation of corn-sunflower-soybean and winter wheat. This study looked at full irrigation management, an average allocation of 10 inches per year and an intermediate irrigation management strategy that limits water applied between that of full irrigation and allocation management.

RESULTS

LaSalle

Reduced irrigation compared to full irrigation reduced corn yields for limited irrigation (Figure 1). Full irrigation grain yields were 182 and 190 bu/acre for 2006 and 2007 respectively. Reducing irrigation during the vegetative growth stage reduced grain yields to 155 and 151 bu/acre for 2006 and 2007 respectively. This was an average yield reduction of 18% for limited irrigation compared to full irrigation. Irrigation was reduced from an average of 28 inches for full irrigation to 15.5 inches for limited irrigation (Table 1). The irrigation for limited irrigation was 55% of full irrigation. Precipitation for both 2006 and 2007 was below average. Average growing season precipitation is approximately 7 inches.

Reducing plant populations may be a strategy to reduce input costs and limit crop evapotranspiration during the growing season. Plant populations did impact grain yield for each of the irrigation strategies. For full irrigation management, 34,000 plants per acre resulted in slightly greater yields as compared to 26,000. Reducing the population to 20,000 plants per acre reduced grain yield by 15 bu/acre. However, with limited water, reducing plant population from 34,000 to 26,000 did not impact grain yield on average. Reducing the plant population to 20,000 plants per acre reduced the grain yield for limited water by 14 bu/acre, which was similar to that of full irrigation. Reducing plant populations below 26,000 plants per acre is not regarded as an economical practice for limited irrigation. If a water savings and increase in yield was to be obtained, 2006 and 2007 should have been optimal years due to the limited amounts of precipitation during the growing season.

Grain yield components such as kernels per ear, ear length and kernel weight were taken. At the optimum plant population for each of the irrigation strategies, the number of kernels per ears was not significantly greater for full irrigation as compared to limited irrigation. Ear length was slightly greater for limited irrigation compared to full irrigation, but was offset by a reduction in the number of kernels around the ear. Kernel weight was less for limited irrigation than full irrigation by almost 20%. This reduction is similar to the reduction in grain yield for limited irrigation compared to full irrigation.

Burlington

Average grain yields for corn and soybeans were reduced when irrigation was limited as compared to full irrigation. However, in 2006, corn grain yields for all irrigation strategies were similar. Precipitation during 2006 was above average for the growing season by 1.0 inches. Timing of irrigation for the reproductive growth stage did increase early season utilization of stored soil moisture (Figure 2). Approximately 1.4 inches of stored soil moisture was utilized for allocation irrigation as compared to full irrigation. Irrigation requirements for allocation management were 8 inches while full irrigation required 12 inches. This is less than what is estimated for full irrigation management in a normal year. However, there is a potential savings of 4 inches of applied irrigation when limiting water during the vegetative growth stage.

Grain yields in 2007 were less than in 2006. Approximately two weeks prior to tassel, a severe infestation of corn rootworm was noted in the entire field with 6 larvae per plant being observed. The allocated and intermediate corn was more severely impacted as compared to full irrigation. An insecticide was applied at planting but apparently failed due to insect pressure. After visual observations of damage were taken, it was noted by entomologist that the reduction in grain yield by damage to the roots was approximately 20% for full irrigation. This would have increased yields too approximately 200 bu/acre which was observed in adjacent fields with this variety. The yield reduction for the allocation irrigation was adjusted at approximately 40%.

Soybean grain yields (Table 2) were greater for full irrigation than either intermediate or allocation irrigation by 7 to 10 bu/acre. Grain yields in 2006 were substantially less than would be expected due to herbicide damage. Residual dicamba was in the farmers' sprayer and damage was done when the soybeans were sprayed with glyphosate. Evidence of herbicide damage was evident by leaf cupping on the top of the soybean plants. Soybean yields of a test plot near this region had soybean yields for this variety average near 70 bu/acre.

In 2007, soybeans were drilled. Grain yields for full irrigation were 56 bu/acre with intermediate and allocation management yields of 50 and 45 bu/acre. Although yields were greater than 2006, harvest loss was significant. A fixed 30 foot wheat header was used for harvest. The ability to adjust the location of the head in the field was difficult and losses for the entire field averaged 28 plus bu/acre. The potential yield of the soybean was 70 to 80 plus bu/acre. These yields were also verified by crop adjuster estimates. After further discussion with the producer, harvesting of the soybeans will be changed to include a flex-header. This harvesting equipment floats along the soil surface and automatically adjusts to terrain differences. Irrigation requirements for full irrigation soybeans in 2007 were 13 inches with 9 inches applied to allocation management.

Sunflowers respond well to limited amounts of irrigation. Sunflower grain yields in 2006 averaged 2500 to 2600 lbs per acre for allocation and intermediate irrigation management (Table 2). Full irrigation yields were 2400 lbs per acre. These yields were 400 to 500 lbs per acre less than hand harvested yield. Harvest losses were greater than expected due to increased lodging from insect pressure. Oil content for the allocation and intermediate management averaged 47% while full irrigation management oil content was 42%. This yield response is similar to previous research which has shown in average precipitation years, sunflowers do not respond to irrigation during the vegetative growth stage. Irrigation requirements for full irrigation management were 8 inches while the allocation management had 4 inches of applied irrigation.

In 2007, grain yields for sunflower were less than 2006. Full irrigation management averaged 2050 lbs per acre while allocation and intermediate irrigation management averaged 1700 and 1550 lbs per acre respectively. Harvest losses were again a significant impact on grain yields. Hand harvested yields were approximately 2500 lbs per acre for each of the three management strategies. The full irrigation management sunflowers were planted approximately 1 week later than the intermediate and allocation management sunflowers due to rainfall. The full irrigation management sunflowers did stand better than the earlier planted sunflowers which may have increased harvested yield of the full irrigation compared to allocation management.

CONCLUSION

Limited irrigation management of crops is management intensive and is potentially more risky than full irrigation management. However, research and demonstration projects in Colorado have successfully shown that irrigation water can be reduced and economical yields obtained. Alternative crops such as sunflower and soybeans can reduce the amount of irrigation needed as compared to corn. Education and marketing will play an important factor in the acceptance of these crops for irrigation conservation.

However, under current water law and regulations, water management such as limited water is not practical in years other than water short years in ditch and reservoir systems. In groundwater management areas, declining water resources and compact litigation may force limited irrigation changes with less water in the future.

Figure 1. Grain yield for irrigation strategies and plant population at LaSalle, Colorado.

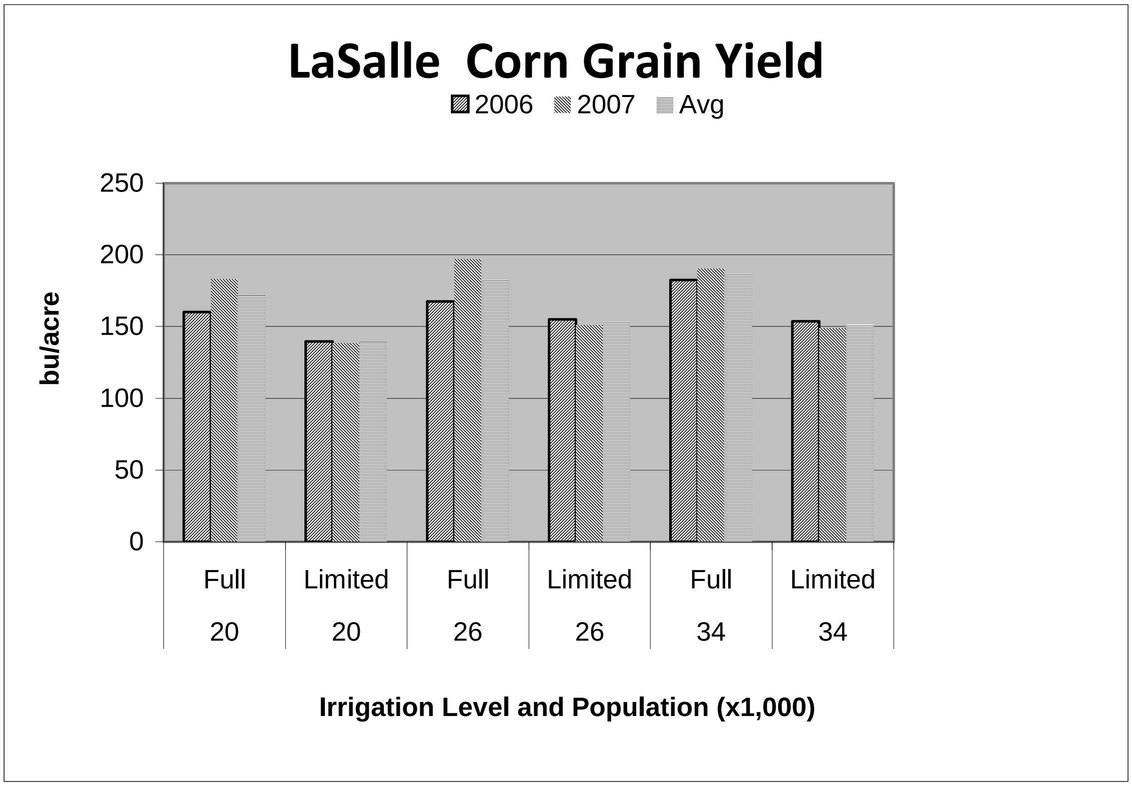

Figure 2. Soil moisture for irrigated corn on July 6, 2006.

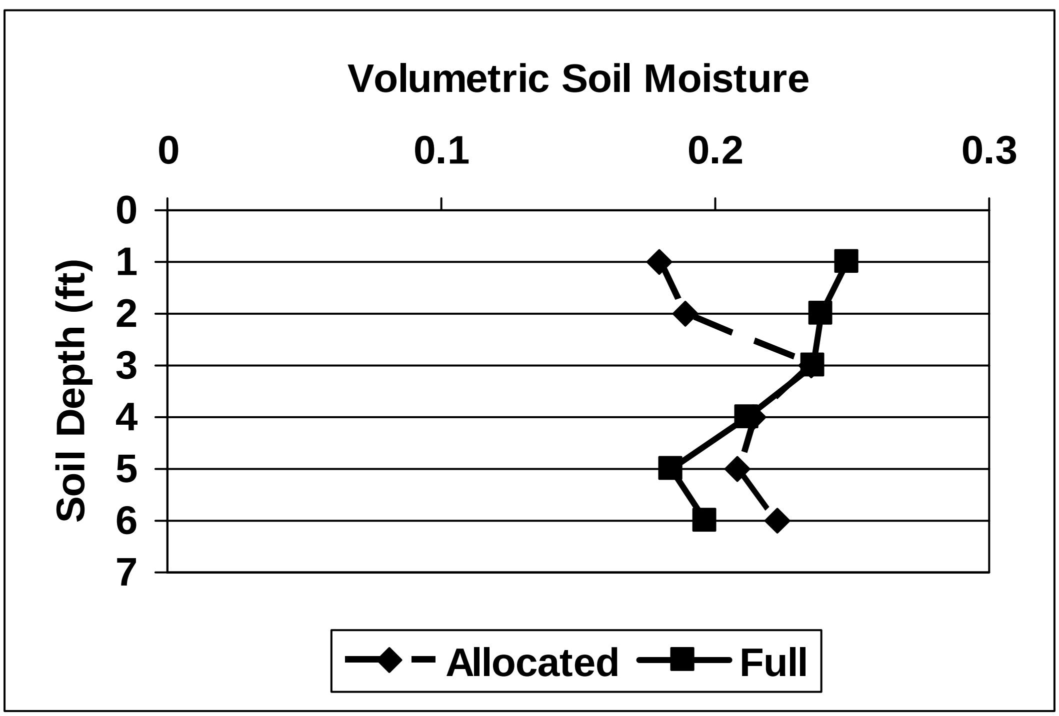

Table 1. Irrigation and precipitation for LaSalle, Colorado.

Year	Full	Limited Inches	Precip.
2006	34.5	18.1	3.0
2007	21	13.1	4.0
Average	27.75	15.6	3.5

Table 2. Grain yields for corn, soybean and sunflower at Burlington, Colorado.

Irrigation	Corn, bu/acre			Soybean, bu/acre			Sunflower, lbs/acre		
Strategy	2006	2007	Avg	2006	2007	Avg	2006	2007	Avg
Allocation	193	127	160	40	45	42.5	2490	1710	2100
Interm.	203	145	174	37	50	43.5	2580	1560	2070
Full	198	160	179	47	56	51.5	2390	2050	2220

LIMITED IRRIGATION CROPPING SYSTEMS FOR CONSERVING WATER RESOURCES IN THE PUMPKIN CREEK WATERSHED

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PROJECT BACKGROUND

Declining ground water is not a new dilemma in Nebraska, however, the drought across the high plains and inter-mountain west the last eight years has magnified the problem. In Nebraska law, surface water is regulated by the Department of Natural Resources (DNR) and ground water is regulated by the 23 Natural Resources Districts (NRDs). In 2002, the North Platte NRD (NPNRD) requested a DNR study to examine the interaction of hydrologically connected ground and surface water in the Pumpkin Creek Watershed (Fig. 1). The report was completed in early 2004 (Patterson, 2004).

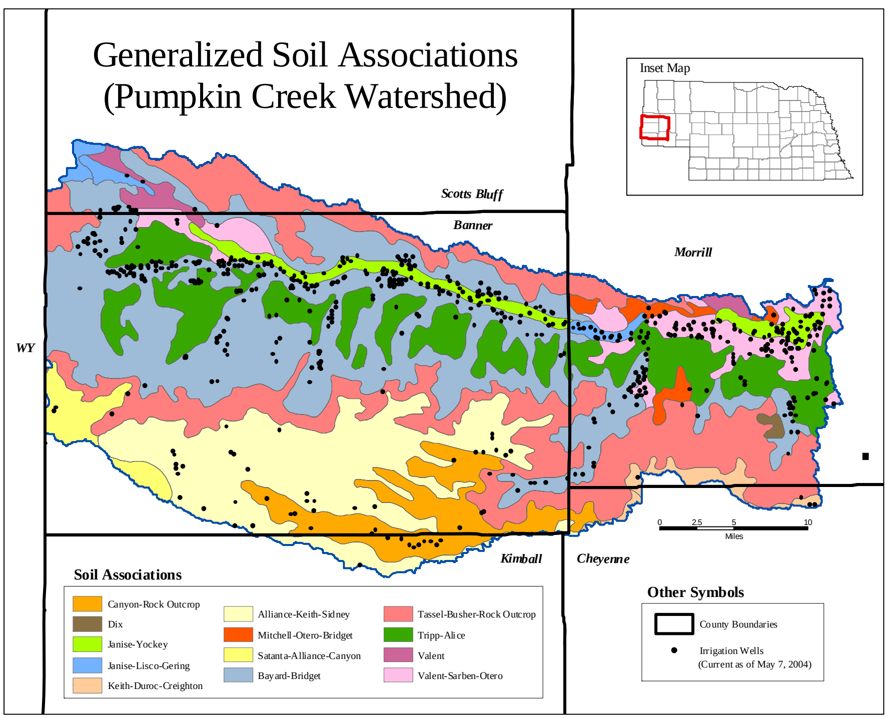


Figure 1. Major soil series and GPS referenced irrigation wells (black dots) in the

Pumpkin Creek Watershed.

The Pumpkin Creek Watershed (PCW) is located in the southern tablelands of the NPNRD. Pumpkin Creek flows into the North Platte River near Bridgeport, NE and on average delivered 20,000 acre feet of water per year until levels began to decline in the 1970's due to ground water development. Pumpkin Creek was closed to new surface water development over 20 years ago due to low stream flow. In 2001 the NPNRD established the Pumpkin Creek ground water management area and ceased new well drilling. Existing wells were metered in 2003 and pumping has been reported since 2004. The NPNRD approved a14 inch allocation in 2004 which has remained in effect.

Reservoir construction in the Rocky Mountains plus diversions of surface flow created irrigation districts in Nebraska beginning in the 1920's. Irrigation from ground water developed slowly in major river valleys through the 1940's until the 1970's, but expanded rapidly in the 1970's due to introduction of center pivots and continued into the 1980's. Research on limited irrigation in Nebraska began in the 1970's at the former UNL Sandhills Ag Lab where Gilley et al., (1980) used line-source sprinkler irrigation to study the effects of water-stressing corn. They found no significant yield reduction when the crop was moderately stressed during the vegetative stage, but significant yield reductions were noted when stress occurred during pollination and grain fill.

Under limited irrigation, less water is applied than is required to meet full evapotranspiration demand. As a result, the crop will be stressed. The goal is to manage cultural practices and irrigation timing such that the resulting water stress has less of a negative impact on grain yield.

The concepts of moisture conservation from dryland no-till ecofallow (Burnside et al., 1980) and the timing of limited irrigation (Gilley et al., 1980) were combined in a project initiated in 1982 at North Platte, NE (Hergert et al, 1993, Schneekloth et al, 1991). Over a 10-year period, this cropping systems approach for stretching limited irrigation (6-inch application per crop) on a silt loam soil showed winter wheat yields were 99% of full irrigation, corn yields were 86% and soybeans were 88% of fully irrigated yields. This area has annual precipitation near 20 inches per year. These concepts have also been successfully tested on producers fields (Klocke et al., 2004). This study showed the obvious--less water means less income, but the good news is that proper management showed that 25-50% reductions in water application only reduced income by 10-20%.

In the Nebraska Panhandle limited irrigation of sugar beet and dry bean showed that late season water stress reduced yield only 7 percent (Yonts, et al., 2003). In a different study (Yonts, 2002), delaying the first irrigation of the season for a one week period, reduced dry bean yield by 5 percent. There had been no major research on no-till limited irrigation cropping systems in the NE Panhandle until

2005, although dryland no-till research had been conduced since the 1960's.

PROJECT OBJECTIVES

The overall goal of this project was to initiate a demonstration project to educate growers about the advantages of using no-till cropping systems to stretch limited irrigation supplies in the Pumpkin Creek Watershed. This project was funded by a USDA NRCS Conservation Innovation Grant with matching support from the NPNRD and the University of Nebraska. The idea was to transfer information from the North Platte research to an area that receives only 15 to 17 inches of annual precipitation.

Individual project objectives were: 1. to demonstrate limited irrigation no-tillage cropping systems that make the best use of natural precipitation and limited ground water supplies 2. to educate area farmers, natural resource groups, local and state government agencies and agricultural businesses about the effect of different management scenarios on production, cultural practices, economics and natural resource impacts, and 3. to develop economic scenario case studies for limited irrigation.

The project built on previous Nebraska limited irrigation research (Hergert et al., 1993, Klocke et al., 2004 Schneekloth et al., 1991). However, part of the innovation and unknown of this project was adapting those concepts to the sandier soils, a different cropping mix (inclusion of dry beans, sunflower, canola, millet) and lower rainfall in western NE compared to North Platte.

PROJECT DESCRIPTION AND RESULTS

A Steering Committee of University specialists, NPNRD and NRCS personnel met to discuss goals and procedure and to help select demonstration sites and cooperators. Cooperators need to currently be practicing no-till and be willing to put up with the extra time required to be a part of a demo project. We also wanted to select representative operations according to size. Cooperators also needed to be willing to host field days and discuss their operations at other educational meetings. Demonstration sites were located to provide easy access during future field days.

Three producers were selected: one in the western part (Alton Lewick), one in the middle (Land and Gary Darnall) and one in the eastern portion (Kirk Laux) of the watershed. The operations also varied in size (Table 1). Current crops grown by the producers were used. We selected one or two halves of a center pivot for the demonstration. Although there is a 14-inch irrigation allocation within the Pumpkin Creek watershed, western portions of the watershed (Lerwick) can only supply 4 to 6 inches of irrigation before water is depleted in early August (it recharges over winter). Irrigation levels of 10 to 11 inches are available in the center (Darnall) whereas the eastern part of the watershed has the deepest aquifer (Laux) and no water limitations. An Extension Educator was hired as the Project Manager.

Table 1. Cooperators, crops and operation description.

Cooperator (irrigation size)	# Pivots	Dry land acres	Crops*	Cows	Range land acres	Feedlot head
Alton Lerwick (small)	2	2,400	WH, SF, Cn, Ml, Fr	300	7,500	0
Kirk Laux (medium)	9	--	C, WH, DB, Fr	300	4,000	3,500
Lane Darnall (large)	15	4,000	C, WH, Cn, Fr	500	8,000	20,000

*C=corn; WH=winter wheat; SF=sunflower; Cn-spring canola; Ml-millet; Fr=forage

Alton Lerwick's site represents a medium size no-till farm and livestock operation and a small irrigated operation located in the western part of the watershed. Alton uses a continuous cropping system with no fallow to maximize crop residue to conserve soil and moisture. Alton Lerwick applies less than 6-inches water per acre to produce various 'conventional' and 'alternative' crops, which require less moisture. These include corn, winter wheat, sunflowers, canola, forage sorghum and millet. Alton's yields were 1,650 lb/ac spring canola in 2005, 60 bu/ac winter wheat (hailed) in 2006 and 1650 lb/ac sunflowers in 2007.

Lane and Gary Darnall's site represents a large no-till farm and livestock operation with a large feedlot in the central part of the watershed. Lane Darnall utilizes his water allocation to grow more conventional crops such as corn and alfalfa for his feeding operation and also grow alternative crops such as winter wheat, irrigated pasture and canola which require less moisture. Lane's yields were 1,100 lb/ac spring canola (high weed infestation) in 2005, 1,200 lb/ac winter canola (winter kill) in 2006 and 52 bu/ac winter wheat in 2007.

Kirk Laux's site represents a medium size no-till farm and livestock operation with a medium feedlot in the eastern part of the watershed. Kirk utilizes a similar water allocation plan as Lane, but with a different cropping system. He uses water from irrigated acres he has 'retired' back to dryland to gain additional water for use on his crops. Kirk grows corn, alfalfa, winter wheat, dry beans and forage turnips for fall / winter grazing for his livestock. Kirk's yields were 48 bu/ac dry beans plus approximately 3.8 tons/ac forage turnips for grazing in 2005 and 40 bu/acre dry beans in 2006; applying approximately 10-inches water each year.

Kirk is also trying something new to the Panhandle - no-till dry beans. He has planted no-till dry beans into corn stalk residue, in 15-inch and 30-inch row spacing's along with drilling. To maintain a no-till system (no undercutting of the dry beans at harvest), he has tried swathing and direct harvest methods. Currently, Kirk has also gone to planting 20-inch row corn and dry beans. The narrow row spacing provides quicker canopy cover to help compete with weeds and help shade the soil surface sooner for moisture conservation. Kirk is also developing a method to direct harvest his dry beans with a Shelbourne Reynolds stripper-header, to maximize crop residue left on the soil surface for soil and moisture conservation.

LESSONS LEARNED

The project has demonstrated that no-tillage can be adapted for the sandy soils in the Pumpkin Creek basin. The three cooperators are using no-till for common and alternative crops and making it work. There is still much work to do to match crops and cropping systems due to the wide range of water availability. Producers practicing limited irrigation must think like a dry land producer who has some irrigation water for only part of the season.

There are also many agronomic and production factors we must ‘perfect’ before making no-till and limited irrigation production systems common practice. There is also the need for additional research information for a wide range of cropping systems to look at conventional and alternative crops that fit the Panhandle plus economics before more producers adopt this system. Work also needs to be done to ‘fine’ tune irrigation systems for improved pumping efficiency.

Field days and tours have demonstrated to neighbors what can be done with less water. Additional field days and / or meetings need to be held to inform more growers and the agricultural community (fertilizer-chemical, implement, financial) to promote the benefits and potential problems with these systems so they can understand them better and work through them.

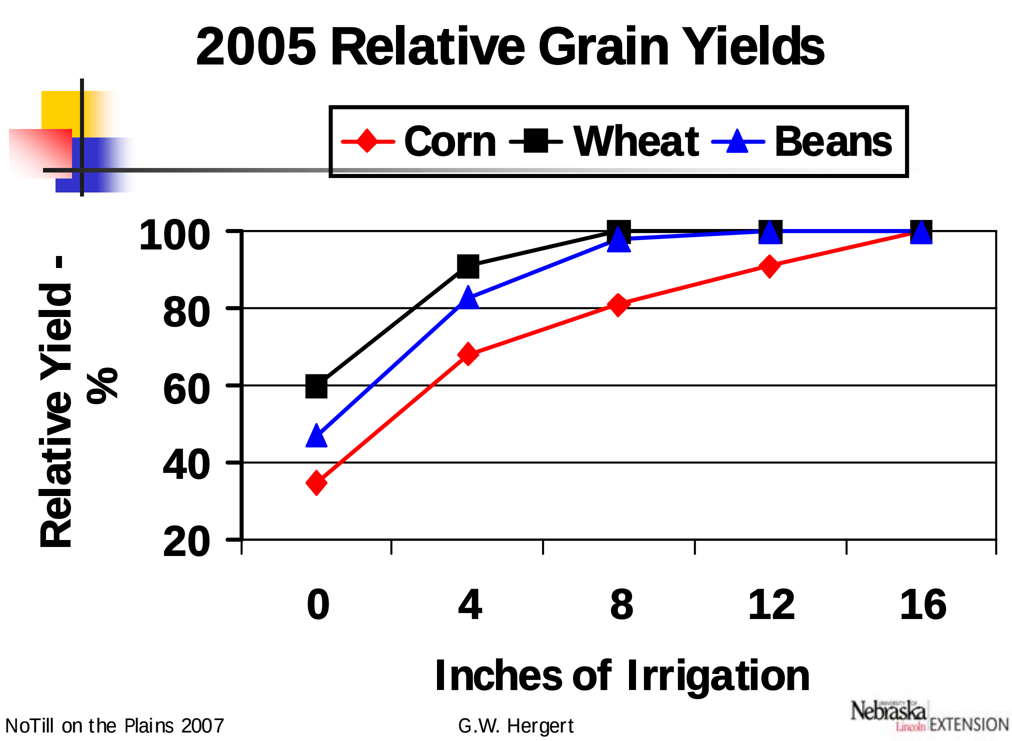
Using limited irrigation cropping and no-till systems can be successfully accomplished if the producer is willing to be patient when switching to these practices. Cropping practices / systems need to be determined and refined by the individual producer for their operation as they become more flexible in their management and marketing practices.

Much of the information about his project ca be found at the following web site: http://www.panhandle.unl.edu/pumpkin_creek/index.htm

SMALL PLOT RESEARCH

Because there were no existing no-till plots at PHREC, complimentary research was started in 2005. A crop rotation including winter wheat-corn-dry bean-spring canola is being used. Irrigation levels are 4, 8 and 12 inches per cropping season except corn which receives 5, 10 and 15 inches. Treatments are replicated four times with each crop present each year in a one-acre block under a linear move system at the Panhanlde R & E Center at Scottsbluff. The soils is a Tripp fine sandy loam (Coarse-silty, mixed, superactive, mesic Aridic Haplustolls) with a pH of 8.4, 1.2% OM and1.3-1.6 inches of plant available water per foot. Rooting depth is usually 4 to 5 feet for a total available root zone water holding capacity of 6 to 8 inches.

Three years of research have been conducted and confirm that the principles applied in the earlier limited irrigation work fit the NE panhandle. The 3 years of the project represented a year with above average precipitation (2005) and tow with below (2006) and much below normal (2007) precipitation. The information will provide the basis to do detailed water balance calculations plus provide information for economic analysis for crops that fit the high plains region and hopefully will be presented next year at this conference.



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SDI CONVERSION--
IMPORTANT CONSIDERATIONS

Bill Carroll
Toro Micro-Irrigation

I.) <u>INTRODUCTION</u>

A.) Brief review of system components (*photo system layout)*

B.) Emitter Types
- 1.) Tape
- 2.) Thin-walled Dripper Line
- 3.) Inline Dripline
- 4.) Permanent SDI Wall -Thickness 13-15 Mil
- 6.) Emitter Spacing – Dependent on Crop / Soil

B.) Benefits of SDI
- 1.) Complete Field Coverage
- 2.) Elimination of Run-off, Evaporation, Deep-percolation, Wind-Drift
- 3.) Spoon-feed Nutrients – Improved Timing
- 4.) Utilize Low Capacity Wells
- 5.) Maximize Yield Throughout Field

C.) Liabilities
- 1.) Rodent / Insect Damage
- 2.) Initial Cost
- 3.) New Irrigation Scheduling Techniques, Maintenance Procedures
- 4.) Germination
- 5.) Clogging
  - a.) Chemical - Precipitates
  - b.) Biological – Algae, Bacteria
  - c.) Physical – Sand, Silt, Clay

II.) <u>DESIGN INPUTS</u>

A.) Field Plat
- 1.) **DIMENSIONS**
- 2.) **SLOPE (FLAT IS 0%)**
- 2.) Well Location
- 3.) Location of Above and Below Ground Infrastructures

B.) **SOIL TYPE**

C.) **WATER SAMPLE – WATER TEST**

D.) **WELL TEST – PRESSURE FLOW CURVE**

E.) Available Well Operating Time
- 1.) Off-Peal Rates / Power Interruption
- 2.) Other Demands On Well

F.) Meet EQIP Design Requirements

III.) <u>SYSTEM CAPABILITIES</u>

A.) Measures of Performance
- 1.) EU
- 2.) Min/Max %
- 3.) Flushing Velocity
- 4.) Application Rate (In/Day)

B.) **FILTRATION** (*photo of filters)*
- 1.) Location
- 2.) Screen
- 3.) Disc
- 4.) Sand Media
- 5.) Centrifugal Separator
- 6.) Disposal of Flush Water

C.) Flushing
- 1.) **FLUSH MANIFOLD**
- 2.) **VELOCITY**
  - a.) Minimum 1.5 ft/sec
  - b.) Quantity of Flush Water (up to 100% + over irrigation)
  - c.) Location of Flush Valves (photo of flush valve)
- 3.) **FREQUENCY**
  - a.) Start-up / Shut-down
  - b.) Pressure/Flow Changes
  - c.) Depends on Water Quality

D.) Irrigation Zones (*photo of PR valve*)
- 1.) **PRESSURE-REGULATING VALVES**
- 2.) Valve Location
  - a.) Accessibility
  - b.) Marking/Recognition
  - c.) Planting, Cultivation, Harvesting Operations
- 3.) Air Vents / Vacuum Release (*photo of air vent)*

E.) System Control
- 1.) Manual
- 2.) Automatic
- 3.) Simple to Complex

4.) Start Small and Simple
5.) Provide for System Expansion and Upgrade
6.) **FLOWMETER / TOTALIZER**
7.) **PRESSURE GAUGES**

D.) Chemigation/Fertigation
1,) **pH CONTROL**
2.) Fertilizer
a.) Nitrogen (moves with wetted front through soil)
b.) Don't mix chemicals (similar to sprayer restrictions)
c.) **WATER SOLUBLE – pH <7.0**
d**.) CLEAR JAR TEST**

IV. INSTALLATION
A.) Good Equipment (*photo of tool bar*)
a.) Tool Bar
b.) Shanks
c.) Reels
d.) **INSPECT SHANKS FOR BURRS, DEBRIS, ETC.**
e.) **DON'T DAMAGE TAPE DURING INSTALLATION**

B.) Plowing In Tape (*photo of installation)*
a.) **SET DEPTH**
b.) **MONITOR CONTINUALLY**
c.) Cover Shank Cuts – Limits Rodent Damage

C.) Connections (*photo of manifold, riser, tape connection)*
a.) Trenching (Trencher – Not Backhoe)
b.) **DRILL PVC – SPECIAL DRILL**
c.) Grommets
d.) **BACKFILL CAREFULLY**
e.) **START UP AND RUN ASAP**

V. OPERATION & MAINTENANCE
A.) Manufacturer's Manuals
B.) As-Built Design
C.) Good Record Keeping

VI. CONCLUSION & QUESTIONS
A.) Do Your Homework
B.) Provide Dealer Good Information
C.) **ASK QUESTIONS**
D.) **CUT CORNERS WITH CAUTION**
E.) **MAKE "APPLES TO APPLES" PRICE COMPARISON**

**Topics in Bold – Vital to System Performance*

CONSIDERATIONS WHEN CONVERTING FROM SURFACE TO MECHANICAL MOVE IRRIGATION

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Summary:

Decisions to make when considering converting from surface irrigation to another form of irrigation can be overwhelming. What type of irrigation to switch to? What changes will need to be made to my management? How do I make this as easy as possible? This paper will focus on suggested steps and irrigation equipment considerations to make the transition easier, more efficient and cost effective when a farmer decides to change to mechanical move irrigation.

Introduction:

The profitability of converting from surface irrigation to a center pivot has been discussed many times in the central plains states (i.e. research by Lamm, 2000) with the focus on differing pumping capacities on crop yield and revenue. In most of these cases the items considered include the cost of the pumping system and the irrigation system, changes to production costs and potential on yield. To a lesser extent some discussion has been on the potential labor savings. The studies date back for many years and include but not limited to Dhuyvetter 1996, Williams, et.al. 1996 and Lamm, et.al. 1997. These studies focused on the impact of sprinkler irrigation capacity on corn yield potential and economics. Some manufacturers offer information for the conversion to mechanical move irrigation, Lindsay, 2003 and Valmont 2003.

In recent years with the help of the EQIP program, the economics have changed and incented farmers to consider conversion to other forms of irrigation to reduce on farm water use. Another driver for conversion is water limitations either through availability or regulation. This is becoming more and more of a consideration throughout the central plains states. Grain prices also have a significant impact on considerations of whether or not to convert. Corn futures are now closing over $5.00 per bushel as compared to corn prices in past studies of $2.50 per bushel.

For a grower today considering conversion to mechanical move irrigation, the following questions need to be taken into consideration: What steps can be taken to ensure the best long term solution? How might a grower proceed? What should be part of the considerations for making a major irrigation change in the grower’s operation?

Discussion:

To begin the process, one should consider the following steps before talking with an irrigation supplier. This prepares the grower and helps focus on the items of particular importance to their operation. Also the irrigation dealer and/or consultants should help encourage the grower to follow through a decision making process to reach the optimum decisions regarding conversion. The crop consultant can be of assistance at several points during the decision making process to provide data and/or recommendations about the production plan.

