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EVALUATION OF WATER CONSERVATION FROM MORE EFFICIENT IRRIGATION SYSTEMS

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EXECUTIVE SUMMARY

Modern irrigation technologies have been adopted by many producers in western Kansas in recent decades. While these technologies have clearly provided economic benefits to producers, their effect on the depletion rate of the Ogallala aquifer is less clear. This places the State of Kansas in a difficult position. In administering water policy, State agencies are required to achieve an absolute reduction in consumptive use of groundwater, while at the same time maintaining the economic viability of irrigated agriculture in western Kansas. In order to maintain the profitability of irrigated agriculture, technological innovations continually need to be developed through research and adopted by the agricultural community. The question is how to allow this process to continue while at the same time reducing water consumption from the Ogallala aquifer.

The State of Kansas currently has a cost share program aimed at increasing irrigation efficiency and reducing water consumption. The purpose of this study is to evaluate the effects of this program on consumptive water use. Unfortunately, due to data limitations, consumptive use can neither be measured nor estimated from data sources at the parcel-level. However, a related measure, non-beneficial use (*NBU*) can be calculated from observations of weather and water pumped. For this reason, we focus on recovering the statistical relationship between *NBU* and a set of causal factors including technology.

Because *NBU* is not the policy variable of interest, we analytically derive the mathematical relationship between *NBU* and consumptive use. Based on this relationship, we show that changes in *NBU* and consumptive use are systematically related. As such our results can be interpreted as an approximation for changes in net aquifer withdrawals.

To conduct our empirical analysis, we assemble a comprehensive, parcel-level database on *NBU* and related variables, including irrigation technology, irrigated acreage, the crop grown, soil attributes, hydrologic data, crop and energy prices, and weather conditions. These data were compiled for all counties in western Kansas with significant areas overlying the Ogallala aquifer for the period 1996-2003. Additionally, we employ another database compiled by the Kansas Water Office, of the Kansas Soil Conservation Commission (SCC) technology cost share contracts issued during the same period. Of the approximately 1,000 contracts in this database, location information was sufficient to match only about 300 of them to particular parcel-level observations of *NBU*.

We analyze the data in three different ways. First, for observations in the *NBU* database where technology was converted during the data period, the data were separated into two datasets containing the records "before" and "after" the conversion occurred. Average irrigated acreage and crop choices were then computed and compared in the two datasets, revealing the effects of technology conversion on these variables. The results of this analysis indicate that farmers converting from center pivots to center pivots with drops do not change irrigated acreage on average, while the average producer converting from flood to center pivot technology increased irrigated acreage by about 13%. Perhaps contrary to conventional wisdom, we found little evidence that farmers choose more water-intensive crops following a technology upgrade.

The second method of analysis was statistical regression of *NBU* on a set of causal factors. These regressions will reveal the effect of technological change on *NBU*, while controlling for other causal factors such as soil type and the hydrologic setting. Using this method, we find that the effect of technology on *NBU* differs by the type of technology adoption taking place and the crop being grown, and that net water use will decrease in certain cases but increase in others. Conversions from center pivot to center pivot with drops were estimated to reduce *NBU* use by about 0.5 acre-inches per irrigated acre, with an expected range of about zero to 1 acre-inch per acre. These are relatively small impacts; the upper end of the range represents about 5% of water pumped for a producer applying irrigation in the range of 18 inches.

The estimates for flood to center pivot conversions were subject to more statistical uncertainty, with estimated *NBU* reductions ranging from about –2.5 to about 4.5 acre inches per irrigated acre, depending on the crop grown. Thus, conversions from flood would appear to reduce *NBU* by larger amounts in certain cases, although in other cases *NBU* may rise. It should also be noted that the upper end of the range depends on a potentially unreliable regression result, which may not be representative of the producer population.

The third analysis was to evaluate the SCC cost share program in terms of efficacy of taxpayer funds. In particular, for each contract in the SCC dataset, the expected reduction in *NBU* due to the contracted technology switch was computed using the results of the earlier analyses. The SCC dataset includes the amount of public funds invested in each contract, allowing us to compute the estimated *NBU* reduction per taxpayer dollar invested. For conversions from center pivot to center pivot with drops, each taxpayer dollar invested in the SCC program was estimated to result in -0.08 to 0.82 acre inches of cumulative *NBU* reduction over a 15 year period. For conversions from flood to center pivot, the estimated range was considerably wider: -1.15 to 4.12 acre inches of cumulative *NBU* reduction per dollar. Here again, however, the upper value of this range depends on a potentially unreliable regression result. If the unreliable result were ignored, the upper end of the range would be a negative number. Thus, it would appear that in at least some cases, the cost share program may have resulted in increased water use.

In general, the estimated cost efficiency of the SCC investments do not appear to compare favorably to an alternative policy such as a water right buyout program. Based on recent research on the likely cost of such a program, a water right buyout was estimated to achieve about 1.125 acre inches of water savings per dollar invested. Taken as a whole, the evidence from this research suggests that the SCC cost share program had a limited effect on groundwater consumption, and may have been counterproductive in this regard in certain cases. While producers apply sound economic judgment in adopting efficiency enhancing technology, and have reduced crop specific water consumption over time, they appear to be using these water savings largely to expand acreage.

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CHAPTER I – INTRODUCTION

In 1990, approximately 3.6 million acre-feet of water were extracted from the Ogallala aquifer. Due to aquifer characteristics, the Ogallala receives only 1.5 million acre-feet of water in recharge (Docking Institute of Public Affairs, 2001). The steady decline of the aquifer's saturated thickness raises concerns about the long-term viability of the irrigation-based economy of western Kansas.

Over the past 30 years there has been a significant increase in the number of irrigated acres in western Kansas. Additionally, an increase in the acreage of water intensive crops, such as corn, has been observed. Each of these factors escalates the rate at which water is extracted from the aquifer. On the other hand, a steady reduction in the per-acre water use for all irrigated crops has been observed. This reduction likely has been the result of a combination of factors, including government regulation, intensive management, advances in technology, public awareness of the situation, and to an extent the lack of water availability.

From a production economic perspective, these trends likely are revealing that the market is allocating scarce water resources to their highest valued use. However, from society's perspective, this economic efficiency may be less important than sustainability. Regarding the Ogallala, the Kansas Water Plan focuses on extending the life of the aquifer through both mandated and voluntary incentive based policies. In order to provide reliable and relevant input into the public policy debate, economists need to be proactive in developing a better understanding of the factors that determine long-term water use, specifically the role that technology plays in this process. Additionally, our profession needs to be on the forefront of developing new and innovative policy instruments aimed at extending the economic life of the aquifer if that is what society desires.[1]

The public policy debate over the depletion of the aquifer is significant. Several policy alternatives have been suggested, including water taxes, mandatory reductions in current water allocations, voluntary water retirement programs, incentive programs aimed at reducing the planted acreage of water intensive crops, incentive programs aimed at increasing irrigation efficiency (center pivot end gun removal, installation of water meters, low energy.precision application (LEPA), sub-surface drip irrigation (SDI), etc.), and incentive programs aimed at temporarily converting irrigated land to dryland production. In order to make informed decisions, policy makers need accurate information from the economic community as to the economic impacts of these various policies.

The Role of Irrigation Technology

Since the 1982 High Plains Study, both research and policy have focused on improving irrigation efficiency as the primary means of extending the aquifer's economic life. There is little doubt that improvements in irrigation technology have provided several benefits to producers and the productivity of irrigated agriculture. To farmers, technological advances have reduced water delivery costs, reduced labor requirements, and have increased crop yields. Several studies have

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[1] Economic life is defined as the number of years during which the presence of the aquifer will add value to the land.

documented these benefits for Kansas irrigators (e.g., Buller et al., 1988; DeLano and Wiliams, 1997; Williams et al., 1996; DeLano et al, 1997). The reader is referred to Peterson and Bernardo (2003) for a more detailed review of these studies and their findings.

Although the economic benefits of technology are well documented, past trends in water consumption and crop mix, as well as recent economic research, suggests that efficiency gains might actually be accelerating water use and increasing the pace at which the aquifer is depleted. For example, Golden (2005) suggests that center pivot irrigation systems equipped with low pressure with drops technology may yield lower application efficiencies than comparable systems with less sophisticated sprinkler packages. From an engineering perspective, Rogers et al. (1997) and Lamm (2004) explain why a low pressure irrigation system equipped with drop nozzles might have a lower season-long application efficiency even though the more current technology reduces evaporation losses and has a higher coefficient of uniformity. From an economic perspective, Peterson and Ding (2005) illustrated that a producer adopting technology that improves efficiency and reduces the marginal cost of water may respond by increasing water consumption.

Study Objectives

One policy aimed at increasing irrigation efficiency is the current cost-share scheme administered by the Kansas State Conservation Commission (SCC). Under this program, irrigators within the High Plains aquifer region of western Kansas are reimbursed a portion of the cost of adopting modern irrigation technologies. The majority of cost share funds have been expended on the adoption of 'low pressure with drops' technology (Figure 1.1).

Figure 1.1 A Low Pressure Center Pivot System with Drop Nozzles

In order to maintain a viable cost-share program, the State of Kansas, policy makers, and stakeholders need input from the economic community on both future program structure as well as likely outcomes of the current cost-share scheme. The purpose of this research is to develop an in-depth understanding of the various factors, including technology adoption, that impact application efficiency and annual water usage for irrigators in the Ogallala aquifer region of western Kansas. The particular objective is to quantify the change in water use following the adoption of new technology for an average irrigator. This quantification will also make it possible to compute the reduction in the gross amount of water pumped per dollar of taxpayer expenditure on cost share programs.

These objectives will be accomplished by statistically characterizing the change in water use by irrigators in the High Plains aquifer who have received cost share funds on irrigation systems, before and after the adoption of new technology. Similar characterizations will be preformed on the entire population of irrigators that have adopted new technology.

Organization of Report

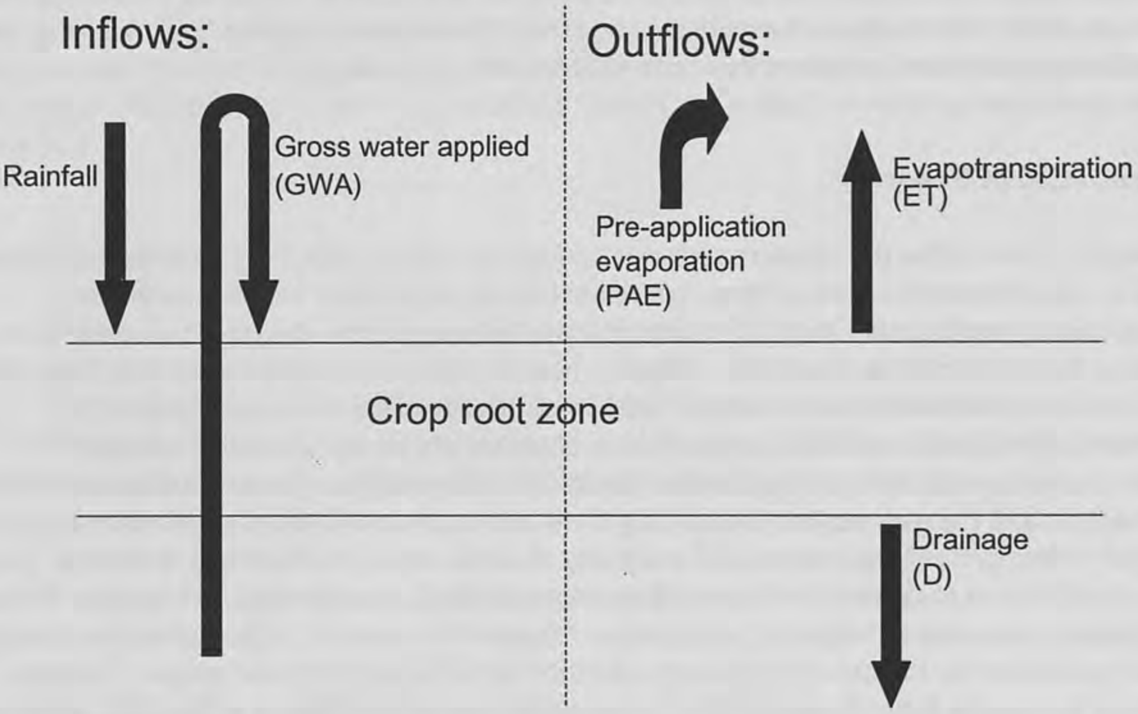
In chapter 2, we define the measure of water savings we will be analyzing, non-beneficial use (*NBU*). This measure is distinct from, but related to, the key policy variable for water management, consumptive use (*CU*). Our analysis focuses on *NBU* because it is the only measure for which data are available. Chapter 2 derives the relationship between *CU* and *NBU* based on water-balance principles at the field-level. Because the two measures are systematically related, our *NBU* results in later chapters can be interpreted as the closest approximation available to the actual changes in *CU*. Chapter 3 discusses the data sources for our analysis and the methods for assembling them into a common spatially-referenced database. Chapter 4 then presents one method of analyzing the data: stratified summary statistics. This analysis allows us to determine whether farmers, on average, change irrigated acreage or crop selections in response to technology upgrades. Chapter 5 is devoted to the regression analysis, which quantifies the impact of technology adoption on *NBU* for particular crops. Chapter 6 employs the results from chapters 4 and 5 to evaluate the cost-efficiency of the SCC technology cost share program. Concluding remarks are offered in chapter 7.

CHAPTER II – CONCEPTS AND DEFINITIONS

Water Inflows and Outflows

Figure 2.1 illustrates the inflows and outflows of water at the field-level, the relationships that lie at the core of our analysis. Inflows to the crop root zone consist of effective precipitation, *P*, and gross water applied as irrigation, *GWA*. The precise definition of *GWA* is the amount of water that is pumped from the aquifer and exits the irrigation delivery system.

Figure 2.1 Field-Level Water Inflows and Outflows



Outflows at the field level come in three forms. Pre-application evaporation, *PAE*, is the amount of water returned to the atmosphere after it exits the delivery system but before it reaches the soil or plant surface. The second outflow is evapotranspiration, *ET*, or the combined amount of water transpired through the crop and evaporated from the soil surface (Scherer et al., 1999). *ET* is determined by the crop type, growth stage of the plant, weather conditions, and cultural practices. In southwest Kansas, corn, soybeans, and alfalfa have the highest *ET* requirement and are often referred to as water-intensive crops. Another label for *ET* is *beneficial use*, as it is the portion of outflows generating economic benefits to the irrigator in the current growing season. The third outflow is drainage, *D*, or the amount of water percolating below the crop root zone.

By the law of the conservation of matter, inflows must equal outflows. The variables in Figure 2.1 therefore are related by the equation

(1) $P + GWA = ET + PAE + D.$

The outflows on the right-hand side of (1) can be grouped in different ways. One grouping stems from the fact that D is a unique outflow because it ultimately percolates back to the aquifer and thus represents water that is potentially reusable in the future.[2] On the other hand, ET and PAE are both "consumed" and irretrievably lost. Accordingly, *consumptive use* (CU) is defined as $CU = ET + PAE$. Substituting this definition into (1) yields an alternative water-balance equation, of the form

$$P + GWA = CU + D. \tag{2}$$

CU is a key variable of interest to water managers because it measures the net draw on the water resource.

Another possible grouping of outflows is based on a fact mentioned above: only ET is beneficially used water. By exclusion, the remaining outflows can be combined into a single measure defined as NBU, or *non-beneficial use*: $NBU = PAE + D$. Substituting NBU into (1) results in yet another form of the water balance equation:

$$P + GWA = ET + NBU \tag{3}$$

In what follows, it will be useful to have a formula that calculates NBU from values of P, GWA, and ET. This formula can be obtained by solving equation (3) for NBU:

$$NBU = P + GWA - ET. \tag{4}$$

While it might seem natural to think of NBU as "wasted" water, this is an inaccurate label because, as noted above, the drainage component, D, is potentially reusable at some future date.

Measures of Irrigation Efficiency

The key question in this study is how the water inflows and outflows change in response to a switch in irrigation technology. A commonly reported measure to compare irrigation technologies is *season-long application efficiency*, denoted SAE. SAE is directly related to the inflow and outflow measures above. It is defined as

$$SAE = \frac{ET}{P + GWA}. \tag{5}$$

That is, SAE can be interpreted as the share of inflows that are beneficially used. This measure allows consistency in comparison between technologies based on potential reductions in groundwater pumped. An improvement in SAE is one justification for cost sharing of new technology. All SCC cost share contracts, for example, include a section that calculates an estimated improvement in irrigation efficiency due to the technology conversion.

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[2] As such, D in this system can be labeled a "return flow." It should be noted, however, that in some locations not all of D reaches the aquifer, and that the speed of the return flow is generally very slow and varies spatially depending on the depth to the aquifer and the geology of the layers above it.

This efficiency definition above also leads to a measure of *inefficiency* that can be related to *NBU*. In particular, we can define season-long application inefficiency (*SAI*) as

$$\begin{aligned} SAI &= 1 - SAE = \frac{P+GWA}{P+GWA} - \frac{ET}{P+GWA} \\ &= \frac{P+GWA-ET}{P+GWA} \qquad (6) \\ &= \frac{NBU}{P+GWA}, \end{aligned}$$

where the last equality follows from the *NBU* formula in equation (4). *SAI* is simply the share of inflows that are not beneficially used.

Practical Limitation: Incomplete Data

If high-quality data were available on all five of the variables in Figure 2.1, all the inflows and outflows could be quantified with a high degree of precision on every irrigated parcel, and the factors affecting any of these variables could be analyzed with a high degree of statistical confidence. Unfortunately, data are available on only three of the five variables, namely *P*, *GWA*, and *ET*. *P* is not recorded for every irrigated field, but accurate daily measurements are recorded at weather stations around the state. Similarly, an approximate value of *ET* on any field can be obtained from weather station records. Data on *GWA*, meanwhile, can be obtained from the annual water-use reports required by Kansas law. In sum, we have relatively complete information in the inflows, *P* and *GWA*, but very incomplete information on the outflows, with data on *ET* but not on *PAE* and *D*.

Our incomplete information on outflows limits our empirical analysis. Unfortunately, it is impossible to construct data on *CU* because information on both *PAE* and *D* are lacking.[3] We can, however, quantify *NBU* from our existing data from the formula in equation (4), as we have data on *P*, *GWA*, and *ET*. As described more fully in the data chapter, we construct our dataset in precisely this manner. *NBU* then becomes the dependent variable in our regression analysis, the goal of which is to explain how various factors affect *NBU* over time and space. Thus, our empirical analysis must be limited to explaining *NBU* even though the most relevant measure is *CU*.

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[3] If observations of *PAE* were available, *CU* could be computed using its definition combined with *ET* data: $CU = PAE + ET$. Alternatively, if data on *D* were available, *CU* could be computed by rearranging equation (2): $CU = P + GWA - D$.

Relationship between *NBU* and *CU*

The mathematical relationship between *NBU* and *CU* can be derived from equations (2) and (3). Together these equations imply that

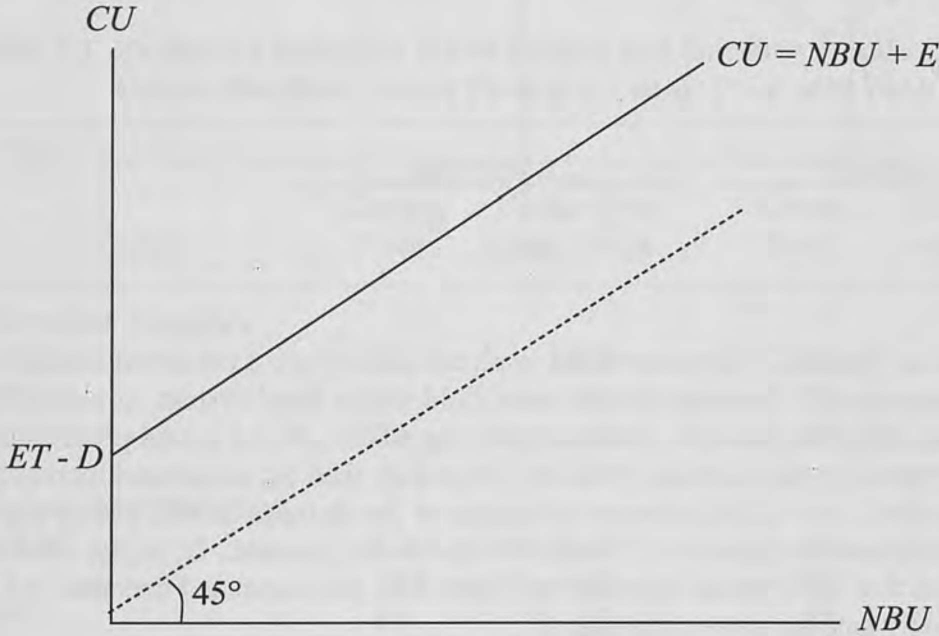
$$CU + D = ET + NBU. \tag{7}$$

Equation (7) simply says that, regardless of how the outflows are grouped, their sum must be the same. Solving (7) for *CU* yields

$$CU = NBU + ET - D. \tag{8}$$

Equation (8) implies that, if drainage data were available, *CU* could be computed for any well by adding the quantity ($ET - D$) to the value of *NBU*. Graphically, this means that the line relating *CU* to *NBU* lies above the 45-degree line, as plotted in Figure 2.2.

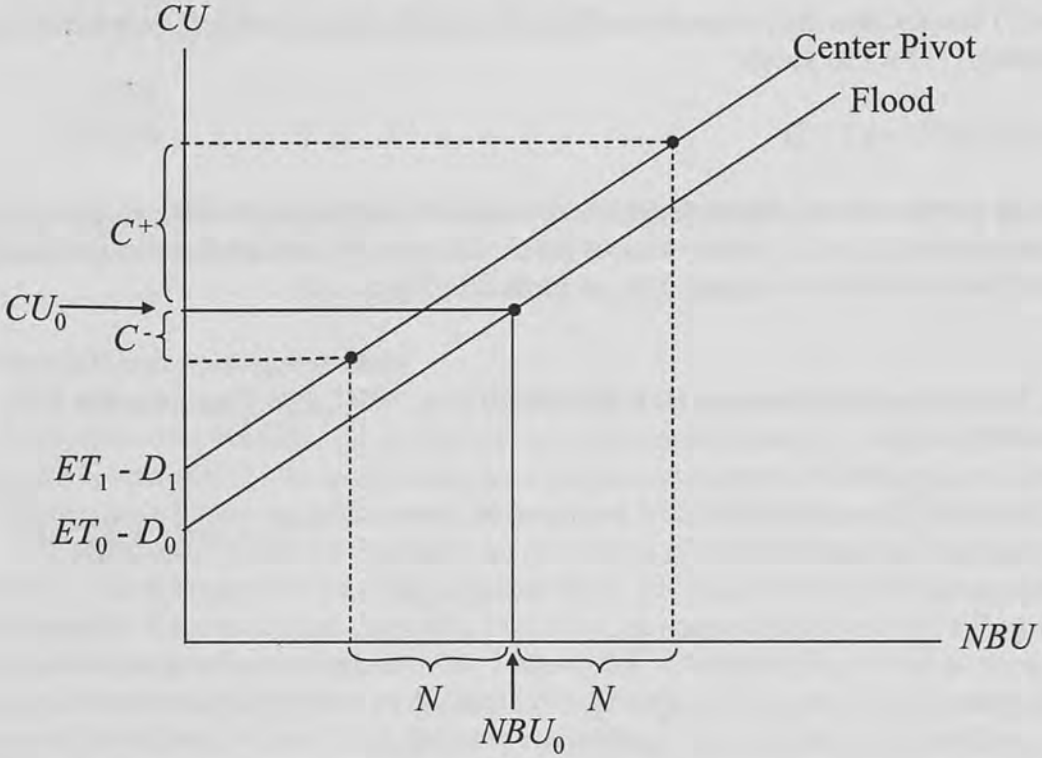
Figure 2.2 Relationship Between Non-Beneficial Use, *NBU*, and Consumptive Use, *CU*



Equation (8) and Figure 2.2 are useful in understanding the implications of our *NBU* predictions from different types of technology changes. Consider first a switch from flood to (any type of) center pivot technology. Figure 2.3 depicts the *CU-NBU* relationships for the two systems. Let ET_0 and D_0 denote the evapotranspiration and drainage under the flood system and let ET_1 and D_1 denote the corresponding measures under the center pivot system. A large body of agronomic and engineering research suggests that the center pivot system will result in more *ET* but less *D*, relative to the flood system (i.e., $ET_1 > ET_0$ and $D_1 < D_0$). Together, these facts imply that $ET_1 -$

$D_1 > ET_0 - D_0$. Accordingly, the *CU* line for the center pivot system lies above that of the flood system. For a given level of *NBU*, in other words, a farmer would obtain more *CU* from a center pivot system than a flood system.

Figure 2.3 ***NBU-CU*** **Relationships for Flood and Center Pivot Irrigation Systems**



The relationships in Figure 2.3 have important implications for how a predicted change in *NBU* relates to the change in *CU*. Suppose that on some field with a flood system, non-beneficial use is NBU_0 acre feet, which translates to a consumptive use of CU_0. If our model predicts that installing a center pivot would increase *NBU* by *N* acre feet, then the associated increase in *CU* would be C^+ acre feet. Part of this increase is because of the increase in *NBU per se* and part of it is because the relationship between *CU* and *NBU* has shifted upward. If, on the other hand, our model predicts that *NBU* would decrease by *N* acre feet, the associated decrease in *CU* would be C^-, a significantly smaller movement than C^+.

This example illustrates the following general relationship for conversions from flood to center pivot systems: increases in *NBU* are accompanied by relatively larger increases in *CU*, while decreases in *NBU* lead to relatively smaller decreases in *CU*. Thus, if our model predicts an increase in *NBU,* say of 5 acre feet, this should be interpreted as a lower-bound estimate of the associated increase in *CU*; we have really predicted that *CU* will increase by *at least* 5 acre feet. On the other hand, if the model predicts that *NBU* would decrease by 5 acre feet, the proper interpretation is that *CU* would decrease by at most 5 acre feet.

Now consider the change from a conventional center pivot system to a "center pivot with drop nozzles" system, which allows the system to deliver water at or below the height of the crop canopy. Here, the relative location of the *CU-NBU* relationships is less clear. Irrigation research suggests that the center pivot with drops system is often, although not always, more efficient overall, with the efficiency gain coming primarily in the form of reduced *PAE*. This implies that a center pivot – center pivot with drops upgrade will probably (although not certainly) lead to an increase in *ET*, while the change in *D* is difficult to predict. This leaves us uncertain about the relative sizes of the term (*ET* – *D*) between the two systems, so that the two *CU-NBU* lines in a graph similar to Figure 2.3 could be stacked in either order.

The examples in Table 2.1 illustrate how changes in *NBU* could be a biased in either direction as a predictor of changes in *CU*. For simplicity, *P* is assumed to equal zero in these examples, and the values of the observable variables (*GWA*, *ET*, and, by calculation, *NBU*) are the same in both cases. Under the center pivot technology, 100 acre feet are applied in both cases, 70 acre feet of which become beneficial use or *ET*. By definition, the remaining 30 acre feet constitute *NBU*. After the technology upgrade, *GWA* remains unchanged at 100 acre-feet, while *ET* increases to 80 acre feet, perhaps because a more water-intensive crop is planted. *NBU* therefore decreases to 20 acre feet in both cases, a reduction of 10 acre feet.

Table 2.1 Example Changes in Water Inflows and Outflows from a Conversion from Center Pivot to a Center Pivot with Drop Nozzles

	Example 1		Example 2	
Variable	Center Pivot	Center Pivot with Drops	Center Pivot	Center Pivot with Drops
Observable Variables				
GWA	100	100	100	100
ET	70	80	70	80
NBU	30	20	30	20
Unobservable Variables				
PAE	15	0	15	8
D	15	20	15	12
CU	85	80	85	88

The unobservable variables (*PAE*, *D*, and, by calculation, *CU*) differ. Example 1 represents a case where the new technology eliminates all *PAE* but results in a small increase in *D* (+5 acre feet). In this case, the effect of technology adoption is to reduce *CU* by 5 acre feet. Here, a reduction in *NBU* results in a relatively smaller decrease in *CU* (10 acre feet versus 5 acre feet). Example 2 illustrates another plausible case where the new system reduces both *PAE* and *D* (–7 acre feet for *PAE* and –3 acre feet for *D*). In this example, *CU* actually increases by 3 acre feet even though there was a 10 acre-foot reduction in *NBU*.

Summary and Implications

To summarize this chapter's main conclusions, we are only able to model changes in *NBU* due to data limitations. As such, our model results cannot and should not be interpreted as a prediction of changes in *CU*, which is almost certainly the more relevant variable for water management purposes. Nevertheless, we showed that the two variables are systematically related and that this relationship implies our results do provide some insight on *CU*, at least for one type of technology change. In particular, assuming that a switch from a flood to (any type of) center pivot system increases *ET* but decreases *D*, our predicted reductions in *NBU* should be interpreted as an upper-bound estimate of the reduction in *CU*; the actual reduction in *CU* could be smaller than our model prediction but it is unlikely to be larger. For a switch from a conventional center pivot to a center pivot with drops system, our predicted changes in the relationship between our predicted change in *NBU* and the real change in *CU* is ambiguous and could not be determined without more field-level data.

CHAPTER III – DATA

Water Information Management and Analysis System Data

The Kansas Water Office (KWO) provided data based on the Water Information Management and Analysis System (WIMAS). In 1991, the U.S. Geological Survey, in cooperation with the Kansas Department of Agriculture-Division of Water Resources, developed the Geographic Information Systems (GIS) application known as the WIMAS. This application is used to assist in the analysis and management of the State's water resources.

The database underlying the WIMAS is compiled from the water-use reports that all water-right holders must submit to the Division of Water Resources annually. These data consist of time-series observations on each point of diversion (PDIV), typically a single water well, in the State. For each PDIV the dataset includes the Public Land Survey System (PLSS) information, the water right number, the county where the PDIV is located, the reported annual acre-foot water usage and how the usage was measured, the number of irrigated acres associated with the PDIV, the crop grown on the irrigated parcel, and the technology used to irrigate the associated parcel.

Our study period spans the years 1996-2003. For the beginning year in this time period, the KWO identified all PDIVs in the WIMAS system for a 33-county region corresponding to the area overlying the Ogallala aquifer. All annual water use reports were then extracted for this set of water rights over our 8-year period. This resulted in a dataset with 13,031 observations. To avoid confusion, an "observation" in this report refers to all annual records for a particular PDIV. Because each observation in this dataset contains eight annual records, it has a total of 8 × 13,031 = 104,248 records.

There were several duplicate PDIV numbers in the data. As a general rule, the second observation within a duplicate PDIV contained data that was missing from the first observation. The duplicates were combined to form a single observation. This modification resulted in 12,808 observations of unique PDIV numbers, which will be referred to as the *population*. On a PDIV basis, key variables were often missing. Table 3.1 provides the percent of missing data, on a yearly basis, for the key variables. Table 3.2 provides the technology codes in the WIMAS dataset and the distribution of technologies by year. Figure 3.1 illustrates the spatial distribution of the population data.

Figure 3.1 Spatial Distribution of the Population of PDIVs

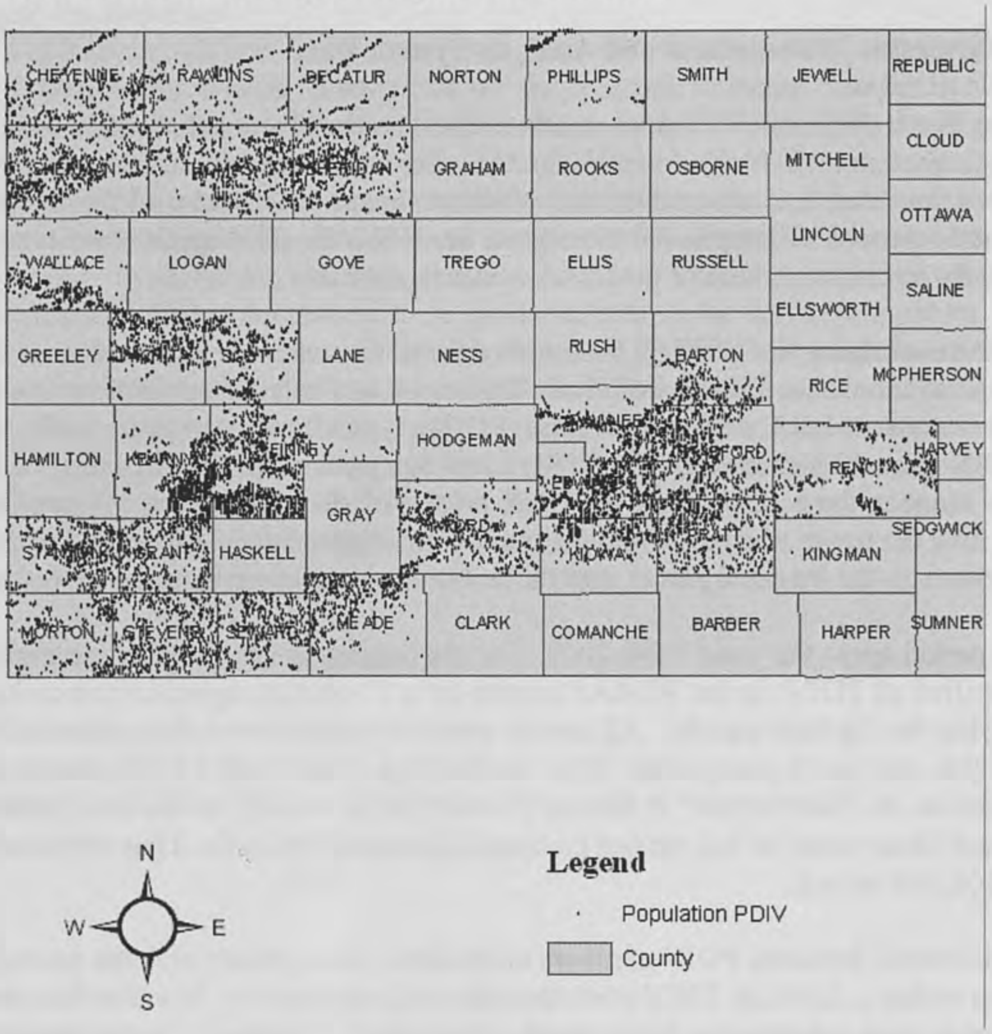


Table 3.1 Percent of Data Missing by Year

Year	Irrigated Acres	Acre Feet Pumped	Crop Code	Technology Code
1996	18.5	18.5	20.2	20.1
1997	16.9	16.9	18.2	17.9
1998	16.9	16.9	19.5	19.5
1999	17.1	17.1	20.1	20.3
2000	16.4	16.4	19.0	19.2
2001	16.1	16.1	19.6	19.8
2002	15.0	15.0	19.1	19.4
2003	15.9	15.9	19.8	20.1

Table 3.2 Technology by Year (Population)

System Name	System Code	1996	1997	1998	1999	2000	2001	2002	2003	Trend Percentage	P-Value Of Trend
Flood	1	2556	2162	1678	1408	1207	967	828	679	-0.184	0.000
Drip (subsurface irrigation)	2	28	11	4	10	11	20	26	42	0.139	0.189
Center Pivot Sprinkler	3	6186	4434	3681	3230	2400	1947	1484	1303	-0.212	0.000
Center Pivot Sprinkler with Drop Nozzles	4	604	2993	4011	4698	5890	6483	7077	7413	0.186	0.000
Sprinkler other than center pivot	5	155	154	142	99	121	123	145	116	-0.032	0.195
Center Pivot and Flood	6	702	759	800	759	717	720	748	607	-0.016	0.197
Drip and other systems	7	0	0	0	0	0	6	13	8	0.490	0.016
Other	8	0	0	0	0	0	0	0	70	0.667	0.134
Missing		2577	2295	2492	2604	2462	2542	2487	2570	0.004	0.512
Total		12808	12808	12808	12808	12808	12808	12808	12808	NA	NA

The WIMAS data provided information on the irrigation technology. The codes (defined in Table 3.2) used to identify these technologies were often missing; however, in certain instances, logic would imply what the missing code should be. Assuming the technology code for year *t* was missing, if the technology code in year *t*-1 was the same as the technology code in year *t*+1, then the technology code for year *t* was assigned to be equal to the technology code in year *t*-1. The same logic was applied if there were two or three missing years of technology data. Additionally, if the technology codes for either the first year (1996) or last year (2003) were missing they were assigned the code for 1997 or 2002 respectively.