1) Start with a review of current management and cropping plans
    a. Does conversion fit into the long term plan for the operation?
        i. Cropping/rotation plans
        ii. Expansion
    b. Consider what are the primary reasons for switching?
        i. Labor availability
        ii. Water availability
        iii. Overall profitability

2) Perform a field resource inventory – the crop consultant may have good input at this stage
    a. Available water supply
    b. Available power supply
    c. Soil types
    d. Field size and shape
    e. Field ‘problems’ – is there an area that has never yielded the way the grower would like? Do challenges such as buildings or power lines exist that would hinder a conversion to mechanical move irrigation?
    f. Changes needed to existing farm equipment if conversion is completed

3) Consider irrigation equipment options that may be a best fit. At this stage do not rule out any options.
    a. Center pivot
    b. Towable center pivot
    c. Center pivot with corner arm
    d. Linear

4) Select a partner to help with the conversion process
    a. Interview potential irrigation equipment suppliers
        i. Explain what is being considered and your needs
        ii. Show the information that has been collected
    b. Look for a partner who:
        i. Is open to listening to you
        ii. Understands your needs and your field

        iii. Understands the value of converting to your operation
        iv. Has product options for consideration
        v. Does not immediately jump to make a quotation
        vi. Has finance options and understand cost share programs
    c. Consider more than just the sales person of the dealership
        i. Service and parts support
        ii. Experience with the options presented
        iii. Talk with your neighbors about their experiences with the dealer
    d. Request a proposal to use as part of the comparison – look for:
        i. Does the proposal offer options?
        ii. Is financing and cost share information presented?
        iii. Is operating cost addressed?
        iv. Is the proposal addressing the overall farms needs?

5) Once the partner is selected review goals – is it to:
    a. Maximize the area covered in the field?
    b. Maximize returns from the field?
    c. Maximize returns for the farm?
    d. Minimize investment?
    e. Minimize labor ?
    f. Minimize operational expense ?

6) Review the management plans and agricultural practices anticipated for the new mechanized irrigation system
    a. Crops
    b. Application of crop production products
    c. Tillage practices

7) Review the options presented by the irrigation dealer
    a. Type of irrigation equipment
        i. Area covered
        ii. Options on the equipment
        iii. Ease of use
    b. Initial investment
        i. Financing plans
        ii. Cost share programs
    c. Operating costs
    d. Life expectancy of the equipment
    e. Labor requirements
    f. Ability to automate

8) Take the time to consider the long term impacts of the decision
    a. Well manufactured, designed and applied mechanical move irrigation equipment should last for at least twenty years

b. Conversion to mechanical move equipment should make life easier and not harder
c. Realize it may take two years to begin to reach the goals

At this point one should be ready to make a decision on how they want to proceed. But before proceeding, consideration should be given to the specific type of irrigation equipment. Many times one automatically assumes the best solution for their situation is a center pivot – and it may well be. But a grower should consider other options and also look for an irrigation equipment supplier who is open to considering options.

Whether the primary goal is maximizing the area irrigated, minimizing operating costs or maximizing profits, several options are available for consideration:

- Towable center pivot
    - Advantages
        - Maximizes the area covered by using one center pivot over multiple fields
        - Can always add a fixed pivot in the future
    - Disadvantages
        - Labor – will require time to go to the field, prepare the center pivot for towing, actual towing and switching back from tow to operating
        - Pumping rate – flowrate needs to be more than what is required for the areas irrigated to allow for downtime and towing

- Center pivot with corner arm
    - Advantages
        - Maximize the area covered – corner arm can be folded in and out to dodge obstructions
        - Uniform watering over the entire field
    - Disadvantages
        - Initial investment
        - In some situations may have more wheel track issues
- Linear
    - Advantages
        - Will maximize the area covered in a square or rectangular field
        - Wheel tracks may fit cropping plan better
    - Disadvantages
        - Initial investment
        - If a hose drag, may require labor to switch the hose
        - If a ditchfeed, ditch maintenance is required

- Options to consider for all mechanical move irrigation equipment

- o Floatation options (not available for towable machines) – to minimize the wheel tracks and avoid getting stuck
- o Sprinkler package – to maximize productivity from the crop and the soil
- o Pipeline materials – different options available depending on the crop production products used
- o Automation capabilities
  - ▪ Control panel for off-peak operation
  - ▪ Automatic changes to manage water applied for different sectors of the field
  - ▪ Remote monitoring and/or control options
- o High speed operation to allow for minimal water applications for germination and application of crop production products.

Conclusions:

Decisions to make when considering converting from surface irrigation to another form of irrigation can be overwhelming. What type of irrigation to switch to? What changes will need to be made to my management? How do I make this as easy as possible? This discussion has focused on eight steps to consider to help make the decision making process simpler. It is critical for the grower to have a goal in mind as to why to convert and then follow through to see that this goal is met. Options need to be considered to determine the best equipment solution for the situation. Lastly, numerous options exist to maximize the coverage with mechanical move irrigation depending on the grower's specific situation.

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USING THE K-STATE CENTER PIVOT SPRINKLER AND SDI ECONOMIC COMPARISON SPREADSHEET - 2008

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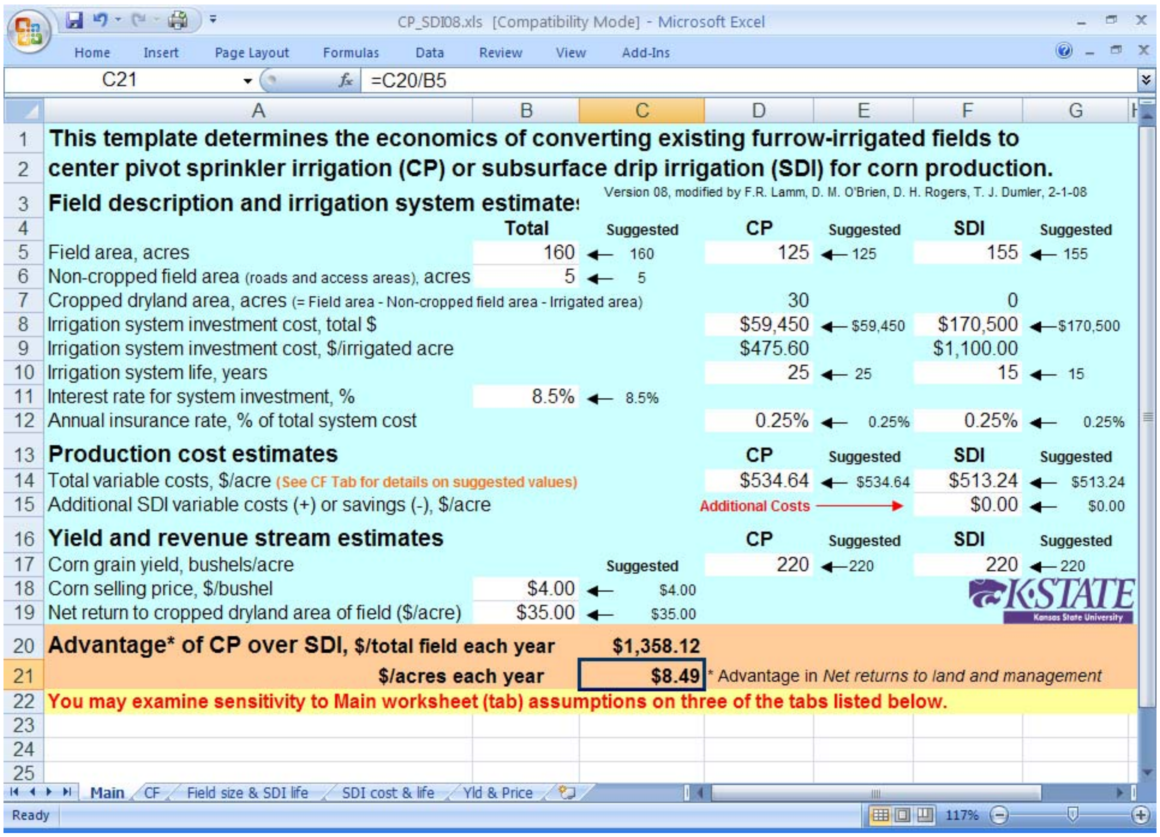
INTRODUCTION

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. In 2004, irrigation water use reports were compiled to obtain a more accurate estimate of SDI acres. 2005 data indicates 9200 acres of fields were exclusively irrigated by SDI systems with another 7600 acres have SDI in combination with another system type. 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.).



CP_SDI08.xls [Compatibility Mode] - Microsoft Excel

C21 =C20/B5

	A	B	C	D	E	F	G
1	This template determines the economics of converting existing furrow-irrigated fields to						
2	center pivot sprinkler irrigation (CP) or subsurface drip irrigation (SDI) for corn production.						
3	Field description and irrigation system estimates			Version 08, modified by F.R. Lamm, D. M. O'Brien, D. H. Rogers, T. J. Dumler, 2-1-08			
4		Total	Suggested	CP	Suggested	SDI	Suggested
5	Field area, acres	160	← 160	125	← 125	155	← 155
6	Non-cropped field area (roads and access areas), acres	5	← 5				
7	Cropped dryland area, acres (= Field area - Non-cropped field area - Irrigated area)			30		0	
8	Irrigation system investment cost, total $			$59,450	← $59,450	$170,500	← $170,500
9	Irrigation system investment cost, $/irrigated acre			$475.60		$1,100.00	
10	Irrigation system life, years			25	← 25	15	← 15
11	Interest rate for system investment, %	8.5%	← 8.5%				
12	Annual insurance rate, % of total system cost			0.25%	← 0.25%	0.25%	← 0.25%
13	Production cost estimates			CP	Suggested	SDI	Suggested
14	Total variable costs, $/acre (See CF Tab for details on suggested values)			$534.64	← $534.64	$513.24	← $513.24
15	Additional SDI variable costs (+) or savings (-), $/acre			Additional Costs →		$0.00	← $0.00
16	Yield and revenue stream estimates			CP	Suggested	SDI	Suggested
17	Corn grain yield, bushels/acre		Suggested	220	← 220	220	← 220
18	Corn selling price, $/bushel	$4.00	← $4.00				
19	Net return to cropped dryland area of field ($/acre)	$35.00	← $35.00				
20	Advantage* of CP over SDI, $/total field each year		$1,358.12				
21	$/acres each year		$8.49	* Advantage in *Net returns to land and management*			
22	You may examine sensitivity to Main worksheet (tab) assumptions on three of the tabs listed below.						

Main / CF / Field size & SDI life / SDI cost & life / Yld & Price

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, 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 15 years for the CP and SDI systems, respectively. No salvage value was assumed for either system. This assumption of no salvage value may be inaccurate, as both systems might have a few components that may be reusable or available for resale at the end of the system life. However, with relatively long depreciation periods of 15 and 25 years and typical financial interest rates, the zero salvage value is a very minor issue in the analysis. System life is an 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 15 to 20 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):

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

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

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.

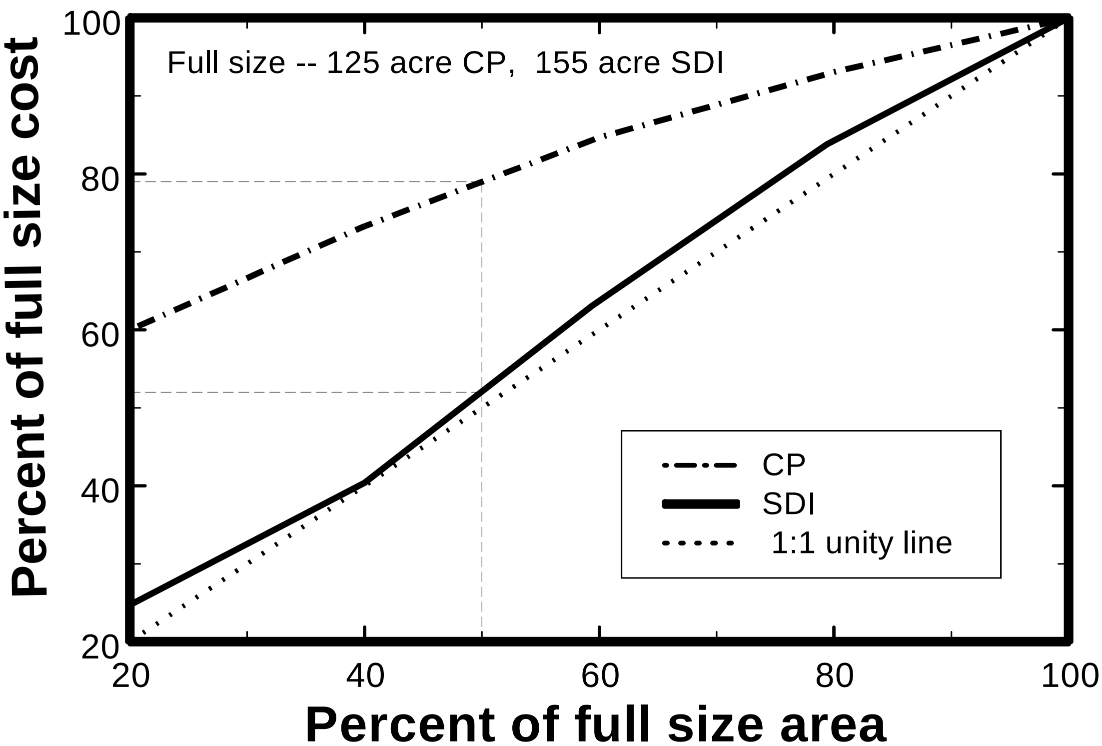


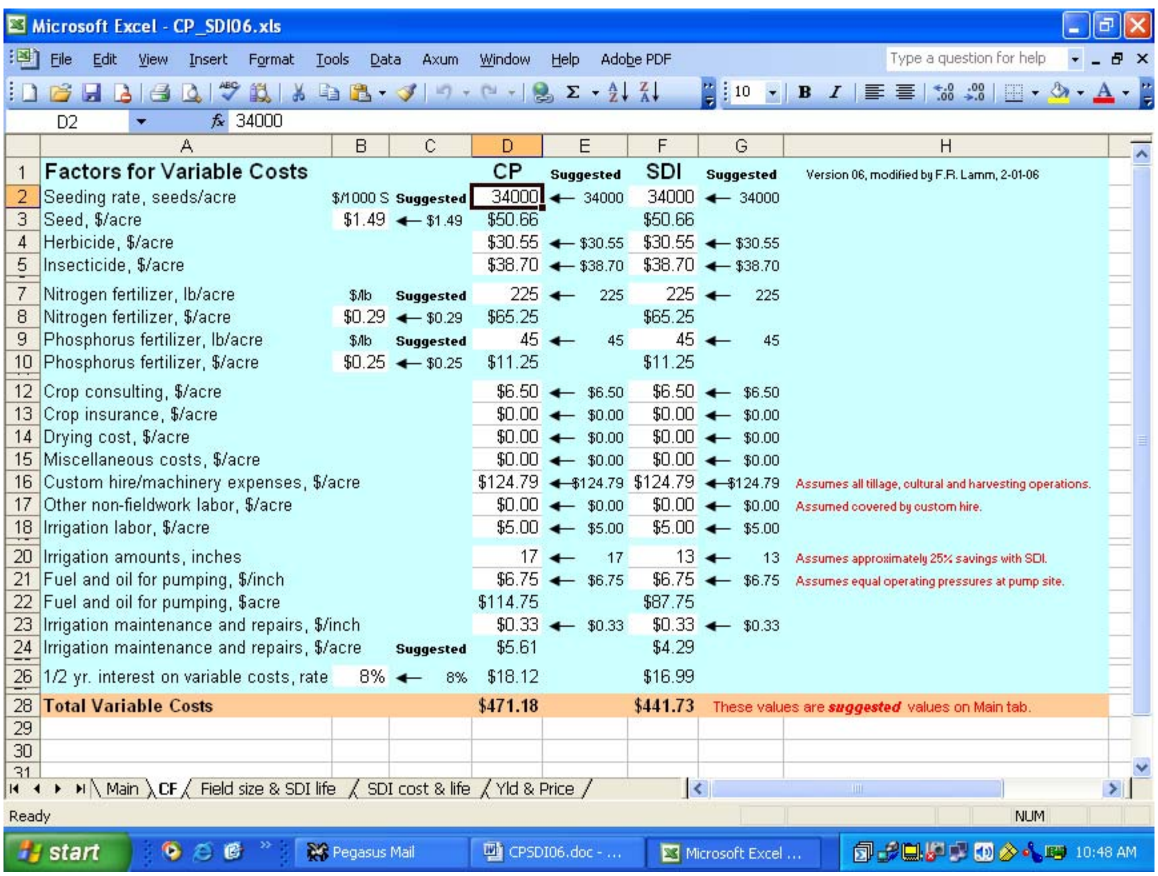
Figure 2. CP and SDI system costs as related to field size. (after O'Brien et al., 1998)

The annual interest rate can be entered as a variable, but is currently assumed to be 8.5%. The total interest costs over the life of the two systems were converted to an average annual interest cost for this analysis. Annual insurance costs were assumed to be 0.25% of each total system cost, but can be changed if better information is available. It is unclear whether insurance can be obtained for SDI systems and if SDI insurance rates would be lower or higher than CP systems. Many of the SDI components are not subject to the climatic conditions that are typically insured hazards for CP systems. However, system failure risk is probably higher with SDI systems which might influence any obtainable insurance rate.

Production cost assumptions and estimates

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

Production costs were adapted from KSU estimates (Dumler et al., 2007). 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.*



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

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 $35.00/acre which is essentially the current dryland crop cash rent estimate for Northwest Kansas. Government payments related to irrigated crop production are assumed to be spread across the overall field size, and thus, do not affect the economic comparison of systems.

Sensitivity analyses

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

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

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

The results are very sensitive to

- any additional production cost savings with SDI.

The results are moderately sensitive to

- corn yield
- corn price
- yield/price combinations

and very sensitive to

- higher potential yields with SDI

with advantages favoring SDI as corn yields and price increase.

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

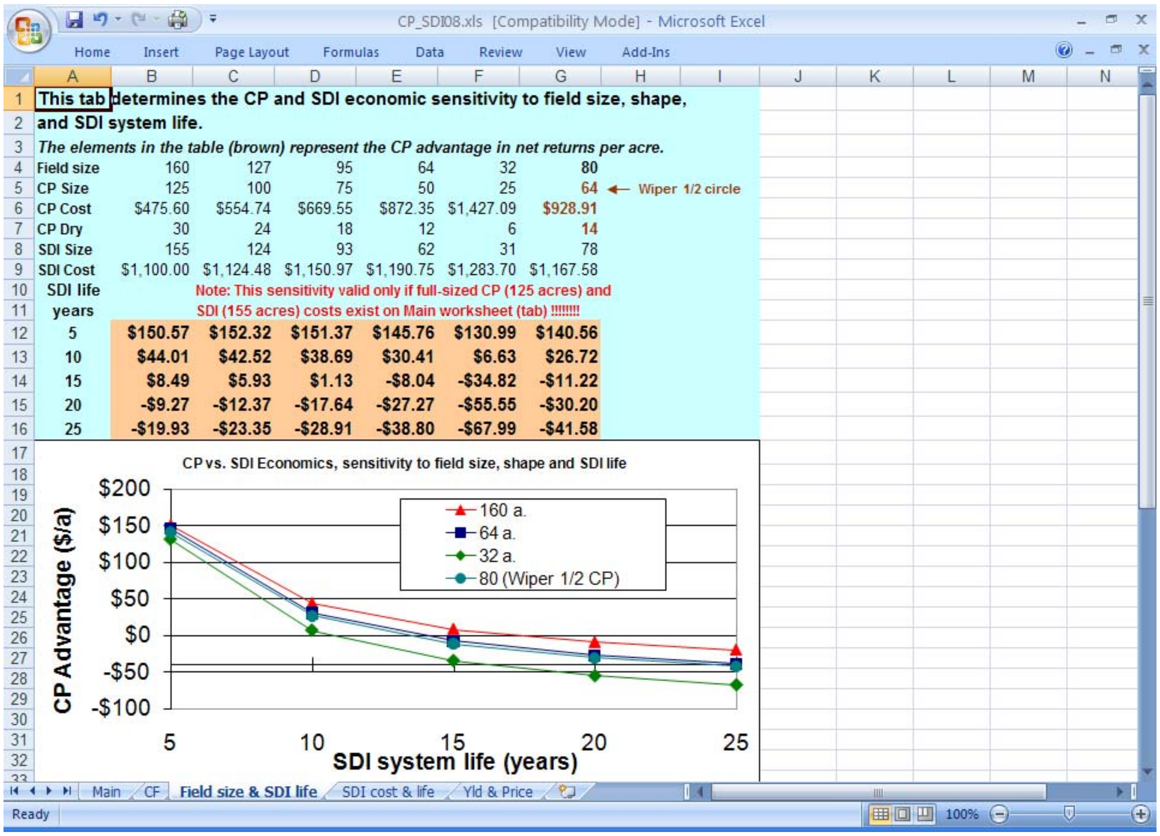


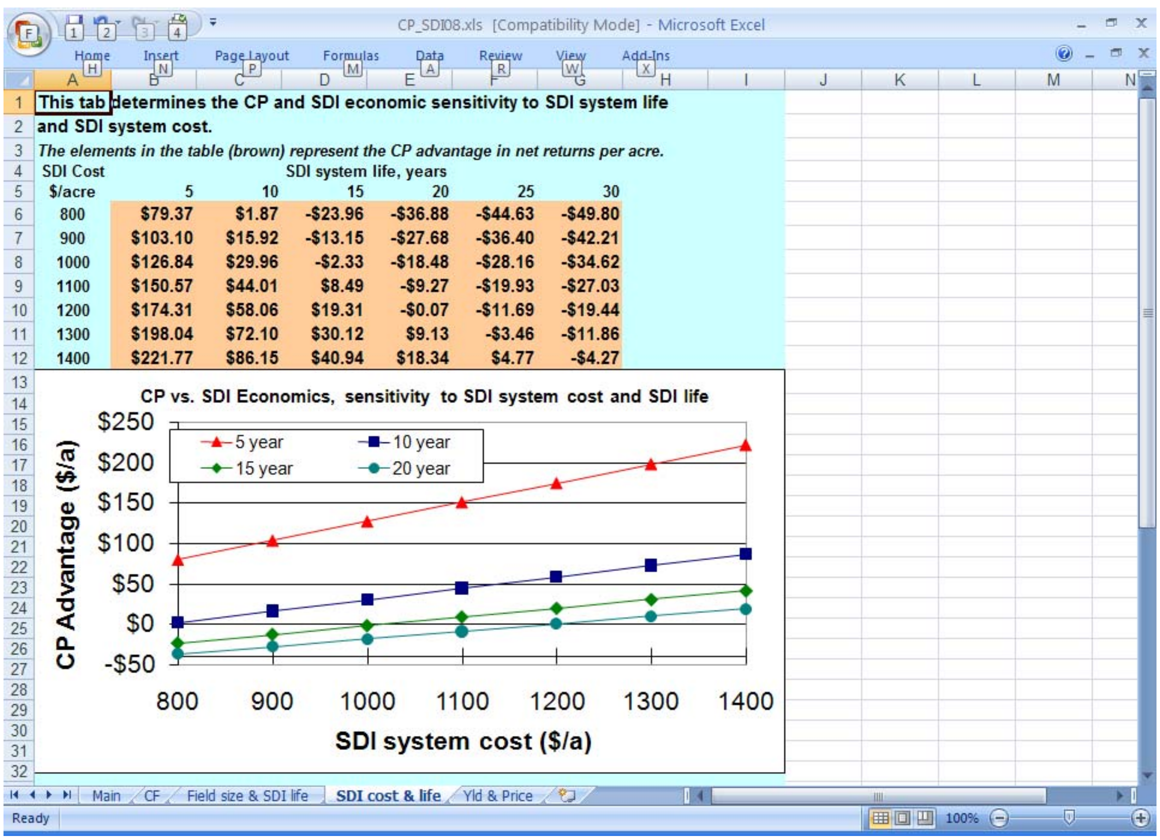
Figure 4. The Field size & SDI life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

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.

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 18 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. In areas where CP life might be much less than 25 years due to corrosive waters, a sensitivity analysis with shorter CP life is warranted.


This tab determines the CP and SDI economic sensitivity to SDI system life and SDI system cost.

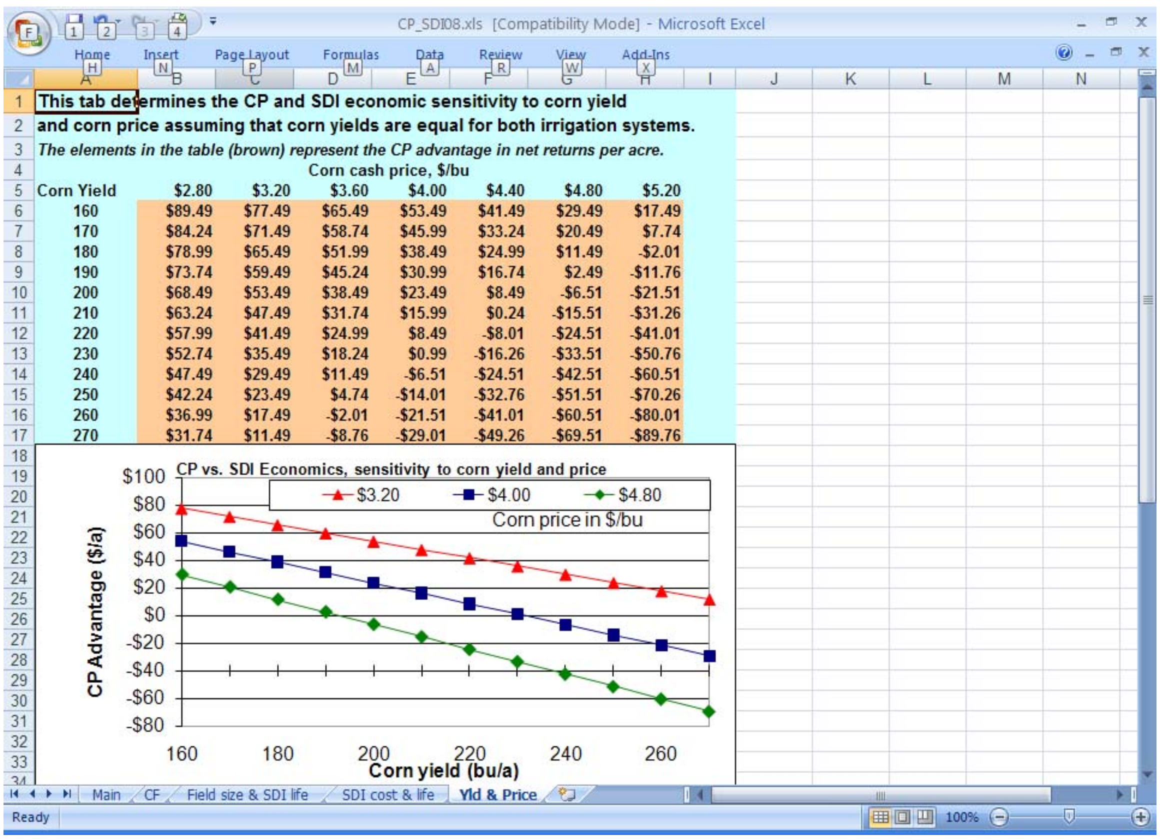
The elements in the table (brown) represent the CP advantage in net returns per acre.

SDI Cost	SDI system life, years					
$/acre	5	10	15	20	25	30
800	$79.37	$1.87	-$23.96	-$36.88	-$44.63	-$49.80
900	$103.10	$15.92	-$13.15	-$27.68	-$36.40	-$42.21
1000	$126.84	$29.96	-$2.33	-$18.48	-$28.16	-$34.62
1100	$150.57	$44.01	$8.49	-$9.27	-$19.93	-$27.03
1200	$174.31	$58.06	$19.31	-$0.07	-$11.69	-$19.44
1300	$198.04	$72.10	$30.12	$9.13	-$3.46	-$11.86
1400	$221.77	$86.15	$40.94	$18.34	$4.77	-$4.27

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).

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

It has already been stated that higher corn yields and higher corn prices favor 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 higher 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 (brown) 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	$89.49	$77.49	$65.49	$53.49	$41.49	$29.49	$17.49
170	$84.24	$71.49	$58.74	$45.99	$33.24	$20.49	$7.74
180	$78.99	$65.49	$51.99	$38.49	$24.99	$11.49	-$2.01
190	$73.74	$59.49	$45.24	$30.99	$16.74	$2.49	-$11.76
200	$68.49	$53.49	$38.49	$23.49	$8.49	-$6.51	-$21.51
210	$63.24	$47.49	$31.74	$15.99	$0.24	-$15.51	-$31.26
220	$57.99	$41.49	$24.99	$8.49	-$8.01	-$24.51	-$41.01
230	$52.74	$35.49	$18.24	$0.99	-$16.26	-$33.51	-$50.76
240	$47.49	$29.49	$11.49	-$6.51	-$24.51	-$42.51	-$60.51
250	$42.24	$23.49	$4.74	-$14.01	-$32.76	-$51.51	-$70.26
260	$36.99	$17.49	-$2.01	-$21.51	-$41.01	-$60.51	-$80.01
270	$31.74	$11.49	-$8.76	-$29.01	-$49.26	-$69.51	-$89.76

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/.

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

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Contribution No. 08-245-A from the Kansas Agricultural Experiment Station.

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WATER SAVINGS FROM CROP RESIDUE MANAGEMENT

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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, Greeley, CO, February 19-20, 2008.

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.

Two mini-lysimeters with the same surface cover treatment were placed in a diagonal pattern between adjacent 30-inch rows under the crop canopy. Comparison of evaporation data (not shown) indicated no statistical difference between the two locations.

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.

All of the surface cover and irrigation frequency treatment data were averaged so that only year-to-year differences could be evaluated (table 2). Annual differences in average daily soil water evaporation (Avg E), average daily crop evapotranspiration (ETc), average daily reference ET (ETr), and the ratios of Avg E with both ETc and ETr were calculated. The climatic conditions in 2004 were cooler and wetter than normal which produced 230 bu/ac of corn with full irrigation. Hail storms during July 2005 and July 2006 caused leaf loss, as indicated by the peak leaf area index measurements, and produced grain yields of 165 bu/ac in 2005 and 185 bu/ac in 2006. The combination of more E and less ETc and ETr in 2004 than in the other two years caused the E/ETc and E/Etr ratios to be more in 2004. The most ETc occurred in 2005 with the least peak LAI; however, more atmospheric demand for water, as indicated by more ETr, may have masked some of the effects of less leaf area.

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.

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

Irrigation Frequency*	Avg E in/day	ETc in/day	E/ETc	ETr In/day	E/ETr	Peak LAI*
2004	0.046a	0.21c	0.25a	0.26	0.18a	4.4
2005	0.043b	0.27a	0.16c	0.36	0.12b	3.4
2006	0.042b	0.22b	0.21b	0.30	0.14a	3.7
$LSD_{.05}$	0.002	0.01	0.02		0.005	

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

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 3). 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 3), potential water savings could be 3.7-4.0 inches with full soil surface coverage.

Table 3. 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 4). 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 4. 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.

More frequent irrigations led to slightly more soil water evaporation and ETc (table 5). The small differences were probably because on average there were two to three more wetting events in the high versus low frequency treatments. More ETc in the high frequency treatment led to slightly smaller ratio of Avg E with ETc.

Table 5. Soil water evaporation (Avg E) and evaporation as a ratio of crop ET (ETc) and reference ET (ETr) for low and high frequency irrigation for all mini-lysimeter treatments in during the 2004-2006 growing seasons.

Irrigation Frequency	Wetting Events	Avg E in/day	ETc in/day	E/ETc in/day	ETr	E/ETr
Low	3	0.043b	0.21b	0.21a	0.30	0.14b
High	5	0.044a	0.25a	0.20b	0.30	0.15a
$LSD_{.05}$		0.0013	0.009	0.02		0.004

Means with same letters in the same columns are not significantly different.

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 6a). 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).

Based on averages of surface cover treatments, twice per week irrigation frequency over a six week period produced 23% more evaporation than the once per week frequency (table 6b).

Summary and Significance of Results

Corn stover and wheat stubble residues that cover 85-100 % of the soil surface have the potential to reduce soil water evaporation (E). During the growing seasons of 2004 – 2006 in Garden City, Kansas, average E measured under a growing corn crop was reduced from 0.06 inch per day for bare soil to 0.03 to 0.04 inch per day for complete surface coverage with corn stover or wheat stubble. The difference in E between bare soil and residue covered surfaces over a 110 day growing season could be 2.2 to 3.3 inches. E as a fraction of crop evapotranspiration (ETc) was 0.30 for bare soil and 0.15 to 0.16 for complete soil surface coverage. The total growing season ETc for corn grown in west-central Kansas is 24-26 inches. Based on the reduction of E as a fraction of ETc, growing season water savings could be 3.4 to 3.9 inches.

Table 6. 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
b. Irrigation* Frequency**		
Low	0.07a	0.20a
High	0.05b	0.18b
$LSD_{.05}$	0.0009	0.003

*Reference ETr (alfalfa based) from weather station data.
**Percent surface covered by residue found from line-transect (visual) methods.
***Once (low) and twice (high) per week irrigation frequency over a six week period.
Means with same letters in the same columns for the same variable are not significantly different at alpha = 0.05.

Crop residues that were distributed across the surface, needed to cover more than 80-85% 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.

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 Natural Resources Conservation Agency (USDA-NRCS, 2000) has calculated net irrigation requirements for corn across Kansas. Net irrigation is the water that infiltrates into the soil and is required for full crop production. The net irrigation value is 14.5 inches in the Garden City, Kansas area (Finney County) for average precipitation without the benefit of no-till management. Gross irrigation is the water delivered to the field. Current center-pivot systems can have an application efficiency of 90% and would pump 16 inches for full irrigation. Results of a field study near Garden City for 2004-2006 show that fully irrigated corn yields with no-till management can be obtained with 11 to 12 inches of irrigation (Klocke et al., 2007). The difference between NRCS estimations of full irrigation and the field study measurements indicate that irrigation savings from no-till management could be 4-5 inches annually. A related field study with fully irrigated continuous corn grown with no-till management was conducted in west-central Nebraska from 1985 to 1999 (Klocke et al., 2007b). Average annual irrigation requirements were 10 inches during the study years with somewhat less evapotranspiration than the Garden City location. Water savings from no-till management from these studies indicate that combined growing season and non-growing season could be 4-5 inches.

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 5 inches of water annually:

Situation 1. 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.

Situation 2. 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 5 inches less water pumped = $45 per acre

Situation 3. The irrigation system cannot provide enough water to meet the full water requirements of the crop. Five inches of water savings from crop residue management can shift soil water evaporation to transpiration.

Corn yields increase 10 bushels per acre for each inch of irrigation that is transferred from evaporation to transpiration.

Corn price is $4.50 per bushel giving a total savings of $225 per acre.

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.