After adding technology codes, as described above, observations with more than four missing technology codes were removed from the population data set. Additionally, observations with technology codes of 5, 6, 7, and 8 were removed due to ambiguity in acreage and water use data. The final dataset, referred to as the *sample*, contained 7,853 observations.

Some observations in the sample had missing information for one or more years on the reported average annual acre-foot water usage, the number of irrigated acres, and the crop grown. No observations were deleted based on these missing data. However, the missing years from a particular observation are automatically skipped when statistical procedures are performed, so that for some variables fewer than 7,853 records are available for each year of data.

Based on the data filters as discussed above, paired t-tests (*p-value* = 0.990) and the Wilcoxon signed rank test (*p-value* = 0.9061) both suggest the distribution of the percent of observations, by county, are comparable between the population and sample data A two sample t-test, assuming equal variance, (*p-value* = 0.1816) suggests that the acre-foot water usage in the population and sample data set are comparable. A paired t-test (*p-value* = 0.8988) and Wilcoxon signed rank test (*p-value* = 0.9491) also suggest that the frequency of observations, by year, are comparable between the population and sample data. As a result there is confidence that the sample dataset represents a random draw from—and therefore is representative of—the population dataset.[4]

Public Land Survey System

The Public Land Survey System (PLSS) is a rectangular survey system, in which land is divided into townships and then subdivided into sections. A regular township is six miles on a side bounded on the North and South by township lines, and on the East and West by range lines. Each township contains 36 sections that are numbered sequentially beginning from the northeast corner of the township. Each section, normally considered to be one mile on a side, is comprised of 640 acres, which was the basic unit under the Land Ordinance Act of 1785. No township or section is mathematically perfect for various reasons, including the fact that the earth's surface is not flat. While not all States use the PLSS system, the system is used in Kansas.

The use of the PLSS system to spatially link data from a variety of sources is becoming common practice. The PDIVs in the WIMAS data are spatially referenced using both the PLSS grid system and with longitudes and latitudes. Where possible, the PLSS system will be used to spatially link other datasets to the WIMAS dataset. A typical irrigated field in western Kansas is

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[4] The null hypothesis for all tests is that the distributions are the same.

a quarter section, or 160 acres. This implies that a typical PDIV is associated with a unique irrigated quarter section, and that each section commonly contains four PDIVs.

Kansas State Conservation Commission Cost Share Data

The State Conservation Commission (SCC) provides cost-share assistance to irrigators for eligible efficiency measures designed to improve or convert existing irrigation systems. This initiative is implemented locally through the county conservation districts. Cost-Share practices eligible for financial assistance include, but are not limited to, SDI conversion from center pivots or flood systems, conversion from flood to center pivot systems, and conversion for high pressure sprinkler to low pressure with drop technology. The goal of providing financial assistance in the form of cost-share payments is to reduce the consumptive use of water in order to achieve the goal of extending the life of the Ogallala for future generations. KWO provided SCC cost share data which included the physical location of the irrigation system in PLSS format, the type of conversion, the cost of conversion, the number of irrigated acres involved, and the estimated efficiency enhancement and water savings associated with the conversion. The SCC cost share data consisted of 1,067 observations, located in 30 counties in western Kansas.

The SCC data, where possible, were merged with the WIMAS data based on the assumption that the PLSS designation listed in the SCC cost share data should match the PLSS data for the PDIV listed in the WIMAS data. This matching process resulted in 359 observations where the type of conversion and year of conversion (plus or minus one year) coincided at the quarter section level. In this sub-sample, we can be fairly confident that each cost share contract is matched with the correct PDIV. However, it consists of a limited number of observations, raising the possibility that it is not representative of all producers with cost share contracts.

To develop a larger and more representative sub-sample, an alternative matching process was developed where unique PLSS data, to only the section level, were obtained from the SCC data. Observations from the WIMAS data, which had a technology change during the sample period, and had matching section level PLSS information were accepted into the sub-sample. This matching process resulted in 731 observations. In this case, some of the observations are possibly "mismatched"—i.e., the cost share location may not correspond to the exact location of the PDIV that is matched with it. However, we are ensured that the two locations are within the same section, where the relevant variables such as climate and aquifer properties are likely to be relatively constant.

Kansas Geological Survey Data

The Kansas Geological Survey High Plains Aquifer Section-Level Database (KGS dataset) consolidates information formerly maintained by several local, State, and federal agencies. The section-level data can be accessed through a web-based portal maintained by the Kansas Geological Survey (http://hercules.kgs.ku.edu/geohydro/section_data/hp_step1.cfm). The KGS dataset contains the necessary information on depth to water, saturated thickness, annual aquifer decline, sustainable yield, and other hydrological parameters. These data were merged to the WIMAS data on a PLSS section-level basis.

Kansas Agricultural Statistics Service Data

The Kansas Agricultural Statistic Service (KASS) data set provides yearly weighted estimates of crop prices, by crop reporting districts. Additionally, KASS collects data on farm operating expenses. Crop and fuel price were merged to the sample data on a crop reporting district basis. That is, all PDIVs in a particular crop reporting district were assigned the values corresponding to the KASS data reported for that district. There are nine crop reporting districts in the State of Kansas, each of which consists of about 15 counties; our study region spans portions of 6 of these districts.

Natural Resource Conservation Service Data

The Natural Resource Conservation Service (NRCS), State Soil Geographic (STATSGO) dataset provides the basis for the soil data used in this analysis. Soil groupings are classified by mapping unit identification numbers (MUID). Each MUID can be composed of several mapping unit sequence numbers (MUIDSEQNUM). A MUIDSEQNUM can be thought of as a distinct soil type. Each MUIDSEQNUM consists of several vertical layers (LAYER) of soil, each layer having distinct soil properties. An algorithm was developed to characterize individual soil properties for a single MUID, by aggregating those soil properties from the LAYER and MUIDSEQNUM levels. MUIDSEQNUMs, which were not suitable for farming, were removed from the MUID level aggregation. This process yielded measures of percent slope, percent clay, water holding capacity, and NRCS soil classification ratings on an MUID basis. Spatial intersection techniques available in ARCGIS were applied to assign these soil values to individual sections of land in the target area. These data were merged with the WIMAS data on a PLSS section-level basis.

Kansas Weather Library Data

Daily precipitation and evapotranspiration data were obtained from the Kansas Weather Library for the three agricultural experiment stations in western Kansas (Colby, Tribune, and Garden City). Based on discussion with weather data experts, only data from these stations were used as the measurements are considered more accurate and the records more complete than other stations in the weather station network. The data sets obtained also included the longitude and latitude of each weather station. Algorithms were developed to aggregate the data temporally into biweekly periods, and then the weather variables were assigned to the WIMAS observations based on the geographically nearest weather station.

Measures of seasonal rainfall and crop-specific *ET* were constructed based on K-State Extension service recommendations regarding optimal planting dates (Table 3.3). The growing season for these crops was considered to be 105 days and *ET* was calculated for this period. The rainfall associated with the growing season, *P*, included the rainfall which occurred during the growing season as well as the month preceding planting.

Table 3.3 Optimal Planting Dates

Crop	Northwest Kansas	West Central Kansas	Southwest Kansas	North Central Kansas	Central Kansas	South Central Kansas
Sorghum	29-May	1-Jun	3-Jun	3-Jun	9-Jun	15-Jun
Corn	5-May	3-May	1-May	1-May	26-Apr	21-Apr
Soybeans	20-May	21-May	23-May	23-May	23-May	23-May

CHAPTER IV – DATA ANALYSIS: SUMMARY STATISTICS

After the datasets described in chapter 3 were merged together, the result was a comprehensive, spatially referenced database on water use and related variables. For each point of diversion in the WIMAS data, this compiled database includes information on soils, climate, hydrologic characteristics, and price conditions. Additionally, some of the parcels receiving SCC cost share funds could be matched to points of diversion in this database. This chapter begins analyzing the comprehensive database and the SCC cost share data via summary statistics, such observation counts, variable means, minima, maxima, and standard deviations.

These methods are simple, but they are helpful in obtaining an overall picture of the information contained in the data. Further, they provide some insight on key questions such as whether irrigators increase acreage or grow different crops after a technology change. To address these questions, we compute and compare variable means in various sub-samples of data. In particular, for the data corresponding to each type of technology conversion, we create separate sub-samples from the records "before" and "after" the conversion occurred. A comparison of the mean irrigated acreage and crop choices from each sub-sample then reveals the effects of technology adoption on the average parcel where such a change took place.

One shortcoming of this approach is that some of the apparent effects from technology may in fact be due to underlying time trends. This possibility arises because the "before" sub-sample, by definition, reflects an earlier time period than the "after" sub-sample. To control for the trend effects, we perform a similar analysis of means where we assemble sub-samples representing "early" and "late" periods for points of diversion with constant technology. To the extent that water use and land use changes are present in the first analysis but not the second, we can make inferences about the independent effects of technological change.

A more basic issue is the forces causing farmers to adopt technology in the first place. This is not specifically addressed in this chapter, but some analyses speaking to this question are reported in Appendix A. The first analysis in Appendix A uses a stratified means analysis similar to the methods in this chapter, in order to compare producers who adopted technology to those who did not. The differences between adopters and non-adopters reveal some of the factors contributing to technological change, or at least identify situations where adoption is most likely to occur. The second analysis is a regression model of producer choice. This is a more rigorous approach to identifying the factors influencing technological change and their relative importance.

Analysis of SCC Contract Data

The SCC cost share data set classified conversion as 'conversion to SDI', 'conversion to center pivot', and 'conversion to drops.' Table 4.1 provides the basic statistics from the cost share contracts based on the of type conversion. Each contract contains a section computing the expected water savings and planned increase in season-long application efficiency (*SAE*) from the technology upgrade. Several observations appeared to have data entry errors in this regard, as the original data had expected efficiency increases of greater than 90% in many cases. In these cases, conversions from flood to center pivot were capped at 50%, and center pivot conversions to drop nozzles were capped at 30%. These are subjective caps based on a worst case to best case efficiency gain.

Table 4.1 Summary Statistics for SCC Contracts

Variable	Observations	Minimum	Maximum	Mean	Standard Deviation
Converting to SDI					
Total Acres Irrigated (acres)	45	7.0	445.0	60.3	71.1
Total SCC Cost ($000)	45	2.0	20.0	7.15	6.2
Cost per Irrigated Acre ($/acre)	45	21	875	223	232
Average Field Slope (%)	21	19.0	24.0	19.9	1.8
Planned Increase in *SAE*[*] (%)	45	5.0	60.0	34.9	11.7
Converting to Center Pivots					
Total Acres Irrigated (acres)	362	12.0	640.0	166.3	111.6
Total SCC Cost ($000)	362	.517	7	2.91	.869
Cost per Irrigated Acre ($/acre)	362	2	167	24	18
Average Field Slope (%)	254	0.50	4.00	0.89	0.73
Planned Increase in *SAE*[*] (%)	362	0.0	50.0	29.5	11.8
Converting to Crop Nozzles					
Total Acres Irrigated (acres)	636	18.0	600.0	129.8	48.5
Total SCC Cost ($000)	636	.24	10.0	2.0	.91
Cost per Irrigated Acre ($/acre)	636	3	222	17	11
Average Field Slope (%)	507	0.50	6.00	1.385	0.90
Planned Increase in *SAE*[*] (%)	636	2.0	30.0	16.2	8.1

[*] *SAE* is season-long application efficiency; see equation (5), page 5.

More detailed statistics on the SCC contracts are in Appendix B (pages 58-68). Table B.1 provides information on the cost share contracts by county and year of completion, while Table B.2 reports the acreage associated with those contracts. Table B.3 provides information on the type of contracts by county, Table B.4 reports the acreage by type of conversion, and Table B.5 reports the average costs associated with the different categories of contracts. Figure B.1 illustrates the months in which cost share contracts occurred. Figure B.2 provides information on the acreage distribution of cost share contracts. Figure B.3 through Figure B.5 provide acreage distribution by the type of cost share contract.

Several general findings can be inferred from the SCC data summary statistics. First, there is a clear time trend in the number of contracts awarded, with a steady increase in contracts up to 2001 and a steady decline thereafter. As one would expect, the spatial distribution of contracts was concentrated in southwest Kansas, in the counties with a large number of irrigated acres and large volume of water available. The top 4 counties receiving cost share contracts during the data period were: Edwards (111), Gray, (71), Haskell (71), and Kiowa (57). Conversion to drops was the dominant type of technology upgrade, accounting for about 60% of all contracts and 56% of the acreage converted with cost-share funds. Conversions to SDI represented less than 5% of all contracts and less than 2% of converted acreage. As illustrated in Figures B.3 – B.5, conversions to SDI appear to occur on smaller fields, compared to the other two conversion types.

Overall Technology and Acreage Patterns

For comparison with the cost-share conversions, Table 4.2 provides statistics on the types of technological change that occurred in our comprehensive database. Of the 7,853 observations in the sample data, 3,062 observations did not have a technology change while 4,791 converted to a new technology. The predominant conversion pattern, approximately 88% of those adopting new technology, was from center pivots to center pivot with drops technology. Thus it appears there were a disproportionately low number of "conversions to drops" in the cost share program.

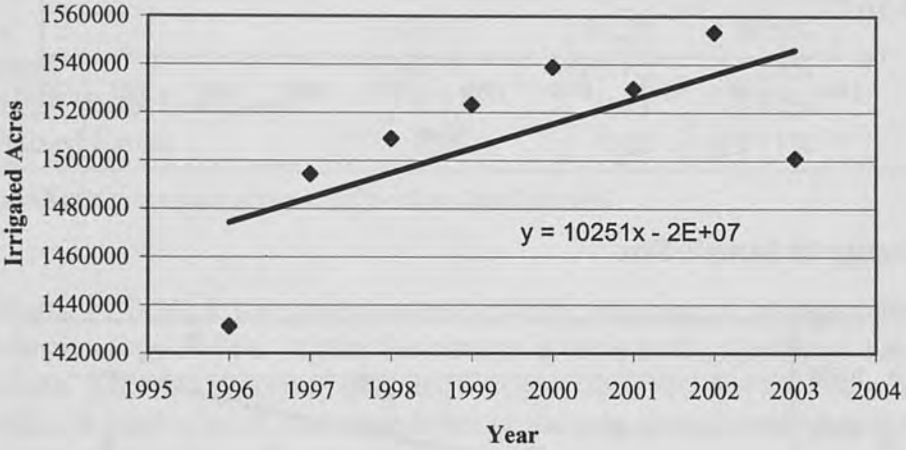
Table 4.2 Type of Technological Change

Technology	Numbers
Observations with No Technological Change	
Flood	1288
Center Pivot	630
Center Pivot with Drops	1138
Sub Surface Drip	6
Total	3062
Observations with Technological Change	
Flood to Center Pivot	86
Flood to Center Pivot with Drops	485
Flood to Sub Surface Drip	16
Center Pivot to Center Pivot with Drops	4195
Sub Surface Drip to Center Pivot	1
Sub Surface Drip to Center Pivot with drops	8
Total	4791

The counts in Table 4.2 are also useful in determining whether sample size is sufficient to reliably analyze the different types of conversions. The sample size is large enough to statistically analyze the conversion process from center pivots to center pivot with drops technology. There is also sufficient sample size to statistically analyze the conversion process from flood irrigation to all center pivots. However, the number of observations is so low that it is felt that there is not sufficient data to statistically analyze the conversion process from other forms of irrigation to sub surface drip (SDI) technology with any degree of accuracy.

An important factor being analyzed in this study is the impact that technological change may be having on expansion of irrigated acreage in western Kansas. Figure 4.1 shows the change in irrigated acreage, over the time period 1996-2003, for the original 13,031 observations in the WIMAS dataset. There can be little discussion as to whether or not reported irrigated acreage has increased. The increasing trend is statistically significant at the 90% level (*p-value* = 0.0689).

Figure 4.1 Change in Irrigated Acreage in Western Kansas



What is less clear is where the increase in acreage is coming from. Figure 4.2 illustrates the change in mean irrigated acreage per PDIV that filed an acreage report with greater-than-zero acres. The mean irrigated acreage per PDIV increased during the study time frame. The increasing trend in mean irrigated acreage is statistically significant at the 90% level (*p-value* = 0.0796). Figure 4.3 provides information on the number of PDIVs that filed acreage reports for a greater-than-zero acreage. The number of reporting PDIVs shows an increasing trend, that is nearly statistically significant at the 90% level (*p-value* = 0.1072). The implication is that the cause of increasing irrigated acreage is ambiguous; it could be coming from either an increase in the mean irrigated acreage per PDIV, or an increasing number of PDIVs reporting, or a combination of the two factors.

Figure 4.2 Change in Mean Irrigated Acreage in Western Kansas

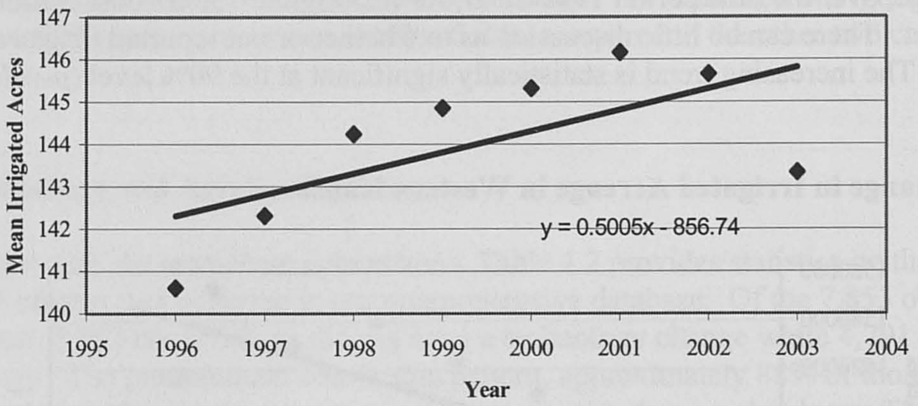
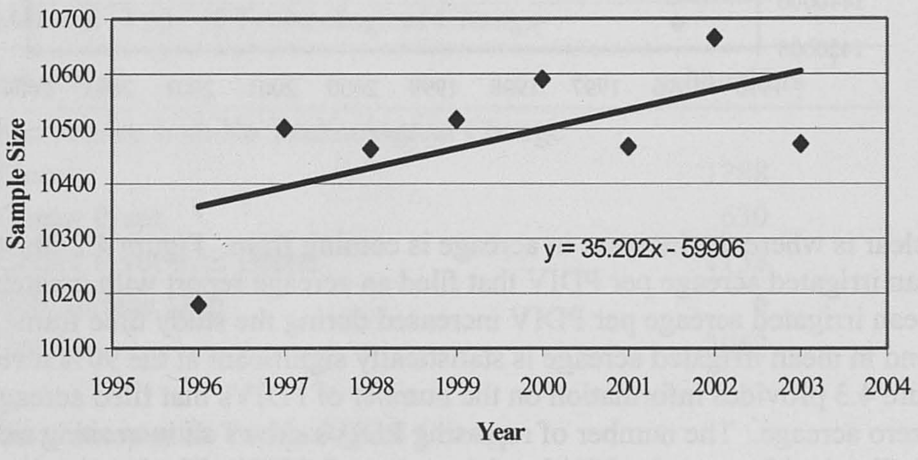


Figure 4.3 Change in Sample Size



Analysis of Conversions from Center Pivot to Center Pivot with Drops

Table 4.3 is a "before and after" comparison for the sub-sample with conversions from center pivot technology to center pivot with drop technology. Each observation in this sub-sample was split into two parts—the first part included the annual records for all years before the adoption occurred, while the second was the remaining records starting in the year of adoption. The "before" and "after" records across all wells in the sub-sample were then assembled and the means of several variables were computed from both data groups.