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CROP RESIDUE AND SOIL WATER

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INTRODUCTION

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

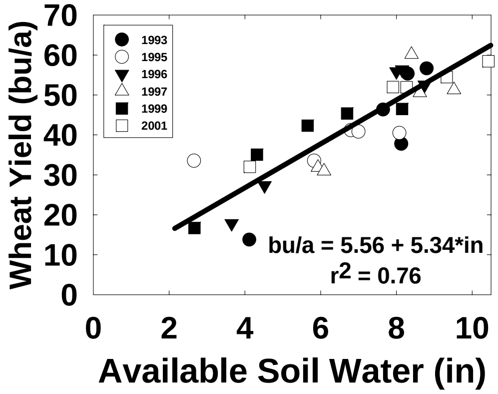

Fig. 1. Relationship between winter wheat grain yield and available soil water at wheat planting at Akron, CO.

FACTORS AFFECTING WATER STORAGE

Time of Year/Soil Water Content

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

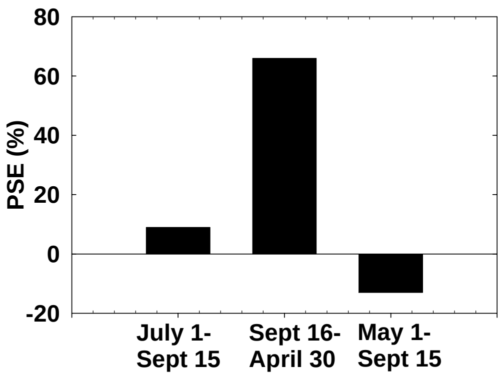

Fig. 2. Precipitation Storage Efficiency (PSE) variability with time of year. (after Farahani, 1998)

Residue Mass and Orientation

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

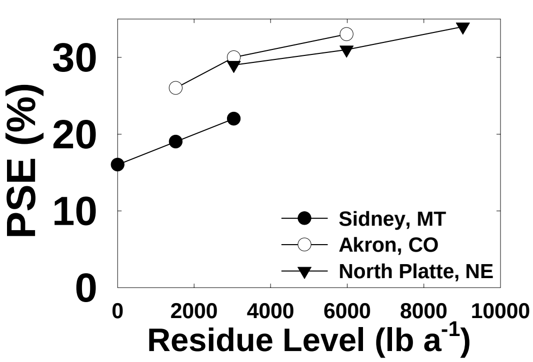

Fig. 3. Precipitation Storage Efficiency (PSE) as influenced by wheat residue on the soil surface. (after Greb et al., 1967)

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

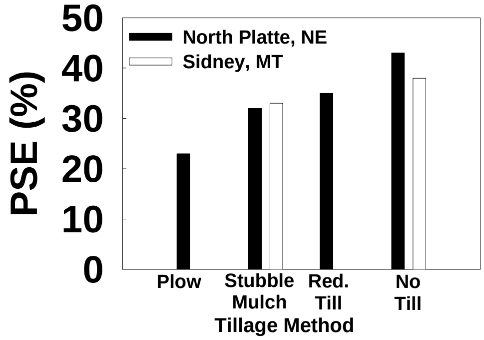

Fig. 4. Precipitation Storage Efficiency (PSE) as influenced by tillage method in the 14-month fallow period in a winter wheat-fallow production system. (after Smika and Wicks, 1968; Tanaka and Aase, 1987)

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

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

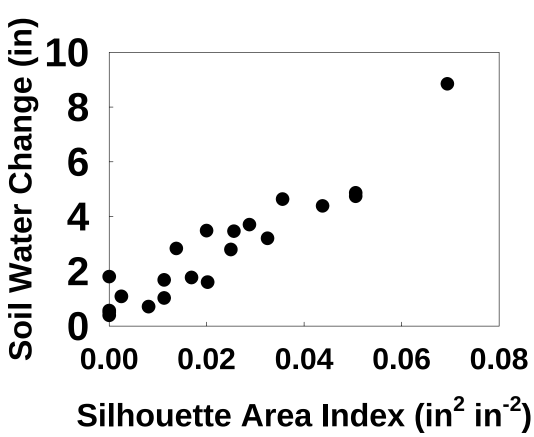

Fig. 5. Influence of sunflower silhouette area index on over-winter soil water change at Akron, CO. (after Nielsen, 1998)

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

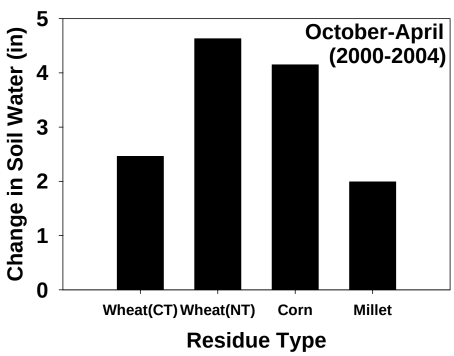

Fig. 6. Change in soil water content due to crop residue type at Akron, CO.

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

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EFFECT OF TILLAGE PRACTICES AND DEFICIT IRRIGATION ON CORN

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ABSTRACT

Corn production was compared from 2004 to 2007 for three plant populations (26,800, 30,100 or 33,300 plants /acre) under conventional, strip and no tillage systems for irrigation capacities limited to 1 inch every 4, 6 or 8 days. Corn yield increased approximately 10% (23 bu/acre) from the lowest to highest irrigation capacity in these four years of varying precipitation and crop evapotranspiration. Strip tillage and no tillage had approximately 8.1% and 6.4% (18 and 14 bu/acre) greater grain yields than conventional tillage, respectively. Results suggest that strip tillage obtains the residue benefits of no tillage in reducing evaporation losses without the yield penalty sometimes occurring with high residue. The small increases in total seasonal water use (< 0.5 inch) for strip tillage and no-tillage compared to conventional tillage can probably be explained by the greater grain yields for these tillage systems.

INTRODUCTION

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

GENERAL STUDY PROCEDURES

The study was conducted under a center pivot sprinkler at the KSU Northwest Research-Extension Center at Colby, Kansas during the years 2004 to 2007. Corn was also grown on the field site in 2003 to establish residue levels for the three tillage treatments. The deep Keith silt loam soil can supply about 17.5 inches of available soil water for an 8-foot soil profile. The climate can be described as semi-arid with a summer precipitation pattern with an annual rainfall of approximately 19 inches. Average precipitation is approximately 12 inches during the 120-day corn growing season.

A corn hybrid of approximately 110 day relative maturity (Dekalb DCK60-19 in 2004 and DCK60-18 in 2005 through 2007) was planted in circular rows on May 8, 2004, April 27, 2005, April 20, 2006 and May 8, 2007, respectively. Three target seeding rates (26,000, 30,000 and 34,000 seeds/acre) were superimposed onto each tillage treatment in a complete randomized block design.

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

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

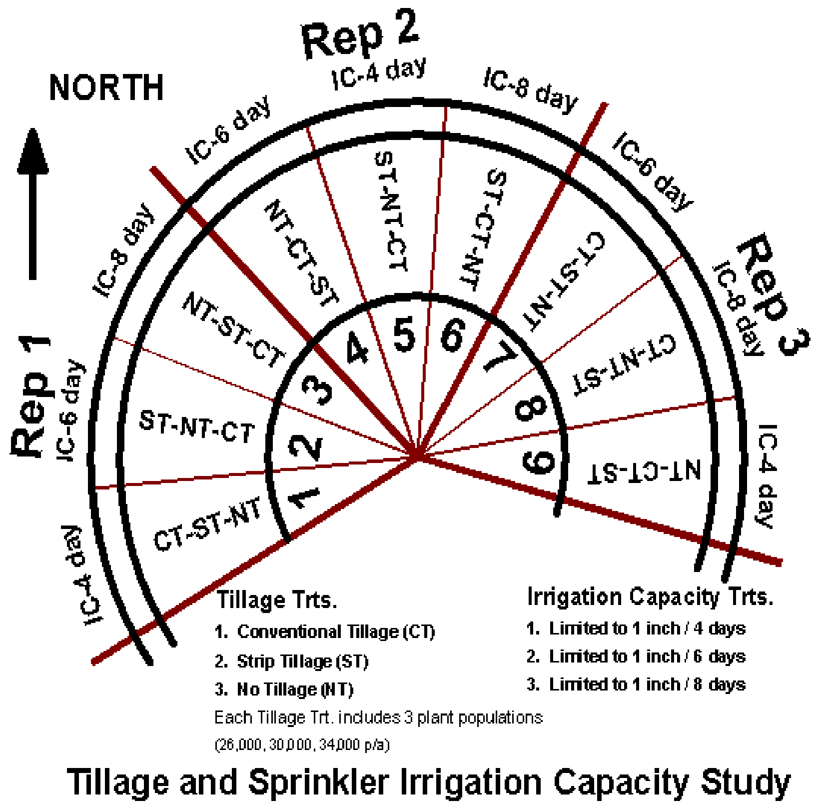

Figure 1. Physical arrangement of the irrigation capacity and tillage treatments.

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

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

Weekly to bi-weekly soil water measurements were made in 1-ft increments to 8-ft. depth with a neutron probe. All measured data was taken near the center of each plot.

Surface crop residue and surface residue cover was sampled in April 2007 prior to planting.

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

Period	Conventional tillage	Strip Tillage	No Tillage
Fall 2003	1) One-pass chisel/disk plow at 8-10 inches with broadcast N, November 13, 2003.	1) Strip Till + Fertilizer (N) at 8-10 inch depth, November 13, 2003.	
Spring 2004	2) Plant + Banded starter N & P, May 8, 2004. 3) Pre-emergent herbicide application, May 9, 2004.	2) Plant + Banded starter N & P, May 8, 2004 3) Pre-emergent herbicide application, May 9, 2004.	1) Broadcast N + Plant + Banded starter N & P, May 8, 2004 2) Pre-emergent herbicide application, May 9, 2004.
Summer 2004	4) Roundup herbicide application near lay-by, June 9, 2004 5) Fertigate (N), June 10, 2004	4) Roundup herbicide application near lay-by, June 9, 2004 5) Fertigate (N), June10, 2004	3) Roundup herbicide application near lay-by, June 9, 2004 4) Fertigate (N), June 10, 2004
Fall 2004	1) One-pass chisel/disk plow at 8-10 inches with broadcast N, November 05, 2004.	*Too wet, no tillage operations*	
Spring 2005	2) Plant + Banded starter N & P, April 27, 2005. 3) Pre-emergent herbicide application, May 8, 2005.	1) Strip Till + Fertilizer (N) at 8-10 inch depth, March 15, 2005. 2) Plant + Banded starter N & P, April 27, 2005 3) Pre-emergent herbicide application, May 8, 2005.	1) Broadcast N + Plant + Banded starter N & P, April 27, 2005 2) Pre-emergent herbicide application, May 8, 2005.
Summer 2005	4) Roundup herbicide application near lay-by, June 9, 2005 5) Fertigate (N), June 17, 2005	4) Roundup herbicide application near lay-by, June 9, 2005 5) Fertigate (N), June 17, 2005	3) Roundup herbicide application near lay-by, June 9, 2005 4) Fertigate (N), June 17, 2005
Fall 2005	1) One-pass chisel/disk plow at 8-10 inches with broadcast N, November 10, 2005.	1) Strip Till + Fertilizer (N) at 8-10 inch depth, November 10, 2005.	
Spring 2006	2) Plant + Banded starter N & P, April 20, 2006. 3) Pre-emergent herbicide application, April 22, 2006.	2) Plant + Banded starter N & P, April 20, 2006 3) Pre-emergent herbicide application, April 22, 2006.	1) Broadcast N + Plant + Banded starter N & P, April 20, 2006 2) Pre-emergent herbicide application, April 22, 2006.
Summer 2006	4) Roundup herbicide application near lay-by, June 6, 2006 5) Fertigate (N), June 13, 2006	4) Roundup herbicide application near lay-by, June 6, 2006 5) Fertigate (N), June 13, 2006	3) Roundup herbicide application near lay-by, June6, 2006 4) Fertigate (N), June 13, 2006

Table 1. *Continued*

Period	Conventional tillage	Strip Tillage	No Tillage
Fall 2006	1) One-pass chisel/disk plow at 8-10 inches with broadcast N, November 28, 2006.	1) Strip Till + Fertilizer (N) at 8-10 inch depth, November 28, 2006.	
Spring 2007	2) Plant + Banded starter N & P, May 8, 2007. 3) Pre-emergent herbicide application, May 8, 2007.	2) Plant + Banded starter N & P, May 8, 2007 3) Pre-emergent herbicide application, May 8, 2007.	1) Broadcast N + Plant + Banded starter N & P, May 8, 2007 2) Pre-emergent herbicide application, May 8, 2007.
Summer 2007	4) Roundup herbicide application near lay-by, June 16, 2007 5) Fertigate (N), June 21, 2007	4) Roundup herbicide application near lay-by, June 16, 2007 5) Fertigate (N), June 21, 2007	3) Roundup herbicide application near lay-by, June 16, 2007 4) Fertigate (N), June 21, 2007

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

RESULTS AND DISCUSSION

Weather Conditions and Irrigation Needs

Summer seasonal precipitation was approximately 2 inches below normal in 2004, near normal in 2005, nearly 3 inches below normal in 2006, and approximately 2.5 inches below normal in 2007 at 9.99, 11.95, 8.99 and 9.37 inches, respectively for the 120 day period from May 15 through September 11 (long term average, 11.79 inches). In 2004, the last month of the season was very dry but the remainder of the season had reasonably timely rainfall and about normal crop evapotranspiration (Figure 2). In 2005, precipitation was above normal until about the middle of July and then there was a period with very little precipitation until the middle of August. This dry period in 2005 also coincided with a week of greater temperatures and high crop evapotranspiration near the reproductive period of the corn (July 17-25). In 2006, precipitation lagged behind the long term average for the entire season. Fortunately, seasonal evapotranspiration was near normal as it also was for the 2004 and 2005 (long term average of 23.08 inches). Although precipitation was smaller than normal in 2007, crop evapotranspiration was much smaller than normal at 19.96 inches which resulted in less irrigation needs.

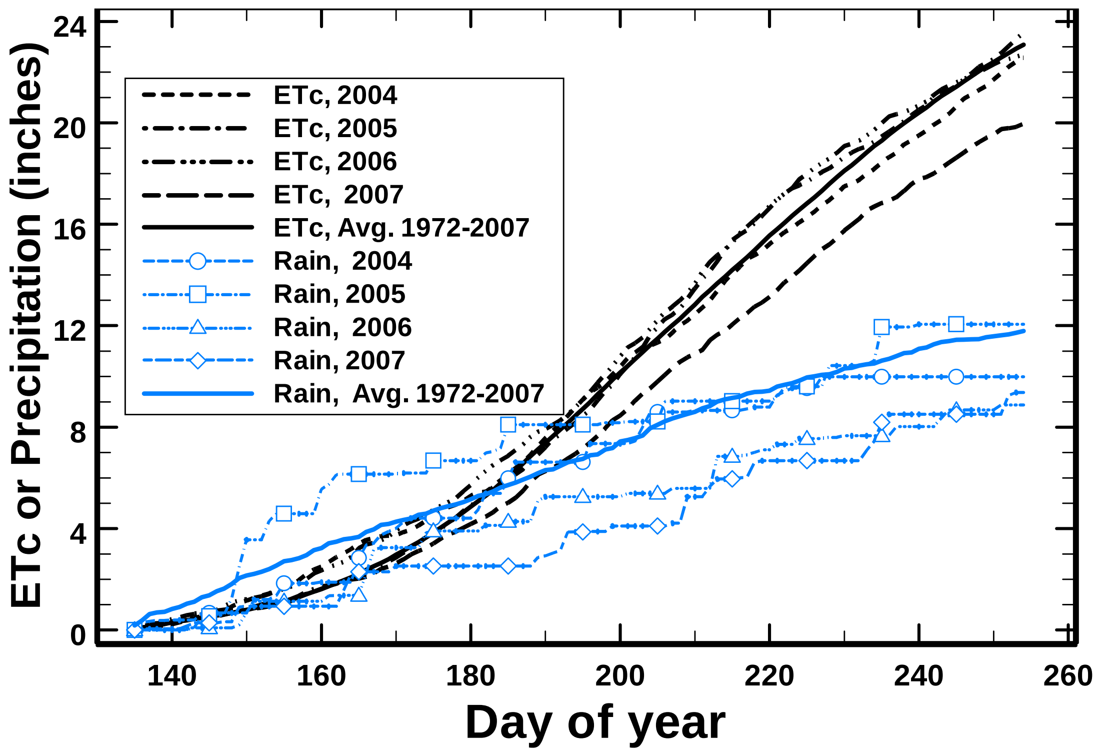

Figure 2. Corn evapotranspiration and summer seasonal rainfall for the 120 day period, May 15 through September 11, KSU Northwest Research-Extension Center, Colby Kansas.

Irrigation requirements were lowest in 2004 with the 1 inch/4 day treatment receiving 12 inches, the 1 inch/ 6 day treatment receiving 11 inches and the 1 inch/8 day treatment receiving 9 inches (Figure 3). The irrigation amounts in 2005 were 15, 13, and 10 inches for the three respective treatments. The irrigation amounts were highest in 2006 at 15.5, 13.5, and 11.50 inches for the three respective treatments. Irrigation amounts in 2007 were 12.5, 11.5 and 10.5 inches for the three respective treatments which were just slightly greater than the low irrigation values of 2004. Although seasonal precipitation was considerably smaller in 2007 compared to 2004, there was very little difference in irrigation requirements. This was because evapotranspiration was considerably smaller than normal in 2007 due to light winds and moderate temperatures during much of the summer.

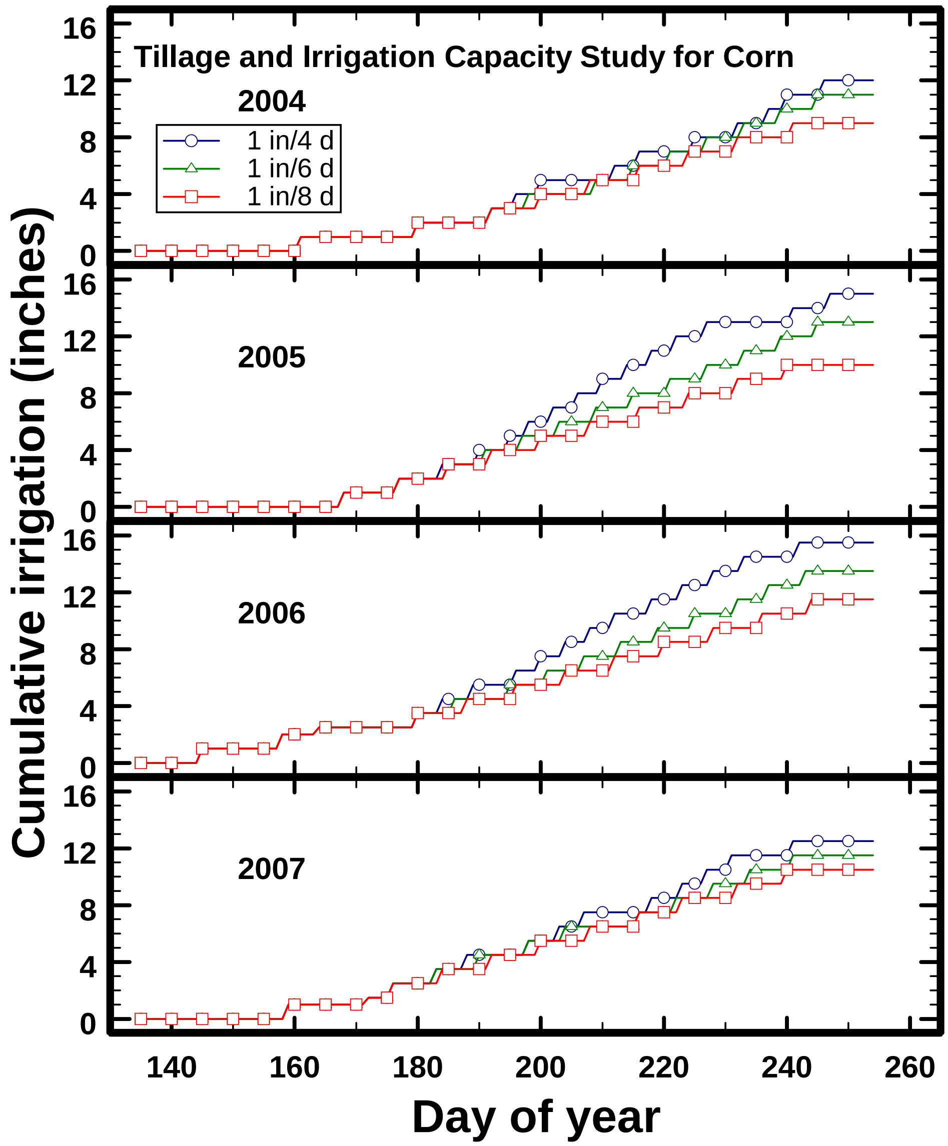

Figure 3. Cumulative irrigation by day of year for the three irrigation capacities during all four years of the tillage and irrigation capacity study of corn, KSU Northwest Research-Extension Center, Colby, Kansas.

Crop Yield and Selected Yield Components

Corn yield was relatively high for all four years ranging from 161 to 279 bu/acre (Table 2 through 5, and Figure 4). Greater irrigation capacity generally increased grain yield, particularly in 2005 and 2006. Strip tillage and no tillage had greater grain yields at the lowest irrigation capacity in 2004 and at all irrigation capacities in 2005 and 2006. In 2007, all tillage treatment yields were very high but strip tillage had slightly greater yields at the lowest and highest irrigation capacity. Strip tillage tended to have the highest grain yields for all tillage systems and the effect of tillage treatment was greatest at the lowest irrigation capacity in the four years of the study. Crop residue and residue cover were similar for no tillage

(20,000 lb/acre and 99%) and strip tillage (14,300 lb/acre and 92%) but much less for conventional tillage (5,200 lb/acre and 79%). These results suggest that strip tillage obtains the residue benefits of no tillage in reducing evaporation losses without the yield penalty sometimes associated with the greater residue levels in irrigated no tillage management.

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

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

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

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

Table 4. Selected corn yield component and total seasonal water use data for 2006 from an irrigation capacity and tillage study, KSU Northwest Research-Extension Center, Colby, Kansas.

Irrigation Capacity	Tillage System	Target Plant Population (1000 p/a)	Grain Yield bu/acre	Plant Population (p/a)	Kernels /Ear	Kernel Weight g/100	Water Use (inches)
1 in/4 days	Conventional	26	239	29330	542	38.1	27.1
(15.5 inches)		30	213	31073	476	36.4	26.6
		34	212	35138	434	36.1	26.9
	Strip Tillage	26	232	29330	514	39.1	27.7
		30	236	31363	483	38.2	27.4
		34	260	33106	522	38.6	27.5
	No Tillage	26	211	28459	497	37.9	26.3
		30	263	31363	535	40.3	27.5
		34	248	34558	516	35.7	27.0
1 in/6 days	Conventional	26	161	29040	422	34.1	24.8
(13.5 inches)		30	208	31944	446	37.1	24.6
		34	169	33977	374	35.0	25.0
	Strip Tillage	26	207	29040	492	36.6	26.1
		30	215	31363	484	36.7	25.9
		34	216	34267	476	34.7	26.5
	No Tillage	26	230	29330	541	36.8	25.9
		30	218	30202	516	35.9	25.6
		34	223	32815	484	36.7	25.5
1 in/8 days	Conventional	26	172	28169	417	37.8	23.5
(11.5 inches)		30	191	31654	411	37.7	22.0
		34	191	33977	385	37.2	22.6
	Strip Tillage	26	214	29330	565	32.7	24.6
		30	220	31944	510	34.4	24.6
		34	230	34558	479	35.7	24.3
	No Tillage	26	204	28750	501	36.9	24.4
		30	220	31363	497	35.8	24.6
		34	216	33977	458	35.6	24.9

Table 5. Selected corn yield component and total seasonal water use data for 2007 from an irrigation capacity and tillage study, KSU Northwest Research-Extension Center, Colby, Kansas.

Irrigation Capacity	Tillage System	Target Plant Population (1000 p/a)	Grain Yield bu/acre	Plant Population (p/a)	Kernels /Ear	Kernel Weight g/100	Water Use (inches)
1 in/4 days	Conventional	26	245	27878	629	34.5	24.7
(12.5 inches)		30	274	32234	652	32.8	26.0
		34	256	34848	611	31.9	24.4
	Strip Tillage	26	254	28169	684	33.5	24.6
		30	270	31073	671	33.0	25.7
		34	279	36010	603	32.9	24.6
	No Tillage	26	246	26717	680	33.0	22.6
		30	265	31654	660	32.8	24.4
		34	254	34848	651	28.7	23.9
1 in/6 days	Conventional	26	244	27878	673	33.2	24.7
(11.5 inches)		30	242	32815	603	31.3	24.5
		34	235	34848	612	28.2	24.0
	Strip Tillage	26	244	26426	678	33.5	24.0
		30	242	32234	620	30.7	24.6
		34	251	35429	658	27.7	24.2
	No Tillage	26	230	27588	635	33.3	24.7
		30	256	31944	655	30.5	22.9
		34	247	36010	605	29.6	24.6
1 in/8 days	Conventional	26	220	27878	606	32.4	24.1
(10.5 inches)		30	248	32815	628	31.0	23.9
		34	249	34267	634	29.3	24.4
	Strip Tillage	26	242	27588	683	32.5	23.7
		30	255	31073	637	32.5	23.0
		34	267	36010	619	30.5	23.2
	No Tillage	26	225	27588	661	31.3	23.9
		30	248	32234	631	30.4	24.0
		34	235	34848	587	29.2	23.3

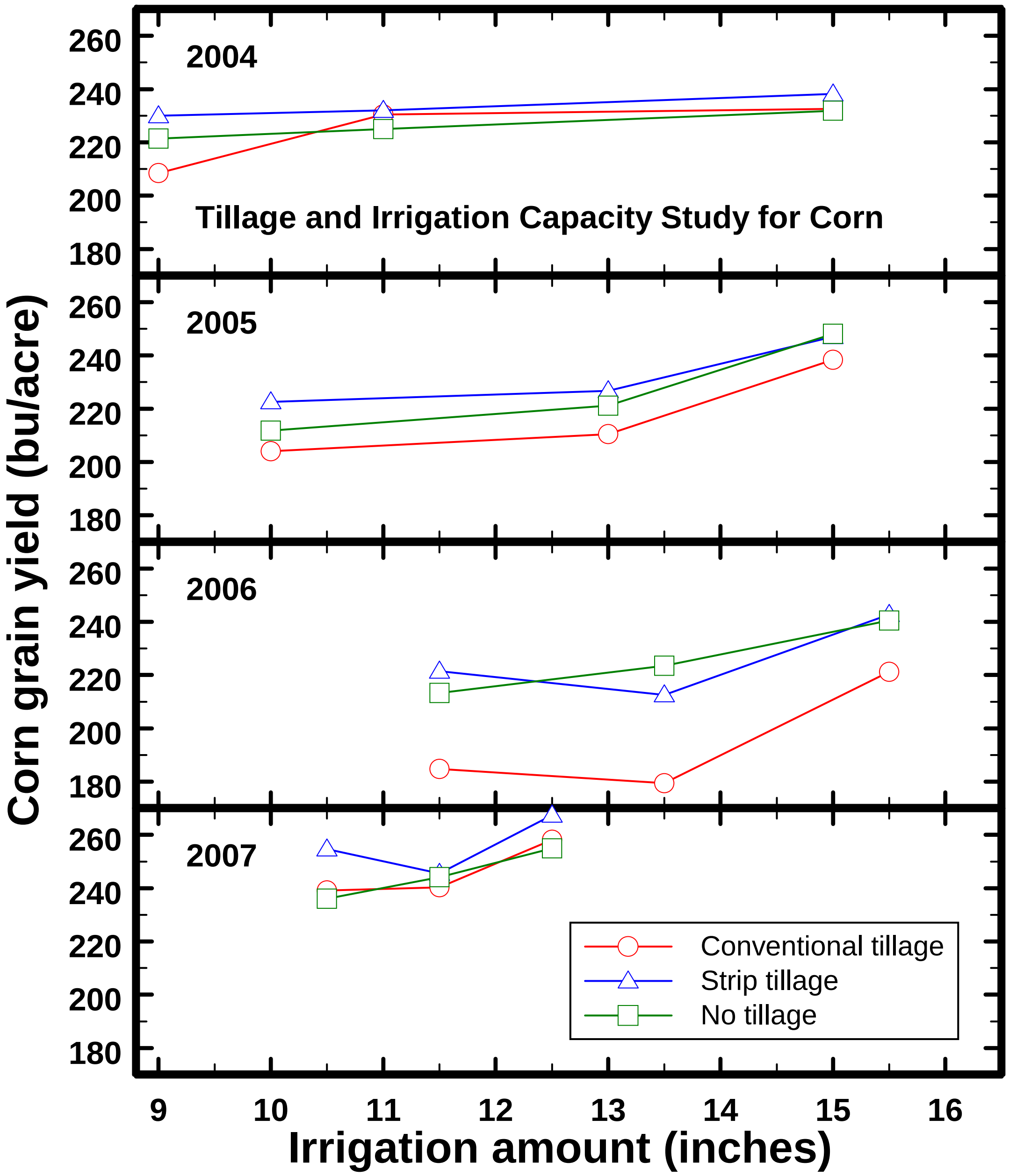

Figure 4. Corn grain yield as affected by irrigation amount and tillage, 2004 to 2007, KSU Northwest Research-Extension Center, Colby Kansas.

Greater plant population had a significant effect in increasing corn grain yields (Tables 2 through 5, Figure 5) on the average about 16 to 17 bu/acre for the lowest and highest irrigation capacities, respectively. Greater plant population gives greater profitability in good production years. Assuming a seed cost of $1.92/1,000 seeds and corn harvest price of $4.00/bushel, this 16 to 17 bu/acre yield advantage would increase net returns approximately $52 to $56/acre for the increase in plant population of approximately 6,500 seeds/acre. Increasing the plant population by 6500 plants/a on the average reduced kernels/ear by 45 and reduced kernel weight by 2.0 g/100 kernels (Tables 2 through 5). However, this was compensated by the increase in population increasing the overall number of kernels/acre by 9.2% (data not shown).

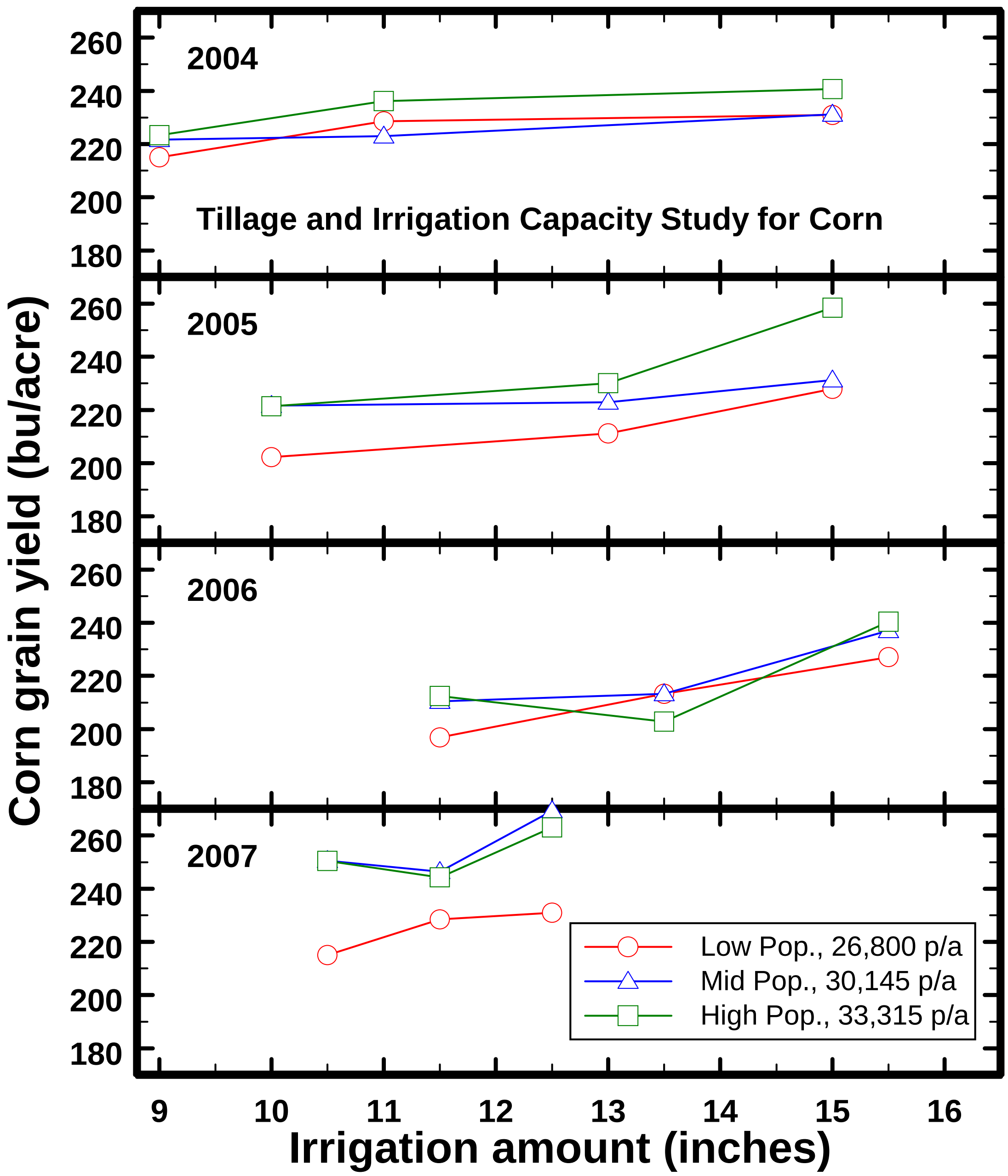

Figure 5. Corn grain yield as affected by irrigation amount and plant population, 2004-2007, KSU Northwest Research-Extension Center, Colby Kansas.

The number of kernels/ear was reduced in 2004 and 2006 compared to 2005 and 2007 (Table 2 through 5, Figure 6). The potential number of kernels/ear is set at about the ninth leaf stage (approximately 2.5 to 3.5 ft tall) and the actual number of kernels/ear is finalized by approximately 2 weeks after pollination. Greater early season precipitation in 2005 (Figure 2) than 2004 and 2006 may have established a greater potential for kernels/acre and then later in the 2005 season greater irrigation capacity or better residue management may have allowed for more kernels to escape abortion. The number of kernels/ear was even greater in 2007 than 2005. Winds and temperatures were very moderate for much of 2007 and the resulting reduced evapotranspiration probably allow a greater potential kernel set.

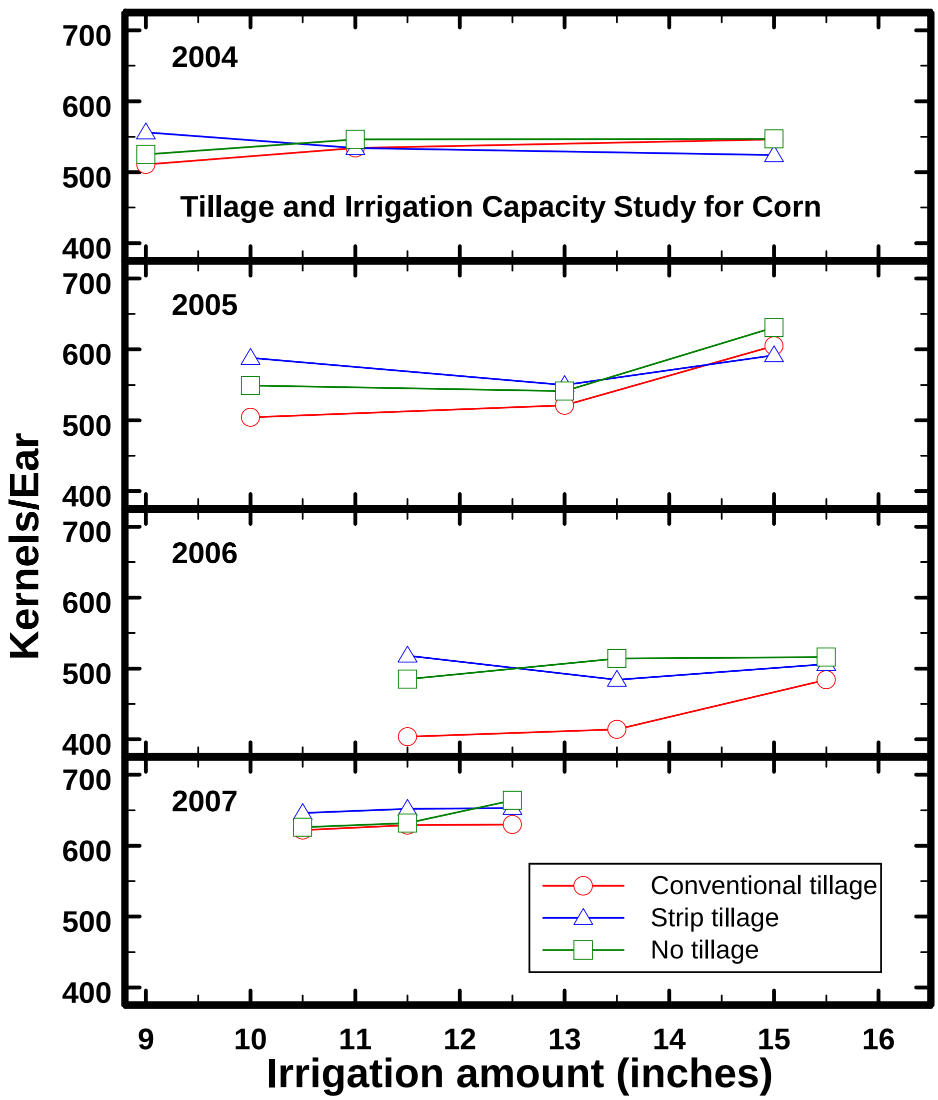

Figure 6. Kernels/ear as affected by irrigation capacity and plant population, 2004-2007, KSU Northwest Research-Extension Center, Colby Kansas.

The number of kernels/ear was generally greater for the strip and no tillage treatments compared to conventional tillage, particularly in 2005 and 2006. This response is probably due to better management of soil water reserves with strip and no tillage.

Final kernel weight is affected by plant growing conditions during the grain filling stage (last 60 days prior to physiological maturity) and by plant population and kernels/ear. Under deficit irrigation capacity, the crop will deplete soil water reserves during the latter portion of the cropping season, so it is not surprising that kernel weight was increased with greater irrigation capacity (Tables 2 through 5, Figure 7). Tillage system also affected kernel weight, but it is thought by the authors that the effect was caused by different factors at the different irrigation capacities. At the lowest irrigation capacity, final kernel weight was often highest for conventional tillage (3 of 4 years) because of the reduced number of kernels/ear. However, this greater kernel weight did not compensate for the decreased kernels/ear, and thus, grain yields were reduced for conventional tillage. Strip tillage generally had greater kernel weights at greater irrigation capacity than the conventional and no tillage treatments for some unknown reason.

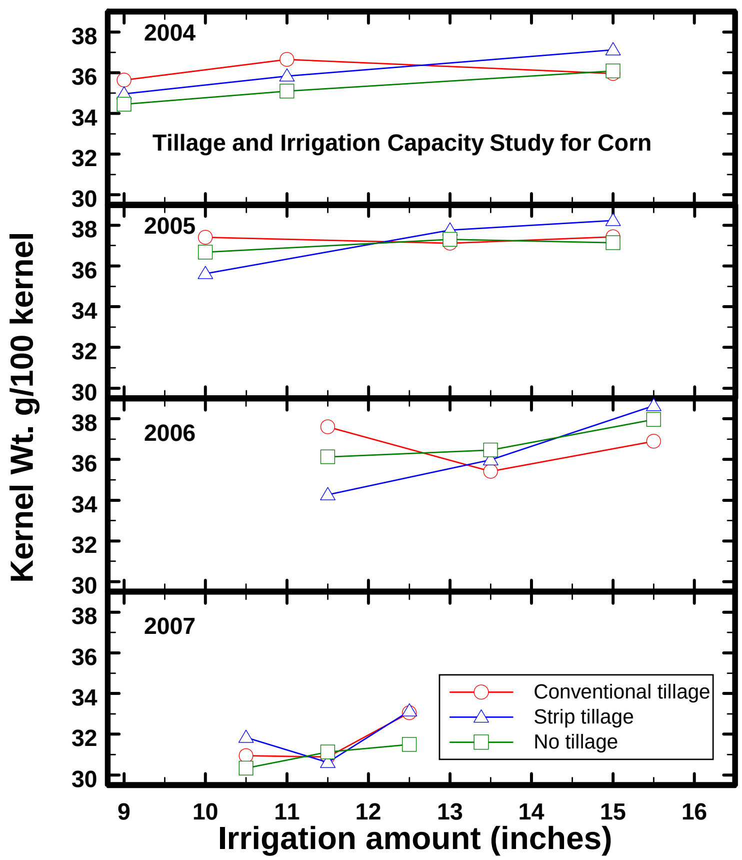

Figure 7. Kernel weight as affected by irrigation capacity and plant population, 2004-2007, KSU Northwest Research-Extension Center, Colby Kansas.

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

Total seasonal water use in this study was calculated as the sum of irrigation, precipitation and the change in available soil water over the course of the season. As a result, seasonal water use can include non-beneficial water losses such as soil evaporation, deep percolation, and runoff. Intuitively, one might anticipate that good residue management with strip tillage and no-tillage would result in reduced water use than conventional tillage because of reduced non-beneficial water losses. However, in this study, strip tillage and no-tillage generally had greater water use (Tables 2 through 5, Figure 8).

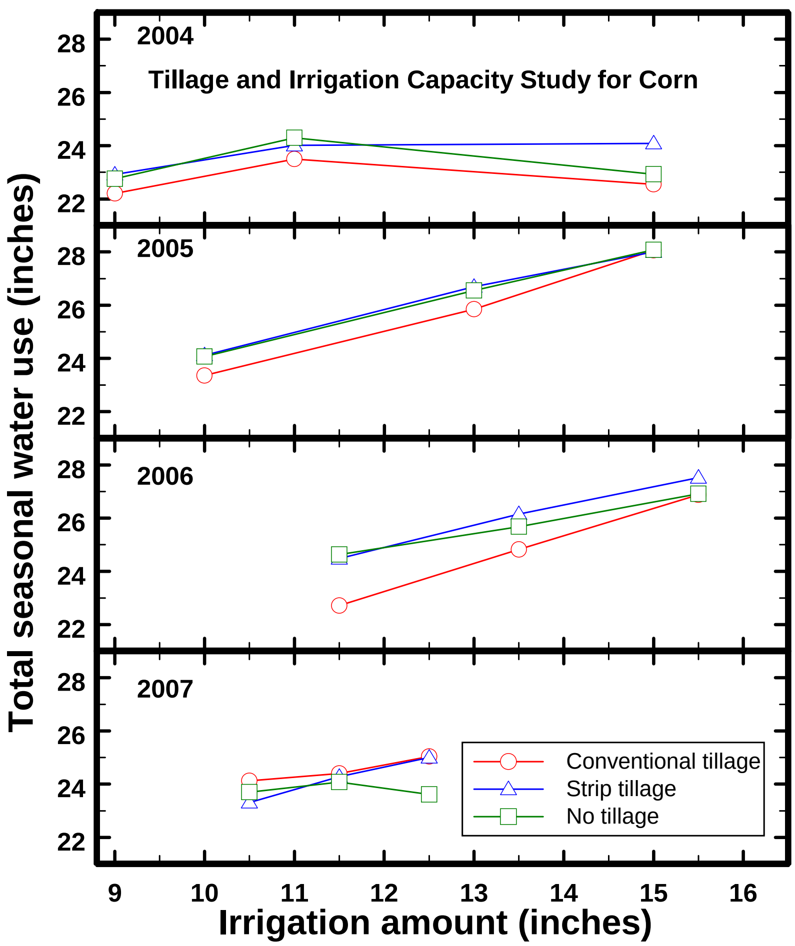

Figure 8. Total seasonal water use (sum of irrigation, precipitation, and seasonal changes in available soil water) as affected by irrigation capacity and plant population, 2004-2007, KSU Northwest Research-Extension Center, Colby Kansas.

The small increases in total seasonal water use (< 0.5 inch) for strip tillage and no-tillage compared to conventional tillage can probably be explained by the greater grain yields for these tillage systems (approximately 16 bu/acre) as well as earlier canopy senescence under conventional tillage.

CONCLUDING STATEMENTS

Corn grain yields were high all four years (2004 to 2007) with varying seasonal precipitation and crop evapotranspiration. Strip tillage and no tillage generally performed better than conventional tillage. Increasing the plant population from 26,800 to 33,300 plants/acre was beneficial at all three irrigation capacities.

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Applying strip tillage treatments in the fall of 2005 in preparation for 2006 cropping season, KSU Northwest Research-Extension Center, Colby, Kansas.

SALINITY IN THE SOUTH PLATTE BASIN

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ABSTRACT

Water is a critical factor in maintaining agricultural lands at optimal yield and crop capacity. Because the most valuable crops grown in Colorado require irrigation, the quality of applied irrigation water is highly influential in determining which crops can be grown. Crop selection may be limited, or yields may decrease as salinity levels of irrigation water exceed critical levels, or if irrigation water is applied at the wrong crop stage. Salinity is an ongoing concern among Colorado growers. As more information is gathered, it is apparent that the problem is spreading.

The Northern Colorado Water Conservancy District (Northern Water), in cooperation with the U.S. Bureau of Reclamation, has undertaken a multi-year study assessing salinity levels throughout the Lower South Platte Basin.

This study involves monitoring the surface waters of the Lower South Platte River and its tributaries, assessing salinity and water levels at several groundwater observation wells, and mapping soil salinity levels throughout the District boundaries. The monitoring began in the spring of 2001 and has continued to expand in its scope. Currently, there are twenty-six automated and twenty-eight manual stations recording salinity levels along the South Platte and its tributaries. Additionally, nine agricultural irrigation systems, a number of natural returned flows and forty-three groundwater observation wells are being monitored. Northern Water has also gathered soil salinity data from several fields.

While salinity is an ever-increasing problem facing Colorado growers, we hope that information gathered from this study will help minimize negative effects of salinity in Northeastern Colorado. Upon completion of the study in 2008, Northern Water hopes to have a compressive overview of salinity levels throughout it's boundaries, how they change spatially and temporally, possible sources and contributing factors, as well as suggestions for growers to more effectively manage their crops with increased awareness. More information can be found on Northern Water's web site www.ncwcd.org.

ACHIEVING A SUSTAINABLE IRRIGATED AGROECOSYSTEM IN THE ARKANSAS RIVER BASIN: A HISTORICAL PERSPECTIVE AND OVERVIEW OF SALINITY, SALINITY CONTROL PRINCIPLES, PRACTICES, AND STRATEGIES

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INTRODUCTION

Nature of Agricultural Salt Problems

Salinity is defined as the concentration of dissolved mineral salts in waters and soils. The concentration can be expressed either on a mass, volume, or chemical equivalent basis. Expressed on a mass basis, readers are probably most familiar with the units of parts per million (ppm), while on a volume basis the typical unit is milligrams per liter (mg/l). Another very useful way of expressing the dissolved mineral concentration is on an equivalent basis since many chemical composition calculations involve equivalence calculations. The unit that is commonly used is milliequivalents per liter (meq/l) which is also the same as millimoles of charge per liter, abbreviated as $m\text{mol}_c$/l. A dissolved mineral constituent expressed in either ppm or mg/l is converted to its equivalence. For any reported value the chemical equivalent (meq/l, $m\text{mol}_c$/l) is equal to the reported value either divided by the ion's equivalent weight , or multiplied by the reciprocal of the equivalent weight. The equivalent weight of any given ion is the atomic mass divided by its valence. For example, calcium which has a valence of $^+2$ and an atomic mass of 40.078 has an equivalent weight of 20.039. Today most laboratories report each constituent in moth mg/l and meq/l. The major solutes comprising dissolved salts are the cations (sodium, calcium, magnesium, and potassium) and the anions (sulfate, chloride, bicarbonate, carbonate, nitrate). Sometimes the term hypersalinity will be encountered. Here, reference is being made to the concentration of not only the dissolved minerals listed above, but also include other constituents that may include manganese, boron, lithium, fluoride, barium, strontium, aluminum, rubidium, and silica and specifically describes land salt sources found in enclosed, inland water bodies that have solute concentration well in excess of sea water.

Salinity is often expressed as one of two coalesced parameters representing the aggregated concentration of the dissolved minerals. The first parameter that most people are familiar is either the electrical conductivity or specific conductance. Sometimes hydrologists like to distinguish specific conductance from measured electrical conductivity. In this case, the electrical conductivity hereby referred to, as EC is the reciprocal of the solution resistance measured between two electrodes and the specific conductance (SC) is then the value accounting for variations in the conductivity cell used in the laboratory or field. For our discussion EC and SC are used interchangeably; both have been multiplied by the appropriate "cell constant" and corrected for temperature and normalized to 25 degrees centigrade. From hereinafter the EC of the applied irrigation water will be referred to as EC_w. Soil salinity is typically measured in a saturation soil extract (EC_e), a saturated paste (EC_p), or *in situ* by electroconductmetric methods by measuring the apparent bulk conductivity, EC_a.

The units for EC can sometimes be confusing. The unit for the conductivity per unit volume of 1 cm^3 is siemens per centimeter (cm) but this unit is much too large. Consequently, the most common working units are the millisiemen per cm (mS/cm), the decisiemen per meter (dS/m) which is equal to the traditional millimhos per cm (mmhos/cm) unit dimension for expressing EC (mS/cm= dS/m= mmhos/cm). The second parameter is the gravimetric measure of the aggregated concentration of the dissolved minerals commonly known as the total dissolved solids, or just TDS expressed in units of ppm or mg/l. Knowledge of the gravimetric content of salts is particularly important in determining loading.

One of the overall effects of salinity and the degradation of soils is the special case where excessive sodium in irrigation water is a contributing factor to infiltration problems. This is referred to as "sodicity."   The two factors that influence the infiltration of water into the soil are (1) the salinity of the water, and (2) the amount of sodium relative to the amount of calcium and magnesium. The index that has been used most commonly to determine the contributing potential of sodium to infiltration problems is the Sodium Adsorption Ratio (SAR). The SAR can be expressed in two ways; it's original form as:

$$SAR_w = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

or it's "adjusted" form accounting for changes associated with calcium dissolution/precipitation at the soil surface:

$$adj_2 R_{Na} = \frac{Na}{\sqrt{\frac{Ca_{eq}+Mg}{2}}}$$

Source of Agricultural Salt Problems

The primary origin of salts is the chemical weathering of geological materials and anthropogenic processes. Congruent, incongruent dissolution, and redox reactions are responsible for salt accumulation in soils and waters by chemical weathering. The anthropogenic salinization processes are driven by evapotranspiration which are discussed briefly as follows.

The concentrations of soluble salts increase in soils as the soil water is removed to meet its atmospheric demand by evaporation and transpiration.   The salts, which are left behind concentrate in the shrinking soil-water volume with each successive applied irrigation; passing through the soil profile.   Furthermore, soils with shallow, saline water tables can become salinized as the result of the upward flux of water and salt into the rootzone. It is these soluble salts that if not managed, will eventually build up in irrigated soils to the point that crop yield is adversely affected.

PHYSIOGRAPHIC FEATURES AND AGROECOLOGY OF THE ARKANSAS RIVER BASIN

Physiographic Features

The Arkansas Valley originates upstream from Leadville, Colorado, at an elevation of more than 14,000 feet. A notable feature of the Arkansas River Drainage Basin, which encompasses about 26,150 square miles including the Cimarron River watershed, is that its headwaters are at the highest point (14,433 ft above mean sea level) in Colorado. The river leaves the state downstream at the lowest point in Colorado of less than 3,400 feet elevation. Between these two points the river flows about 360 miles through Colorado. The river's transition from the mountains to the plains is near Canon City, 36 miles west of Pueblo. West of this transition the river gradient averages about 40 feet per mile; east of this point the river gradient is reduced to a little less than nine feet per mile.

The Sawatch Mountain Range separates the basin from the Colorado River Drainage Basin on the northwest; the Rio Grande Drainage Basin by the Sangre de Cristo, and Culebra Ranges on the southwest. There are 23 peaks in these three mountain ranges that have elevations greater than 14,000 feet above sea level. On the north, the Mosquito Mountain Range and Monument Divide also referred to as the Palmer Lake Divide or Palmer ridge separates the northern boundary from the South Platte River Drainage Basin.

The basin is typically divided into two physiographic provinces; to the west is the Southern Rocky Mountain Province while to the east is the Great Plains Province. The division between the two provinces is approximately at the 105-degree parallel (longitude). The Southern Rocky Mountain Province consists primarily of the mountain area underlain by Precambrian igneous and metamorphic rock formations. Late Cretaceous marine shales and limestones underlie the Great Plains Province. The Great Plains Province can be further divided into the "Colorado Piedmont" and the "Raton Section." A parallel line divides them approximately 25 miles south of the Arkansas River representing the elevated plain north of the line and the trenched peneplain south of the line.

Surface and groundwater irrigation water, return flows, and irrigation ditch overflow are the primary water sources. Surface water supplies consist of both direct-diverted, native waters and transmountain diverted water imported in to the Arkansas River Basin. Since 1996 all diversions of tributary groundwater (wells) for irrigation including those within the proposed project area are subject to specific augmentation requirements. Based on whether the groundwater source is used as supplemental or sole source water supply for irrigation purposes, a percentage of the total water pumped is to be replaced to the Arkansas River. This replacement of these so-called presumptive stream depletions are placed to prevent material injury to senior surface water rights and depletions to the Colorado-Kansas stateline flows under the Colorado-Kansas Compact.

Agroecology

Settlers arriving in the area relied on cultivated irrigated crops. As early as 1853 it was recorded that in addition to corn and wheat, the potato, rutabaga, and beet were easily cultivated. Other crops that drove the early production system of the region were alfalfa, watermelon, first grown in 1878; and cantaloupe, first grown in 1884. In 1896, the Rocky Ford Melon Growers Association was organized to bring producers together into one marketing group. Melons were shipped with the brand name "Rocky Ford" cantaloupe, a name that remains widely known across the country.

By 1905, four seed companies had developed businesses in Rocky Ford. By 1907, one of these, the Rocky Ford Seed Breeders Association, was selling 30 tons of cantaloupe seed per year to growers in the Imperial Valley of California. By 1925 ninety percent of the cucumber seed and 75 percent of the cantaloupe seed planted in the United States were grown in Otero County. However, the perishability of these commodities and price fluctuations led farmers to seek a more diversified irrigated agriculture.

The crop introduced to fill the void turned out to be the sugar beet. Much of the original irrigation development has been tied to the sugar beet industry. At the peak of the industry, 22 sugar beet processing facilities operated in southeastern Colorado. Ultimately, the valley had more factories than the farmers and land were able to support. This coupled with lower yields, caused by poor quality irrigation water, sugar-pricing problems, and outbreaks of beet blight ("curly top") resulted in sharp decline and elimination of profits. All but one of the factories had closed by 1967 and all are presently closed.

Another key crop in the development of the agricultural heritage was Pascal celery. It was through the efforts, in part, of the Pierce Seed Company of Pueblo that the "Pueblo celery" became recognized as high quality celery surpassing that of the products produced in Michigan and California. The Pueblo Pascal celery, which was characterized by its crispness, whiteness, and distinctive nutty flavor, soon became the preferred choice over the Golden celery grown elsewhere. By 1919, shipments amounted to 500 refrigerated railcars, each carrying 40,000 pounds.

The celery grown from what were called the Booth Gardens fields near Pueblo was being served on the tables of hotels in New Orleans and St. Louis during the early 1900's. The celery was served in the dining cars of the Missouri Pacific and Santa Fe railroads. Between 1923 and 1927 it was this celery grown near Pueblo, Colorado, that President Coolidge and his wife wanted for their holiday White House dinners.

One of the most notable celery producers by the name of Charley Barnhart became the largest celery producer in the area (Evans, 1994). He was considered the leader in celery production, overcoming the many cultural problems including the method of planting the stalks back three times during the year. Although most of the crop went to market during the Thanksgiving and Christmas holidays, Barnhart advanced the storage technique of placing celery in trenches covered with straw and soil. Under favorable conditions this allowed the celery to be kept as late as April of the following year and marketed when prices were high. Celery met a similar fate to that of the sugar beet. The sugar beet leafhopper and the aster yellows virus proved disastrous to the local celery industry. The last celery crop was grown in 1981.

Although the "Rocky Ford" cantaloupe, sugar beet, and the "Pueblo Pascal" celery were two of the earliest crops critical to development of the valley, other crops have proved to be adaptable to the area. Crops currently grown include corn, grain sorghum, alfalfa, soybean, dry bean, wheat, onions, tomato, potato, watermelon, honeydew, cucumber, cabbage, cantaloupe, chile, wine grapes, cabbage, apples, sweetcorn, raspberries, pumpkins, black-eyed peas, green beans, squash, cherry, plum, okra, barley, parsnip, winter turnip, garlic, turf, and zinnia flowers for seed.

One will find a cornucopia of fresh vegetables in today's roadside markets including a host of chile pepper varieties, spelled "chile" not "chili" (Domenici, 1983). The first pepper to be grown was the cherry pepper. In 1961 just a year later, Denver's Dreher Pickle Packing Co. contracted three acres. By 1996, the acreage grew to almost 800 acres and has come to include many of the pungent as well as non-pungent chile peppers with household names such as 'Big Jim', and 'Anaheim'. Just as the "Pueblo celery" dominated the early 20th century, the "Pueblo chile", is becoming a recognized important part of the agricultural commodity system. A mirasol (meaning 'looking at the sun') chile, it is a preferred pungent type for many culinary uses including salsas.

Two seed companies remain as leaders in the development, culture, and marketing of curcurbit and other specialty seeds worldwide. Melon development continues as well. The "Rocky Sweet," a cross between a cantaloupe and honeydew was grown commercially for the first time in 1985 and is steadily becoming a favorite for the melon connoisseur.

A part of the special agricultural production heritage of the middle reach of the basin relates to the dominance of the small farmer many of who are of southern European decent. Most came to the United States during the early 1900's to work in the Colorado Fuel and Iron (CF&I) steel mill. Looking for alternate income sources during mill slowdowns, they started small truck farms and developed roadside markets. Although the farms have tended to become larger over time the small truck farm operations still play a very important role in today's production system.

A HISTORIAL PERSPECTIVE OF IRRIGATION DEVELOPMENT AND ITS CURRENT STATUS

Regional Irrigation History

Much of the interesting irrigation history in the southwest surrounds the debate that all puebloan groups including the Rio Grande Valley of New Mexico practiced irrigation before the Coronado expedition. It has been asserted without a great deal of evidence that these puebloans learned to irrigate from the Chacoan Anasazi. It is important to note though that protohistoric Sonorant irrigated agriculture was observed by both the Coronado and Ibarra expeditions. However, the records of Coronado did not mention anything about the engagement of Rio Grande puebloans in irrigated agriculture.

This other side of the debate suggests that not all puebloan groups inherited the knack for irrigation; that it were the encomenderos and missionaries that imposed the irreversible reliance on irrigated culture (Wozniak, 1998) on the native peoples of this region that would eventually become Colorado and New Mexico. One substantial piece of evidence to support the push of intensive agriculture came out of the Espejo expedition starting in 1582. The expedition included visits to a number of pueblos including those of the Piro and Salinas Provinces in the vicinity of present-day Socorro, New Mexico. It was reported that corn was being irrigated with dams and canals apparently from the Rio San Jose or Rio Cubero Rivers that looked to have been built by the Spaniards (Hobbs, 1997). Just previous to the Espejo expedition, reports from the Rodriguez-Chamuscado expedition in 1581 provided positive evidence of puebloan irrigation just north of present-day Bernalillo. Cornfields were being irrigated from what is assumed to be Las Huertas Creek that drains the north slopes of the Sandia Mountains. In a region that neither Espejo nor the

Chamuscado expeditions had explored, Gasper Castano de Sosa reported all six pueblos in the Sante Fe area that his expedition visited in 1591 had canals for irrigation.

The generally accepted beginning of Spanish irrigation in the region, however, was marked by the construction start of an irrigation ditch or *Acequia madre* (mother ditch) for the Tewa Pueblo in 1598. Under the Spanish repartimiento and encomienda system the demands compelled the Puebloans to intensify agricultural production through irrigation during the seventeenth century. The demanding system for labor, the inclination for Puebloans to hunt rather than farm; economic exploitation and religious persecution as history recounts, led to the Pueblo Revolt of 1680 which decimated the Spanish settlements.

This brings us to the Spanish Colonial New Mexico period following the Reconquest of New Mexico. This period was ushered in with a new economic regime; one that focused on land grants rather than encomiendas. With the exception to Diego de Vargas himself, the Spanish settlers were required to support themselves by their own labors. Rehabilitation and development of new acequia madres was of primary consideration.

Much of Colorado's irrigation history is centered in the Arkansas River Basin. The richness of the agricultural heritage as related to irrigation is significantly enhanced from the geographic setting where the Arkansas River divided the future state. This was the border separating Mexico and the United States between the years 1803 (Louisiana Purchase) and 1848 (Treaty of Guadalupe Hidalgo), which signaled the end of the Mexican-American War.

The first known attempt at modern irrigation within this region of the Spanish Territory is documented to have been near Pueblo. In the summer of 1787 ten years after his appointment, Juan Bautista de Anza, the Governor of the Spanish New Mexico Province entered into a treaty with the Jupe tribe of the Comanche Indians (McHendrie, 1952). It was one of the outcomes of this treaty that led to the establishment of the first recorded irrigation system.

Leading up to the treaty there were hit-and-run raids by the Comanche Indians on the Ute villages, Spanish hamlets, and pueblos along these northern regions of the territory. Previous attempts to squash the Jupe Commanche raids were unsuccessful. The Spanish would advance over Raton Pass or Sangre de Cristo Pass only to have the Jupe Comanche Indians spot dust clouds and campfires of Spanish soldiers and then perspicaciously retreat to western Kansas to safety (Quillen, 1994). The raids, led primarily by Chief Cureno Verde (Green Horn), tormented and menaced the Spanish settlers and villagers to the point that in 1779, Governor Anza led a military party to the Jupe Comanche hunting grounds on Greenhorn Creek. It was a location on Greenhorn Creek, a tributary to the St. Charles River where Verde was engaged in battle and killed (Aschermann, 1994). An ancestor of Anza's cartographer has recently disputed the original marked site of this battle (Vigil, 2001). Because of the original mistranslation of the Spanish word "zanja" coupled by retracing the mileage in Anza's diary it is now thought that the battle was fought near the intersection of Water Barrel Road and Burnt Mill Road. Greenhorn Peak, the highest within the Wet Mountains, just southwest of present-day Pueblo and readily visible from the proposed project area is named in honor of this battle.

Anza had not only demonstrated his leadership abilities as a military leader but also as an expert frontiersman. He had already founded San Francisco (San Francisco Presidio) and Mission

Dolores in 1776 and earned the name "Great Colonizer." As a part of the treaty that Governor Anza had orchestrated with the Jupe Comanche following the untimely death of Verde, Anza sent about 20 Spanish farmers and artisans to settle a colony with the tribe who had given in to the Spaniards and were willing to settle in villages.

This colony was built on the banks of the San Carlos (St. Charles) River at the confluence of the Arkansas River. It was named "San Carlos de Jupes." Provided with seeds to plant and sheep and cattle, the Spaniards with their Comanche counterparts constructed a ditch that took water from the San Carlos (St. Charles) to irrigate a large tract of land that had been sodbroken and put into cultivation. The Colony was eventually abandoned.

There are at least two accounts for the lack of success of the venture. The lack of leadership by the successor to Governor Anza who died in 1788 coupled with the Commanche's lack of enthusiasm for the manual labor required for irrigated farming and homes contributed to the Colony's demise. Another account suggests that the death of a woman who had been admired by Chief Paruanarimuco contributed to abandonment; that the Comanche viewed the woman's death as a divine sign of disapproval (Aschermann, 1994). As a result they deserted the settlement and other Spanish colonists weren't interested in moving to San Carlos.

There are accounts of several early unsuccessful attempts of irrigation and farming in the basin following the Louisiana Purchase. These include a ditch that was built near Bent's Fort in 1832 in which about 40 acres of corn, beans, squash, and melons were planted. However, Indian ponies grazing on the growing crops thwarted any kind of productive harvest.

Probably the first record of what could be considered a successful irrigation venture was the establishment of the settlement in 1841 of what would become known as "El Pueblo" (Fort Pueblo). Along with the trading post there was extensive acreage cultivated until Ute and Apache Indians killed the Mexican inhabitants in 1854. An irrigation enterprise was established in 1846 where the Taos Trail crossed Greenhorn Creek (Ashermann, 1994). The location became known as John Brown's Store near present day Rye. In the same area a settlement of French-Canadian hunters and their Indian wives were reported farming in the Greenhorn Valley in 1847 by G.F. Ruxton (Taylor, 1963). In the same year, the Bent Brothers under the guidance of John Hatcher, downstream of present day Trinidad on the Purgatoire River (El Rio de Las Animas Perdidas en Purgatorio) dug an irrigation ditch.

In 1853 a report by Lieutenant Beckwith traveling with Gunnison's exploration party showed that six Mexican families were diverting water out of Greenhorn Creek using the ditches previously constructed by John Brown. It was also in 1853 that a ditch was dug for purposes of irrigation by Charles Autobees on the west bank of the Huerfano River.

In 1859, at the same location where Beckwith reported the diversion of water from Greenhorn Creek, Zan Hicklin and his wife Estefana who was Charles Bent's daughter established one of the largest irrigated farming operations. Using the ditches originally dug by John Brown and employing large numbers of Mexican laborers, the Hicklin's cultivated a total of 380 acres. This water right associated with the appropriation of this water was the earliest adjudicated appropriation in the basin (March 31, 1859) in the name of Hicklin Ditch on Greenhorn Creek.

The first two water rights on the main-stem of the Arkansas were decreed 30 days apart in 1861; the second to be that of the Bessemer ditch. By the middle 1880's the main-stem and tributaries of the Arkansas were fully appropriated. Water right decrees later than 1887 are little more than flood rights providing water only during snow melt and after summer rainstorm events; the last decreed right is 1933. Major irrigation development required large scale financing to enlarge the very early diversions. Most of the systems were constructed between 1874 and 1890.

Contemporary Irrigation

Historically, the area of land irrigated in the Arkansas Valley has remained relatively stable. In 1969 the U.S. Bureau of Reclamation (1969) estimated the land-irrigated equal to about 415,000 acres. In the mid 1980's the estimated number of irrigated acres was cited to be about 411,000 acres, of which 56,000 acres are located in the upper portions of the basin (Dash and Ortiz, 1996, Litke and Appel, 1986). The seasonal water supply in the basin is subject to considerable fluctuation. Waters native to the Arkansas River, its tributaries, and water imported into the basin via the Frying Pan Arkansas Project, are used and reused. The basin also includes a number of storage reservoirs. Institutionally Arkansas River Drainage Basin (Water Division II) is divided into 13 Water Districts. For a complete description of the operations of the various water systems, the reader is referred to Abbott (1985).

Arkansas River Mainstem. In the upper reach of the Arkansas River above Pueblo Reservoir (Districts 11, 12) water is diverted to irrigate alfalfa, hay, or irrigated pasture, and serves small orchards. Major conveyance systems include the South Canon Ditch, Pump Ditch and the Crooked Ditch, Canon City Hydraulic Ditch, Fruitland Ditch, Grandview Ditch, Canon City and Oil Creek (Mill) Ditch, Fremont County Ditch, Union, Hannenkratt ditch, and the Lester and Atteberry ditch.

Below Pueblo Reservoir Major irrigation conveyances diverting from the main stem of the Arkansas River in Water District 14 are the Bessemer Ditch, Colorado Canal, Rocky Ford Highline Canal, and Oxford Farmers Ditch. There are also several small irrigation ditches including the Hamp-Bell, West Pueblo, Riverside Dairy, Excelsior, and Collier.

Above John Martin Reservoir the Otero, Catlin, Holbrook, Fort Lyon Storage, Rocky Ford, Fort Lyon, and Las Animas Consolidated Canals headgates are all in Water District 17. The canal and ditch systems on the mainstem below John Martin Reservoir are in Water District 67; these include the Fort Bent Canal, Keesee, Amity Canal, Lamar Canal, Hyde, Manvel, X-Y Canal and Graham Ditch, Buffalo Canal and Sisson Ditch. Although the diversion of the Frontier Ditch is physically located in Colorado just west of the state line it irrigates cropland in Kansas and therefore considered a Kansas ditch.

Arkansas River Tributaries. There are a number of significant water conveyance systems that divert water from Arkansas River tributaries. Included in the Wet Mountain Valley, located in Custer and Fremont County is the DeWeese-Dye ditch; located on Fourmile, Hardscrabble, and Beaver Creeks are Park Center, Hardscrabble ditch, and Brush Hollow Supply Ditch.