As the table shows, the average well after this type of conversion irrigated slightly more acres than the average well before conversion, and the change was statistically significant at the 99% level of confidence. Considering the hardware involved in such a conversion, this change is somewhat puzzling. In practice, this conversion is almost always accomplished by installing drop tubes on an existing center pivot system, the length of which was fixed during the original installation. If the length is fixed, acreage irrigated normally would not change.[5] Possibly, the change in irrigated acreage is a data anomaly caused by an underlying trend to bring more acreage under irrigation over time.

Table 4.3 Before and After Comparison for PDIVS that Converted to Drop Nozzles

	Before	After	Increase	Statistically Significant
Irrigated Acres	141.11	144.29	2.25%	Yes
Acre-Feet Pumped	163.90	185.83	13.38%	Yes
Proportion of High Water Use Crops	0.73	0.71	-2.62%	Yes
Proportion of Mixed Crops	0.14	0.12	-13.11%	Yes

All statistically significant mean comparisons had p-values less than 0.01.

The second variable in Table 4.3 is water pumped (*GWA*), the mean of which is about 13% higher after the technology switch. Again this change is statistically significant t at the 99% level of confidence. Like the change in irrigated acreage, however, this may be related to other underlying trends. In particular, the increase in water use was almost certainly related to the rather steady decline in rainfall during the data period.

If water use and technology adoption are indeed linked, one possible explanation is that irrigators plant more water-intensive crops following conversion. To gain some insight on whether this is the case, the third comparison in the table is for the mean proportions of parcels with "high water use" crops. Here, we use a somewhat arbitrary classification where alfalfa, corn, soybeans, and any combination of these crops are labeled "high water use" crops while all other cropping patterns are considered "low water use" crops. As shown in the table, there was actually a small and statistically significant decrease in high water use crops following conversion. This result casts doubt on the claim that technology causes a switch to more water-demanding crops.

Economists have also hypothesized that in water-scarce conditions, producers might combine high water use crops with low water use crops on a single parcel to balance water use with water availability. If this hypothesis is true, then there should be a decreased need for mixed crops following the adoption of a more efficient technology that ameliorates water scarcity to some extent. The comparison of means in Table 4.3 is consistent with this line of argument; 14% of parcels in the "before" group had mixed crops while 12% of the "after" group had them.

In sum, the comparisons in Table 4.3 suggest that irrigated acreage and water use may rise following a conversion from center pivot to center pivot with drop technology. If there is an increase in water use, this might be partly explained by the increase in irrigated acreage and a tendency to eliminate mixed cropping plans once a more efficient technology is installed. However, farmers do not appear to plant a higher proportion of water intensive crops, on

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[5] In order to increase irrigated acreage, an end-gun or corner-watering-device would also have to be added during the technology conversion. Alternatively, if the original system did not irrigate a full-circle, additional acreage might be added by increasing the arc of coverage.

average, after the conversion. Further, the increases in irrigated acreage might simply reflect underlying trends rather than the technology switch per se.

We can get some indications of the underlying trends by comparing the variable means during an "early" and "late" period in the data, for a sub-sample where technology remained constant. Table 4.4 provides such a comparison for that group of producers with either center pivot technology or center pivot with drop technology during the entire study period. Here "early" refers to the period 1996-1999, while "late" refers to 2000-2003. Due to the arbitrary nature of these categories, the columns in Table 4.4 are not directly comparable to those in Table 4.3, but the direction of movement does provide an indication of the trends present.

Table 4.4 Before and After Comparison for PDIVS with Any Type of Center Pivot that Did Not Convert to Drop Nozzles

	Early	Late	Increase	Statistically Significant
Irrigated Acres	149.17	154.53	3.59%	Yes
Acre-Feet Pumped	147.14	187.78	27.62%	Yes
Proportion of High Water Use Crops	0.24	0.34	40.10%	Yes
Proportion of Mixed Crops	0.09	0.12	28.69%	Yes

All statistically significant mean comparisons had *p*-values less than 0.01.

Table 4.4 suggests that there is indeed an underlying trend toward increased irrigated acreage and increased water use. In fact, the increases in Table 4.4 are both larger in percentage terms than the corresponding changes in Table 4.3, suggesting that technology adoption may have actually slowed these trends. More rigorous testing of these hypotheses can only be conducted in a regression framework, which will be presented in chapter 5. Interestingly, those with the same technology had large increases in the proportions of high-water use crops and mixed crops, compared to the small decreases in both categories in Table 4.3. This supports the hypothesis that producers who convert from center pivots to drop nozzles technology, are doing so in an attempt to maintain current cropping practices, possibly due to limited water availability.

Another striking difference between the tables is that the magnitude of the high water use crop proportions are much lower for the group with no technology change (0.24 – 0.34 versus 0.71 – 0.73). A possible explanation for this difference is that in nearly depleted areas of the aquifer, where low-water use crops are likely to dominate, there is little incentive to switch technology. With limited water availability, a more efficient system will not generate enough additional income to recoup the capital cost.

Analysis of Flood to Center Pivot Conversions

Tables 4.5 and 4.6 are similar to 4.3 and 4.4, except that they consider the conversion from flood to center pivot technology. The statistics in Table 4.6 are calculated from the sub-sample of producers who maintained flood technology during the entire period. The comparison suggests that both groups increased irrigated acreage, however, the group that converted to center pivots increased substantially more. Both groups increased the acreage of water intensive crops; however the group that converted had a mean difference that was not significant at the 90% level. The group that converted reduced the proportion of mixed crops grown while the flood irrigators that did not convert increased the proportion of mixed crops grown. These findings suggest that producers who convert from flood irrigation to center pivot irrigation may do so in an endeavor to increase irrigated acreage as well as to avoid the irrigation of a mixed crop scheme.

Table 4.5 Before and After Comparison for PDIVS that Converted from Flood to Center Pivot Technology

	Before	After	Increase	Statistically Significant
Irrigated Acres	114.84	130.22	13.39%	Yes
Acre-Feet Pumped	134.97	147.37	9.18%	Yes
Proportion of High Water Use Crops	0.50	0.52	3.28%	No
Proportion of Mixed Crops	0.24	0.19	-18.92%	Yes

All statistically significant mean comparisons had p-values less than 0.01.

Table 4.6 Before and After Comparison for PDIVS with Flood Technology that Did Not Convert to Center Pivot Technology

	Early	Late	Increase	Statistically Significant
Irrigated Acres	149.17	154.53	3.59%	Yes
Acre-Feet Pumped	147.14	187.78	27.62%	Yes
Proportion of High Water Use Crops	0.24	0.34	40.10%	Yes
Proportion of Mixed Crops	0.09	0.12	28.69%	Yes

All statistically significant mean comparisons had p-values less than 0.01.

CHAPTER V – DATA ANALYSIS: REGRESSION

This chapter presents our regression analysis. The purpose of this analysis is to determine the effects of various causal factors, including technology adoption, on *NBU*. The results allow us to isolate the impact of technology while controlling for other factors that also affect water use.

Model Specification

The engineering literature suggests that *NBU* might increase as the soil becomes sandy, the slope increases, as a sprinkler package pressure increases, when sprinklers are located above the center pivot truss or below the crop canopy, when the instantaneous application rate exceeds the infiltration rate as is the case with large center pivots, and in the case of flood irrigation. The economic literature suggests that *NBU* will decrease as water becomes scarcer and as the marginal cost of water increases, and increase as the marginal value product of the crop increases. This would suggest that as fuel prices rise or the depth to water increases, *NBU* will decline; as crop prices increase *NBU* will increase; as the total volume of water in storage increases, as measured by the saturated thickness, *NBU* might increase; and as rainfall increases the supply of water, *NBU* might increase. Due to increased awareness of declining aquifer levels coupled with improved water management tools we would expect, that over time, *NBU* would decrease.

With the above definitions and relationships in mind, a statistically fitted model of non-beneficial groundwater use can be defined as

$$\begin{aligned} NBU = \beta_0 + \beta_1 Time + \beta_2 Acres + \beta_3 Acres^2 + \beta_4 CP + \beta_5 Flood + \beta_6 Slope + \\ \beta_7 Clay + \beta_8 SCI + \beta_9 ST + \beta_{10} DTW + \beta_{11} CRP + \\ \beta_{12} FP + \sum_{i=13}^{16} \beta_i GMD + \beta_{17} P \end{aligned} \tag{9}$$

The explanatory variables on the right-hand side of (9) can be divided into six categories. The first category includes just one variable, *Time*. This measures a time trend (*Time*= 1996, …., 2003) and captures the impact of changing producer management. *Time* will have a negative effect on *NBU* (implying that $\beta_1 < 0$) if farmers improved management to increase irrigation efficiency during the study period.

The second group of variables includes parcel-specific attributes from the WIMAS data. *Acres* is the size of the irrigated parcel, measured in acres irrigated; it will likely have a negative impact on *NBU* because as irrigated acreage increases the same amount of water pumped will be spread over a larger area, thereby increasing crop *ET* and reducing drainage. The inclusion of the $Acres^2$ variable allows the effect of crop acreage to be non-linear. *CP* is a binary variable which is equal to one if the irrigation system was a center pivot and zero otherwise, while *Flood* is a binary variable which is equal to one if flood technology was used and zero otherwise. The signs of the coefficients on these variables, β_4 and β_5, are the empirical questions at the core of this study: they indicate the impacts of flood and center pivot technology on *NBU* relative to center pivot with drop technology. For example, if β_4 is positive (negative), then a center pivot system results in more (less) *NBU* compared to a center pivot with drops system, all else equal.

Soil characteristics are the third group of variables. *Slope* is the percent slope of the parcel, while *Clay* represents the percent of clay in the soil, and *SCI* represents the interaction between these two variables (i.e., $SCI = Slope \times Clay$). These soil attributes affect *NBU* by influencing the speed of runoff and drainage; more runoff or drainage would increase *NBU*.

Fourth are the hydrologic attributes, *DTW* and *ST*. *DTW* is the depth to the static water level and *ST* is the saturated thickness of aquifer. As noted above, economic principles predict that *NBU* would decline as the resource becomes scarcer, because scarcity enhances the incentive to improve efficiency. As such, *DTW* and *ST* would be expected to have negative and positive impacts on *NBU*, respectively.

The fifth group includes the prices affecting the producers' economic incentives to save water, specifically the prices of crops, *CRP*, and fuel, *FP*. Economic arguments suggest that *NBU* would respond positively to an increase in crop prices and negatively to an increase in the fuel price.

The final category captures climatic differences across regions. Season-long precipitation, *P*, is expected to positively impact *NBU* because some fraction of rainfall is always lost to runoff and deep drainage. Because *NBU* is likely to differ by region even after controlling for all of the above factors, a series of binary variables representing different groundwater management districts (*GMD*) have been included in the model. The groundwater management district with the most observations, on a per crop basis, will serve as the default *GMD*.

Because of biological differences, the shape of the *NBU* function is certain to differ across crops. To allow for the parameter estimates to vary by crop, the above described model will be estimated separately for each crop.

Estimation Procedures

In order to estimate the benefits associated with a cost share contract, the purpose of this model is to estimate the change in *NBU* associated with various technologies. The development of the above described model, its functional form, and the choice of variables was based on iterative out-of-sample testing. The model described above yielded the best out-of-sample fit and least bias to the predicted dependent variable. While the model includes a variety of variables, these variables were included in order to avoid omitted variable bias, thus ensuring the least bias on parameter estimates for the technology variables. As a general rule, parameter estimates on non-technology variables will not be discussed below.

The reader is cautioned against placing too much emphasis on the parameter estimates for the groundwater management district binary variables. Evapotranspiration data were available for only the three KSU experiment stations in western Kansas. The application of these estimates to surrounding counties could very well bias the parameter estimates on these binary variables, and should be interpreted with caution. Additionally, alfalfa is a perennial, and different than corn or soybeans, as it responds to more water through the growing season with more growth. As a result, parameter estimates for the alfalfa models should be interpreted with caution. Finally caution is recommended when interpreting parameter estimates on the intercepts in all models, as this parameter will shift based on how evapotranspiration and season-long rainfall are calculated. While different methods of calculating evapotranspiration and season-long rainfall impact the intercepts, the other parameter estimates remain fairly robust to different calculation methods.

The above described model was estimated on four distinct samples of data for each crop. These four samples, labeled Group 1 – Group 4 in what follows, are evaluated because there was insufficient data to analyze only those producers that participated in the cost share program and could be matched to an exact point of diversion. Group 1 (N = 7,853) consists of all observations in the original WIMAS sample. This group includes both those producers who changed technology during the sample period as well as those who did not. Group 2 (N = 4,791) consists of only those observations with a change in technology during the sample period. Group 3 (N = 731) consists of those observations that had a technology change during the sample period and were spatially located in a section where a cost share contract occurred. Group 4 (N = 359) consists of the individual technology adopters that were matched from both the SCC and WIMAS data set.[6]

To construct crop-specific datasets for estimation, the yearly records corresponding to the four major irrigated crops in western Kansas (corn, alfalfa, soybean, and grain sorghum) were extracted from each group. Thus there are a total of 16 possible regression models (i.e., 4 crops in each of the 4 groups). However, as described in more detail below, we do not have sufficient data to estimate all models. Tables B.6 – B.9 provide the summary statistics, on a crop basis, for the model variables.

Results

Table 5.1 provides the parameter estimates for the four crop models based on the entire sample data set (Group 1). These results are the most general and broadest estimates of how model variables impact non-beneficial water use. Note first that the estimated parameters on the *Time* variable are negative and statistically significant for all crops. This indicates that *NBU* has decreased over time, or equivalently that irrigation efficiencies have increased holding all else constant. This finding is consistent with Golden (2005).

To clarify the interpretation of the estimates for the *CP* and *Flood* variables, recall that the model (equation (9)) defines center pivot with drop technology is the "base" group. As such, a positive estimate on the *CP* variable, for example, indicates that a center pivot system results in more *NBU* compared to the center pivot with drops system, all else equal. The results in Table 5.1 suggest there is little difference in *NBU* between center pivots and center pivot with drop technology. For corn, center pivot technology is estimated to have less *NBU* than center pivot with drop technology, although this effect is very small in magnitude (about 0.14 acre-inches per acre). For soybeans and sorghum, *NBU* with center pivots is larger than with center pivots with drops (by 0.436 inches and 0.029 inches, respectively), although the effects are again small and

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[6] N is the number of unique PDIV in the data set. This number will not match with statistics based on the number of yearly observations. Each unique PDIV may have as many as eight yearly observations.

statistically insignificant in the case of sorghum. These findings are consistent with Rogers et al. (1997) and Lamm (2004).

With the exception of alfalfa, flood technology is estimated to result in more *NBU* than center pivot with drop technology. The large negative coefficient on the *Flood* variable for alfalfa may have arisen because of the biological differences between alfalfa and the other crops. Because alfalfa is a perennial plant with significantly deeper roots, it may capture much of the deep percolation that would be lost by the other crops. For the most part, parameter estimates on the remaining variables are consistent with prior expectations.

Table 5.1 Group 1: Parameter Estimated for All Crop Models

Variable	Corn	Soybeans	Alfalfa	Sorghum
Intercept	-1.760***	1.443*	-26.178***	-1.852
Time	-0.620***	-0.557***	-0.870***	-0.475***
Acres	-0.008***	-0.010*	-0.004	-0.013
Acres^2	0.000***	0.000	0.000***	0.000
CP	-0.144*	0.436**	-0.043	0.029
Flood	1.518***	0.714*	-2.191***	0.182
Slope	0.176***	0.281***	-0.092**	0.032
Clay	-0.030***	-0.057***	-0.143***	-0.072
SCI	-0.004***	-0.011**	0.004	0.005
ST	0.011***	0.004***	0.009***	0.007***
DTW	0.010***	0.005**	0.006***	0.003
CRP	0.242***	-0.323***	NI	0.966***
FP	0.085	0.621***	-1.015***	0.283***
GMD1	1.494***	0.205	0.016	-1.224
GMD2	-0.971***	-0.113	-9.483***	-1.803
GMD3	1.699***	1.548***	NI	NI
GMD4	0.852***	-0.416	-1.651***	-0.990***
GMD5	NI	NI	-6.894***	0.177
P	0.681***	0.707***	1.018***	0.784***
RMSE	4.167	3.725	5.088	4.653
R^2	0.50	0.480	0.637	0.497
N	19192	3050	4367	840

*significant at the 90% confidence level
** significant at the 95% confidence level
*** significant at the 99% confidence level
Each observation represents a single PDIV for a single year.

In order to more closely focus on the group of producers who converted from center pivot technology to center pivot with drop technology, the above described models were estimated for Group 2. Table 5.2 provides the parameter estimates for the four crop models based on this sub-sample. Once again the model suggests that *NBU* has declined over time for this group of producers. The parameter estimates on the *CP* binary variable are consistent with parameter estimates from Group 1. For corn, center pivots are estimated to result in less *NBU* than center pivot with drop technology, but by a slight and statistically insignificant margin.