Other tributaries with minor diversions include Fountain Creek and the Apishapa River. Serving the terrace lands on Fountain Creek between Colorado Springs and Pueblo are the Fountain Mutual ditch and the Chilicott Canal. Limited water is diverted for irrigation In the upper reach of the Apishapa River from the Escondito, Salisbury and Widderfield ditches

As previously mentioned the main tributary of the St. Charles River, is Greenhorn Creek the location of the earliest priority in the Arkansas River basin: the Hicklin ditch, with a water right from spring 1859. Smaller ditches include St. Charles Flood, Tucker, Fairhurst,, McDowell, Chase, Wagner, Eagle, Fisher,Bryson, and Anderson.

Diversions on the upper Huerfano River include the Medano Ditch and small direct diversions on Pass, Williams, and Turkey Creeks convey water to a number of ranches near Red Wing, Colorado. Other diversions include the Orlando Ditch, Huerfano Valley, Farmers Nepesta, and Welton Ditch. Also there are waters used for irrigation supply from the Cucharas River, tributary to the Huerfano River. These are Middle Creek, Wahatoya Creek, Abeyta Creek, Bear Creek, and Santa Clara Creek, and the Gomez Ditch.

The other tributary supplying significant water for irrigation is the Purgatoire River. Diverted through eight structures on the Purgatoire River's, water is delivered to 11 ditch companies and entities from the Bureau of Reclamation's "Trinidad project." Diverting water from the north side of the river include the Salas, Burns and Duncan, Hoehne, Model Inlet/Johns Flood, El Moro, and Picketwire. The Lewelling-McCormick, South Side, Victor Florez, and Chilili Ditches divert water from the south side of the Purgatoire River. Downstream from the Purgatoire Canyon and above the confluence with the Arkansas River are the headgates of the Ninemile and the Highland Canals.

Drainage Districts. Within the Arkansas River Drainage Basin, at least 30 separate drainage districts, many of which are now inactive, were established under statute during the early twentieth century. These included the May Valley, Wiley of Big Bend, Pleasant Valley, Vista del Rio, East May Valley, McClave, Deadman, Lubers, Kornman, Riverview, Granada, Holly, Hasty, Arbor, Prowers, A.B.S. Company East Farm, Las Animas Consolidated, Consolidated Extension, A.B.S. Company No.1, A.B.S. Company No. 2, Olney Springs, King Center, Ordway No.1, Valley View, Crowley, Numa, Grand View, Patterson Hollow, Holbrook and Fairmont.

Authorized under the 1911 and 1919 Colorado *Drainage District Acts*, the organization of these districts in Water Districts 17 and 67 led to the construction of an extensive drainage infrastructure consisting of about 107 miles of open drains and about 84 miles of subsurface tile drains[1]. This network that served nearly 100,000 acres was constructed for the purpose of maintaining productivity while providing return flows, is now in varied state of disrepair, deterioration, and dysfunction. Much of the original underground infrastructure, which upon completion by 1925, can no longer be located.

[1] Personal communication, 2004, J. Welkins-Wells, Department of Sociology, Colorado State University, Fort Collins, Colorado.

RELATIONS OF SALINITY TO SELECTED PHYSIOGRAPHIC FEATURES IN THE ARKANSAS RIVER BASIN

The areal and seasonal salinity characteristics within the Arkansas River Basin have been studied extensively (Cain, 1985, Dash and Ortiz, 1996). The information has included data for both the surface and groundwater resources. The information has emphasized electrical conductivity (specific conductance), its areal spatial, temporal variability and relationship to streamflow. Concentrations of dissolved solids and major ions have also been examined.

One of the first comprehensive studies was that conducted by Miles (1977). A key finding of this study was that an estimated 14 percent of the total salt load within the basin can be attributed to irrigation; industrial and municipal uses contributes about 8 percent with the remaining 78 percent resulting from natural sources. For the period studied (1965-1972) approximately 1.4 million tons of salt were diverted annually in the irrigation water from Canon City to the Colorado-Kansas stateline.

Areal and Temporal Distribution of Salinity and Relationship to Streamflow

The median electrical conductivity (EC) of the Arkansas River increases with increasing distance downstream (Figure 1). The lowest values occur in the upper reach. Small increases occur above Canon City. At Canon City the median EC is 0.3 dS/m or about 240 ppm. Between Canon City and Pueblo the salinity nearly doubles. The largest increases occur between La Junta and Las Animas. From the headwaters of the river to the Colorado-Kansas State line the salinity increases nearly 30 fold. The median salinity at the stateline is about 4.1 dS/m. The maximum salinity is about 6.5 dS/m. The total electrolyte concentration within the basin (Figure 2) ranges from about 0.97 meq/l ($m\text{mol}_c$/l) to 61 meq/l ($m\text{mol}_c$/l). In terms of the TDS the gravimetric salt content ranges between 76 mg/l to 4058 mg/l

The distribution of the dissolved chemical constituents and relationships of EC to dissolved solids are also very important particularly in evaluating waters suitability and calculating mass balances. The waters of the Arkansas River are primarily gypsiferous (calcium sulfate). The sulfate concentration ranges from about 40 percent (0.71 meq/l) of the total anions (1.78 meq/l) in the headwaters to 85 percent (47.8 meq/l) at the stateline.

In terms of cations, there occurs almost 6 times as much dissolved calcium (0.9 meq/l) as sodium (0.15 meq/l) in the upper reaches. The ratio of calcium to sodium decreases with increasing distance downstream. The concentrations become almost equal below John Martin Reservoir.

As expected the lowest salinity occurs during late spring and the irrigation season (May-Sep); the periods of high snowmelt and flow. Conversely, the greatest salinity occurs during the winter months and the non-irrigation season (Oct-Apr) in periods of low surface flow (Figure 2). As such there is strong correlation between salinity and streamflow. Seasonally and spatial log-log relations have been shown to best represent the inverse relation between salinity and streamflow. These relationships can be used to accurately estimate EC_w (specific conductance) from measured or simulated streamflows.

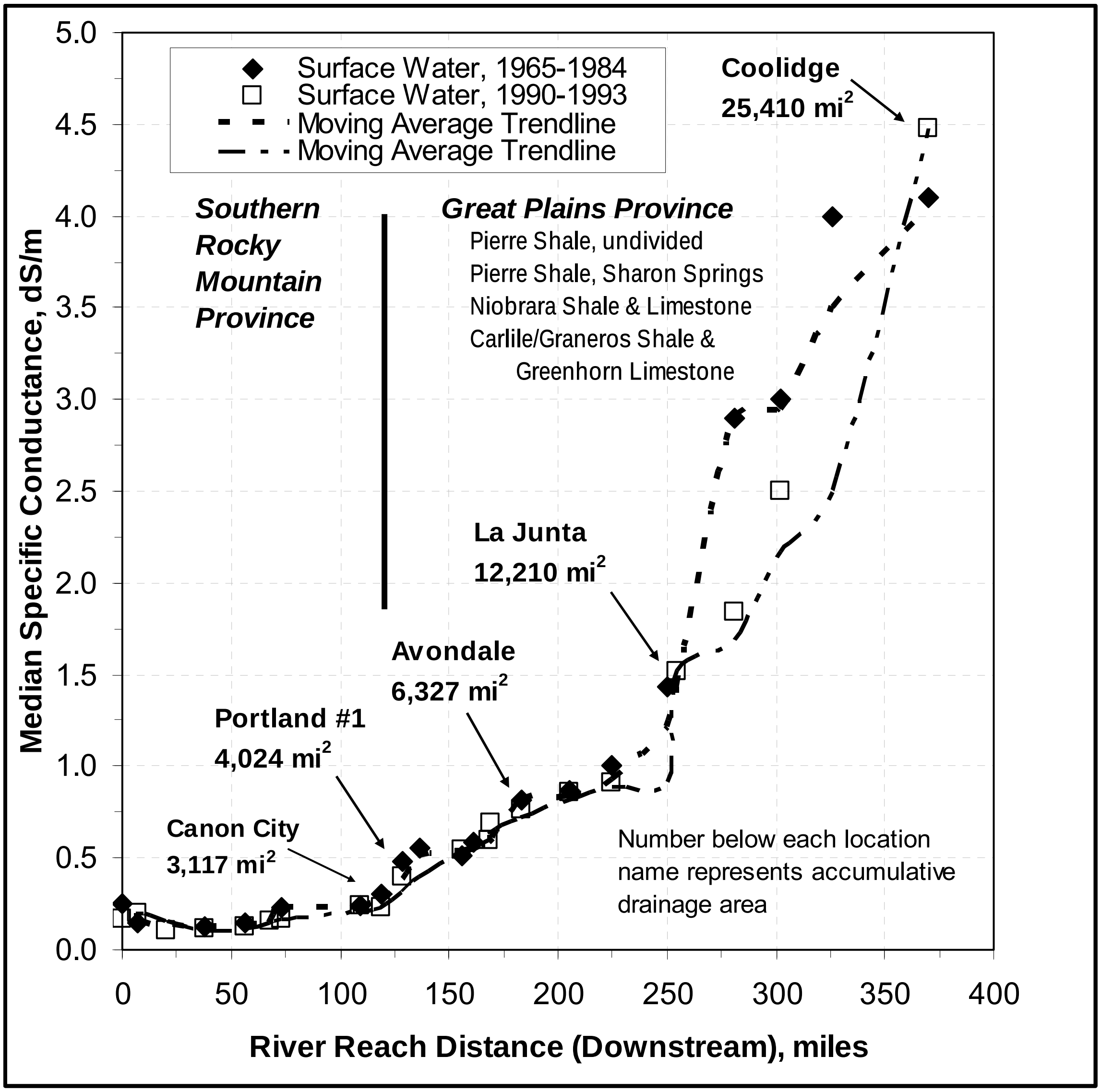

Figure 1. Spatial variation of surface water salinity in the Arkansas River Drainage Basin.

Looking closer in Figure 4 the relationship between river streamflow and specific conductance comparing the irrigation season and non-irrigation season is significantly different for an upstream location (Avondale) as compared to a downstream location (Coolidge). During the non-irrigation season and low native surface flow the higher proportion of groundwater return flow to the river accounts for the overall streamflow and high specific conductance at the downstream location.

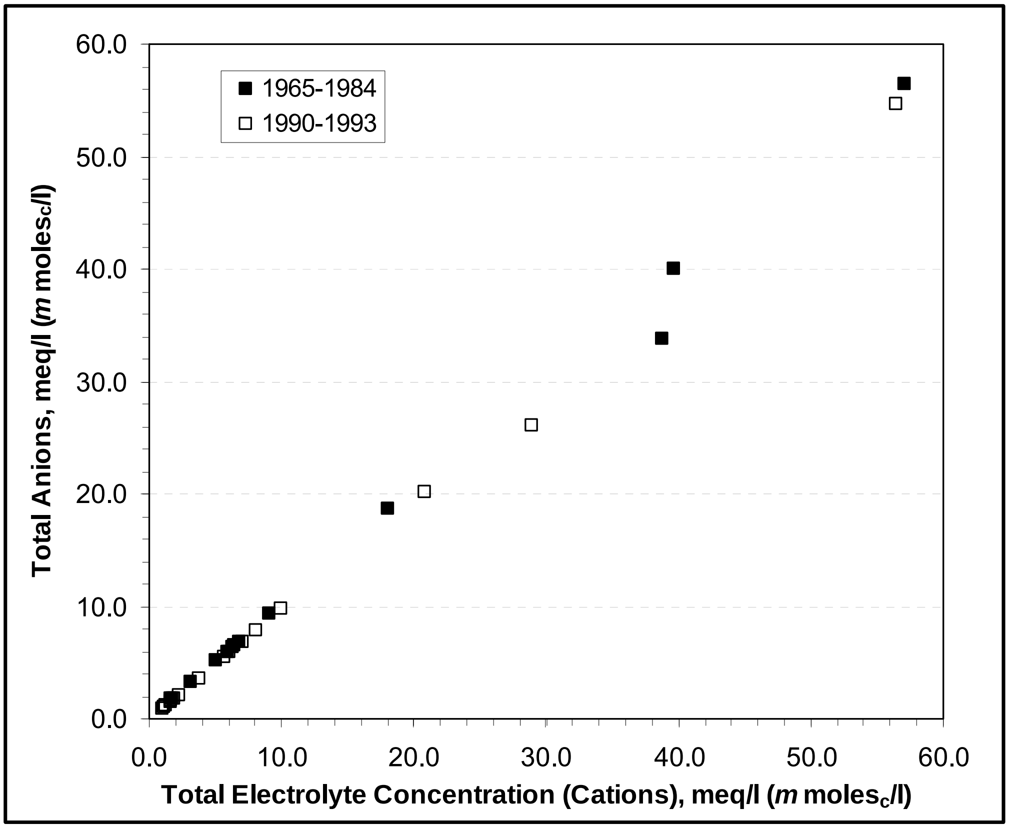

Figure 2

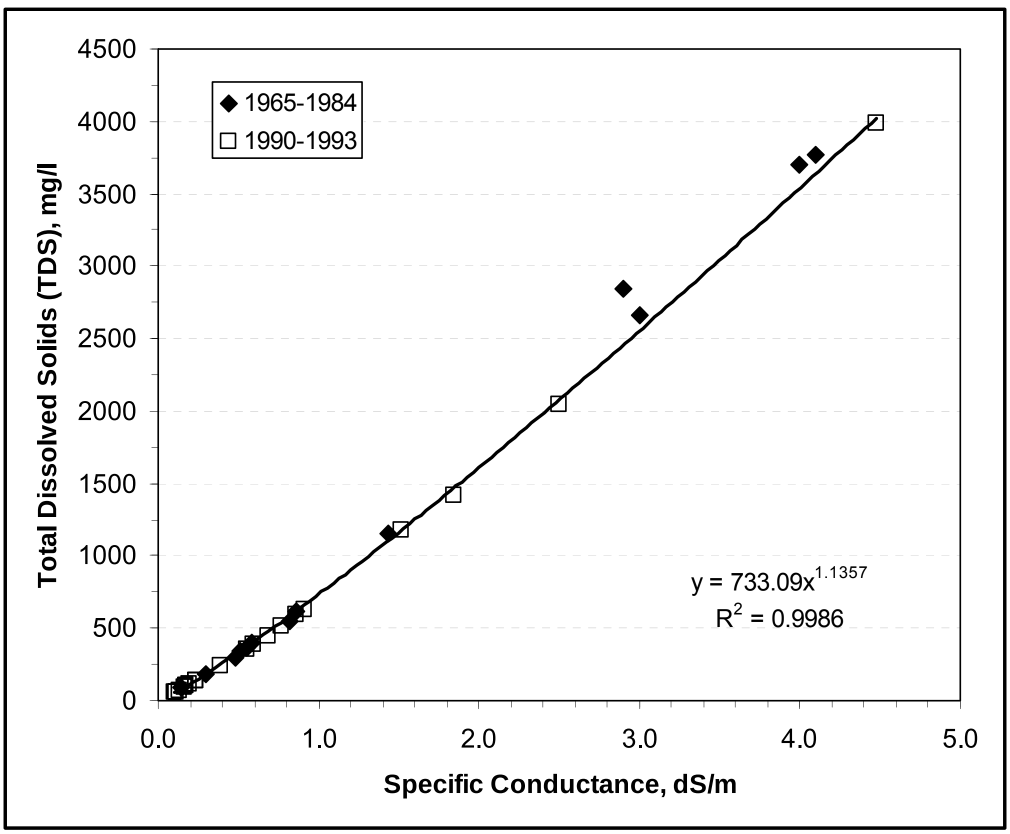

Figure 3

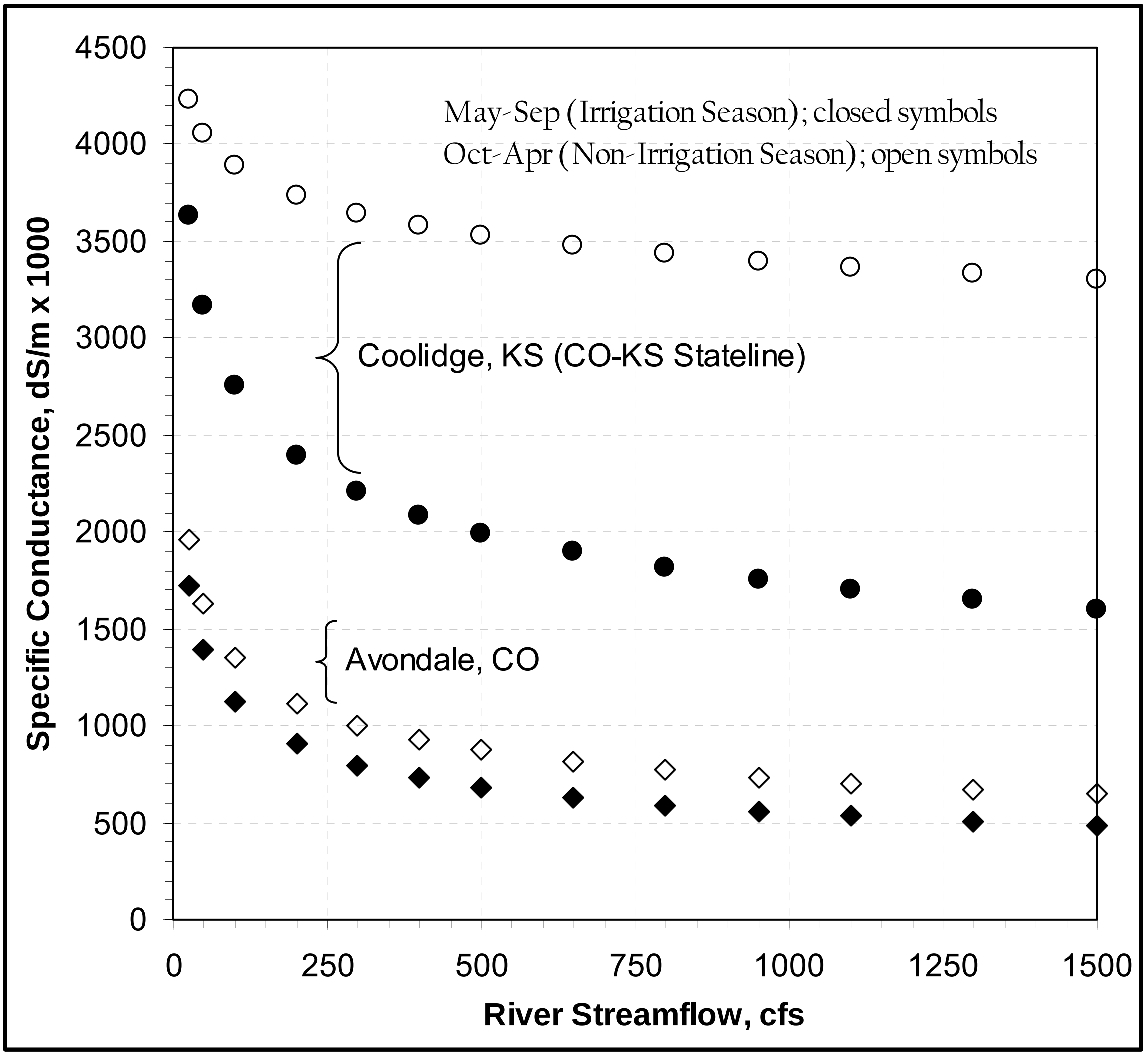

Figure 4. Relationship between river streamflow and specific conductance during periods of the year for an upstream location (Avondale) as compared to a downstream location (Coolidge).

MANAGING FOR SUSTAINED CROP PRODUCTIVITY AND WATER RESOURCE PROTECTION

As an anthropogenic cause of salinity, irrigation has a profound effect on introducing soluble salts into irrigated agroecosystems. There are four rules regarding irrigation and salinity that need to be understood:

- **RULE #1:** *ALL* waters used for irrigation contain salts of some kind in some varying amount.
- **RULE #2:** Salinization of soil and water is inevitable to some extent.
- **RULE #3:** An irrigated agroecosystem cannot be sustained without drainage, either natural or artificial.
- **RULE #4:** Rules 1 through 3 can't be changed.

Figure 2 illustrates the salinization process in irrigated terrestrial system and is described as follows. The anthropogenic salinization process by irrigation is driven by evapotranspiration. The concentrations of soluble salts increase in soils as the soil water is removed to meet its atmospheric demand by evaporation and transpiration. The salts, which are left behind as a consequence of plant uptake of nearly pure water concentrate in the shrinking soil-water volume are added to the existing quantity of salt in the root zone with each successive irrigation that is applied and passed through the soil profile. As an example, an irrigation source with a salt content of 850 ppm is introducing 1.16 tons of salt for every acre-foot of water applied.

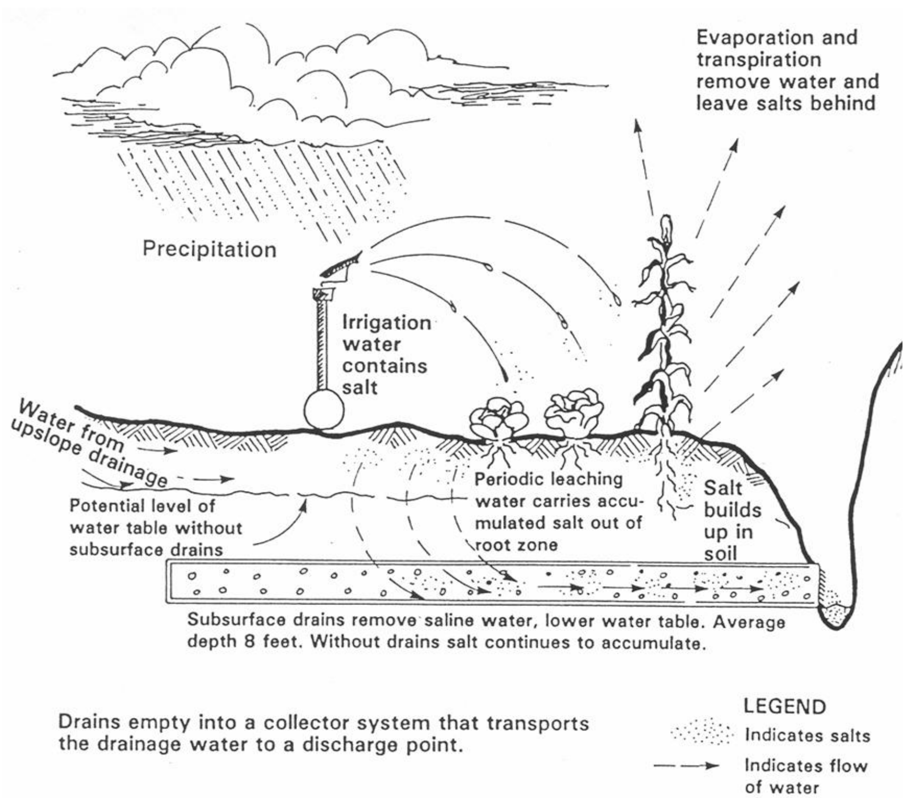

Figure 5. Mechanics of the salinization process in irrigated cropland systems (adapted from Tanji, et al., 1986).

Furthermore, soils with shallow, saline water tables can become salinized as the result of the upward flux, probably more familiarly known as capillary rise, of water and salt into the rootzone. Simply stated, these shallow water tables result when the natural discharge is less than the irrigation-induced recharge. There is a very close correlation between the level of salt accumulation in the soil with the water table depth, the salt content of the groundwater, and the soil's hydraulic properties. It is these soluble salts, that, if not leached, managed, and disposed of properly with drainage, will eventually build up in irrigated soils to the point that crop yield is adversely affected.

There is not usually a single prescription for an effective salinity management strategy. Rather, different practices and approaches need to be combined into a management scheme that is satisfactory in addressing an existing salinity problem or preventing one from manifesting itself into the terrestrial system. A given solution to a salinity problem can be complex. Not only are there the hydrogeology and edaphic, factors but economic and social factors to be carefully considered. The following discussion outlines an important guiding principle and its elements in the development and adoption of appropriate management strategies.

Since it's the chemical composition of the irrigation water that creates the adverse soil condition to begin with it seems logical to form a problem-solving framework starting with assessing the given water's suitability for use. In this regard perhaps the one overarching guiding principle that the practitioner needs to understand in order to develop the most effective salinity control strategy for a given situation should be evaluated on the basis of the potential use of a given source of water. Simply stated the principle is as follows:

> **"Water has no intrinsic quality, except in the resource setting for which it is to be used. The suitability of any given water source relies strictly on what can be done with it under the specific conditions of use."**

In as much there are several important elements in the development and adoption of appropriate management strategies within this cornerstone principle. These essential elements are (1) grow suitable salt tolerant crops, (2) use planting and tillage procedures that prevent excessive salinity accumulation in the seedbeds, (3) deliver irrigation water to fields efficiently, (4) apply irrigation water in an efficient manner that minimizes the leaching fraction and resulting deep percolation, (5) provide adequate drainage, and (6) monitor irrigation adequacy and soil profile salinity.

Grow Suitable Salt Tolerant Crops

The adverse effects of salts on plants are generally divided into three parts; 1) the osmotic effect (total salt effect), 2) specific ion effects, and 3) the indirect effects caused from soil dispersion due to excess sodium. The emphasis of this section is directed at the first two categories; osmotic effects and to lesser importance the tolerance of plants to foliar salt injury caused by specific ion effects. The indirect soil dispersion effect and the management of infiltration problems will be addressed in a later section.

Osmotic Effect. The plant extracts water from the soil by exerting an absorptive force in response to a gradient along the soil-plant-atmospheric-continuum; one that is greater than that adsorptive force that holds water within the soil matrix. When the plant cannot exert enough energy to extract sufficient water from the soil matrix the plant develops water stress.

Similarly, as the salt concentration of the water within the soil matrix increases, the energy that the plant needs to exert also increases. Increased salt concentrations narrows the gap between the soil water and internal plant energy potential. This is referred to as the osmotic effect caused by the increase in the osmotic potential of the root-zone soil solution. In order to maintain a suitable energy gradient for water uptake to occur, non-halophytes (glycophytes) require additional expenditure of metabolic energy. This additional energy expenditure shift would normally go to building dry matter and other plant functions.

For our purposes here, soil salinity is expressed as the mean electrical conductivity of a saturated-soil extract of the root zone, $EC_e(_{avg})$. The SI unit expressing electrical conductivity is decisiemens per meter. The osmotic potential (bars) of the root zone soil water at field capacity can be approximated with the relation, $OP_{fc}= -0.725EC_{e(avg)}^{1.06}$.

All crop plants do not respond to salinity in the same way; some produce acceptable yields at higher soil salinity levels than others do. Each crop species has an inherent ability to make the needed osmotic adjustments enabling them to extract more water from a saline soil. This ability for some crops to adjust to salinity is extremely useful. In areas where the accumulation of salinity within the soil profile cannot be controlled at acceptable levels, an alternative crop can be selected that is more tolerant resulting in the production of better economical yields.

Yield Response Functions. The relative salt tolerance of most agricultural crops is known well enough to provide general guidelines about salt tolerance for making management decisions. The salt tolerance of any given crop can best be illustrated by plotting the potential yield, sometimes referred to as the relative yield, as a function of soil salinity. The potential yield (Yr) or relative yield, expressed as a percent, is defined as the yield under saline conditions (Ya) relative to the yield under non-saline conditions (Ym):

$$Yr= (Ya/Ym)100 \qquad (1)$$

Although it has been shown that the relation between potential yield and soil salinity follows a sigmoidal curve, a piece-wise linear response function is used to easily describe the potential yield/soil salinity relation for acceptable crop yields (Figure 3). Two intersecting straight-line segments represent this linear piece-wise response function. One of the segments has a slope of zero. This means that the yield potential is constant across a range of soil salinity. The second line segment is a salinity-dependent line whose slope describes the yield reduction per unit increase in soil salinity. The point where the two line segments intersect specifies the threshold soil salinity ($EC_{e(ct)}$) or the maximum average root zone soil salinity at which yield reductions will not occur. Yield reductions will occur when soil salinity levels exceed this threshold value.

Mathematically, this piece-wise function can be represented as follows:

When, $EC_{e(avg)}$ is greater than or equal to $EC_{e(ct)}$,

$$Yr= 100- b(EC_{e(avg)}-EC_{e(ct)}) \qquad (2)$$

and when,

$EC_{e(avg)}$ is less than $EC_{e(ct)}$,

$$Yr= 100 \qquad (3)$$

where b is the slope of the second line segment expressed as the percent yield decrease per unit increase in soil salinity, $EC_{e(avg)}$.

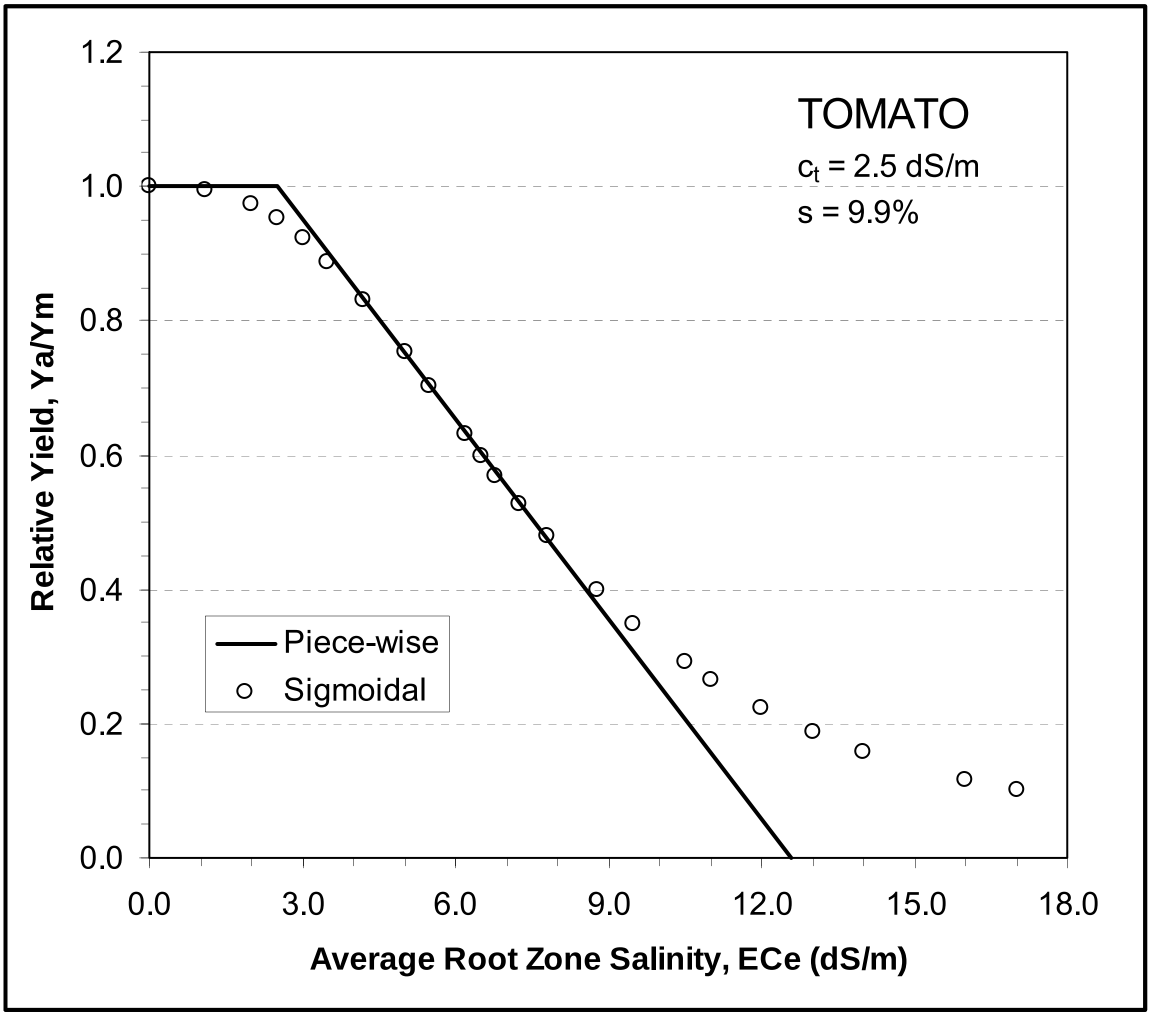

Figure 6. Yield response to soil salinity for tomato.

Rearranging Equation 2 the soil salinity at which a given yield potential can be obtained may also be calculated:

$$EC_e(avg) = (100 + bEC_{e(ct)} - Yr)/b \quad (4)$$

Likewise, the slope (b) of the line can also be calculated by rearranging Equation 2,

$$b = 100/(EC_{e(avg)}[0\%\ Yield] - EC_{e(avg)}[100\%\ Yield]) \quad (5)$$

where $EC_{e(avg)}$[0% Yield] and $EC_{e(avg)}$[100% Yield] are soil salinities at 0 yield potential and 100% yield potential, respectively. The analysis of tolerance field data shows that crops with similar tolerances form groups. The upper boundaries and relative tolerance rating have been assigned to these groups as shown by the thick-segmented lines (Figure 4). The four (4) regions between the lines define specific divisions for relative crop salt tolerance. These groups are classified as sensitive (S), moderately sensitive (MS), moderately tolerant (MT), and tolerant (T). Field soil salinity values that fall beyond the dotted line are considered to be unsuitable for most crops of economic importance.

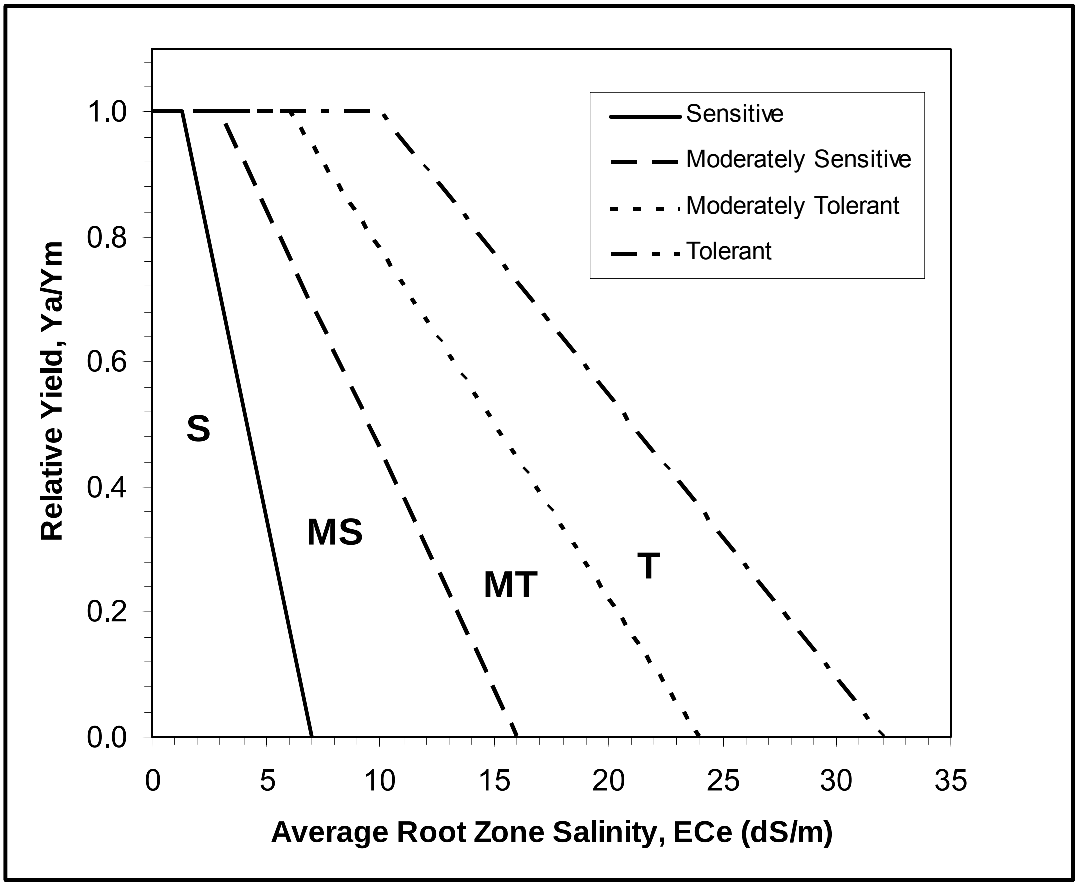

Figure 7. Crop yield response to salinity and categories for classifying salinity tolerance.

Although these groups are arbitrary, they are particularly useful in those instances where insufficient field data for a crop is available, but a relative rating can be assigned based on field experiences and local observations. The yield response of a crop that has been given a relative tolerance can be then be described (Table 1).

Table 1. Relative crop salt tolerances.

Relative Crop Salinity Tolerance Rating	$EC_{e(avg)}$ [0% Yield]	$EC_{e(avg)}$ [100% Yield]	Slope (b) [Equation 5]
	-------------------- dS/m	--------------------	-% per dS/m -
Sensitive (S)	7.0	1.3	17.5
Moderately Sensitive (MS)	16.0	3.0	7.7
Moderately Tolerant (MT)	24.0	6.0	5.6
Tolerant (T)	32.0	10.0	4.6

Appendix 1 lists the salinity thresholds ($EC_{e(ct)}$) and slopes, (b) for the most common crops and plants. In addition, these species have been rated as sensitive (S), moderately sensitive (MS), moderately tolerant (MT), and tolerant (T). The reader is referred to Maas (1990) for an expanded list of crops and their salinity tolerance.

It has been suggested that using the piece-wise linear relation is somewhat flawed (Shannon and Grieve, 1999). The reasons cited are that (1) there's a significant error in evaluating the slope near the threshold, that few studies include treatments to accurately determine the threshold value, and (2) the slope decreases with increasing soil salinity at the upper end of the curve. One of the more popular sigmoidal models for quantifying crop salt tolerance has been the logistic model that incorporates the parameter representing the salinity (dS/m) at which the yield is reduced by 50%, designated as C_{50} as presented by van Genuchten and Hoffman (1984). The general logistic model numerical expression takes the form, then, as:

$$Yr = 1/(1+ (C/C_{50})^{p}) \times 100 \qquad (6)$$

where C is the soil salinity expressed as EC_e. When too few data points are available to precisely evaluate the salinity threshold, the value of C_{50} and p, a crop dependent constant determining the curves shape, provides a more definitive and stable characterization of the yield response to salinity. However, the values of C_{50} and p have been evaluated for a limited number of crops.

It is important to note that for the most part the threshold soil salinity values that are cited were established from field studies where chloride was the predominant anion. In preparation of saturated-soil extracts in the laboratory, gypsum ($CaSO_4$) will be dissolved. For soils that are dominated by gypsum, the $EC_{e(avg)}$ may range from 1 to 3 dS/m higher than non-gypsiferous soils at the same moisture content and electrical conductivity of the soil water, EC_{sw}. This means that values of $EC_{e(ct)}$ for crops grown on soils dominated by gypsum may exceed table values by as much as 2 dS/m.

If the soil salinity levels greatly exceed the tolerance of all of the crop selections options and yield potentials of less than 100 percent are not acceptable, "reclamation" leaching may be necessary prior to any cropping. There are two conditions where reclamation leaching are most likely to be neccesary. The first condition is where an inverted soil salinity profile (accumulated salts decreases with soil depth) has developed. This condition is most familiar where salts have accumulated in the presence of a shallow water table. The second condition is where a regular soil salinity profile (accumulated salts increases with soil depth) exists at excessive levels caused by inadequate leaching. The goal of reclamation leaching must be to reduce the salt concentration in the upper portion of the root zone to a level that approaches the crop tolerance.

Susceptibility of Crops to Foliar Salt Injury Due to Sprinkler Irrigation. Foliar salt injury has been observed on a number of crop species. Similarly to the varying response of crops to soil salinity, species vary widely in their response to this injury from sprinkler irrigation utilizing saline waters. The foliar injury, commonly referred to as "salt burn", is caused by leaf absorption of excess concentrations of sodium and chloride.

Of all crop species evaluated, citrus and deciduous fruit trees, like apricot, plum, and almond, are the most susceptible to foliar injury. The extent of the injury may go beyond considerable leaf necrosis and may also include leaf defoliation. Among the herbaceous crops, plants' belonging to the Solonaceae family is generally the most sensitive. This would include potato, tomato, and peppers.

Table 2 provides some general guidelines for determining the susceptibility of crops to foliar salt injury from sprinkler irrigation based on the concentrations of sodium or chloride. These data represent field studies where the sprinkling occurred during daytime hours. There appears not to be a correlation between a crops tolerance to soil salinity and its susceptibility to foliar injury. Two examples include strawberry and avocado; both are very salt sensitive crops, but field data shows the risk of foliar injury to be negligible. Changes in management have been shown to reduce the risk of foliar salt injury. These include irrigating at night, avoiding periods of hot, dry winds, increasing sprinkler droplet size, and increasing rates of application.

Table 2. Tolerance of crops to foliar salt injury from water applied using sprinkler irrigation methods.

Critical Sodium (Na+) or Chloride (Cl-) Concentrations (meq/l)			
Tolerant >20	10-20	5-10	Sensitive <5
Cauliflower	Alfalfa	Grape	Plum
Sugarbeet	Sorghum	Pepper	Citrus sp
Cotton	Safflower	Tomato	Almond
Sunflower	Barley	Potato	Apricot
	Corn		

Stages of Growth. The soil salinity/crop tolerance relations in Appendix 1 apply primarily to responses from the late seedling growth stages to maturity. Field data on the variable crop tolerance during the early stages of growth (i.e. germination, emergence and seedling growth) are extremely limited. As a general rule most plants are tolerant during germination. After germination, plants may then become sensitive during emergence and the development of the seedling. Past studies have shown that increased salt concentrations may delay emergence, but does not affect final emergence. However, secondary conditions such as soil crusting could result in reduced crop stands. A general recommendation is that a soil salinity level of 4 dS/m in the seed zone will delay emergence seedling growth.

Use Planting and Tillage Procedures that Prevent Excessive Salinity Accumulation in the Seedbed

A number of crops tend to be sensitive to salinity during germination and seedling establishment. Stand losses can occur particularly when raised beds or ridges are employed. These losses can be significant even when the average salinity levels in the soil and in the irrigation water are moderately low particularly under furrow irrigation. Since salts move with the water, the salt accumulates progressively towards the surface and center of the raised bed or ridge. Thus the greatest damage occurs when a single row of seeds is planted in the middle of the bed. This is so because salts tend to accumulate under furrow irrigation in those regions of the seedbed where the water flows converge and evaporate this problem is magnified when saline waters are used for irrigation (Bernstein and Fireman, 1957).

Seedbed planting systems and furrows need be designed to minimize this problem. This can be accomplished by considering alternative bed-furrow configurations and irrigation practices that involve seedbed shape, seed placement and irrigation techniques including alternate furrow irrigation. Figure 3 illustrates typical salt patterns in flat and sloping beds.

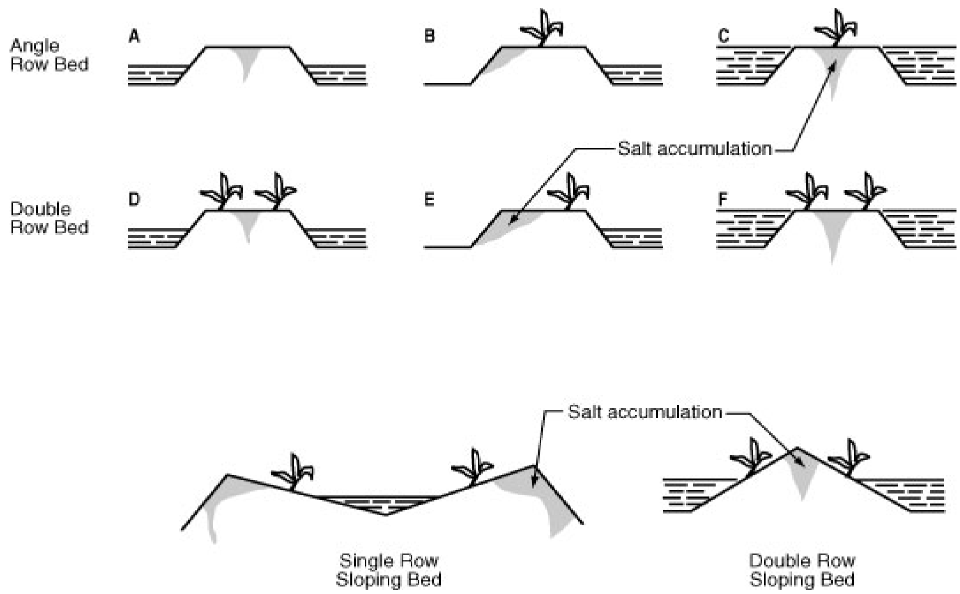

Figure 8. Salt accumulation patterns of flat and sloping beds as influenced by irrigation practice (Adapted from Bernstein and Fireman, 1957; Bernstein, *et al.*, 1955).

With the expansion of the use of subsurface drip irrigation in the Arkansas River basin, it is important to consider the distribution of salts within the root zone and bed. The patterns that form under subsurface irrigation are distinct and differ significantly from the pattern where the drip tubing is on the soil surface. Common to both cases salinity gradually increases as the horizontal distance from the line increases and the greatest salinity occurs at the leading edge of the wetting front very high salinity levels can occur near the soil surface (Figure 9).

While adequate leaching occurs below the buried tubing, the accumulation of salts above the drip tubing presents a dilemma. A salinity hazard can develop if insufficient non-crop season precipitation occurs and moves the surface soil accumulated salts back into the immediate seed zone that can be detrimental to the subsequent year’s crop. One strategy is to leach the salts with sprinkler irrigation.

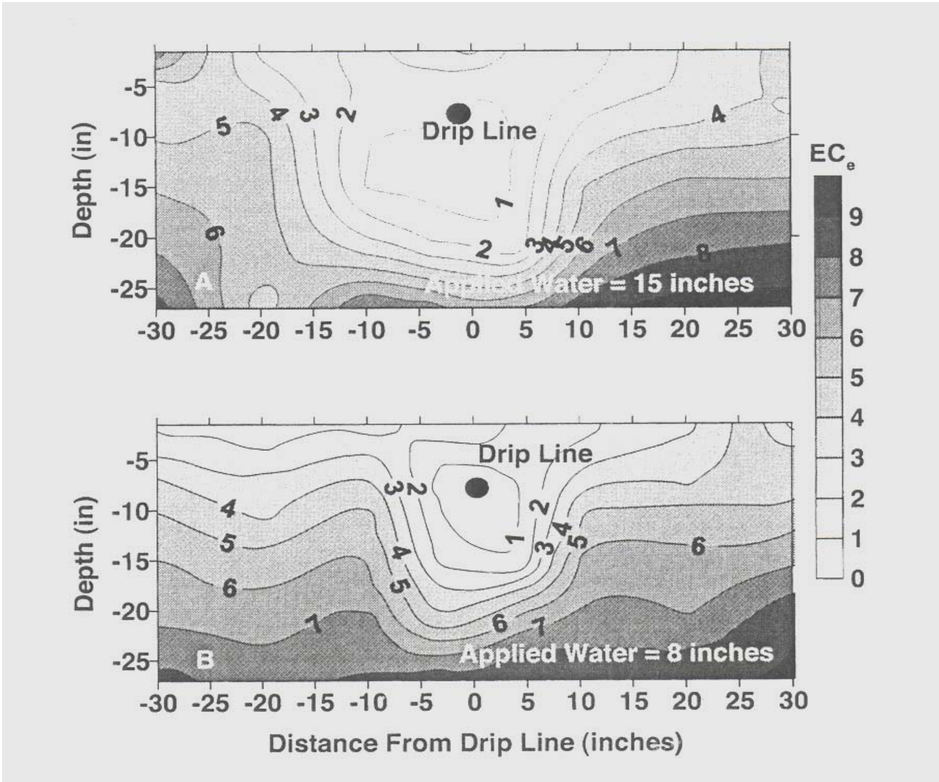

Figure 9. Root zone salt distribution with subsurface drip irrigation system.

Deliver Irrigation Water to Fields Efficiently

Unmistakably, the strategy for sustaining crop productivity and reducing the risk of salinity hazards of irrigated lands requires good irrigation management. The basis for good irrigation management for salinity control is timely uniform irrigations, applied in an adequate quantity to meet the crop's consumptive use (evapotranspiration) and at the same time satisfy the leaching requirement.

In addition, the causal and interacting elements of good irrigation water management include the delivery system and the method and manner of irrigation. For example water delivery based on predetermined amounts or preset periods without consideration of seasonal variations generally encourages over-irrigation. A consequence of these institutional constraints is limited adoption of higher efficient irrigation such as sprinkler and drip. The optimum water delivery infrastructure is one that can provide metered, controlled water nearly on a continuous basis so that the soil water content in the rootzone can be kept within prescribed limits.

The other two factors that must be considered as an overall strategy are controlling (i) seepage losses and (ii) maintaining drainage systems. Excessive loss of irrigation water from canals constructed in permeable soil contributes to not only the mineral dissolution of the underlying geologic materials, but contributes significantly to the manifesting of high water tables and soil salinization. Every effort should be taken to minimize these seepage losses.

The maintenance of the drainage system is also a key factor. Both in-field tile lines and open drains should be kept in working order. As far as sustaining irrigated agriculture it may well be necessary to reactivate many of the drainage districts in the basin.

Apply Irrigation Water in an Efficient Manner that Minimizes the Leaching Fraction and Resulting Deep Percolation

As discussed earlier some salt accumulation is inevitable attributed to two processes. Salt loading occurs from mineral weathering and dissolution of soluble salts. Moreover, salt concentration occurs from plant uptake of water driven by evapotranspiration, thus leaving the salts behind. When the accumulation of salts in the soil root zone becomes excessive to the point of affecting crop yield, they can easily be leached in the absence of a water table. The goal is to move a portion of the salts below the root zone (deep percolation) by passing irrigation water through the root zone.

The ability to pass a specific volume of water through and passed the root zone is dependent on sufficient water-entry at the soil surface or infiltration. The negative effect of salinity, specifically the amount of calcium and magnesium, relative to the amount of sodium is the interference in the normal infiltration rate and subsequent percolation of the infiltrated water (also referred to as permeability) through the vadose zone. When an infiltration problem results from the deleterious effect of the adsorbed sodium it is most commonly referred to as a sodium hazard or “sodicity”.

This section discusses the leaching fraction (LF), the proper calculation of the LF and assessing sodium hazards.

Leaching and Deep Percolation. Clearly, if the volume of water applied can be minimized in a quantity not to exceed a crop’s requirement, then the amount of salt added to the soil can be minimized. For example, water immediately below John Martin Reservoir contains about 3.3 tons of salt for every acre-foot of water diverted.

Leaching, as the key factor in controlling the soluble salts, is accomplished by applying an amount of water that is in excess of the crops seasonal evapotranspiration and runoff. This excess amount of water is called the leaching fraction (LF), normally expressed in the decimal form. As an example, a LF of 0.5 means that 50% of the water infiltrating into the soil profile passes through and out of the root zone.

The strategy is to optimize the leaching fraction to an acceptable minimum. The basis for attaining a minimum LF is two-fold. First as the LF decreases the precipitation of the dissolved salts applied in the irrigation water increases. The precipitation of salts consists of calcium, bicarbonate, and sulfates as carbonates and gypsum. The salt precipitation results in a decrease of the amount of salt in the soil and subsequent discharge from the rootzone. Second, reducing the amount of water passing through the root zone reduces the risk of additional dissolution of weathered minerals from substrata from the percolating water. The extent to which the LF can be minimized is limited by (i) the irrigation system, (ii) a crop’s tolerance to an increase in the root zone salinity.

To demonstrate the effect of leaching fraction on soil profile salinity, an example is given using the expected dissolved salt constituents of water diverted at two different landscape positions and six different leaching fractions. Figures 10a and 10b compare the soil profile salinity distribution and the precipitation-dissolution of gypsum when irrigated with water composition expected of that below John Martin Reservoir compared to that expected between John Martin and Pueblo Reservoirs.

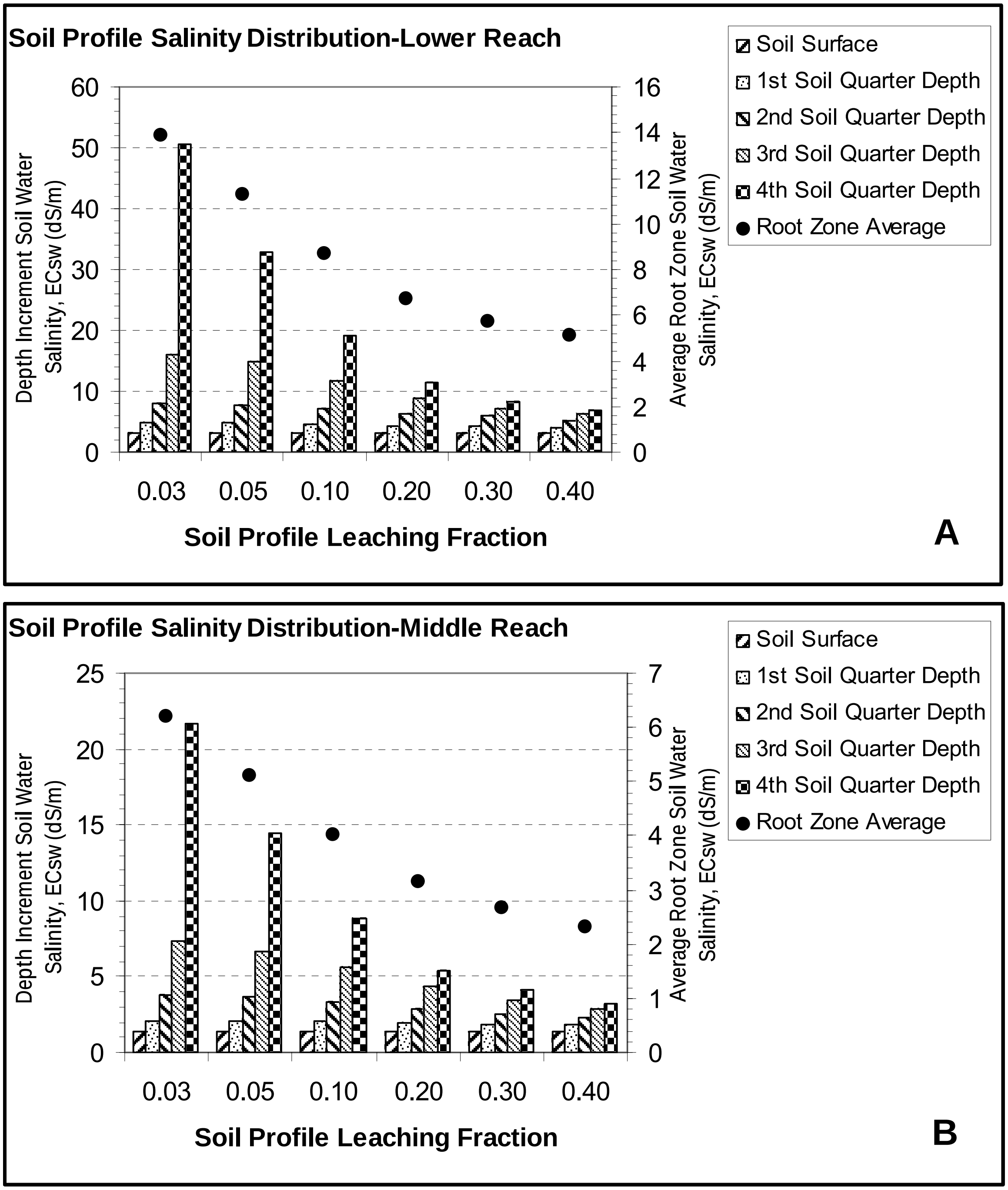

Figure 10. Soil profile salinity distribution as a function of the leaching fraction for the (A) lower reach and (B) middle reach of the Arkansas River basin.

Below John Martin Reservoir (Figure 4a) the leaching fraction increases as the average expected soil EC_e in the absence of a water table decreases ranging from 6.9 dS/m at a 3 percent LF to an EC_e of 2.5 dS/m at LF equal to 40 percent. [Note that the EC_e is about half of the EC of the soil water.] Above John Martin (Figure 4b) the average expected soil EC_e in the absence of a water table ranges from 3.1 dS/m at a 3 percent LF to an EC_e of 1.2 dS/m at LF equal to 40 percent. This illustrates the greater potential of reducing the leaching fraction of waters within the middle reach. To keep the salts balanced so that the soil profile EC_e is equal to 2.5 (EC_w= 5) we can minimize the LF to 40 percent and 5 percent using water diverted below and above John Martin Reservoir, respectively.

Leaching Fraction Estimation. In order to estimate the LF and the amount of water required, only three pieces of information are needed; (i) the crop threshold soil salinity, $EC_{e(ct)}$, (ii) the salinity of the irrigation water, EC_w, and (iii) seasonal maximum evapotranspiration (ET_m) of the crop. Figure 7 shows the relation between the leaching fraction, LF, and the ratio, F_c.

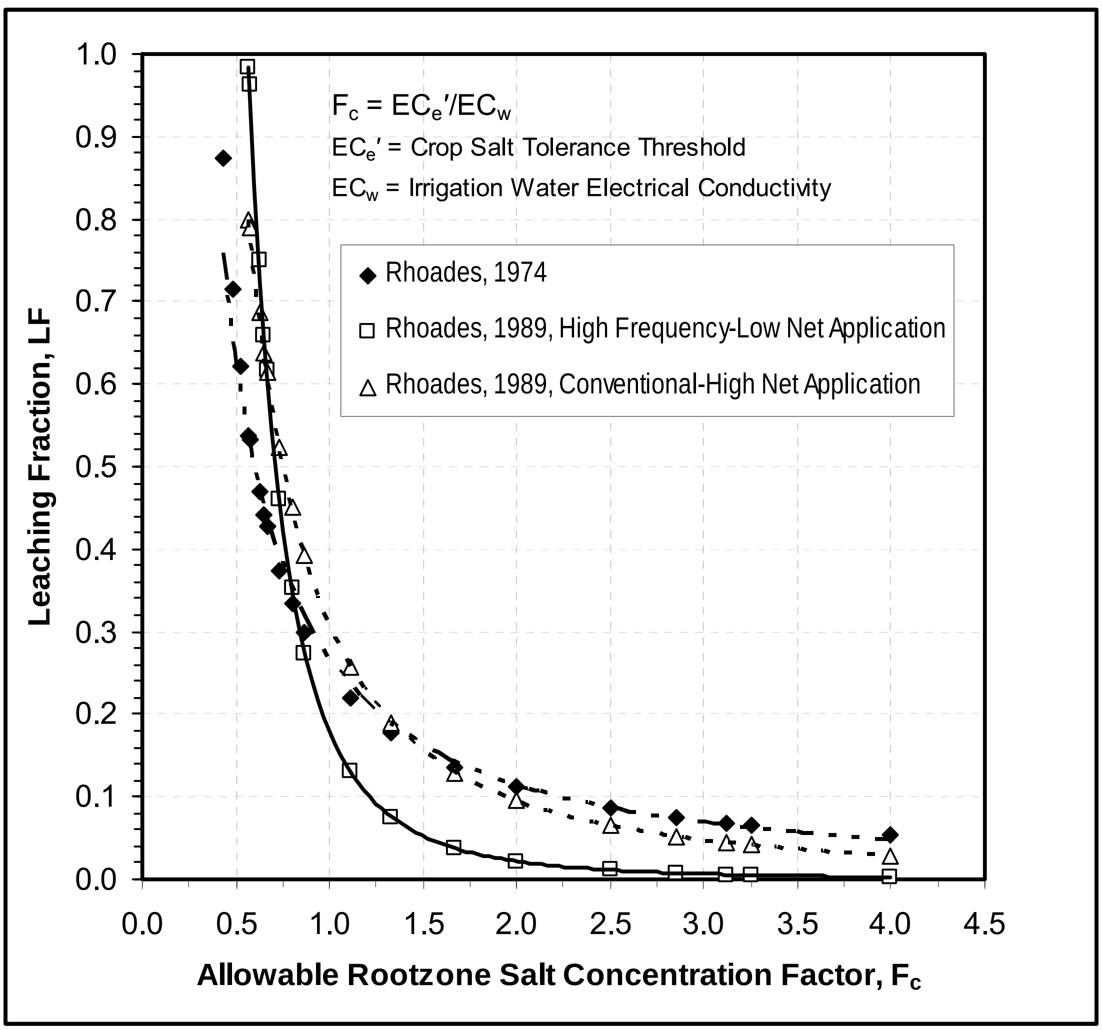

Figure 11. Relationship between the allowable rootzone salt concentration factor, F_c, and the leaching fraction, LF.

This ratio (F_c) is the crop threshold salinity divided by the irrigation water salinity ($F_c = EC_{e(ct)}/EC_w$). This relation shows that for any particular crop, the LF exponentially increases as the salinity of the water increases (ratio decreases).

Knowing the threshold salinity, $EC_{e(ct)}$, for a given crop and the electrical conductivity of the irrigation water, EC_w, the necessary leaching fraction (LF) can be graphically determined from Figure 11. For a more accurate LF estimation the exponential relations shown in Figure 11 can be simplified for any particular crop. The "classical" method (Rhoades, 1974; Ayers and Westcot, 1985) of determining the LF is described by the following equation:

$$LF = EC_w/(5EC_{se(ct)} - EC_w) \quad (7)$$

where $EC_{se(ct)}$ is the average EC_e at which the yield potential is 90% or greater.

In recent years (Rhoades, *et al*., 1989) it has been shown that the LF is affected by the net water application. To account for this effect an alternative method of determining the LF has been developed based on the allowable root zone concentration factor, F_c. Since the net water application can be related to the irrigation system these relations are divided into two categories, namely (i) conventional and (ii) high frequency. Under "conventional irrigation" where there are relatively large net water applications, a higher leaching fraction is required at the same value of F_c as compared to high frequency irrigation (small net water applications). Conventional irrigation scenarios where net water applications are relatively large include deep rooted crops grown under surface irrigation. High frequency irrigation scenarios include shallow rooted crops under surface irrigation or where sprinkler or drip irrigation systems are used.

The exponential relations for the conventional irrigation (CI) and high frequency irrigation (HF) can be calculated as follows:

$$LF = 0.1794/(Fc)^{3.0417} \quad \text{(High Frequency Irrigation-HF)} \quad (8)$$

$$LF = 0.3086/(Fc)^{1.7020} \quad \text{(Conventional Irrigation-CI)} \quad (9)$$

The net annual depth of irrigation water (D_w) that is required to meet both the crop evapotranspiration (ET_m) and the leaching requirement, D_{sw}' (excluding runoff) is equal to:

$$D_w = ET_m + D_{sw}' \quad (10)$$

Relative to the crop's total annual evapotranspiration the net annual depth of irrigation water can then be calculated:

$$D_w = ET/(1-LF) \quad (11)$$

where the ET and D_w are expressed in inches. From Equation 10, the portion of water that is applied for the leaching can then be calculated as:

$$D_{sw}' = D_w - ET \quad (12)$$

or,

$$D_{sw}' = \{ET/(1-LF)\}LF \quad (13)$$

Field studies and observations have shown that as a general rule the timing of leaching is not critical as long as the crop tolerance threshold is not exceeded during critical periods or extended time periods. Alternative timings include every irrigation, at selected seasonal irrigations or less frequently. It must be noted that water losses attributed to deep percolation that occur during the season, particularly with surface irrigation systems, are often in excess of the leaching fraction. A careful analysis must be done to determine whether or not the amount of water required for salt leaching will be satisfied by the field's irrigation inefficiency.

Infiltration and the Sodium Hazard. Salinity and sodicity affect soil structure in which the aggregate stability provides a network of conducting pores or optimum infiltration and permeability to take place. As previously introduced, a negative effect of salinity and the amount of sodium is the interference in the normal infiltration rate and subsequent percolation of the infiltrated water (also referred to as permeability) through the vadose zone. In the presence of sodium surface crusting, swelling, and dispersion are the primary processes responsible for an infiltration problem occurring In the presence of sodium which is reflected in the reduction in the soils hydraulic conductivity.

The soil’s sodicity can be described based on the exchangeable sodium ratio (ESR) or the more familiar term; the exchangeable sodium percentage (ESP) which is the percentage of the total exchange complex (or cation exchange capacity, CEC) saturated with sodium. Although the sodium hazard is a direct function of the soils exchangeable sodium percentage (ESP) the sodium adsorption ratio (SAR) of the soil solution is the variable that is used to describe the sodic condition since the SAR is more easily ascertained.

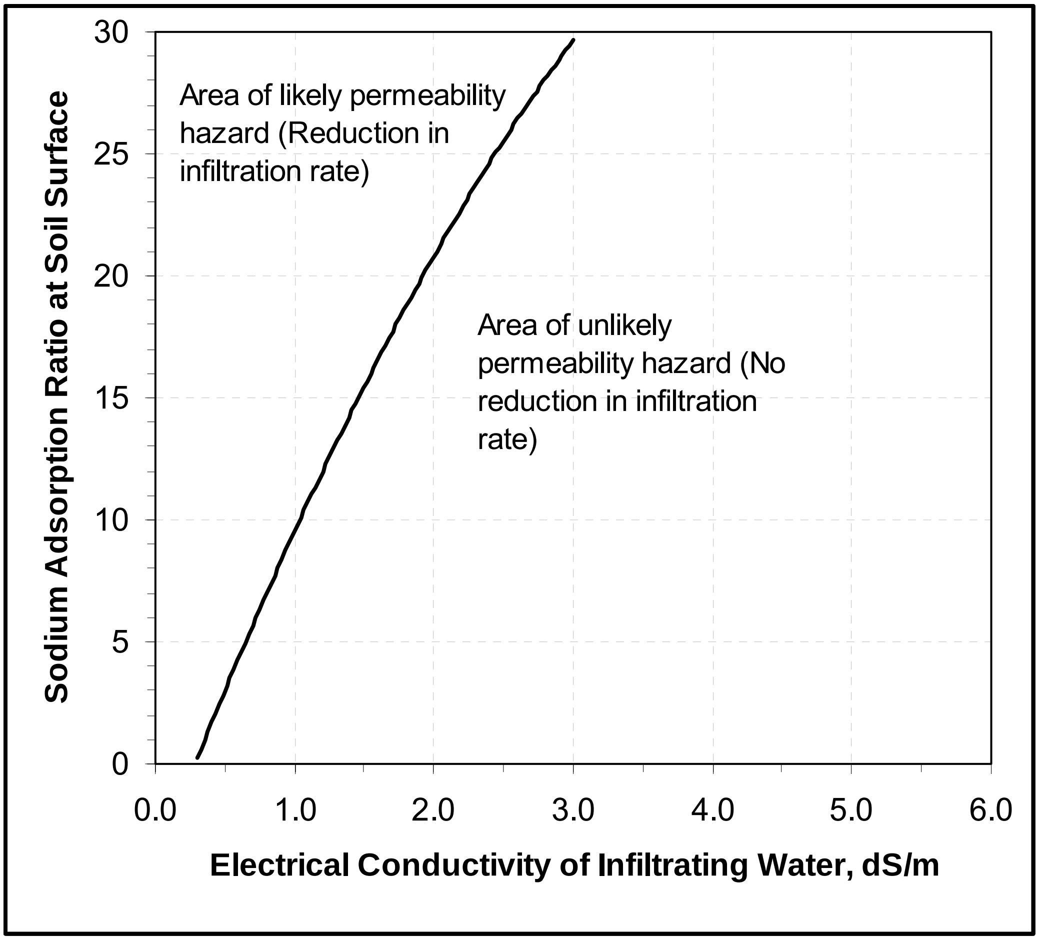

Figure 12. Soil permeability hazard as influenced by salinity of infiltrating water and sodium and SAR.

In review, we said that the two factors that affect water infiltration are the (1) water's salinity and, (2) its sodium content in relation to the content of calcium and magnesium. The following general precepts are good few rules of thumb to remember:

- High salinity water (i.e. high EC) increases infiltration
- Conversely, low salinity water (i.e. low EC) decreases infiltration
- Water with a high sodium content relative to the calcium and magnesium content (i.e. high SAR) decreases infiltration.

The principle to keep in mind is that both factors, the salinity of the water and sodium content, operate at the same time. In other words, just because a certain water's electrical conductivity (EC_w) is low or the water's SAR is high doesn't necessarily mean that an infiltration problem will be manifested. This can be thought of in another way. That is to say that if there is sufficient calcium to offset the dispersing effect of the excessive sodium and that the total electrolyte concentration of the applied water is above the critical flocculation concentration, the soil pore sealing and soil dispersion causing reduced infiltration is unlikely.

Since the SAR is the criterion for describing the sodium dispersing effect and the EC_w can be used as the criterion for describing the electrolyte concentration of the infiltrating water, one may guess then that the SAR and EC_w can be considered together in properly assessing a potential infiltration problem. That is indeed the case; a very useful relationship has been established that the conservation planner can use. In Figure 12, the SAR at the soil surface is plotted on the y axis and the electrolyte concentration or the salt content of infiltrating water on the x axis. Since the SAR at the soil surface is very near the same as the SAR of the infiltrating water the SAR of the water being applied is used while the salt content of the infiltrating water is merely the specific conductance or electrical conductivity of the water. There are two areas separated by the line that is the threshold electrolyte concentration. The area to the left of the line represents the combinations of SAR and EC_w where a permeability hazard is likely to occur. Conversely the area to the right of the line represents the combinations of SAR and EC_w of stable permeability where it is unlikely for a permeability hazard to occur.