Table 5.2 Group 2: Parameter Estimated for All Crop Models (Conversion from Center Pivot to Center Pivot with Drop Technology)

Variable	Corn	Soybeans	Alfalfa	Sorghum
Intercept	-0.469	2.269**	-26.021***	4.758
Time	-0.603	-0.588***	-0.895***	-0.531**
Acres	-0.014***	-0.007	0.004	-0.025
Acres^2	0.000***	0.000	0.000***	0.000
CP	-0.173	0.588***	0.025	1.032
Slope	0.165*	0.270***	-0.091**	-0.299
Clay	-0.039***	-0.066***	-0.135***	-0.203***
SCI	-0.002***	-0.007	0.013***	0.023
ST	0.010*	0.003**	0.008***	-0.001
DTW	0.008***	0.006**	0.004**	0.008
CRP	0.148***	-0.447***	NI	0.813**
FP	0.002**	0.603***	-0.947***	0.250
GMD1	1.778	0.775	-1.986**	-6.669***
GMD2	-1.180***	-0.293	-11.264***	-1.757
GMD3	2.188***	1.706***	NI	NI
GMD4	0.935***	-0.560	-2.800***	0.425
GMD5	NI	NI	-7.373***	-0.505
P	0.681***	0.702***	0.986***	0.674***
RMSE	3.892	3.584	4.898	4.526
R^2	0.538	0.508	0.647	0.497
N	14622	2457	3591	342

*significant at the 90% confidence level
** significant at the 95% confidence level
*** significant at the 99% confidence level
Each observation represents a single PDIV for a single year.

In order to more closely focus on the group of producers who converted from flood technology to any type center pivot technology, the corn model was estimated for Group 2. There was insufficient data to estimate the model for the other crops. Table 5.3 provides the parameter estimates for the corn model based on this sub-sample. Consistent with the findings above, this model suggests that over time this group of producers has decreased *NBU*. The parameter estimates on the flood binary variable are consistent with parameter estimates from Group 1. For corn, flood technology results in more *NBU* than center pivots with drops, by approximately 2.5 acre inches per acre.

Table 5.3 Group 2: Parameter Estimated for the Corn Model (Conversion from Flood to Any Center Pivot Technology)

Variable	Corn
Intercept	-6.830***
Time	-0.627***
Acres	-0.001
Acres^2	0.000*
Flood	2.544***
Slope	0.226
Clay	0.016
SCI	-0.007
ST	0.020***
DTW	0.015***
CRP	0.593**
FP	0.482**
GMD1	1.909***
GMD2	5.333*
GMD3	0.297
GMD4	1.322*
P	0.696
RMSE	5.083
R^2	0.433
N	1450

*significant at the 90% confidence level
** significant at the 95% confidence level
*** significant at the 99% confidence level
Each observation represents a single PDIV for a single year.

Group 3 is comprised of producers who changed technology during the study period and whose points of diversion are located in a PLSS section where a SCC cost share contract was funded. Table 5.4 provides the parameter estimates for the corn, soybean, and alfalfa model for this sample of producers. There was insufficient sample size to estimate the grain sorghum model or include the binary variable for flood irrigation. The estimates on the *CP* variable suggest that center pivots result in slightly more *NBU* than center pivots with drops, although this finding is not statistically significant.

Table 5.4 Group 3: Parameter Estimates for Crop Models (Conversion from Center Pivot to Center Pivot with Drop Technology)

Variable	Corn	Soybeans	Alfalfa
Intercept	1.789	-2.630	-37.615***
Time	-0.646***	-0.589***	-0.989**
Acres	-0.018*	0.024	-0.022
Acres^2	0.000	0.000	0.000
CP	0.161	0.538	1.148
Slope	0.311***	0.394**	-0.065
Clay	0.014	0.004	-0.106
SCI	-0.025***	-0.022	-0.042
ST	0.011***	0.000	0.023**
DTW	0.010***	0.007	0.073***
CRP	-0.506**	-0.284	NI
FP	-0.058	0.679*	-1.013
GMD1	5.252***	2.316	7.385**
GMD2	-5.111***	-3.667	NI
GMD3	2.097***	3.364**	NI
GMD4	1.478**	-0.691	NI
GMD5	NI	NI	5.976*
P	0.688***	0.729***	0.868***
RMSE	3.853	3.487	4.924
R^2	0.569	0.613	0.731
N	1660	352	262

*significant at the 90% confidence level

** significant at the 95% confidence level

*** significant at the 99% confidence level

Each observation represents a single PDIV for a single year.

Group 4 is comprised of producers who changed technology on a parcel matching the legal description of an SCC cost share contract. Table 5.5 provides the parameter estimates for the corn model for the sample of producers in this group who converted from center pivot to center pivot with drop technology. There was insufficient sample size to estimate models for other crops. The parameter estimate on the *CP* variable suggests that center pivots result in approximately 0.8 inches more *NBU* relative to center pivots with drops, and this estimate is statistically significant.

Table 5.5 Group 4: Parameter Estimates for the Corn Model (Conversion from Center Pivot to Center Pivot with Drop Technology)

Variable	Corn
Intercept	0.476
Time	-0.487***
Acres	-0.002
Acres^2	0.000**
CP	0.816***
Slope	0.243***
Clay	0.011
SCI	-0.029***
ST	0.010***
DTW	0.009***
CRP	-0.459*
FP	-0.193
GMD1	5.220***
GMD2	-4.808***
GMD3	2.544***
GMD4	2.168***
P	0.687***
RMSE	3.720
R^2	0.581
N	1133

*significant at the 90% confidence level
** significant at the 95% confidence level
*** significant at the 99% confidence level
Each observation represents a single PDIV for a single year.

Group 4 also consisted of producers who converted from flood technology to center pivot technology. The sample size for this group is very small, however, and the reader is cautioned against placing too much emphasis on the following discussion. Of the 369 producers who received cost share contracts, 48 conversions from flood were identifiable in the data set. Table 5.6 provides data on the means of selected variables for this group, based on before and after conversion. The data suggest that those producers in Group 4 converting from flood to center pivot technology reduced irrigated acres, reduced groundwater pumped, and increased the proportion of water intensive crops grown. However, only the increase in the proportion of water intensive crops grown was statistically significant.

Of the 48 producers identified, 33 grew corn both before and after conversion. Table 5.7 provides parameter estimates for this model. The model suggests that, for this group of producers, *NBU* under the flood system was 4.558 inches higher than under center pivots with drops. This finding is consistent with the results in Tables 5.1 and 5.3, both of which indicated that the flood system results in more *NBU* when corn is grown. However, the magnitude of this coefficient is much larger than in the previous models (the corresponding estimates from the previous models were 1.5 and 2.5, respectively). This unexpectedly large coefficient, combined with the small sample size used in estimation, call into question the statistical reliability of this model. That is, although the model depicts the behavior of the small number of producers in the sample, these few producers could be unrepresentative (and hence poor predictors) of the producer population. Rather than "throw out" this result, however, we will include it in our subsequent analysis, noting how our findings would be impacted if it were ignored.

Table 5.6 Group 4: Selected Means, by Time Period, for Corn Producers Converting from Flood to Center Pivot Technology

	Before	After	Difference
Irrigated Acres	155.42	140.88	-14.53
Acre-Inches of Groundwater Use	14.66	13.90	-0.76
Proportion of Water Intensive Crops	0.33	0.54	0.21^{***}

*significant at the 90% confidence level
** significant at the 95% confidence level
*** significant at the 99% confidence level

Table 5.7 Group 4: Parameter Estimates for the Corn Model (Conversion from Flood to Center Pivot Technology)

Variable	Corn
Intercept	-3.336
Acres	-0.002
Acres^2	0.000
CP	-4.558^{***}
ST	0.008
DTW	-0.001
CRP	-0.532
FP	-0.370
GMD1	4.063
GMD3	7.827^{*}
GMD4	5.409^{*}
GMD5	4.730
P	0.836^{***}
RMSE	5.298
R^2	0.480
N	111

*significant at the 90% confidence level
** significant at the 95% confidence level
*** significant at the 99% confidence level

Summary of Estimated Changes in *NBU*

Table 5.8 summarizes the main findings of the analyses in this chapter. The regression analyses above produced similar results regarding the effects of different technologies on *NBU*, but of course they are not numerically identical. Taken together, these various regression models give us ranges of the estimated reduction in *NBU* from the technology changes of interest. The top portion of the table presents the ranges, by crop, for conversions from center pivot to center pivot with drops. These ranges are quite consistent across crops in that the midpoint of each range is in the neighborhood of 0.5 acre inches per acre. Thus, it appears a one-half inch reduction in *NBU* is a rather robust estimate of the average effect of this type of technology switch. The extremes of the ranges differ across crops, however, with the range for soybeans being considerably narrower than those for the other crops. For corn and alfalfa, the range includes negative values, implying that some producers would actually increase *NBU* in response to the installation of drop nozzles.

Table 5.8. Summary of Estimated Ranges in *NBU* Reduction

	Estimated *NBU* Reduction (acre-in/acre)	
Crop	Low	High
Conversions from center pivot to center pivot with drops		
Corn	- 0.18	0.82
Soybean	0.44	0.59
Alfalfa	- 0.04	1.15
Sorghum	0.03	1.03
Conversions from flood to center pivot		
Corn	1.52	4.56
Soybean	0.71	0.71
Alfalfa	- 2.19	- 2.19
Sorghum	0.18	0.18

* Small sample result; represents only Group 4 corn producers converting from Flood to Center Pivot. If this result were ignored, the value in this cell would be -1.52.

The estimated ranges for conversions from flood to center pivot, in the bottom of the table, are far less consistent across crops. For soybean, alfalfa, and sorghum, data were sufficient for estimation in only one model (Table 5.1). Consequently, the ranges for all crops except corn collapse to the single value from this regression. Data for corn were far more plentiful, so the range for corn reflects the result in Table 5.1 as well as the results from Tables 5.3 and 5.7. The resulting range for corn is very wide (1.52 – 4.56 inches). As noted above, however, the upper end of this range is based on a small sample regression (Table 5.7), and one could debate whether this result should be ignored. If it were ignored and the range were computed from the remaining regressions with larger samples, the resulting range would be 1.52 to 2.54. This range would predict that *NBU* on corn would decrease by about 2 acre inches, plus or minus 0.5 acre inch, from a conversion from flood to center pivot. For soybean and sorghum, there is a smaller estimated reduction in *NBU*, and the value for sorghum was not statistically different from zero (Table 5.1). In stark contrast to the other crops, *NBU* was actually estimated to increase on alfalfa. The deep rooting pattern of alfalfa likely allows it to avoid almost all losses due to deep drainage; *NBU* would then rise as a result of converting from flood to center pivot, because new losses, in the form larger *PAE*, would be introduced.

CHAPTER VI – EVALUATION OF THE SCC COST SHARE PROGRAM

This chapter presents the final portion of our analysis. Based on the results in previous chapters, the cost efficiency of the SCC cost share program is evaluated. In particular, for each contract in the SCC dataset, we estimate the reduction in *NBU* due to the contracted technology switch using the regression results from chapter 5 and the mean acreage changes from chapter 4. The SCC dataset also includes the amount of public funds invested in each contract, allowing us to compute the estimated *NBU* reduction per taxpayer dollar invested.

By averaging the computed cost efficiency values across all contracts supporting a particular type of technology upgrade, we estimate the overall cost efficiency of the taxpayer funds invested in each type of conversion (flood to center pivot and center pivot to center pivot with drops). As noted in chapter 5, our various regression models produce a range of estimated *NBU* reductions from each type of technology upgrade, rather than a single value. Using the extremes of these ranges, as reported in Table 5.8, we develop and report both a "best case" and a "worst case" scenario for each type of technology change. To put our results in context, we also estimate the cost efficiency of a water right buyout program.

Additionally, we use our results to estimate one portion of producers' private benefits from technology changes: that of reduced water deliver costs. Producers may also benefit from reduced labor costs and increased crop yields, but these are beyond the scope of the current study.

Cost Efficiency of SCC Technology Investments

The regression analysis in chapter 5 allows us to estimate the change in *NBU* due to a technology change assuming a particular crop is grown (Table 5.8). However, we do not have reliable field-level data on the crop mix for each parcel receiving SCC funds, as many of them could not be linked to specific points of diversion in the WIMAS database. In the analysis that follows, we use the county-level shares of irrigated acreage planted to the various irrigated crops (based on KASS data) as an estimate of the crop mix on each parcel. In effect, our estimated *NBU* reductions are a weighted average of the crop-specific *NBU* changes from Table 5.8, where the county-level crop shares are the weights. The crop acreage shares used in our analysis are presented in Table 6.1.

As noted above, we develop both best-case and worst-case scenarios that reflect the extremes of the estimated *NBU* ranges. In both scenarios, we assume no change in crop mix after a technology upgrade, as the categorical means in chapter 4 suggest little or no change in this regard (Table 4.3). The categorical means also suggest that irrigated acreage does not change in response to conversions from center pivots to center pivots with drops, but that irrigated acreage increases by 13%, on average, due to conversions from flood to center pivot conversions (Table 4.5). On the other hand, for the flood to center pivot conversions in group 4 (the sub-sample of SCC contracts that could be matched to an exact WIMAS observation), irrigated acreage decreased by 14.5 acres or 9% (Table 5.6). Accordingly, for conversions from center pivots to center pivots with drops, we assume no change in irrigated acreage in both the best- and worst-case scenarios. For flood to center pivot conversions, however, the best-case scenario assumes a

Table 6.1 County Crop Mix Used in Cost-Benefit Analysis

County	Alfalfa	Corn	Sorghum	Soybean
Barton	0.16	0.54	0.08	0.21
Cheyenne	0.07	0.83	0.02	0.08
Decatur	0.10	0.81	0.03	0.06
Edwards	0.14	0.66	0.02	0.19
Finney	0.42	0.52	0.02	0.03
Ford	0.06	0.79	0.06	0.09
Grant	0.28	0.63	0.08	0.01
Gray	0.27	0.66	0.03	0.04
Greeley	0.03	0.92	0.04	0.00
Haskell	0.02	0.95	0.00	0.02
Kearny	0.57	0.41	0.01	0.01
Kiowa	0.07	0.66	0.02	0.25
Meade	0.10	0.84	0.05	0.02
Morton	0.11	0.47	0.38	0.04
Norton	0.10	0.81	0.05	0.05
Pawnee	0.26	0.47	0.05	0.22
Pratt	0.04	0.77	0.02	0.17
Rawlins	0.16	0.74	0.05	0.05
Reno	0.05	0.54	0.06	0.36
Scott	0.04	0.80	0.16	0.01
Seward	0.25	0.65	0.04	0.07
Sheridan	0.03	0.90	0.02	0.04
Sherman	0.05	0.89	0.02	0.05
Stafford	0.07	0.70	0.01	0.22
Stanton	0.19	0.77	0.04	0.00
Stevens	0.07	0.90	0.02	0.01
Thomas	0.02	0.90	0.02	0.07
Wallace	0.09	0.87	0.03	0.01
Wichita	0.03	0.79	0.15	0.03

9% reduction in irrigated acreage following the technology change, while the worst-case scenario assumes a 13% increase.

Table 6.2 provides our cost-efficiency estimates for conversions from center pivots to center pivots with drops. In the best case scenario, the State achieved an annual reduction in *NBU* of 0.85 inches per acre from an average contract. Assuming a technology life of 15 years, this implies an average cumulative *NBU* reduction of 12.75 acre inches per acre. Given the average cost of $15.51 per acre, this implies a cost of $1.22 per acre inch (or equivalently, the State obtained 0.82 acre inches of *NBU* reduction per taxpayer dollar invested). In the worst case scenario, the cumulative *NBU* reduction is actually negative on average, implying that the average contract resulted in an *increase* in cumulative *NBU* of 1.2 acre inches per acre. The resulting cost is -$27.61 per acre inch, or, put differently, *NBU* increased by an estimated 0.08 acre inches for every dollar invested in the program.

Table 6.2 Estimated Cost Efficiency of SCC Investments in Center Pivot Conversion to Drop Nozzles

					Best Case		Worst Case	
County	N	Irrigated Acres	Public Investment	Investment/ Irrigated Acre	Annual *NBU* Reduction	Cost/unit (cumulative)	Annual *NBU* Reduction	Cost/unit (cumulative)
			$	$/acre	acre-inches	$/acre-in	acre-inches	$/acre-in
Barton	6	761	10,217	13.43	0.84	1.07	-0.01	-167.80
Cheyenne	26	3322	50,597	15.23	0.83	1.23	-0.11	-9.43
Decatur	15	1107	18,089	16.34	0.84	1.30	-0.11	-9.68
Edwards	106	13854	214,274	15.47	0.82	1.25	-0.04	-28.55
Finney	27	3512	84,787	24.14	0.95	1.69	-0.09	-17.46
Ford	23	2964	35,193	11.87	0.83	0.95	-0.10	-8.16
Grant	12	1482	30,739	20.74	0.92	1.50	-0.11	-12.39
Gray	49	5889	98,160	16.67	0.90	1.23	-0.11	-10.41
Greeley	2	249	5,186	20.83	0.83	1.66	-0.16	-8.93
Haskell	12	1718	35,255	20.52	0.82	1.67	-0.16	-8.82
Kearny	17	3311	44,112	13.32	1.00	0.88	-0.09	-10.10
Kiowa	57	7309	100,952	13.81	0.79	1.17	0.00	-209.79
Meade	5	610	14,995	24.58	0.85	1.92	-0.14	-12.07
Morton	6	996	19,122	19.20	0.93	1.38	-0.06	-22.45
Norton	2	105	2,664	25.32	0.85	1.99	-0.12	-14.35
Pawnee	29	3337	32,194	9.65	0.86	0.75	0.01	117.79
Pratt	39	4788	44,618	9.32	0.79	0.78	-0.06	-11.06
Rawlins	9	747	13,427	17.98	0.87	1.38	-0.11	-11.05
Reno	10	1251	11,751	9.40	0.76	0.82	0.06	9.76
Scott	13	1865	25,445	13.64	0.86	1.06	-0.13	-6.99
Seward	16	2791	46,358	16.61	0.89	1.24	-0.09	-12.29
Sheridan	13	1564	32,165	20.57	0.82	1.67	-0.14	-10.09
Sherman	31	3879	68,647	17.70	0.82	1.43	-0.13	-8.92
Stafford	38	4863	45,677	9.39	0.79	0.79	-0.03	-23.33
Stanton	2	256	6,326	24.71	0.89	1.85	-0.14	-11.94
Stevens	35	5757	102,189	17.75	0.84	1.40	-0.15	-7.74
Thomas	23	2411	35,689	14.80	0.81	1.22	-0.12	-7.99
Wallace	22	2762	67,660	24.50	0.85	1.92	-0.15	-10.93
Wichita	2	248	2,000	8.06	0.85	0.63	-0.12	-4.55
Average	647	83708	1,298,487	15.51	0.85	1.22	-0.08	-27.61

Based on the crop mix in Table 6.1 and crop specific reductions in groundwater pumped in Table 5.8. Average is weighted by irrigated acres. Acre inches reduction is an annual estimate of the reduction in *NBU*. Cost per acre inch is based on an expected life of 15 years.