Provide Adequate Drainage

The third rule of salinity control and its management is that if a field is to be irrigated it must be drained. The lack of adequate drainage leads to (i) waterlogging, (ii) secondary soil profile salinization resulting from the upward capillary flux, and (iii) impaired movement and operation of farm equipment.

In order to reduce the risk of waterlogging and secondary soil profile salinization, drainage should be provided. In the absence of natural drainage artificial drainage will be needed. There are fundamentally two purposes of drainage. First, sufficient drainage is required to discharge the excess precipitated salts that have accumulated from previous irrigation and those salts of the infiltrated water into the soil which are in excess of the crop evapotranspiration demand. Second, the water table, if present needs to be kept at the proper depth. This permits adequate root development by minimizing the net flux of salt-laden groundwater upwards into the rootzone.

Monitor Irrigation Adequacy and Soil Profile Salinity

A very important consideration in achieving a sustainable irrigated agroecosystem susceptible to salinity hazards is to monitor rootzone soil salinity levels and distributions. The periodic assessment and inventory can serve as critical means to guide management including the adequacy of leaching and drainage. On a large-scale or regional basis temporal and spatial information can be useful to delineate regions of drainage problem areas and salt-loading areas.

The proper framework to guide management practices in controlling salnity can be best outlined as follows (Rhoades, 1997, Rhoades, *et al*., 1997):

1) Adequate knowledge of the temporal trends in the level, extent, magnitude and spatial distribution of rootzone soil salinity within irrigated cropland fields.
2) Ability to ascertain the impact of changes in management practices and provide a course of action for evaluating irrigation and drainage system adequacy and effectiveness.

3) Ability to pinpoint salinity hazards and analyzes the inherent causes, whether management-induced.
4) Capability to isolate parts of individual fields and areas of large-scale irrigated regions where excessive deep percolation is occurring.

If the outcomes identified within this framework are to be achieved traditional observation methods are no longer appropriate. The framework requires the need for repeated measurements in both time and space that accurately describe salinity patterns. Obtaining the needed information using conventional soil sampling and laboratory-analysis procedures is not practical and cost prohibitive.

A set of practical salinity assessment procedures and *in situ* techniques for measuring soil salinity in the field has been developed. Large intensive and extensive data sets can be collected using these techniques and methodologies; they provide a systematic means for describing salinity condition both spatially and temporally. Most importantly it allows practitioners to evaluate management effects. These salinity assessment procedures involve the geospatial measurement of the bulk soil electrical conductivity (ECa) directly in the field. The methodology and instrumental techniques can be integrated into a system that is rapid and mobile. Several variations of the mobile apparatus, including what has become known as the “Salty-Dawg”, and the “Salt-Sniffer”, are currently being utilized. These self-propelled units are comprised of commercially available components.

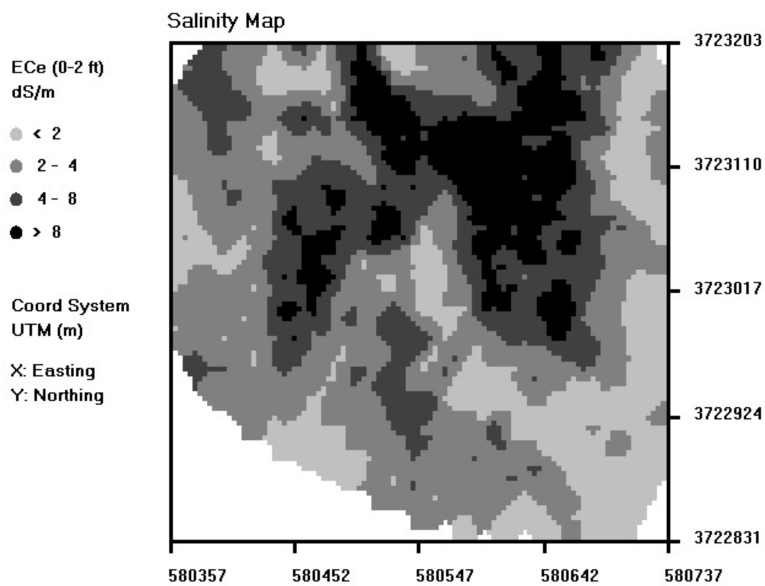

Figure 13. Example map produced showing the spatial pattern of soil salinity.

An example of the application of this technology in the Arkansas River Drainage Basin is shown in Figure 13. In order to assess alternative conservation treatment the field-scale soil salinity conditions where characterized and mapped using the dual pathway parallel conductance model (DPPC). The description of the model, its theory, mechanization, and example applications are provided elsewhere (Rhoades, 1990, 1992, 1993, l994; Rhoades, *et al.* 1989a, 1989b, 1990, 1999; Lesch *et al*., 1992, 1995a, 1995b, 1997, 1998, 2000).

ALTERNATIVE STRATEGIES FOR CONTROLLING SALINITY OF WATER RESOURCES

Interception, Isolation of Drainage Water and its Subsequent Reuse

One alternative strategy to control the salinity is to intercept drainage waters before they are returned to the river. These waters are then substituted for the less saline water of the original water supply. The drainage waters that have been intercepted and isolated from can then be applied during the irrigation season to the more salt-tolerant crops grown in the rotation. The process is repeated with the continued successive resuse of the drainage water and its application to the increasingly salt tolerant crops. Once the water's capacity has been depleted and become too saline for any of the crops in the rotation the water can be discharged or treated. This kind of irrigation scheme was been shown to be extremely successful (Rhoades, 1989, Rhoades*, et al*., 1988a, 1988b, 1989c).

Changes in Landuse

Another alternative is one that removes land from irrigation that has been shown to adversely affect receiving water supplies. There may be circumstances where irrigation is occurring on hydrogeologic landscapes, where the salt-loading and degradation of the water resource is severe enough, that warrants the consideration of eliminating irrigation of those lands.

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APPENDIX I- Salt Tolerance of Selected Crops

		Soil Salinity, C									Soil Solution Osmotic Potential		
		Piecewise Linear Threshold-Slope Model		Sigmoidal ("Compound Discount") Model			Modified Sigmoidal ("Compound Discount") Model						
				C_{50} (EC_e), dS/m									
	Botanical Crop Name	**Threshold Salinity, C_t (EC_e), dS/m**	**Slope, % per dS/m**	**experimental**	**calculated**	**p (shape parameter)**	calculated, C_{mid}	2nd Derivative Function, Fn(p)	**s (response curve steepness)**	Salinity Tolerance Index, ST-Index	**Threshold OP_{fc}, bars**	**Slope, % per bar**	**Rating**
Alfalfa	*Medicago sativa*	2.0	7.3		8.49	2.69	8.849	0.753	0.116	***9.5***	-1.51	-1.94	MS
Almond	*Prunus duclis*	1.5	19.0		3.83	3.30	4.132	0.901	0.312	***5.0***	-1.11	-1.25	S
Apple	*Malus sylvestris*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Apricot	*Prunus armeniaca*	1.6	24.0		3.39	3.8	3.683	1.021	0.394	***4.7***	-1.19	-1.24	S
Artichoke, globe	*Cynara scolymus*	6.1	11.5		10.07	5.8	10.448	1.493	0.174	***11.8***	-4.93	-5.06	MT
Asparagus	*Asparagus officinalis*	4.1	2.0		28.50	2.4	29.100	0.691	0.031	***29.4***	-3.24	-4.99	T
Avocado	*Persea americana*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Barley	*Hordeum vulgare*	8.0	5.0	18.0	17.53	3.9	18.000	1.041	0.077	***18.9***	-6.57	-11.77	T
Bean, dry	*Phaseolus vulgaris*	1.0	19.0	3.6	3.34	2.9	3.632	0.797	0.316	***4.4***	-0.73	-0.88	S
Bean, lima	*Phaseolus lunatus*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Bean, mung	*Vigna radiata [Phaseolus aureus]*	1.8	20.7		3.91	3.7	4.215	1.006	0.337	***5.2***	-1.35	-1.42	S
Beet, red	*Beta vulgaris*	4.0	9.0		9.19	3.7	9.556	0.991	0.142	***10.5***	-3.15	-3.66	MT
Bermudagrass	*Cynodon dactylon*	6.9	6.4		14.28	4.1	14.713	1.096	0.099	***15.7***	-5.62	-7.96	T
Blackberry	*Rubus sp.*	1.5	22.0		3.48	3.5	3.773	0.954	0.362	***4.7***	-1.11	-1.20	S
Boysenberry	*Rusus ursinus*	1.5	22.0		3.48	3.5	3.773	0.954	0.362	***4.7***	-1.11	-1.20	S
Broadbean (faba bean)	*Vicia faba*	1.6	9.6		6.47	2.7	6.808	0.760	0.154	***7.5***	-1.19	-1.51	MS
Broccoli	*Brassica oleracea botrytis*	2.8	9.2		7.88	3.2	8.235	0.870	0.147	***9.0***	-2.16	-2.58	MS
Bromegrass, meadow	*Bromus biebersteinii*	4.4	6.8		11.36	3.4	11.753	0.918	0.107	***12.6***	-3.49	-4.40	MT
Bromegrass, mountain	*Bromus marginatus*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Bromegrass, smooth	*Bromus inermis*	7.0	5.1	16.1	16.35	3.7	16.804	0.987	0.079	***17.6***	-5.70	-9.02	MT
Brussel sprouts	*Brassica oleracea gemmifera*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Burnet	*Sanguisorba minor*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Cabbage	*Brassica oleracea capitata*	1.8	9.7	7.0	6.62	2.8	6.955	0.781	0.156	***7.7***	-1.35	-1.68	MS
Canarygrass, reed	*Phalaris arundinacea*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Canola (rapeseed)	*Brassica napus*	10.0	11.2		14.04	9.5	14.464	2.397	0.160	***16.3***	-8.32	-9.87	T
Cantaloupe (muskmelon)	*Cucumis Melo*	1.3	5.7	7.5	9.70	2.4	10.072	0.683	0.090	***10.6***	-0.96	-1.30	MS
Carrot	*Daucus carota*	1.0	14.0		4.26	2.7	4.571	0.747	0.229	***5.2***	-0.73	-0.92	S
Casava	*Manihot esculenta*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Castorbean	*Ricinus communis*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Cauliflower	*Brassica oleracea botrytis*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Celery	*Apium graveolens*	1.8	6.2	11.0	9.49	2.5	9.865	0.719	0.098	***10.4***	-1.35	-1.79	MS
Cherry, sand	*Prunus Besseyi*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Cherry, sweet	*Prunus avium*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Chick pea (Garbonzo bean)	*Cicer arietinum*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Chinese cabbage (Pe-tsai)	*Brassica campestris*	3.2	10.0		7.85	3.5	8.200	0.942	0.159	***9.1***	-2.49	-2.87	MS
Clover, alsike	*Trifolium hybridum*	1.5	12.0		5.35	2.8	5.667	0.787	0.194	***6.4***	-1.11	-1.37	MS
Clover, berseem	*Trifolium alexandrinum*	1.5	5.7		9.90	2.4	10.272	0.694	0.090	***10.8***	-1.11	-1.50	MS
Clover, ladino	*Trifolium repens*	1.5	12.0		5.35	2.8	5.667	0.787	0.194	***6.4***	-1.11	-1.37	MS
Clover, red	*Trifolium protense*	1.5	12.0		5.35	2.8	5.667	0.787	0.194	***6.4***	-1.11	-1.37	MS
Clover, strawberry	*Trifolium gragiferum*	1.5	12.0		5.35	2.8	5.667	0.787	0.194	***6.4***	-1.11	-1.37	MS
Clover, sweet	*Melilotus sp.*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Corn, forage	*Zea mays*	1.8	7.4		8.20	2.6	8.557	0.740	0.118	***9.2***	-1.35	-1.75	MS
Corn, grain	*Zea mays*	1.7	12.0	5.9	5.54	2.9	5.867	0.812	0.194	***6.6***	-1.27	-1.54	MS
Corn, sweet	*Zea mays*	1.7	12.0		5.54	2.9	5.867	0.812	0.194	***6.6***	-1.27	-1.54	MS
Cotton	*Gossypium hirsutum*	7.7	5.2	17.0	16.86	3.9	17.315	1.041	0.081	***18.2***	-6.31	-10.66	T
Cowpea (forage)	*Vigna unguiculata*	2.5	11.0		6.71	3.3	7.045	0.890	0.176	***7.9***	-1.91	-2.23	S
Cowpea (pulse)	*Vigna unguiculata*	4.9	12.0	9.1	8.71	5.0	9.067	1.307	0.185	***10.3***	-3.91	-3.99	MT
Crambe	*Crambe abyssinica*	2.0	6.5		9.32	2.6	9.692	0.737	0.103	***10.3***	-1.51	-1.97	MS
Cucumber	*Cucumis sativus*	2.5	13.0		6.02	3.5	6.346	0.948	0.208	***7.3***	-1.91	-2.13	MS
Currant	*Ribes sp.*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Date palm	*Phoenix dactylifera*	4.0	3.6		17.42	2.7	17.889	0.751	0.057	***18.4***	-3.15	-4.50	T
Eggplant	*Solanum melongena esculentum*	1.1	6.9		7.99	2.4	8.346	0.685	0.110	***8.9***	-0.80	-1.08	MS
Fennel	*Foeniculum vulgare*	1.2	15.7	4.8	4.08	2.9	4.385	0.796	0.258	***5.1***	-0.88	-1.07	S
Fescue, meadow	*Fesuca pratensis*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Fescue, tall	*Festuca elatior*	3.9	5.3		12.92	2.9	13.334	0.815	0.084	***14.0***	-3.07	-4.08	MT
Fig	*Ficus carica*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Flax (Linseed)	*Linum usitatissimum*	1.7	12.0		5.54	2.9	5.867	0.812	0.194	***6.6***	-1.27	-1.54	MT
Foxtail, meadow	*Alopecurus pratensis*	1.5	9.6		6.38	2.7	6.708	0.751	0.154	***7.4***	-1.11	-1.42	MS
Garlic	*Allium sativum*	3.9	7.4	7.4	10.28	3.3	10.657	0.905	0.117	***11.5***	-3.07	-3.78	MT
Gooseberry	*Ribes sp.*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Grama, blue	*Boutteloua gracilis*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Grape	*Vitis sp.*	1.5	16.0		4.32	3.1	4.625	0.851	0.262	***5.4***	-1.11	-1.30	MS
Grapefruit	*Citrus paradisi*	1.8	16.0		4.61	3.3	4.925	0.905	0.260	***5.8***	-1.35	-1.52	S
Green bean	*Phaseolus vulgaris*	1.0	19.0		3.34	2.9	3.632	0.797	0.316	***4.4***	-0.73	-0.88	S

APPENDIX I- Salt Tolerance of Selected Crops

	Botanical Crop Name	Soil Salinity, C: Piecewise Linear Threshold-Slope Model: Threshold Salinity, C_t (EC_e), dS/m	Piecewise Linear Threshold-Slope Model: Slope, % per dS/m	Sigmoidal ("Compound Discount") Model: C_{50} (EC_e), dS/m: experimental	Sigmoidal ("Compound Discount") Model: C_{50} (EC_e), dS/m: calculated	Sigmoidal ("Compound Discount") Model: p (shape parameter)	Modified Sigmoidal ("Compound Discount") Model: calculated, C_{mid}	Modified Sigmoidal: 2nd Derivative Function, Fn(p)	Modified Sigmoidal: s (response curve steepness)	Modified Sigmoidal: Salinity Tolerance Index, ST-Index	Soil Solution Osmotic Potential: Threshold OP_{fc}, bars	Soil Solution Osmotic Potential: Slope, % per bar	Rating
Guar	*Cyamopsis tetragonoloba*	8.8	17.0		11.35	14.5	11.741	3.603	0.236	***14.0***	-7.27	-5.60	T
Guayule	*Parthenium argentatum*	15.0	13.0		18.37	23.7	18.846	5.814	0.172	***21.5***	-12.79	-23.50	T
Harding grass	*Phalaris tuberosa*	4.6	7.6		10.79	3.6	11.179	0.978	0.119	***12.1***	-3.65	-4.46	MT
Jerusalem artichoke	*Helianthus tuberosus*	0.4	9.6	5.8	5.29	2.3	5.608	0.651	0.154	***6.1***	-0.27	-0.38	MS
Kale	*Brassica oleracea acephala*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Kochia, forage (perennial)	*Kochia prostrata (Bassia protrata)*	15.0	15.0		17.86	32.5	18.333	7.933	0.195	***21.3***	-12.79	-16.40	T
Kohlrabi	*Brassica oleracea gongylode*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Lemon	*Citrus Limon*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Lettuce	*Lactuca sativa*	1.3	13.0	5.2	4.83	2.8	5.146	0.776	0.212	***5.9***	-0.96	-1.18	MS
Lime	*Citrus aurantifolia*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Mango	*Mangifera indica*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Milkvetch, Cicer	*Astragalus cicer*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Millet, foxtail	*Setaria italica*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Millet, pearl	*Pennisetum gloucum*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Oats	*Avena sativa*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Okra	*Abelmoschus esculentus*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Olive	*Olea europaea*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Onion	*Allium cepa*	1.2	16.0	4.1	4.02	2.9	4.325	0.799	0.263	***5.1***	-0.88	-1.06	S
Orange	*Citrus sinensis*	1.7	16.0		4.52	3.2	4.825	0.886	0.260	***5.7***	-1.27	-1.45	S
Orchardgrass	*Dactylis glomerta*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Papaya	*Carica papaya*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Parsnip	*Pastinaca sativa*	0.8	17.5		3.36	2.7	3.657	0.747	0.291	***4.3***	-0.57	-0.72	S
Pea	*Pisum sativum*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Peach	*Prunus Persica*	1.7	21.0		3.78	3.7	4.081	0.987	0.343	***5.1***	-1.27	-1.35	S
Peanut (groundnut)	*Arachis hypogaea*	3.2	29.0		4.61	7.6	4.924	1.935	0.440	***6.6***	-2.49	-1.87	MS
Pear	*Pyrus communis*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Pecan	*Carya illinoiensis*	1.9	16.6		4.60	3.5	4.912	0.937	0.269	***5.8***	-1.43	-1.58	MS
Pepper	*Capsicum annum*	1.5	14.0		4.76	3.0	5.071	0.818	0.228	***5.8***	-1.11	-1.33	MS
Persimmon	*Diospyros virginiana*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Pigeon pea (forage)	*Cajanus cajan*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Pineapple	*Ananus comosus*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Plum (fruit-bearing)	*Prunus domestica*	2.6	31.0		3.91	6.6	4.213	1.685	0.481	***5.8***	-2.00	-1.59	S
Plum (seedling)	*Prunus domestica*	1.5	18.0		3.97	3.2	4.278	0.884	0.295	***5.1***	-1.11	-1.27	S
Pomegranate	*Punica granatum*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Potato	*Solanum tuberosum*	1.7	12.0	6.2	5.54	2.9	5.867	0.812	0.194	***6.6***	-1.27	-1.54	MS
Prune	*Prunus domestica*	1.5	18.0		3.97	3.2	4.278	0.884	0.295	***5.1***	-1.11	-1.27	S
Pummelo	*Citrus maxima*	1.5	18.0		3.97	3.2	4.278	0.884	0.295	***5.1***	-1.11	-1.27	S
Pumpkin	*Curcurlita. pepo pepo*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Purslane	*Portulaca oleraceae*	6.3	9.6		11.12	5.1	11.508	1.333	0.146	***12.7***	-5.10	-5.77	MT
Radish	*Raphanus sativus*	1.3	13.0		4.83	2.8	5.146	0.776	0.212	***5.9***	-0.96	-1.18	MS
Raspberry	*Rubus idaeus*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Rice	*Oryza sativa*	1.9	9.1	3.6	7.05	2.8	7.395	0.780	0.146	***8.1***	-1.43	-1.79	S
Rye	*Secale cereale*	11.4	10.8		15.59	10.8	16.030	2.708	0.153	***18.0***	-9.56	-13.52	T
Ryegrass, Italian	*Lolium italicum multiflorum*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Ryegrass, perennial	*Lolium perenne*	5.6	7.0		12.34	3.8	12.743	1.031	0.109	***13.7***	-4.50	-5.76	MT
Safflower	*Carthamus tinctoris*	7.5	6.0	14.0	15.39	4.2	15.833	1.107	0.093	***16.8***	-6.14	-9.43	MT
Sesame	*Sesamum indicum*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Sesbania	*Sesbania exaltata*	2.3	7.0		9.08	2.7	9.443	0.768	0.111	***10.1***	-1.75	-2.24	MS
Sorghum	*Sorghum bicolor*	6.8	16.0	15.0	9.55	9.2	9.925	2.314	0.232	***11.8***	-5.53	-4.59	MT
Soybean	*Gycine max*	5.0	20.0		7.16	8.3	7.500	2.098	0.295	***9.3***	-3.99	-3.11	MT
Spinach	*Spinacia oleracea*	2.0	7.6		8.22	2.7	8.579	0.759	0.121	***9.2***	-1.51	-1.93	MS
Squash, scallop (winter)	*Cucurbita pepo melopepo*	3.2	16.0		6.00	4.5	6.325	1.193	0.251	***7.5***	-2.49	-2.46	MS
Squash, summer	*Cucurbita pepo melopepo*	4.7	9.4		9.65	4.1	10.019	1.096	0.147	***11.1***	-3.74	-4.24	MT
Strawberry	*Fragaria sp.*	1.0	33.0		2.23	3.5	2.515	0.954	0.564	***3.5***	-0.73	-0.78	S
Sudangrass	*Sorghum sudanense*	2.8	4.3		14.00	2.6	14.428	0.727	0.068	***15.0***	-2.16	-2.94	MT
Sugarbeet	*Beta vulgaris*	7.0	5.9	15.0	15.04	4.0	15.475	1.058	0.091	***16.4***	-5.70	-8.46	T
Sugarcane	*Saccharum officinarum*	1.7	5.9		9.80	2.5	10.175	0.708	0.094	***10.7***	-1.27	-1.70	MS
Sunflower	*Helianthus annus*	4.8	5.0		14.37	3.1	14.800	0.851	0.079	***15.5***	-3.82	-5.28	MT
Sweet potato	*Impomoea batatas*	1.5	11.0		5.72	2.8	6.045	0.772	0.178	***6.7***	-1.11	-1.39	MS
Swiss chard	*Beta vulgaris*	11.0	5.7	17.5	19.28	5.2	19.772	1.369	0.086	***20.9***	-9.21	-29.45	T
Tangerine	*Citrus reticulata*	1.3	17.5		3.86	3.0	4.157	0.837	0.288	***5.0***	-0.96	-1.12	S
Tepary bean	*Phaeseolus acutifolius var. acutifolius*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Timothy	*Phleum pratense*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Tomato	*Lycopersicon lycopersicum*	2.5	9.9	7.6	7.21	3.1	7.551	0.859	0.158	***8.3***	-1.91	-2.28	MS

APPENDIX I- Salt Tolerance of Selected Crops

	Botanical Crop Name	Soil Salinity, C									Soil Solution Osmotic Potential		Rating
		Piecewise Linear Threshold-Slope Model		Sigmoidal ("Compound Discount") Model			Modified Sigmoidal ("Compound Discount") Model						
		Threshold Salinity, C_t (EC_e), dS/m	Slope, % per dS/m	C_{50} (EC_e), dS/m experimental	C_{50} (EC_e), dS/m calculated	p (shape parameter)	calculated, C_{mid}	2^{nd} Derivative Function, Fn(p)	s (response curve steepness)	Salinity Tolerance Index, ST-Index	Threshold OP_{fc}, bars	Slope, % per bar	Rating
Trefoil, birdsfoot (big)	*Lotus uliginosus*	2.3	19.0		4.62	4.1	4.932	1.089	0.305	***6.0***	-1.75	-1.78	MS
Trefoil, birdsfoot (broadleaf)	*Lotus corniculatus arvenis*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Trefoil, birdsfoot (narrowleaf)	*Lotus corniculatus*	5.0	10.0		9.63	4.4	10.000	1.176	0.155	***11.1***	-3.99	-4.41	MT
Triticale	*X Triticoseale*	6.1	2.5		25.53	2.7	26.100	0.759	0.039	***26.5***	-4.93	-8.76	T
Turnip, forage	*Brassica rapa*	3.3	4.8		13.30	2.7	13.717	0.765	0.076	***14.3***	-2.57	-3.46	MT
Turnip, root	*Brassica rapa*	0.9	8.9	6.5	6.19	2.4	6.518	0.689	0.143	***7.1***	-0.65	-0.87	MS
Vetch, common	*Vicia angustifolia*	3.0	11.0		7.20	3.5	7.545	0.954	0.175	***8.5***	-2.32	-2.63	MS
Walnut	*Juglans sp.*	1.7	16.1		4.50	3.2	4.806	0.888	0.262	***5.7***	-1.27	-1.45	MT
Watermelon	*Citrullus lanatus*	3.0	7.7		9.13	3.1	9.494	0.841	0.122	***10.2***	-2.32	-2.87	MS
Wheat, common	*Triticum aestivum*	6.0	7.1	13.0	12.63	4.0	13.042	1.075	0.110	***14.0***	-4.84	-6.25	MT
Wheat, Durum	*Triticum turgidum*	5.9	3.8		18.58	3.0	19.058	0.834	0.060	***19.7***	-4.76	-7.53	T
Wheat, semidwarf	*Triticum aestivum*	8.6	3.0		24.71	3.2	25.267	0.871	0.047	***25.9***	-7.09	-18.65	T
Wheatgrass, crested	*Agropyron sibiricum*	3.5	4.0		15.56	2.7	16.000	0.747	0.063	***16.5***	-2.74	-3.79	MT
Wheatgrass, fairway crested	*Agropyron cristatum*	7.5	6.9		14.32	4.5	14.746	1.201	0.106	***15.8***	-6.14	-8.75	T
Wheatgrass, intermediate	*Agropyron intermedium*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Wheatgrass, NewHy	*Elytrigia repens x Pseudoroegneria spicata*	4.8	4.3		15.98	2.9	16.428	0.815	0.068	***17.1***	-3.82	-5.47	T
Wheatgrass, tall	*Agropyron elongatum*	7.5	4.2		18.92	3.4	19.405	0.936	0.065	***20.2***	-6.14	-11.16	T
Wheatgrass, western	*Agropyron smithii*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Wildrye, beardless	*Leymus triticoides*	2.7	5.9		10.79	2.7	11.175	0.766	0.093	***11.8***	-2.08	-2.71	MS
Wildrye, Canada	*Elymus canadensis*	6.0	5.6		14.50	3.6	14.929	0.961	0.087	***15.8***	-4.84	-6.85	MT
Wildrye, Russian	*Psathyrostachys Junceus*	10.0	4.6		20.37	4.2	20.870	1.120	0.071	***21.8***	-8.32	-24.34	T

NORTHERN WATER EFFORTS TO IMPROVE IRRIGATION SCHEDULING PRACTICES

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ABSTRACT

Northern Water formally established an IMS (Irrigation Management Service) in 1981 to promote improved on-farm water management. A principal IMS effort has been the advancement of irrigation scheduling practices through field-by-field demonstrations of improved practices. This was supported by establishment of a district-wide weather station network along with promotion of accurate on-farm water measurement.

The field-by-field demonstrations of improved irrigation scheduling utilized the root zone water balance method, or checkbook method, coupled with soil moisture sensors. These efforts proved effective and received good acceptance by local growers.

Water measurement is a key to improved irrigation management. Needed measurements include flow deliveries to the field, crop water use (calculated from weather station data), available water stored in the crop root-zone, local rainfall, tail water runoff, etc. Such measurements allow calculation of on-farm irrigation efficiency. This is a major step beyond just scheduling irrigations. It allows for an estimation of the volume of water used beneficially.

The full benefits of improved irrigation scheduling are directly tied to the flexibility in water available for deliveries to the farm turnout or field. However, improved delivery flexibility comes at a cost. An appropriate balance must be achieved.

Northern Water's IMS programs have experienced considerable success. However, institutional and economic barriers continue to curtail needed improvements in some areas.

BACKGROUND

Northern Water is comprised of 1.6 million acres in eight counties on the East Slope of the Rocky Mountains. Irrigated land totals approximately 693,000 acres. Northern Water has aggressively promoted improved on-farm water management for more than 26 years. From its inception in 1981, IMS has been focused on education, training, and demonstration. It shares information regarding new technologies, increases public awareness, and enables producers to implement practical improvements with confidence. It does not focus on policies or politics. To date cooperators have not paid any fees to participate in the program. With a foundation based on information and technology, it has avoided the controversy and resistance often associated with political mandates and regulatory enforcement.

WEATHER STATION NETWORK

Northern Water operates a network of remote, solar powered, automated weather stations throughout its service area for disseminating crop water use information. The Weather Station Network is currently composed of 22 stations. Station sites are carefully selected to ensure readings representative of cropped field conditions, always well within a surface-irrigated field of alfalfa hay or over large areas of well-irrigated urban turf grass. Stations are approximately 25 to 30 miles apart to provide the best practical coverage and are operated year-round. In recent years, station density has increased near metropolitan areas. Each station collects air temperature, relative humidity, wind speed and solar radiation data. These data are used to calculate ETR (reference evapotranspiration) on a daily basis using the ASCE standardized Penman-Montieth combination equation for alfalfa. Precipitation, wind direction, and soil temperature are also collected. The weather station data is automatically transmitted hourly to Northern Water headquarters via cdma modem (cellular 1xRTT network). Each sensor at each weather station is checked and calibrated annually to ensure data accuracy and to maintain high network reliability. Station performance is monitored regularly and any problems detected are promptly corrected.

ETR is factored or adjusted using crop coefficients based on plant growth stages to calculate crop ET or water use for all of the area's major crops. Weather summaries and crop water guides are readily available via the Internet at www.ncwcd.org and also via a telephone voice-messaging system or “Call Center.” The “Call Center” can be accessed using a touch-tone telephone by dialing (970) 593-1605 or (888) 662-6426 (NOCOH2O) toll-free. Voice instruction and menu options allow the user to quickly access information for a selected area.

Accurate and reliable crop ET information supports efficient irrigation scheduling, thereby allowing producers to determine how much water to apply given their specific crop and irrigation practices. Crop ET information is widely accepted and its use continues to grow.

ON-FARM WATER MEASUEMENT

Northern Water began promoting low-cost electronic flow monitoring in 2000 under grant funding from the U.S. Bureau of Reclamation. These flow measurements allow calculation of on-farm irrigation efficiency. This is a major step beyond just scheduling irrigations. It allows estimation of the volume of water used beneficially. It provides needed tools and information that increase the effectiveness of efforts to improve irrigation scheduling practices.

Local interest in on-farm electronic flow monitoring has increased in recent years. Lower purchase costs for equipment, coupled with increased confidence in irrigation decisions, are key factors.

Additionally, increased urbanization of the Northern Water service area has increased the operational challenges and constraints facing local ditch companies. As productive agricultural lands are sold for development and the associated water rights transferred to cities, irrigation and ditch companies are faced with reduced flow rates, decreased exchange opportunities, and shorter delivery seasons. On-farm efficiency is largely affected by the flexibility in water deliveries available to the farm turnout or field. Improved flow measurement, remote monitoring, and gate automation are increasingly required for successful water delivery operations.

FIELD-BY-FIELD IRRIGATION SCHEDULING DEMONSTRATIONS

Since 1981, Northern Water has provided field-by-field demonstrations of irrigation scheduling practices to growers within its boundaries. These demonstrations have aided irrigation decision-making and supported efficient use of available water. They provided irrigators with a better understanding of soil moisture management throughout the growing season. They often gave the grower needed confidence to lengthen the time between irrigations.

The field-by-field irrigation scheduling demonstrations consistently utilized the root zone water balance method, or checkbook method, coupled with soil moisture sensors. Soil moisture holding capacity and an allowable depletion percentage were estimated. Readings from the soil moisture sensors were used to calculate remaining available moisture. Changes in soil moisture readings were compared to the calculated crop ET from Northern Water’s weather station network to validate the accuracy of both data. To estimate the number of days before the next irrigation was needed, the remaining soil moisture in the crop root zone was divided by the predicted daily crop water use from the nearest weather station. The success of these field-by-field irrigation scheduling demonstrations was directly dependent upon the quality of the crop water use information obtained from the weather station network.

These efforts targeted assistance to 50 area producers annually, with one to two fields per cooperator each season. Cooperators generally participated in the program for two to three seasons, after which new cooperators replaced past participants. Regular status reports were either e-mailed or hand delivered to cooperators.

Through 2003, tensiometers were the primary soil moisture device utilized by the program. Instruments were manually read and serviced during a weekly site visit.

However since 2004, efforts expanded to include automated electronic soil moisture sensors. Automation allowed continuous monitoring and recording of soil moisture at multiple levels within the crop root zone. Several manufacturers now market lower cost electronic soil moisture sensors, data loggers, and telemetry equipment. Cooperator support for automated soil moisture monitoring was dramatic.

CONCLUSIONS

Utilization of the root zone water balance method, or checkbook method, coupled with soil moisture sensors proved both effective and reliable for field-by-field irrigation scheduling. The success of these efforts was directly reliant upon the availability of accurate crop water use information, obtained from the District-wide weather station network. Additionally, proper measurement of water delivered to the farm turn-out or field was similarly important.

Soil moisture monitoring significantly improved with the transition from manual instruments to electronic sensors coupled to a data logger with cellular telemetry. Reduced costs and increased reliability of automated instruments has assisted in the adoption of these improved methods.

The full benefits of irrigation scheduling efforts are directly tied to the delivery flexibility of available water to cropped fields. If deliveries are restricted in available frequency, flow rate, or duration irrigators are often unable to implement improved irrigation scheduling practices. The consequence is reduced on-farm irrigation efficiency. Reduced delivery flexibility may result from ditch or canal operations, lack of capacity in irrigation equipment (wells, pumps, screens, etc.), water right administration, drought conditions, etc. Delivery flexibility may be increased through more senior water rights, use of groundwater wells, on-farm storage ponds, canal automation, etc.

Irrigation delivery constraints can prevent an irrigator from providing the proper amount of water at the right time to minimize crop water stress. Minimal restrictions may be overcome by maximizing soil moisture storage in the crop root zone as a buffer against time periods when water availability is limited or restricted.

Northern Water continues to maintain a strong commitment to assisting local irrigators to implement improved irrigation scheduling practices and realize increased on-farm water use efficiency.