The estimated cost efficiency of the flood to center pivot contracts are in Table 6.3. In the best case scenario, the State achieved an annual average reduction of 4.84 inches per acre at a one-time average cost of \$17.62 per acre. This leads to an estimated average cost of \$0.25 per acre inch of *NBU* reduction over the 15 year period, or a cumulative *NBU* reduction of 4.56 acre inches per dollar invested. However, it is important to note that the magnitude of this result hinges on the regression results for corn producers in group 4, which, as explained in chapter 5, may be subject to small sample bias. If the small sample results were ignored and the best case scenario was re-calculated using the results from the remaining larger samples, the estimated *NBU* reduction would become a negative value.[7] In the worst case scenario, the average cumulative *NBU* reduction was negative, resulting in an estimated cost of -\$0.98 per acre inch of cumulative *NBU* reduction (or an *NBU increase* of 1.03 acre inches per dollar invested).

Table 6.4 summarizes our estimated ranges in cost efficiency. To put these results in context, Table 6.5 presents the estimated cost efficiency of a water right buyout program, an alternative public policy for reducing consumptive groundwater use. Recent research from land transactions sales from western Kansas (Golden, 2005) suggests that the fair market value of a typical water right would be in the neighborhood of \$800 per irrigated acre. Accordingly, the analysis in the table assumes that taxpayers would have to spend \$800 to retire one water right. It also assumes that the seller of the water right would have diverted 18 acre-inches per acre of groundwater as consumptive use (*CU*) for the next 50 years, implying the retirement would reduce consumptive use by a cumulative total of 900 acre inches. On a per unit basis, taxpayers would then obtain 1.125 inches of *CU* reduction per dollar invested.

Although changes in *CU* and *NBU* are not equivalent (chapter 2), these results suggest that cost sharing for conversions from center pivots to center pivots with drops do not compare favorably to water-right buyouts in terms of cost efficiency. For this type of cost sharing, even the best case scenario lies below the estimated *CU* reduction from a water right buyout. Here, of course, the policy goal is presumed to be one of reducing net water use at the lowest cost to taxpayers. For conversions from flood to center pivot, the reported best case estimate is relatively high (4.84 acre inches per dollar), but relies on results obtained from a small sample size. As discussed above, if the small sample regression were ignored, the best case estimate would be a negative value.[8]

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[7] An "alternative best case" scenario was computed using the *NBU* reductions from the regressions in Tables 5.1 and 5.3. These remaining larger sample results gave us a smaller *NBU* reduction for corn (2.54 inches) but did not affect the reductions for the other crops. Additionally, irrigated acreage in this scenario was assumed to increase by 13%, as the 9% decrease was obtained form the same small sample (indeed, the 9% estimate was not statistically significant even in this sample—see Table 5.6). The resulting cost efficiency estimate was –0.20 acre inches of *NBU* reduction per dollar invested.

[8] Further, there are other reasons to believe the estimated *NBU* reduction for this type of conversion are inflated. First, as discussed in chapter 2, the estimated reduction in *NBU* from this type of conversion is likely to be an over-estimate of the reduction in *CU*, which is the policy relevant variable. Second, the calculations in table 6.4 assume that the producer would continue using flood technology for the entire 15 years if cost share funds were not available. Recent research by Ding (2005) suggests that cost share programs only induce flood irrigators to upgrade to center pivot systems 2 or 3 years earlier than otherwise.

Table 6.3 Estimated Cost Efficiency of SCC Investments in Flood to Center Pivot Conversions

					Best Case		Worst Case	
County	N	Irrigated Acres	Public Investment	Investment/ Irrigated Acre	Annual *NBU* Reduction	Cost/Unit (cumulative)	Annual *NBU* Reduction	Cost/unit (cumulative)
			$	$/acre	acre-inches	$/acre-in	acre-inches	$/acre-in
Barton	8	782	18,617	23.81	4.10	0.39	-1.51	-1.05
Decatur	9	573	19,706	34.39	5.20	0.44	-1.09	-2.11
Edwards	5	650	14,890	22.91	4.60	0.33	-1.31	-1.16
Finney	26	3918	85,441	21.81	3.87	0.38	-2.25	-0.65
Ford	9	1315	30,295	23.03	5.12	0.30	-1.02	-1.51
Grant	19	4218	62,310	14.77	4.34	0.23	-1.79	-0.55
Gray	14	1820	30,715	16.88	4.52	0.25	-1.69	-0.67
Greeley	8	1301	31,172	23.96	5.69	0.28	-0.81	-1.98
Hamilton	8	1014	24,212	23.89	2.70	0.59	-3.00	-0.53
Haskell	44	8033	122,094	15.20	5.83	0.17	-0.74	-1.38
Kearny	14	1745	44,909	25.74	3.32	0.52	-2.76	-0.62
Meade	31	3940	100,988	25.63	5.31	0.32	-1.06	-1.61
Morton	14	2165	45,632	21.08	3.69	0.38	-1.58	-0.89
Norton	1	95	2,500	26.32	5.18	0.34	-1.09	-1.62
Pawnee	17	2042	41,671	20.40	3.77	0.36	-1.82	-0.75
Rawlins	5	366	8,738	23.89	4.89	0.33	-1.31	-1.21
Scott	20	4208	37,630	8.94	5.13	0.12	-0.99	-0.60
Seward	24	5715	91,596	16.03	4.48	0.24	-1.64	-0.65
Sheridan	11	1181	33,814	28.62	5.60	0.34	-0.82	-2.33
Sherman	4	373	9,538	25.57	5.56	0.31	-0.86	-1.99
Stafford	3	330	9,448	28.63	4.83	0.40	-1.06	-1.80
Stanton	30	6633	88,814	13.39	4.98	0.18	-1.39	-0.64
Stevens	10	1762	44,879	25.47	5.58	0.30	-0.93	-1.83
Thomas	9	998	19,202	19.24	5.62	0.23	-0.76	-1.68
Wallace	6	661	13,717	20.76	5.46	0.25	-1.02	-1.36
Wichita	25	5822	54,210	9.31	5.14	0.12	-0.95	-0.65
Average	374	61660	1086740	17.62	4.84	0.25	-1.35	-0.98

Based on the crop mix in Table 6.1 and crop specific reductions in groundwater pumped in Table 5,8. Average is weighted by irrigated acres. Acre inches reduction is an annual estimate of the reduction in *NBU*. Cost per acre inch is based on an expected life of 15 years.

Table 6.4 Estimated Taxpayer Cost of *NBU* Reductions

Item	Worst Case	Best Case
Conversions from center pivot to center pivot with drops		
Average investment per acre ($/acre)	15.51	15.51
Annual reduction in *NBU* (acre-inches/acre)	- 0.08	0.85
Cumulative *NBU* reduction, 15 yrs (acre-inches)	- 1.2	12.75
Cumulative *NBU* reduction per dollar invested	- 0.08	0.82
Conversions from flood to center pivot		
Average Investment per acre ($/acre)	17.62	17.62
Annual reduction in *NBU* (acre-inches/acre)	- 1.35	4.84*
Cumulative *NBU* reduction, 15 years (acre-inches)	- 20.25	72.60
Cumulative *NBU* reduction per dollar invested	- 1.15	4.12

* Based on small sample result

Table 6.5 Estimated Taxpayer Cost of Consumptive Use (*CU*) Reductions from Water-Right Buyouts

Item	Value
Average investment per acre ($/acre)	800
Annual reduction in *CU* (acre-inches/acre)	18
Cumulative *CU* reduction, 50 years (acre-inches)	900
Cumulative *CU* reduction per dollar invested	1.125

Another means of comparison comes from the estimated water savings on the cost share contracts themselves. As noted previously, each contract includes a "Benefits of Treatment" section where an estimate of the planned "water savings" from the conversion must be reported. The contracts do not specify whether this reported value refers to savings in water pumped, *CU*, or *NBU*. The imputed cost of water savings based on these estimates are in Tables 6.6-6.7. The average contract for center pivot to center pivot with drops conversions was estimated to result in 3.99 acre-inches per acre of water savings annually, implying a cost of $0.32 per cumulative acre-inch saved over the 15-year period. This is equivalent to an estimated cumulative water savings of 3.125 acre inches per dollar invested, a figure roughly four times larger than the best case scenario of estimated *NBU* savings. For flood to center pivot conversions, the contract estimates suggest an average cost of $0.16 per cumulative acre inch saved, or an average of 6.25 acre inches saved per dollar invested. This figure exceeds even our optimistic best case scenario of 4.84 acre inches of *NBU* savings per dollar invested. Although the interpretation of "water savings" is ambiguous in this analysis, the results suggest that planned water conservation benefits may not have been realized.

Table 6.6 Estimated Water Savings from Cost Share Contracts: Conversions from Center Pivots to Center Pivots with Drops

County	N	Irrigated Acres	Public Investment	Investment/ Irrigated Acre	Planned Annual Water Savings	Cost/Unit (cumulative)
			$	$/acre	acre-inches	$/acre-in
Barton	6	761	10,217	13.43	2.08	0.43
Cheyenne	26	3322	50,597	15.23	1.35	0.75
Decatur	15	1107	18,089	16.34	2.95	0.37
Edwards	106	13854	214,274	15.47	2.66	0.39
Finney	27	3513	84,787	24.14	7.22	0.22
Ford	23	2964	35,193	11.87	1.73	0.46
Grant	12	1482	30,739	20.74	25.48	0.05
Gray	49	5889	98,160	16.67	2.52	0.44
Greeley	2	249	5,186	20.83	11.01	0.13
Haskell	12	1718	35,255	20.52	3.95	0.35
Kearny	17	3311	44,112	13.32	7.25	0.12
Kiowa	57	7309	100,952	13.81	3.08	0.30
Meade	5	610	14,995	24.58	4.33	0.38
Morton	6	996	19,122	19.20	5.94	0.22
Norton	2	105	2,664	25.32	4.71	0.36
Pawnee	29	3337	32,194	9.65	4.04	0.16
Pratt	39	4788	44,618	9.32	2.47	0.25
Rawlins	9	747	13,427	17.98	4.86	0.25
Reno	10	1251	11,751	9.40	1.42	0.44
Scott	13	1865	25,445	13.64	4.68	0.19
Seward	16	2791	46,358	16.61	3.16	0.35
Sheridan	13	1564	32,165	20.57	5.11	0.27
Sherman	31	3879	68,647	17.70	6.08	0.19
Stafford	38	4863	45,677	9.39	2.59	0.24
Stanton	2	256	6,326	24.71	2.50	0.66
Stevens	35	5757	102,189	17.75	3.06	0.39
Thomas	23	2412	35,689	14.80	4.40	0.22
Wallace	22	2762	67,660	24.50	6.42	0.25
Wichita	2	248	2,000	8.06	0.95	0.57
Average	647	83708	1,298,487	15.51	3.99	0.32

Table 6.7 Estimated Water Savings from Cost Share Contracts: Conversions from Flood to Center Pivot

County	N	Irrigated Acres	Public Investment	Investment/ Irrigated Acre	Planned Annual Water Savings	Cost/unit (cumulative)
			$	$/acre	acre-inches	$/acre-in
Barton	8	782	18,617	23.81	6.86	0.23
Decatur	9	573	19,706	34.39	4.12	0.56
Edwards	5	650	14,890	22.91	8.39	0.18
Finney	26	3918	85,441	21.81	9.70	0.15
Ford	9	1315	30,295	23.03	12.31	0.12
Grant	19	4218	62,310	14.77	12.12	0.08
Gray	14	1820	30,715	16.88	5.72	0.20
Greeley	8	1301	31,172	23.96	3.51	0.46
Hamilton	8	1014	24,212	23.89	7.13	0.22
Haskell	44	8033	122,094	15.20	8.46	0.12
Kearny	14	1745	44,909	25.74	12.35	0.14
Meade	31	3940	100,988	25.63	4.94	0.35
Morton	14	2165	45,632	21.08	4.76	0.30
Norton	1	95	2,500	26.32	1.68	1.04
Pawnee	17	2042	41,671	20.40	6.67	0.20
Rawlins	5	366	8,738	23.89	6.20	0.26
Scott	20	4208	37,630	8.94	6.15	0.10
Seward	24	5715	91,596	16.03	13.35	0.08
Sheridan	11	1181	33,814	28.62	7.69	0.25
Sherman	4	373	9,538	25.57	13.95	0.12
Stafford	3	330	9,448	28.63	2.95	0.65
Stanton	30	6633	88,814	13.39	8.65	0.10
Stevens	10	1762	44,879	25.47	12.13	0.14
Thomas	9	998	19,202	19.24	11.79	0.11
Wallace	6	661	13,717	20.76	12.62	0.11
Wichita	25	5822	54,210	9.31	7.75	0.08
Average	374	61660	1086740	17.62	8.72	0.16

Private Benefits of New Technology: Reduced Pumping Cost

Although the public benefits in terms of groundwater conservation appear to be rather small, cost share programs do provide financial benefits to individual producers. As noted in chapter 1, these benefits may come in at least three forms: reduced pumping costs, reduced labor costs, and increased crop yields. Although changes in labor costs and yields are beyond the scope of this study, our results do allow us to estimate the change in pumping costs. A producer converting to drop nozzle technology will normally realize reduced pumping cost due to lower sprinkler package pressure requirements. The annual fuel cost savings (*AFCS*) can be defined as

$$(10) \qquad AFCS = \frac{(AAI)(0.114)(P_f)(\Delta TDH)}{(E_f)},$$

Where *AAI* is the average annual acre-inches of water pumped, E_f is the energy efficiency coefficient for the selected fuel expressed as the horsepower hours generated per volume of fuel, P_f is the price of fuel measured in dollars per volume of fuel, and ΔTDH is the change in total dynamic head resulting from the conversion measured in feet. Assuming an annual water usage of 16 inches, a pressure reduction of 10 psi, a natural gas price of $5.20 per million cubic feet, and on the energy efficiency coefficient of 58.6 yields an annual average savings of $4.72 per acre. The cost savings associated with the annual reduction in groundwater pumped of 0.85 inches per acre (our best case scenario) will depend upon the site specific depth to water. For our purposes this is estimated at $2.87.[9] Assuming a 15 year life yielded total savings of $113.95 per acre.

A producer converting from flood to center pivot technology will actually incur higher pumping cost per unit pumped due to increased head requirements, but pumping costs may fall if less water is pumped after the conversion. Using our best case scenario estimate (4.84 acre inches per acre) as a prediction of the reduction pumping, and assuming that pumping pressure increases by 20 psi, then the net fuel cost savings is $4.50 per acre or $66.76 per acre for the life of the technology. If water pumped remains constant, then pumping costs would increase by $9.44 per acre.

Chapter Summary

Based on the data analyses discussed in chapters 4 and 5, this chapter presented the estimated cost efficiency of the SCC technology cost-share contracts. For conversions from center pivot to center pivot with drops, each taxpayer dollar invested in the SCC program was estimated to result in -0.08 to 0.82 acre inches of cumulative *NBU* reduction over a 15 year period. For conversions from flood to center pivot, the estimated range was considerably wider: -1.15 to 4.12 acre inches of cumulative *NBU* reduction per dollar. However, the upper value of this range depends on a potentially unreliable regression result. If the result in question were ignored, the upper end of the range would be a negative value. These results indicate that, in at least some cases, the cost share program may have resulted in increased water use.

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[9] Based on KSU irrigation energy worksheet at www.agmanager.info.

In general, the estimated cost efficiency of the SCC investments do not appear to compare favorably to a water right buyout program. Based on recent research on the likely cost of such a program, a water right buyout was estimated to achieve about 1.125 acre inches of water savings per dollar invested. In addition, the estimated "water savings" reported on the SCC contracts themselves appear to be gross over estimates, in comparison to our estimated reductions in *NBU*.

While the water savings of technology cost share programs appear to be rather small, the new technologies have provided benefits to producers. For example, farmers converting from center pivots to center pivots with drops would observe a substantial reduction in pumping costs. Additionally, the engineering literature suggests that drop nozzle technology applies water more uniformly. The uniformity of water application should result in improved yields, although data limitations precluded quantifying the dollar value of this benefit in this study.

CHAPTER VII – CONCLUSIONS

This study has evaluated the effects of irrigation technology adoption on net groundwater use in western Kansas. We find that the effect differs by the type of technology adoption taking place and the crop being grown, and that net water use will decrease in certain cases but increase in others. Conversions from center pivot to center pivot with drops were estimated to reduce non-beneficial water use by about 0.5 acre-inches per irrigated acre, with an expected range of about zero to 1 acre-inch per acre. These are relatively small impacts; the upper end of the range represents about 5% of water pumped for a producer applying irrigation in the range of 18 inches.

The estimated water savings from flood to center pivot conversions were subject to more statistical uncertainty, with estimated reductions in non-beneficial use ranging from about –2.5 to 4.5 acre inches per irrigated acre, depending on the crop grown. Thus, conversions from flood would appear to save more water in certain cases, although in other cases water use may rise. It should also be noted that the upper end of the range depends on a potentially unreliable regression result that may not be representative of the producer population.

Our results suggest that previous estimates of irrigation efficiencies might be overstated. In the best case scenario, center pivot with drop technology is 5% more efficient than conventional center pivot technology. In a worst-case scenario, for corn, conventional center pivot technology is 1% more efficient than drop nozzle technology. Additionally, parameter estimates imply that, at best, center pivot technology is only 25% superior to flood technology. The majority of the parameter estimates would imply the center pivot technology is between 5% and 10% more efficient. Parameter estimates for flood irrigation on alfalfa imply that flood irrigation may be more efficient than center pivot technology.

The wide range of results for flood to center pivot conversions was probably due to variety of factors. In our study, the type of center pivot technology after the conversion (conventional versus drop nozzle) was not distinguished. It is likely that the change in non-beneficial use differs between these categories. We also had a relatively small number of data points where flood systems were converted, limiting our ability to obtain estimates for certain crops and, as noted, raising reliability concerns about same of the estimates we did produce.