NEW DEVELOPMENTS IN IRRIGATION SCHEDULING

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Background

Although scientific irrigation scheduling techniques have been available for over 30 years, most growers do not use them. Reasons include complexity, time required, and lack of confidence in the predictions. The three primary approaches are soil water monitoring, plant stress monitoring, and weather-based water use predictions. Soil water monitoring is either labor intensive or equipment intensive. Many automatic sensors have been developed and marketed in the last few years, but all have shortcomings. Reliable methods tend to be expensive or labor intensive. Soil water monitoring is tedious as a primary monitoring technique, but valuable as a periodic check on other methods. Plant stress based techniques are poorly developed for most crops, although they may become more useful as remote sensing methods and our understanding of plant stress improve.

Weather-based irrigation scheduling remains the most common and practical method. Direct estimation of water use by a crop using surface energy balance techniques (Bowen Ratio or Eddy Correlation) remain too complex for other than research use. Exciting new surface energy balance methods using remotely sensed information from satellites is being tested. These techniques include SEBAL, METRIC, and RESET, which are all based on the same basic concepts. However, all require thermal infrared data which is not readily available in the frequency or resolution required to schedule irrigations on fields.

The most common method to estimate crop water use and schedule irrigations is through use of reference evapotranspiration, ETo, calculated from local weather parameters, and a crop coefficient, based on crop and stage of growth (Allen et al. 1998). Many irrigated regions in the Central Plains have weather station networks to calculate regional ETo (eg: Colorado Agricultural Meteorological Network (CoAgMet) http://ccc.atmos.colostate.edu/~coagmet/ , High Plains Regional Climate Center network http://www.hprcc.unl.edu/ , and Texas High Plains Evapotranspiration Network http://txhighplainset.tamu.edu/). Several scheduling programs are available to assist users in estimating crop water use from ETo (eg. Wateright http://www.wateright.org/ , KanSched http://www.oznet.ksu.edu/mil/Resources/User%20Guides/KanSchedExcel.pdf Oregon Irrigation Scheduling OnLine http://oiso.bioe.orst.edu/RealtimeIrrigationSchedule/index.htm , and Basic Irrigation Scheduling http://biomet.ucdavis.edu/irrigation_scheduling/bis/BIS.htm).

The weakest link in this weather based approach to predict crop water use and irrigation requirements is the difficulty in reliably estimating the crop coefficient. Crop coefficients are commonly estimated based on days since planting or (occasionally) growing degree days (Allen et al. 1998). A wide variety of irrigated crops are grown under a wide range of conditions, and dependable crop coefficients are not available for many of the crops and growing conditions. This is especially true for horticultural and other specialty crops that are increasingly important in irrigated areas. These crops are often not well studied and include widely varying varieties grown under a wide range of planting densities and cultural practices.

Crop water use is related to the interception of incoming solar radiation and the amount of transpiring leaf surface. Sunlit leaves transpire at a higher rate than shaded leaves. Both leaf area index (LAI) and crop light interception have been related to crop transpiration. Light interception, as represented either by the portion of the ground surface that is shaded or the crop canopy cover, is much easier to measure than LAI. Although light interception varies with the crop canopy structure and the sun angle, several studies have found that mid-day shading, or equivalently, canopy cover measured vertically, provides a good relative representation of crop transpiration (Johnson et al. 2004, Williams and Ayars 2005, Trout and Gartung 2006, Grattan et al. 1998).

Previous studies have shown that various spectral vegetation indices, calculated from visible and near-infrared reflectance data, are linearly related to the amount of photosynthetically active radiation absorbed by plant canopies. Related efforts have tried to estimate crop coefficients in specific crop systems by ground-based and airborne spectral data (Bausch, 1995; Hunsaker et al. 2005; Johnson and Scholasch 2005). Moran et al. (1997) describe the potential and limitations of using satellite imagery for crop management.

Functional relationships between remotely sensed vegetation indices and crop light interception, and light interception and basal crop coefficient, Kcb, allow efficient estimation of crop water use where reference ETo is available. This could allow estimation of crop water use in near real time for individual fields on a regional scale. Such a process was proposed in the DEMETER project in southern Europe (Calera-Belmonte et al. 2003). In this paper, I present preliminary relationships between vegetation indices, light interception, and Kcb developed from data collected in the San Joaquin Valley on horticultural crops, and propose a possible structure for an irrigation scheduling system based on remotely-sensed vegetation indices and ETo.

VEGETATION INDEX vs. CANOPY COVER

On July 1, 2005, and June 19-20, 2006, canopy cover, CC, of 12 high value crops (watermelon, cantaloupe, pepper, bean, tomato, lettuce, onion, garlic, cotton, pistachio, almond, grape) in various stages of growth was measured on 33 fields on the west side of the San Joaquin Valley in California. Most fields were drip irrigated and essentially weed free with a dry soil surface. These fields were selected to represent a wide range of major SJV perennial and annual horticultural crops with widely varying canopy cover. Fields were selected that had uniform cropping patterns. Most fields were at least 200 m in the smallest dimension. Details of this study are given in Trout et al. (2008).

Canopy cover was measured with a TetraCam®[1] ADC multispectral camera suspended from a frame directly above the crop and aimed vertically downward. The camera was designed for capture of red, green and near-infrared wavelengths of reflected light. The photos were analyzed to determine the percentage of the photo area that contained live vegetation. Landsat 5 satellite images of the study area for July 1, 2005 and June 18, 2006 were acquired from the U.S. Geological Survey Landsat Project (http://landsat.usgs.gov/gallery/). On both days there were no clouds over the study area. The Landsat red and near infrared (NIR) data were converted to surface reflectance (SR) and used to calculate the normalized difference vegetation index, NDVI (Tucker, 1979) as:

$$NDVI = (SR_{NIR} - SR_{red}) / (SR_{NIR} + SR_{red}) \qquad (1)$$

for each Landsat image pixel (100 x 100 ft).

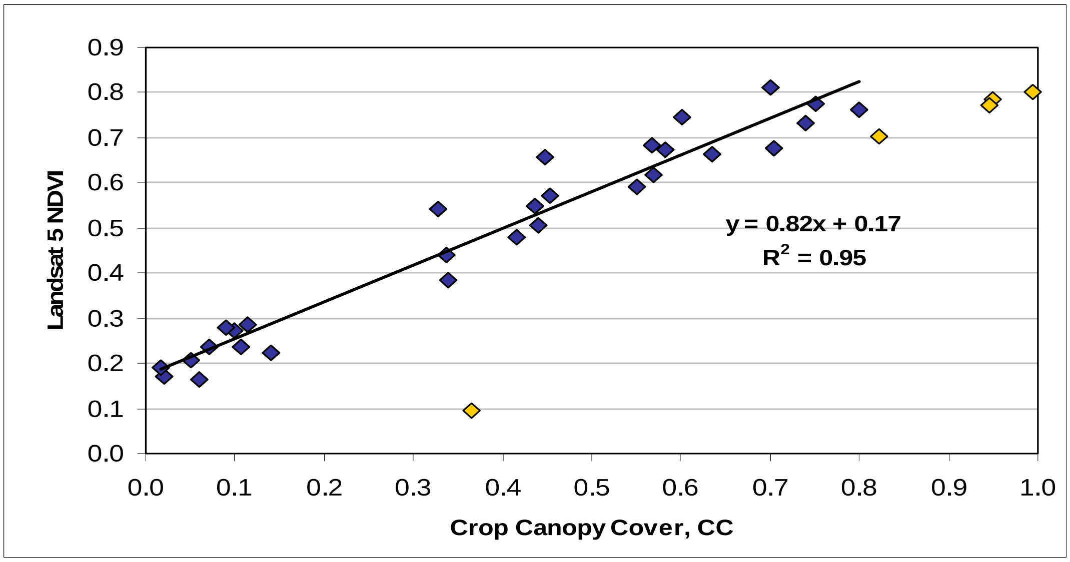

Figure 1. Relationship between Landsat NDVI and Camera Canopy Cover, CC, and the linear regression line for the data represented by blue diamonds.

[1] Reference to specific equipment and brand names are for the benefit of the reader and do not imply endorsement of the product by USDA

Figure 1 shows the relationship between NDVI and CC. NDVI increased linearly with CC to about 0.8, but did not increase further with increasing CC. This finding agrees with past work showing that NDVI levels off at high vegetation biomass. One field of dark red lettuce had a very low NVDI (= 0.1) in comparison to CC and was excluded as an outlier.

For the remaining 28 fields containing 12 different crops, NDVI correlated well with CC (R^2=0.95). The intercept value (0.17) represents the NDVI value for bare soil in the area. These results confirm that NDVI can be a good indicator of crop canopy cover for a wide range of crops with large differences in canopy structure and cover. The linear relationship is valid up to a CC of 0.8. For most crops, water use does not increase for canopy cover above 0.8, so this limitation does not impact estimates of crop water use.

We also estimated CC for each field using measurements of canopy widths or crown diameters and estimates of percent shade within the canopy. Our estimates were consistent (R^2 = 0.93) but tended to be about 10% lower than that measured with the camera. This indicates that visual measurements can provide useful estimates when NDVI measurements are not available.

CANOPY COVER vs. BASAL CROP COEFFICIENT

The USDA-ARS Water Management Research Unit in Fresno, CA uses weighing lysimeters to develop crop coefficients for horticultural crops. Past lysimeter research has shown that the basal crop coefficient for grape vines and fruit trees are closely related to mid-day light interception (Johnson et al., 2000, Williams and Ayars, 2005). Current research is determining the relationship between light interception and basal crop coefficient for annual vegetable crops. The objective is to develop relationships between light interception, represented by canopy cover, and basal crop coefficient. Results from lettuce, bell pepper, and garlic crops were presented by Trout and Gartung (2006) and are summarized here.

Canopy cover was measured several times throughout the growing season by the same camera technique described above. The crop coefficient was calculated as the ratio of the daily crop water use from the lysimeter to ETo (grass reference) measured by the CIMIS weather station #2 (CDWR 2006) located on an adjacent grass field. The crops were sub-surface drip irrigated and only data from days with a dry soil surface were used so that soil surface evaporation was very small and the calculated crop coefficient represented the basal crop coefficient, Kcb. Figure 2 shows the daily crop coefficient and measured canopy cover for the bell pepper crop. The early season Kc spikes result from sprinkler irrigations under low plant cover and illustrate the effects of soil surface evaporation. The late Kc decline results from termination of irrigation on day of year 226 and plant stress due to declining soil water content.

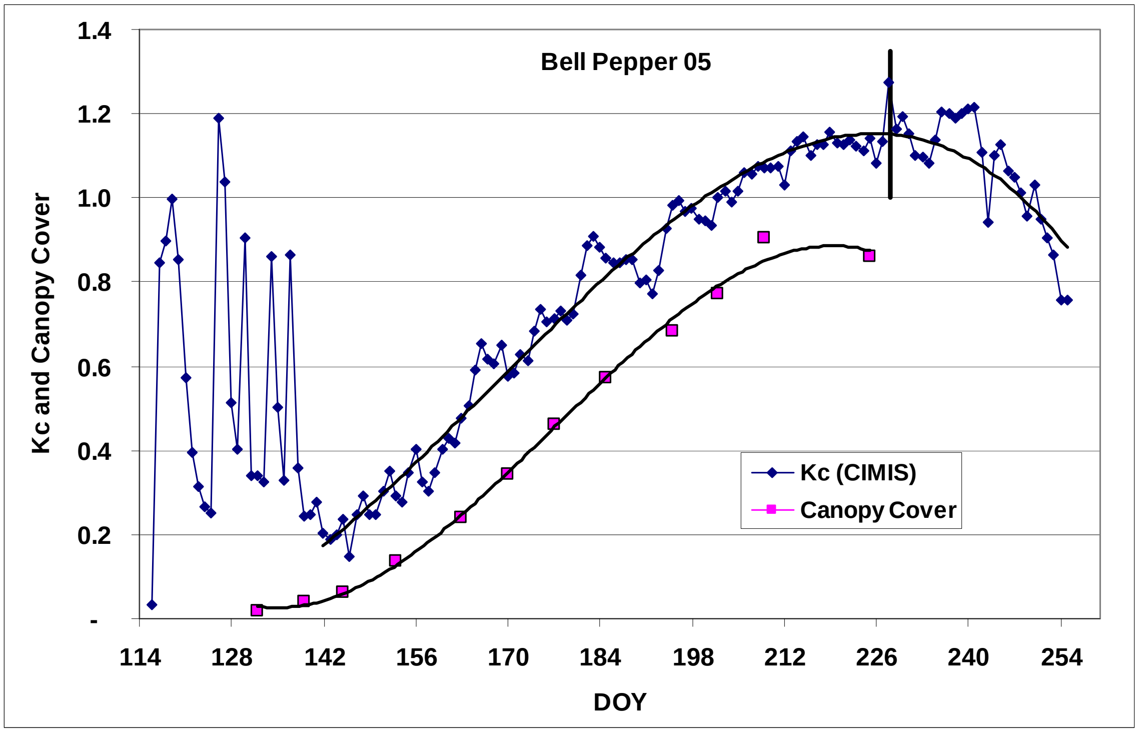

Figure 2. Daily crop coefficient, Kc, and canopy cover for a bell pepper crop grown on a weighing lysimeter on the west side of the San Joaquin Valley, CA in 2005. Peppers were transplanted on day of year (DOY) 115, five sprinkler irrigations were applied before DOY 140, and irrigation was terminated on DOY 226.

Figure 3 shows the relationship between Kcb and CC for the three crops. The lettuce and bell pepper crops, although structurally very different, followed the same linear relationship with an intercept of 0.14 and slope of 1.13 and a very high correlation coefficient. The garlic crop exhibited a higher intercept but smaller slope than the other two crops. The positive intercept is expected because with a sparse canopy during early growth, actual sunlight interception by the crop substantially exceeds vertical light interception and air movement within the canopy is high, resulting in a higher Kcb to CC ratio. As canopy cover increases, most light is intercepted by the top of the canopy and air movement within the canopy is reduced. Once the canopy approaches maximum cover (about 0.9 for these crops), the ratio should approach 1.0 to 1.2 (based on a grass reference), depending on crop height and roughness (Allen et al., 1998). The garlic crop exhibited unexpectedly high Kcb values, possibly due to its upright but fairly dispersed canopy structure.

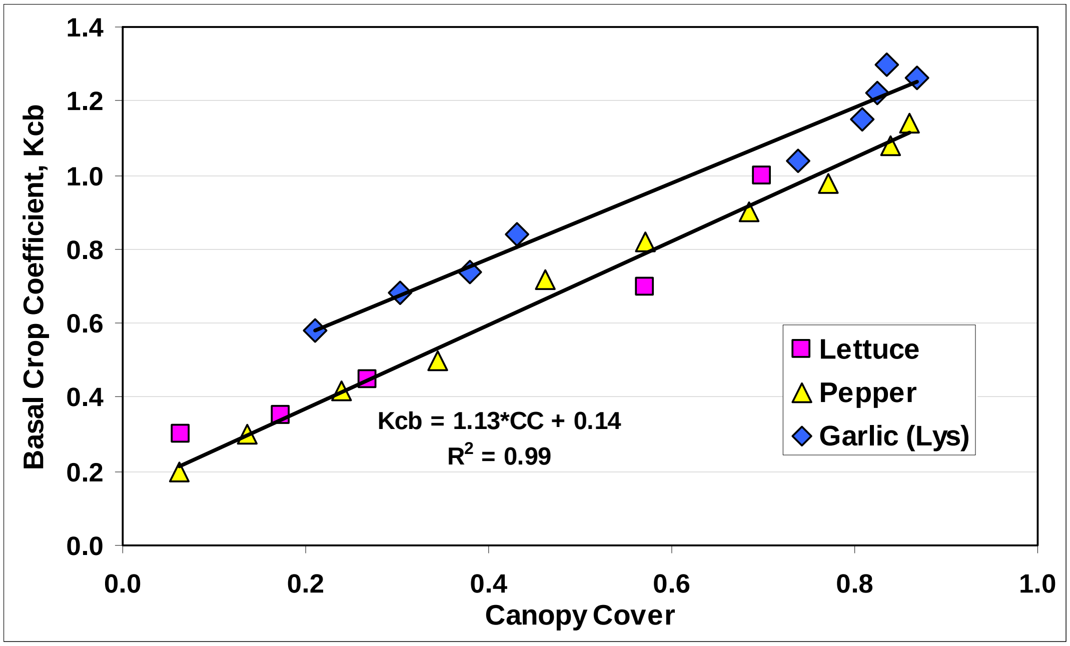

Figure 3. Relationships between basal crop coefficient, Kcb, and canopy cover for three crops grown on a weighing lysimeter on the west side of the San Joaquin Valley, CA. Regression equation is for lettuce and pepper data.

ESTIMATION OF FIELD AND REGIONAL CROP WATER USE

The two above relationships can be used to estimate Kcb from remotely sensed reflectance information.

$$CC = 1.22 * NDVI – 0.21 \qquad (2)\ \text{(from Fig 1)}$$

$$Kcb = 1.13 * CC + 0.14 \qquad (3)\ \text{(from Fig 3)}$$

This process should be carried out in two steps rather than attempting to directly link Kcb to NDVI. The intermediate step allows interpolation and extrapolation of CC between and beyond NDVI measurements, ground truthing of CC estimates, and crop specific Kcb:CC relationships.

Imagery to calculate NDVI will only be available at intermittent times, depending on the source, cost, and weather. For example, Landsat photos are available on 16 day intervals. Curve fitting of CC values or simple crop simulation models can be used to fill in between and extend beyond measured values. For a crop that has been studied previously, a generic CC vs. growing degree day (or days since planting) relationship can be developed and then adjusted using NDVI measurements for the current crop. Many crop simulation models output information on plant growth and phenology that can be converted to CC. Measured NDVI estimates of CC can be used to calibrate the models for the current crop and improve model CC projections into the future. When NDVI measurement intervals are long, visual estimates of CC can be used in place of NDVI-based estimates.

The measurements (Fig. 3) indicate that the Kcb:CC relationships are highly linear, and may be similar for broad crop types. Current data are inadequate to confidently project Kcb:CC relationships for a wide range of crops. Collecting these basic data should be a priority. Lysimetry is the most accurate way to develop this relationship. Surface energy balance measurements can also be used to estimate crop ET (bowen ratio, eddy correlation, SEBAL) and Kcb. Crop simulation models coupled with atmospheric energy balance relationships may be able to generate Kcb:CC relationships if the models have been adequately calibrated with field data.

Daily values of Kcb calculated from measured or interpolated CC values can be converted to Kc values by adding the soil evaporation coefficient, Ke. Soil evaporation can be estimated from irrigation schedule and method, canopy cover, soil type, and ETo (Allen et al 1998, chap. 8). Kc is then used with values for ETo from local weather stations, or interpolated ETo maps (Lehner et al. 2006) to estimate total water use for a field.

Information required to estimate crop water use/requirements includes:

1. Daily canopy cover from NDVI measurements and interpolation models
2. Daily ETo from weather stations
3. Soil type
4. Crop
5. Irrigation method and previous irrigation schedule

The first three items can be generated regionally from satellite or aerial images and ETo and soils databases. The last two can be provided by the farmer or from government or water district surveys. The first, second, and fourth items are required to estimate crop transpiration. The first, second, third, and fifth items are required to estimate soil evaporation, which becomes relatively less important as canopy cover increases. Farmer inputs of crop type, planting date, soil type, and irrigation method are common for irrigation scheduling programs.

When this method is used to generate regional estimates of crop water use, field-specific crop and irrigation method/schedule information will generally not be available. In this case, regional crop surveys may be used to assign the most appropriate Kcb:CC relationships, and regional irrigation methods/patterns used to estimate soil evaporation losses. Where crop information is altogether lacking, a generic Kcb:CC relationship can be assumed.

Figure 4 shows an example of maps of a 200 square kilometer region of San Joaquin Valley fields depicting NDVI, CC, Kcb and crop transpiration values for about 350 fields for July 1, 2005 based on a Landsat 5 image, Eqs. 2 and 3, and a daily ETo for the region on that day of 6 mm. Farmers could use such maps in a GIS framework to identify fields, verify crop canopy cover, and input and store crop and irrigation information for individual fields. The system could then estimate daily crop water use for the field up to the current day, project crop water demand based on historical ETo averages or weather forecasts, and produce maps and tables of cumulative crop water use for a chosen time period. This system would be more accurate than current methods for most crops. Aggregated information such as is shown on the maps, can be used by water suppliers to estimate water demand for individual canals or the whole district. By virtue of large-scale measurements offered by remote sensing and efficient data processing capabilities, such a system could be very efficient and require fewer ground-based measurements, than most current scheduling programs. Instead or providing users with information they would then use to calculate crop water use for their fields, it would provide growers with direct estimates of water use tailored to their crop and field.

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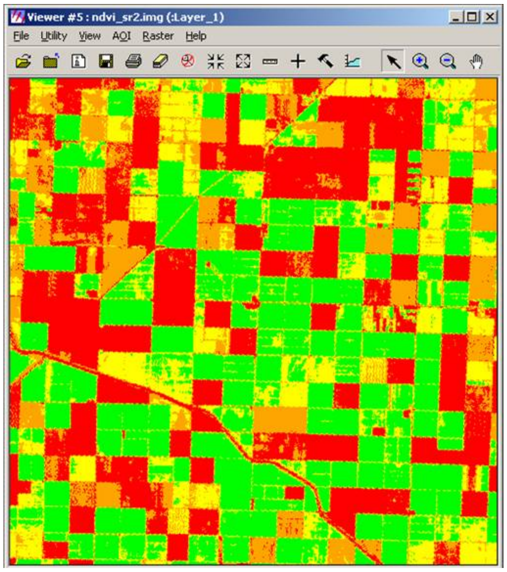
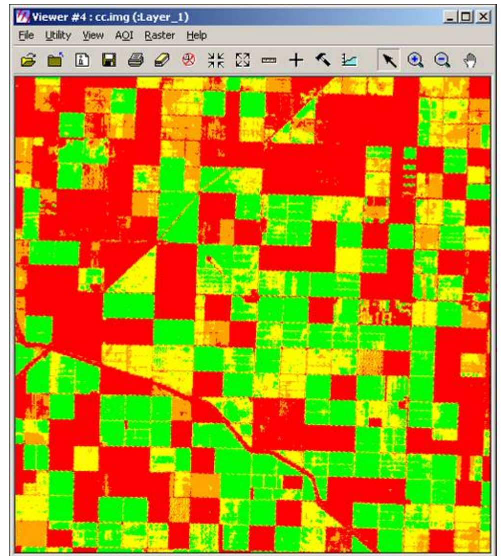
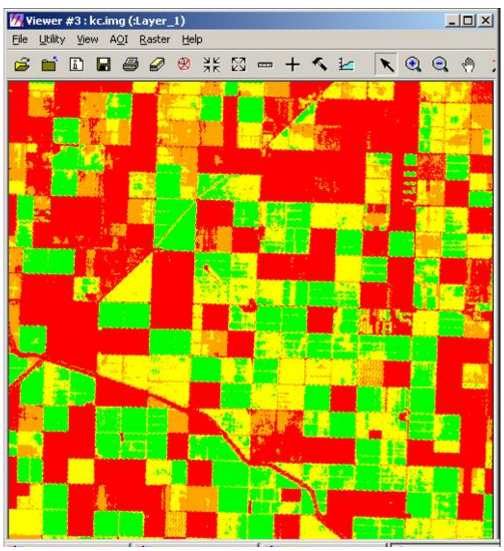


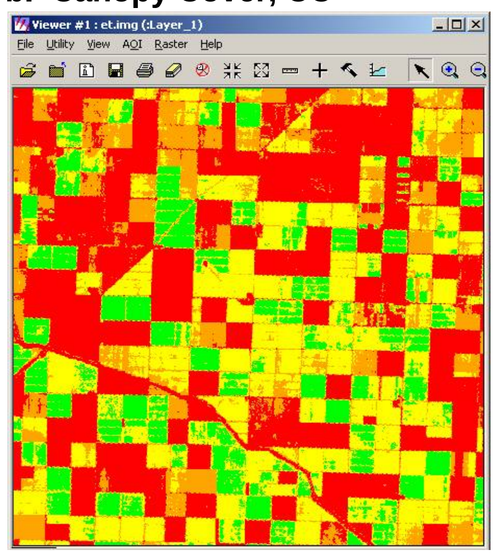
a. NDVI



b. Canopy Cover, CC



c. Kcb



d. Tc

Figure 4. Maps of (a) NDVI from a July 1, 2005 Landsat 5 image, (b) Canopy Cover converted from (a) with Eq. 2, (c) Kcb from Eq 3, and (d) Crop Transpiration for the day based on ETo = 6 mm from the regional CIMIS weather station.

	NDVI, CC	**Kcb**	**Tc *(mm/day)***
	<0.2	<0.3	<2
	0.2-0.4	0.3-0.6	2-4
	0.4-0.6	0.6-0.9	4-6
	>0.6	>0.9	>6

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COLORADO CROP WATER ALLOCATION TOOL

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Introduction

Many farmers in Colorado face limited irrigation water supplies. Limitations are imposed by a variety of circumstances including declining groundwater levels, significantly higher energy costs, evolving water case law and decreasing return flows in river systems. Regardless of the circumstance, farmers face the same question: what is the “best” allocation of limited water resources?

This presentation assists farmers by examining limited irrigation’s impacts on asset efficiency, cost efficiency and debt management. A spreadsheet decision tool has been designed for Colorado farmers making limited irrigation crop allocation decisions. The spreadsheet allows farm managers to input their own business information and contrast potential limited irrigation strategies. Crops examined in the spreadsheet tool include corn, alfalfa, wheat, dry beans and sunflowers. A copy of the spreadsheet and a technical document describing its use can be found at: http://limitedirrigation.agsci.colostate.edu/ under the resources tab.

A Farm’s Changing Financial Position

Under full irrigation, farm managers purchase inputs and choose crops in order to maximize profits with existing resources. As available irrigation water decreases, the manager’s original input purchases and crop choices will not maximize profits. This is reasonable because when making a whole farm plan, the farm manager chooses equipment, land, and financial capital jointly, and all of these choices assume adequate irrigation supplies.

Farm managers shifting from full to limited irrigation need to reconsider strategic choices if facing perpetual water limitations. One approach to making these decisions is to consider the farm’s asset efficiency, cost efficiency and ability to use borrowed funds when maximizing profits.

Limited Irrigation and Asset Efficiency

Farm profits rely importantly on the ability to generate revenues from the existing asset base. A convenient way to measure this ability is the asset turnover ratio (ATR):

(1) ATR = Gross Revenues ÷ Total Farm Assets

where

(1a) Gross Revenues = Yield per acre × Acres Cropped × Crop Price

The asset turnover ratio summarizes how well the farm's resource inputs (assets) generate gross revenues (output). Note that expenses are not included in the asset turnover ratio; rather only farm sales (gross revenues) are present.

Limited irrigation reduces the ATR of a typical farm by reducing the level of gross revenues. Gross revenues are the product of the farm's yield per acre times cropped acres times the selling price of the crop as indicated by equation (1a). Yields decrease as irrigation is limited because less water is available for consumptive use, and gross revenues fall with decreased yields. In equation (1), the gross revenues are decreased which makes the ATR smaller.

A lower ATR means the farm is less efficient in producing revenues from its existing asset base. The farm may adopt several strategies to mitigate this shortcoming. One strategy is to time irrigations in order to reduce the vegetative growth of a row crop saving water for the important grain fill period. This mitigates the impact of reduced yields for the fixed cropping area shown in equation (1a). The farm manager might also choose a crop whose price and yield combination are higher than other crops. The Colorado Crop Water Allocation Tool reduces gross revenues to reflect decreasing yields that follow limited irrigation. In addition, the spreadsheet user can adjust prices according to market conditions.

Alfalfa is an interesting alternative when mitigating ATR reduction. When alfalfa is stressed with insufficient water supplies, the relative feed value of the crop actually increases. The feed value is important to dairies and feedlots, and alfalfa with a greater relative feed value garners a higher price. As a result, farm managers can partially offset ATR reductions by marketing a hay crop's quality more effectively.

Long term water shortages may lead to using some assets more intensively and culling less productive assets. As an example, a farm manager may choose to fully irrigate a portion of the farm and allow the rest to lie fallow. This "rotational" fallow approach leaves other resources, namely equipment and farm labor, underutilized. Taking advantage of a slack resource, the farm manager can lease the farm's equipment to another operation, or might consider performing custom work for other operations. Gross revenues are increased when slack resources are put to use, so the limited irrigation ATR will increase by using the same asset base more intensively.

Culling the least productive assets might also improve the ATR ratio. However, selling assets, such as underutilized equipment, reduces the opportunity for the farm to expand operations if circumstances change. Selling equipment might also alter the farm's cost structure as the manager may need to hire custom work or lease equipment occasionally.

Limited Irrigation and Cost Efficiency

In the previous section, asset efficiency described the farm's ability to generate revenues from its available resources. The farm's efficiency in retaining these revenues as profits is its cost efficiency. Operating profit margin (OPM) measures cost efficiency and is calculated as:

(2) OPM = Operating Income ÷ Gross Revenues

where

(2a) Operating Income = Gross Revenues – Operating Expenses

In equation (2a), gross revenues become operating income once expenses have been differenced. Operating income represents the funds available for paying creditors and income taxes with the remainder compensating owners.

The OPM calculated in equation (2) can be no greater than 1.0; after all, operating income cannot exceed gross revenues. An increase in OPM implies improved cost efficiency because the farm is retaining more of its gross revenues as operating income. A reduction in farm's gross revenues, or a sudden increase costs, will alter the OPM.

Limited irrigation will reduce the gross revenues of the farm operation as discussed previously. Operating expenses will change too. Expenses that decline are those closely tied to production levels including harvesting costs, irrigation energy costs, and irrigation labor expense. Additionally, fertilizer rates are reduced to match a lower target yield, and managers may limit seeding rates of row crops like corn. Yet, herbicide and insecticide costs may increase under limited irrigation because a water stressed crop is more susceptible to pests.

In contrast, overhead expenses, such as general farm labor, depreciation and insurance, do not change even though irrigation amounts are reduced. For this reason, cost efficiency generally suffers when limited irrigation is compared to full irrigation under the same cropping pattern. Evidence of this effect is found in equation (2), where OPM declines as operating income is reduced at a proportionally greater rate than gross revenues.

Changing the crop rotation might save irrigation water and alter the farm's cost structure. As an example, managers may seek to adopt a corn-wheat rotation in place of continuous corn to conserve water. The rotation also reduces costs significantly as wheat requires fewer inputs than corn.

The Colorado Crop Water Allocation Tool is designed so that the user can change the expected allocation to reflect differing input levels including fertilizer, chemical, seed and tillage operations well as differing crop rotations. The operating return per acre is calculated for each operation so that limited irrigation alternatives can be compared.

Asset Efficiency, Cost Efficiency and Profits

Farm profitability is a direct result of the efficiency with which the farm uses its assets and manages it costs. Indeed, the following mathematical relationship is true:

(3) Rate of Return to Farm Assets (ROFA) = ATR × OPM

OR

(3a) ROFA = ATR × OPM = Operating Income ÷ Total Farm Assets

Operating income divided by total farm assets is the rate of return to farm assets (ROFA) as written in equation (3a). More simply, the ROFA represents the percent rate of return that a farm can generate with its assets – a percent that can be compared against similar farms. Those farms with higher ROFA's are said to be more efficient in deploying and using farm assets to generate operating income.

ROFA is a product of the farm's asset efficiency and cost efficiency as shown in equation (3). If a farm seeks to increase its profitability, it may adopt a strategy that generates a greater revenue stream from its resources (increases ATR) or improves its cost efficiency (OPM). Unfortunately, reduced water supplies typically decrease both ATR and OPM by reducing gross revenues and operating income. As a result, the ROFA of a limited irrigation farm declines.

A declining ROFA is especially problematic for a firm whose interest expense is relatively high. The operating income used to calculate the ROFA also represents the funds available to compensate the lender(s) for the use of borrowed capital. If ROFA consistently falls below the average interest rate on borrowed capital, then the farm will have to find another means in order to make payments to the lender.

The relationship between borrowed capital and limited irrigation is considered in the next section.

Limited Irrigation and Borrowed Funds

Borrowed capital permits farmers grow their business more quickly and control a larger asset base than if the owner were to grow based solely on retained earnings. In order to secure borrowed capital, farms often pledge their land as collateral. Shifting from full to limited irrigation impacts the farm's ability to secure borrowed funds in two ways: it limits the ability to repay debt by restricting cash flow and it undermines the security of the farm's collateral by decreasing the market value of its assets. Each effect will be discussed in turn.

Limited Irrigation and Repayment Capacity

Repayment capacity is an important measure of the cash available to make existing term debt payments and/or to seek additional financing. Lenders calculate repayment capacity according to:

(4) Repayment Capacity = Operating Income + Depreciation + Contributions

Repayment capacity reflects the available cash in the farm operation; therefore, depreciation is added to operating income in equation (4). (Depreciation is a non-cash expense that is usually subtracted from gross revenues when calculating operating income). Likewise, off farm income might represent an important cash contribution to the farm operation, so it is added to operating income to reflect the ability to repay.

Operating income declines with limited irrigation reducing the funds available to repay scheduled principal and interest payments. Increasing off-farm contributions, custom farming and expanding the operation may enhance repayment capacity by increasing cash flow. Yet, declining repayment capacity will limit opportunities to buy or lease additional farm acres. Furthermore, limited irrigation reduces farm's collateral.

Limited Irrigation and Loan Collateral

Market values for farmland change with expected profits – farmland that is more productive and profitable is in greater demand fetching higher prices and cash rents. A farm evolving from full to limited irrigation will experience a decrease in the market value of its land.

Land is often pledged as collateral for the farm operation. Lenders are acutely aware of circumstances that alter expected farming profits and may attach more stringent covenants to loans on land that adopts limited irrigation cropping in place of full irrigation Example covenants include the use of crop insurance and maintaining a specific working capital level in the farm business bank account. Farm manages should communicate frequently with their lender when examining limited irrigation alternatives.

Conclusions

Farms transitioning from full to limited irrigation will find their financial position is altered. Assets, especially land and equipment, may not be used to their full potential so that gross revenues are reduced. The cost efficiency of the farm operation will suffer, in a large part because overhead costs remain the same but the revenues available to compensate are reduced. Farm managers may be able to improve efficiency by carefully examining and reducing inputs such as fertilizer and the seeding rate. Finally, farm managers adopting limited irrigation practice should recognize shrinking cash flows will limit repayment capacity, and the declining values of farm assets decrease opportunities to grow the business with borrowed funds. Farm managers can address the changes with a variety of activities that range from timing irrigations to expanding the farm operation. The Colorado Crop Water Allocation Tool is one resource to assist in choosing among limited irrigation alternatives.