Perhaps contrary to conventional wisdom, there is little evidence that irrigators switch to more water-intensive crops following a technology change. However, farmers do appear to increase acreage in the case of flood to center pivot conversions. Taken as a whole, our results imply that the number of acres irrigated is a more important determinant of changes in aquifer levels than the irrigation technology in use. That is, if irrigated acreage remained constant as new technology is adopted, net water use would increase in some cases and decrease in others, with little change on average. On the other hand, if irrigated acreage were to decline with constant technology, a reduction in net water use would be assured.

In this light, it is not surprising that technology cost-share programs were found to be less effective at reducing water use than retiring water rights. Nevertheless, these two policies would have very different economic impacts, the estimation of which is beyond the scope of this study. Among the various economic benefits of modern technologies, we were only able to estimate the reduction in pumping costs, and in the case of drop nozzle conversions the reduction in pumping costs alone was found to be substantial. In sum, the evidence from this study is that SCC cost share programs clearly benefited producers but had a relatively small impact on the rate of aquifer decline.

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APPENDIX A

Summary Statistics by Technology Adoption Group

This section provides several comparisons between the producers adopting technology sometime during the data period (usually the group labeled "Technology Change" in what follows) and those who did not adopt (labeled "No Technology Change"). To be clear, the "Technology Change" group reflects the data from all years in the sample, both before and after the technology change occurred. The purpose of these comparisons is to reveal any systematic differences in the observed variables in the dataset between producers who changed technology and those who did not.

Differences in Irrigated Acreage

Table A.1 compares the yearly mean irrigated acres between producers with and without a technology change. Over the period 1996 to 2003, neither group displayed a statistically significant tendency to either increase or decrease acres[10]. Based on a two sample t-test assuming equal variance (*p-value* < 0.001) and the Kolmogorov-Smirnov test (*p-value* < 0.001), the average producer changing technology irrigated approximately 20 acres more than the average producer with constant technology. A possible hypothesis would be that producers are adopting technology in order to maintain higher than average irrigated acreage.

Table A.1 Irrigated Acres by Technology Group, by Year

	No Technology Change			Technology Change		
Year	N	Mean	Standard Deviation	N	Mean	Standard Deviation
1996	1622	109.8	89.9	4546	135.8	62.3
1997	1643	112.1	89.9	4656	138.5	64.9
1998	1589	115.3	90.8	4705	140.5	72.6
1999	1606	122.9	95.3	4679	140.6	67.6
2000	1672	122.3	93.5	4682	141.2	68.4
2001	1668	122.1	92.1	4673	140.5	71.4
2002	1800	125.0	96.7	4645	140.1	74.6
2003	1851	121.5	94.2	4564	137.6	66.1

Table A.2 compares the yearly mean irrigated acres between those producers who changed technology based on type of conversion. Over the period 1996 to 2003, the group of producers who converted from center pivots to center pivot with drops displayed no statistically significant tendency to either increase or decrease acres (*p-value* on the trend variable parameter estimate =

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[10] Unless otherwise noted all statistical significance is based on alpha = 0.05.

0.543). The group who converted from flood to center pivots displayed a statistically significant trend to decrease acres (*p-value* on the trend variable parameter estimate = 0.002), while the group of producers that converted from flood to center pivot with drops displayed a statistically significant tendency to increase acres by approximately 6.4% over the study period (*p-value* on the trend variable parameter estimate = 0.098). While this is apparently contradictory evidence on how conversion from flood to center pivot impacts irrigate acreage, the difference in sample size would suggest that acreage increases.

Table A.2 Mean Irrigated Acres by Type of Conversion

Year	Center Pivot to Center Pivot with Drops	Flood to Center Pivot	Flood to Center Pivot with Drops
1996	138.194	133.013	115.647
1997	141.244	133.815	116.065
1998	143.268	128.086	118.812
1999	142.983	126.407	122.414
2000	143.448	125.476	125.914
2001	143.337	121.175	118.857
2002	141.998	124.962	123.729
2003	139.94	121.897	120.726

Differences in Water Use

Figure A.1 illustrates the trends in water use (acre-feet per acre) for the two technology groups during the study period. The reader is cautioned that these data are gross water pumped from the aquifer as reported to the Division of Water Resources and have not been adjusted to include rainfall. As the figure shows, the technology adopters used approximately 0.17 acre-feet more water compared to non-adopters. Based on a paired t-test this difference is statistically significant (*p-value* < 0.001) and suggests that technology adoption is systematically linked to higher levels of water use. The water use for both groups exhibit statistically significant upward trends during the data period, although the difference between the groups is diminishing from a statistical perspective.[11] Figure A.2 further delineates the trends in water use (acre-feet per acre) by the type of technology adopted.

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[11] However, little inference about changes in farmers' behavior can be made from the statistical significance in this case, as the data period is very short. The increasing water use in this period is likely explained by the beginning of the drought cycle occurring during these years.

Figure A.1 Historic Aquifer Water Use By Group

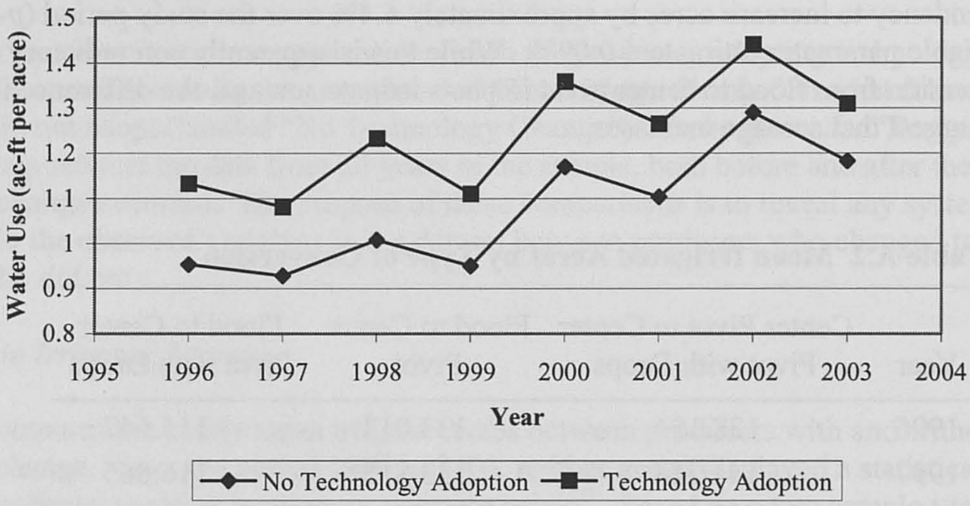
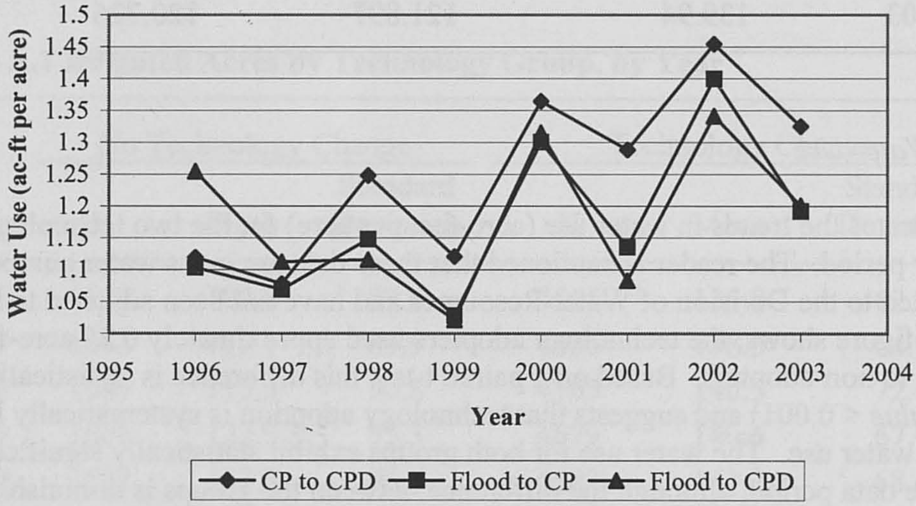
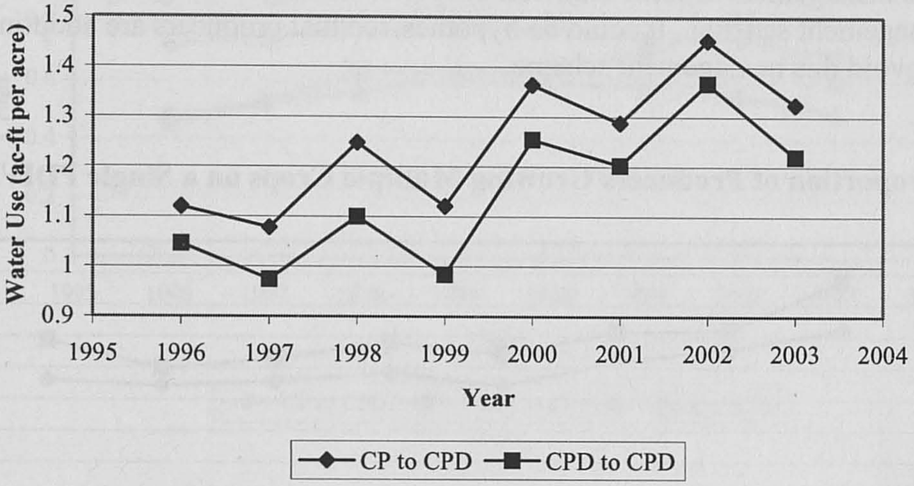


Figure A.2 Historic Aquifer Water Use By Type of Conversion Groups



As noted above, the most common type of technology adoption in the dataset was from center pivot to center pivots with drops. Figure A.3 compares the water use of those producers who used center pivot with drop technology the entire study period to those who converted to the technology from strictly center pivot technology. Not only do the technology adopters use statistically more water (approximately 0.10 acre-feet with a *p-value* < 0.001) than non-adopters, but the gap between these groups did not diminish over time.

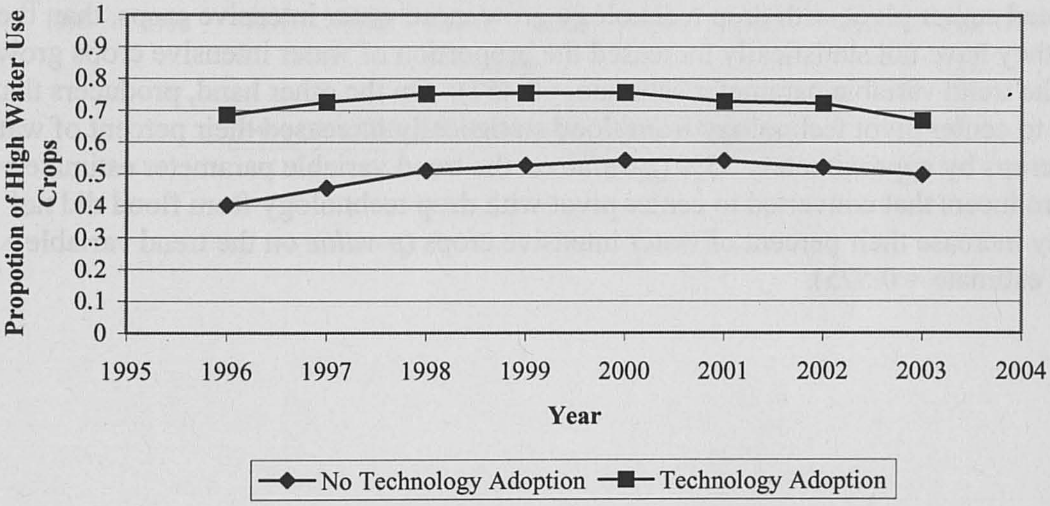
Figure A.3 Comparison of Aquifer Water Use for Producers that Used Drop Technology the Entire Period to those Who Converted to Drop Technology



Differences in Crop Choices

Figure A.4 shows the share of producers growing water-intensive crops. The figure reveals that, as is often claimed, producers that grow more water-intensive crops tend to be the producers that are currently adopting newer irrigation technologies.

Figure A.4 Proportion of Producers Growing High Water Use Crops



Economists have also hypothesized that in water-scarce conditions, producers might combine high water use crops with low water use crops on a single parcel to balance water use with water availability. Figure A.5 suggests that technology adopters have a slightly higher tendency to incorporate this management scheme than non-adopters, although both groups are reducing the use of this management scheme. It could be hypothesized that producers are adopting newer technology to avoid this management scheme.

Figure A.5 Proportion of Producers Growing Multiple Crops on a Single PDIV

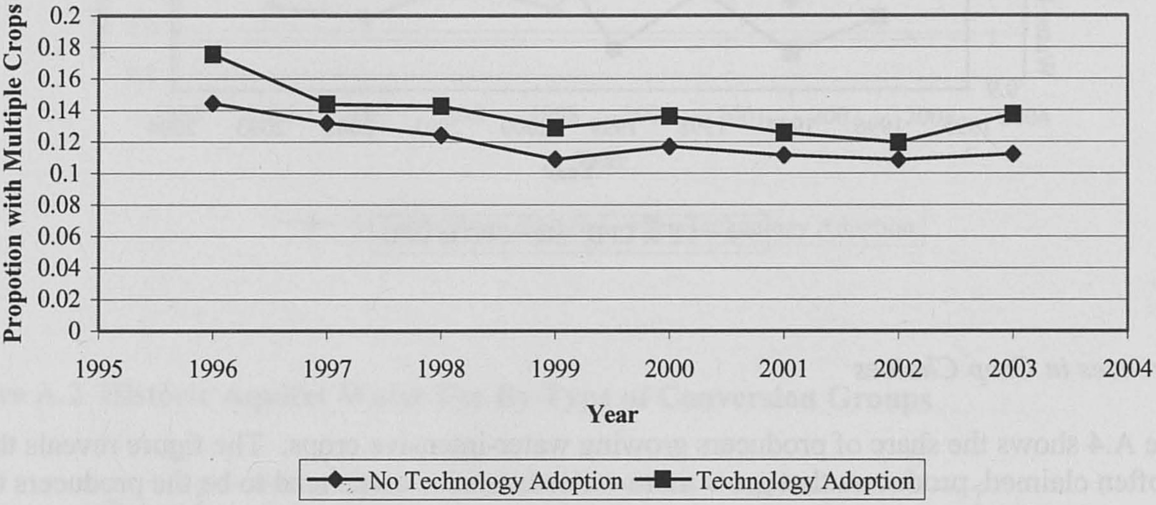


Figure A.6 and Figure A.7 suggests that those producers converting from center pivots to center pivot with drop technology tend to grow more water intensive crops and rely less on a mixed management scheme compared to other irrigation technology adopters. While producers that have adopted center pivot with drop technology grow more water intensive crops, than the other adopters, they have not statistically increased the proportion of water intensive crops grown (*p-value* on the trend variable parameter estimate = 0.457). On the other hand, producers that converted to center pivot technology from flood statistically increased their percent of water intensive crops by approximately 15% (*p-value* on the trend variable parameter estimate = 0.047). Producers that converted to center pivot with drop technology from flood did not statistically increase their percent of water intensive crops (*p-value* on the trend variable parameter estimate = 0.575).

Figure A.6 Proportion of Producers Growing High Water Use Crops by Conversion Type

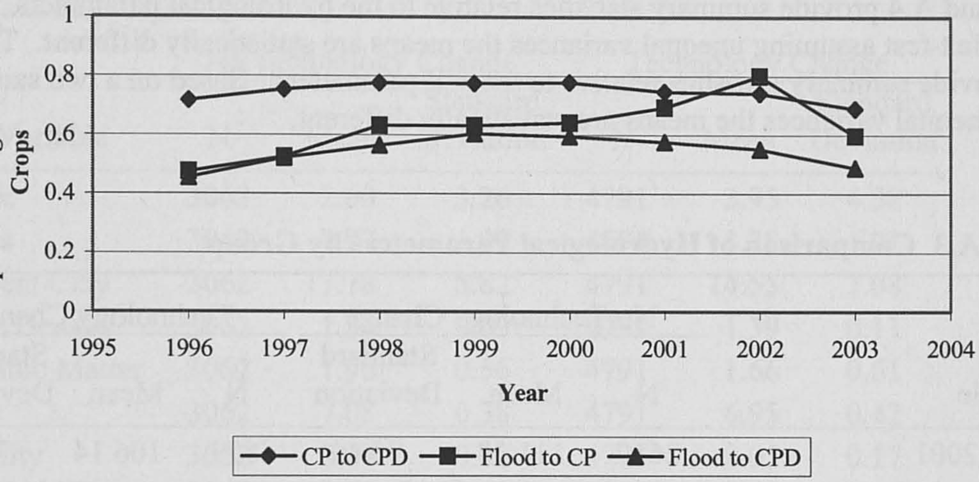
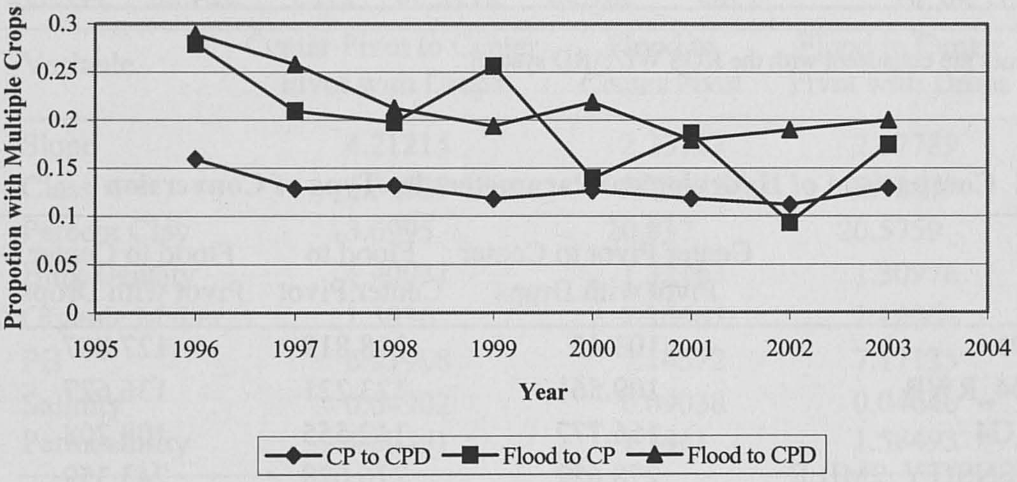


Figure A.7 Proportion of Producers Growing Multiple Crops on a Single PDIV by Conversion Type



Differences in Hydrologic and Soil Characteristics

Table A.3 and A.4 provide summary statistics relative to the hydrological parameters. Based on a two sample t-test assuming unequal variances the means are statistically different. Table A.5 and A.6 provide summary statistics relative to the soil parameters. Based on a two sample t-test assuming unequal variances the means are statistically different.

Table A.3 Comparison of Hydrological Parameters by Group

	No Technology Change			Technology Change		
Variable	N	Mean	Standard Deviation	N	Mean	Standard Deviation
DTW_2001	2610	111.38	75.40	4509	106.14	73.51
DTW_2004_RWB	2617	115.89	76.23	4516	112.44	75.00
ST_2002_G4	2599	142.76	272.12	4534	151.77	94.37
WUSE_DENSITY_2MILE	2912	236.02	187.79	4689	275.01	194.97
WL_CHG_96_02_G4	2599	-4.08	7.85	4534	-5.45	8.24
YRS_DEPL_96_01	1385	581.58	2752.30	2723	524.26	3495.52

Variable names are consistent with the KGS WIZARD system

Table A.4 Comparison of Hydrological Parameters by Type of Conversion

Variable	Center Pivot to Center Pivot with Drops	Flood to Center Pivot	Flood to Center Pivot with Drops
DTW_2001	103.45	118.819	127.887
DTW_2004_RWB	109.561	123.221	136.627
ST_2002_G4	156.777	142.555	108.208
WUSE_DENSITY_2MILE	278.652	276.628	243.359
WL_CHG_96_02_G4	-5.5987	-4.916	-4.2463
YRS_DEPL_96_01	527.319	2287.06	225.417

Variable names are consistent with the KGS WIZARD system

Table A.5 Comparison of Soil Parameters by Group

	No Technology Change			Technology Change		
Variable	N	Mean	Standard Deviation	N	Mean	Standard Deviation
Slope	3062	2.60	3.26	4791	3.95	4.38
Class	3062	2.97	1.02	4791	3.28	1.21
Percent Clay	3062	17.78	5.82	4791	14.55	7.08
Bulk Density	3062	1.36	0.09	4791	1.39	0.11
Organic Matter	3062	1.90	0.56	4791	1.66	0.61
PH	3062	7.08	0.38	4791	6.95	0.42
Salinity	3062	0.08	0.22	4791	0.05	0.17
Permeability	3062	3.05	3.13	4791	4.85	4.17

Table A.6 Comparison of Soil Parameters by Type of Conversion

Variable	Center Pivot to Center Pivot with Drops	Flood to Center Pivot	Flood to Center Pivot with Drops
Slope	4.21215	2.23127	2.07789
Class	3.34027	2.72812	2.82579
Percent Clay	13.6995	20.837	20.5759
Bulk Density	1.40031	1.32163	1.30976
Organic Matter	1.5936	2.16665	2.12064
PH	6.91908	7.14572	7.17135
Salinity	0.04902	0.09038	0.04646
Permeability	5.30561	1.7461	1.58493

Model of Producer Choice

Discrete choice models are often used to evaluate the impact that exogenous variables have on a consumer's choice to purchase a product. In our case, a Probit model will be used to evaluate a producer choice of adopting center pivot with drop technology or staying with conventional center pivot technology. The econometric model can be specified as

$$\begin{aligned} Choice = \beta_0 + \beta_1 CWIC + \beta_2 IA + \beta_3 Slope + \beta_4 Clay + \beta_5 SCI + \beta_6 ST + \\ \beta_7 DTW + \sum_{i=13}^{16} \beta_i GMD \end{aligned} \tag{11}$$

where *Choice* is a binary variable equal to one if the producer converted to center pivot with drop technology and zero otherwise, *CWIC* is the change to a more water intensive cropping practice, and *IA* is the observed increase in acreage over the study period. Both *CWIC* and *IA* were estimated based on simple time trend regression on a point of diversion basis. The remaining variables are as previously described. Table A.7 provides the descriptive statistics for the model variables, while Table A.8 provides the summary statistics for the parameter estimates.

Table A.7 Descriptive Statistic for the Model of Producer Choice

Variable	N	Minimum	Maximum	Mean	Standard Deviation
Choice	4825	0	1	0.87	0.34
AI	4825	-502	160	0.03	13.03
CWIC	4825	-0.19	0.19	-0.01	0.08
Slope	4825	0.53	16.14	4.10	4.43
Clay	4825	1.18	32	13.97	7.00
SCT	4825	7.48	260.53	36.07	31.26
ST	4573	0.74	558.75	155.21	94.73
DTW	4540	0	342	104.15	74.20
GMD1	4825	0	1	0.03	0.17
GMD2	4825	0	1	0.02	0.15
GMD3	4825	0	1	0.37	0.48
GMD4	4825	0	1	0.19	0.39
GMD5	4825	0	1	0.36	0.48

Table A.8 Parameter Estimates for the Model of Producer Choice

Variable	Estimate
Intercept	-1.53414***
AI	-0.0015
CWIC	-0.59613**
Slope	-0.00545
Clay	0.02566**
SCI	0.002448***
ST	-0.00088***
DTW	0.001471***
GMD1	-0.08649
GMD2	0.242211
GMD4	-0.64623***
GMD5	0.032638

*significant at the 90% confidence level
** significant at the 95% confidence level
*** significant at the 99% confidence level

Parameter estimates obtained from a Probit model infer an impact on the probability of a producer choosing center pivot with drop technology. The model suggests that the increasing acres or producing more water intensive crops are not important in the choice to change technology. The parameter estimates on *CWIC* suggests that producers that do change technology actually trend to less water intensive crops. This raises the possibility that producers with declining well capacity may be more inclined to change technology, in order to sustain the production of irrigated crops, even though those crops might be less valuable. Parameter estimates on *Clay* and *SCI* suggest that producers that have high values of these variables tend to choose low-pressure with drop technology. As the wetted diameter of a sprinkler package decreases (a result of the conversion to low-pressure with drop technology), instantaneous application rates increase, run off increases, and application efficiency decreases. As clay content of the soil increases and the slope increases declining application efficiency could be expected. These factors may explain why the adoption of center pivot with drop technology is not resulting in efficiency gains. The parameter estimates on *ST* and *DTW* suggest that as the saturated thickness of the aquifer increases, producers are less likely to adopt the technology, while as the depth to water increases producers have a higher probability of adopting center pivot with drop technology.

APPENDIX B

Table B.1 Cost Share Contracts by County and Year of Completion

County	1997	1998	1999	2000	2001	2002	2003	2004	Total
Barton	0	0	0	6	3	6	0	0	15
Cheyenne	0	2	7	6	10	2	0	0	27
Decatur	1	6	5	2	6	3	0	0	23
Edwards	1	32	28	15	19	12	4	0	111
Finney	0	4	9	9	12	18	1	2	55
Ford	0	2	5	9	15	2	0	0	33
Grant	0	4	6	7	4	5	1	0	27
Gray	1	3	10	11	22	20	4	0	71
Greeley	0	1	1	4	2	2	0	0	10
Hamilton	0	0	1	3	1	1	1	0	7
Haskell	0	1	16	13	19	21	0	1	71
Kearny	0	0	8	4	5	11	3	0	31
Kiowa	0	16	6	16	10	9	0	0	57
Meade	0	3	3	11	12	9	2	0	40
Morton	1	2	5	5	3	4	0	0	20
Norton	0	0	1	0	0	2	0	0	3
Pawnee	0	0	11	10	16	9	0	0	46
Pratt	0	2	8	16	10	3	0	0	39
Rawlins	0	1	2	5	5	1	0	0	14
Reno	0	0	0	6	2	2	0	0	10
Scott	0	3	4	12	5	11	0	0	35
Seward	0	4	6	10	13	6	0	0	39
Sheridan	0	1	5	7	6	5	0	0	24
Sherman	0	2	9	8	12	4	0	0	35
Stafford	0	4	7	13	11	6	0	0	41
Stanton	5	6	9	4	6	4	0	0	34
Stevens	0	2	6	10	11	19	0	0	48
Thomas	0	0	8	8	13	5	0	0	34
Wallace	0	0	4	6	7	8	2	1	28
Wichita	0	1	9	8	7	2	1	0	28
Total	9	102	199	244	267	212	19	4	1056

Table B.2 Acreage in Cost Share Contracts by County and Year of Completion

County	1997	1998	1999	2000	2001	2002	2003	2004	Total
Barton	0	0	0	615	391	553.5	0	0	1559.5
Cheyenne	0	243	932	725	1167	275	0	0	3342
Decatur	110.3	415.1	342.9	132	536.9	136	0	0	1673.2
Edwards	130	4151	3565	1950	2428	1770	510	0	14504
Finney	0	555	1335	1113	1594.6	2469	150	256	7472.6
Ford	0	269.3	855	1085	1802	290	0	0	4301.3
Grant	0	549	857.7	1579.6	1177	862	59	0	5084.3
Gray	120	284.5	1289	1246.8	2552	2112	522	0	8126.3
Greeley	0	320	43	692	248	247	0	0	1550
Hamilton	0	0	306	271.7	120	147	52.8	0	897.5
Haskell	0	125	3461	2017.3	2167	2925.9	0	18	10714.2
Kearny	0	0	1039	549	667.2	2491	310	0	5056.2
Kiowa	0	1977.6	785.3	2064.1	1299	1183.1	0	0	7309.1
Meade	0	380	390	1382.8	1472	914.7	90	0	4629.5
Morton	157.4	310	807.2	721.2	418.9	746.2	0	0	3160.9
Norton	0	0	85.2	0	0	115	0	0	200.2
Pawnee	0	0	1326.8	1009.6	2004	1038.8	0	0	5379.2
Pratt	0	260	973.2	1895	1270	390	0	0	4788.2
Rawlins	0	55	255.4	355	387	60	0	0	1112.4
Reno	0	0	0	757	242	251.6	0	0	1250.6
Scott	0	684	642	2443	930	1546	0	0	6245
Seward	0	802.9	947.2	3068.3	2580.2	969.2	0	0	8367.8
Sheridan	0	152	791	740.1	541	521.3	0	0	2745.4
Sherman	0	280	1117	920	1358	577	0	0	4252
Stafford	0	530	858.6	1631.5	1451.6	721	0	0	5192.7
Stanton	942.1	1248.7	1536.7	905.3	1985.6	508.6	0	0	7127
Stevens	0	500	815	1832.66	1980	2870.9	0	0	7998.56
Thomas	0	0	933.7	767.8	1431	298	0	0	3430.5
Wallace	0	0	549	689	828	980.7	250	125.7	3422.4
Wichita	0	350	1815	1993	1626	197	129.4	0	6110.4
Total	1459.8	14442.1	28653.9	35151.8	36655	28167.6	2073.2	399.7	147003.1

Table B.3 Cost Share Contracts by County and Type of Conversion

		Conversion		
County	SDI	CP	Drop	Total
Barton	1	8	6	15
Cheyenne	1	0	26	27
Decatur	0	9	14	23
Edwards	0	5	106	111
Finney	2	26	27	55
Ford	1	9	23	33
Grant	1	18	8	27
Gray	8	14	49	71
Greeley	0	8	2	10
Hamilton	0	7	0	7
Haskell	16	43	12	71
Kearny	0	14	17	31
Kiowa	0	0	57	57
Meade	4	31	5	40
Morton	0	14	6	20
Norton	0	1	2	3
Pawnee	0	17	29	46
Pratt	0	0	39	39
Rawlins	0	5	9	14
Reno	0	0	10	10
Scott	2	20	13	35
Seward	0	23	16	39
Sheridan	0	11	13	24
Sherman	0	4	31	35
Stafford	0	3	38	41
Stanton	2	30	2	34
Stevens	3	10	35	48
Thomas	4	8	22	34
Wallace	0	6	22	28
Wichita	1	25	2	28
Total	46	369	641	1056

Table B.4 Acreage in Cost Share Contracts by County and Type of Conversion

County	Conversion			Total
	SDI	CP	Drop	
Barton	16.5	782	761	1559.5
Cheyenne	20		3322	3342
Decatur		573	1100.2	1673.2
Edwards		650	13854	14504
Finney	42	3918.1	3512.5	7472.6
Ford	22	1315.3	2964	4301.3
Grant	59	4057.7	967.6	5084.3
Gray	417.7	1820	5888.6	8126.3
Greeley		1301	249	1550
Hamilton		897.5		897.5
Haskell	1013	7983.2	1718	10714.2
Kearny		1744.9	3311.3	5056.2
Kiowa			7309.1	7309.1
Meade	80	3939.5	610	4629.5
Morton		2165.1	995.8	3160.9
Norton		95	105.2	200.2
Pawnee		2042.3	3336.9	5379.2
Pratt			4788.2	4788.2
Rawlins		365.7	746.7	1112.4
Reno			1250.6	1250.6
Scott	172	4208	1865	6245
Seward		5577.1	2790.7	8367.8
Sheridan		1181.4	1564	2745.4
Sherman		373	3879	4252
Stafford		330	4862.7	5192.7
Stanton	237.6	6633.4	256	7127
Stevens	480	1762	5756.5	7998.5
Thomas	130	924	2376.5	3430.5
Wallace		660.7	2761.7	3422.4
Wichita	40	5822.4	248	6110.4
Total	2729.8	61122.3	83150.99	147003.1

Table B.5 Average Cost of a Cost Share Contract

Type	Acreage	N	Mean	Standard Deviation	Minimum	Maximum
Drop Nozzle	120 - 160	525	15.73	6.45	2.57	35.73
Conversion to Center Pivot	120 - 180	227	21.96	6.42	4.56	47.21
Conversion to SDI	20 - 40	17	288.31	237.1	65.79	750.75

Table B.6 Group 1: Summary Statistics for the Corn Model

Variable	N	Minimum	Maximum	Mean	Standard Deviation
Time	20243	1	8	4.31	2.22
Acres	20243	1	960	130.68	58.55
CP	20243	0	1	0.34	0.47
Flood	20243	0	1	0.09	0.29
Slope	20243	0.53	16.14	3.72	4.03
Clay	20243	1.18	32	15.16	6.89
ST	19370	0.02	571.59	148.84	93.13
DTW	19295	0	342	107.39	72.71
CRP	20243	2.47	6.18	3.67	0.98
FP	20243	1.80	4.13	2.65	0.80
GMD1	20243	0	1	0.05	0.23
GMD2	20243	0	1	0.02	0.14
GMD3	20243	0	1	0.31	0.46
GMD4	20243	0	1	0.26	0.44
GMD5	20243	0	1	0.33	0.47
P	20243	2.51	30.56	12.88	4.27
ET	20243	18.43	26.76	21.79	2.49
GWA	20243	5	35	16.30	5.31
NBU	20243	-5.00	34.28	7.39	5.91

Each observation represents a single PDIV for a single year.

Table B.7 Group 1: Summary Statistics for the Soybean Model

Variable	N	Minimum	Maximum	Mean	Standard Deviation
Time	3291	1	8	5.00	2.05
Acres	3291	1	445	119.33	30.49
CP	3291	0	1	0.29	0.45
Flood	3291	0	1	0.07	0.25
Slope	3291	0.53	16.14	3.17	2.99
Clay	3291	1.18	32	13.79	6.48
ST	3138	0.74	415.06	128.35	68.41
DTW	3067	0	325	58.31	56.96
CRP	3291	4.24	7.30	5.29	1.01
FP	3291	1.80	4.13	2.81	0.78
GMD1	3291	0	1	0.01	0.09
GMD2	3291	0	1	0.10	0.31
GMD3	3291	0	1	0.12	0.32
GMD4	3291	0	1	0.10	0.30
GMD5	3291	0	1	0.65	0.48
P	3291	5.44	28.59	13.68	4.09
ET	3291	15.87	24.00	20.76	2.17
GWA	3291	5	34.51	14.90	4.67
NBU	3291	-4.80	29.28	7.83	5.12

Each observation represents a single PDIV for a single year.

Table B.8 Group 1: Summary Statistics for the Alfalfa Model

Variable	N	Minimum	Maximum	Mean	Standard Deviation
Time	4678	1	8	4.72	2.33
Acres	4678	2	640	128.96	45.01
CP	4678	0	1	0.36	0.48
Flood	4678	0	1	0.05	0.23
Slope	4678	0.53	16.14	7.49	6.44
Clay	4678	1.18	32	9.95	7.85
ST	4411	0.02	571.59	188.50	98.14
DTW	4419	0	308	109.42	73.59
FP	4678	1.80	4.1275	2.70	0.76
GMD1	4678	0	1	0.02	0.13
GMD2	4678	0	1	0.01	0.08
GMD3	4678	0	1	0.59	0.49
GMD4	4678	0	1	0.05	0.21
GMD5	4678	0	1	0.31	0.46
P	4658	6.1	34.34	16.94	5.05
ET	4678	45.59	63.13	54.79	4.37
GWA	4678	5.05	35	18.38	6.62
NBU	4658	-51.25	4.71	-19.43	8.49

Each observation represents a single PDIV for a single year.

Table B.9 Group 1: Summary Statistics for the Sorghum Model

Variable	N	Minimum	Maximum	Mean	Standard Deviation
Time	1036	1	8	4.41	2.59
Acres	1036	1	400	90.60	55.34
CP	1036	0	1	0.20	0.40
Flood	1036	0	1	0.47	0.50
Slope	1036	0.53	16.14	2.26	2.39
Clay	1036	1.18	32	18.59	5.57
ST	866	0.74	546.08	99.59	75.76
DTW	865	0	300	89.43	64.25
CRP	1036	2.47	6.18	3.94	1.02
FP	1036	1.80	4.1275	2.64	0.76
GMD1	1036	0	1	0.22	0.41
GMD2	1036	0	1	0.05	0.21
GMD3	1036	0	1	0.29	0.45
GMD4	1036	0	1	0.10	0.30
GMD5	1036	0	1	0.30	0.46
P	1036	5.22	26.72	13.66	4.06
ET	1036	12.26	18.77	15.73	2.25
GWA	1036	5	31.82	11.71	4.85
NBU	1036	-4.89	36.82	9.64	6.61

Each observation represents a single PDIV for a single year.

Figure B.1 Frequency of Cost Share Contract by Month of Completion

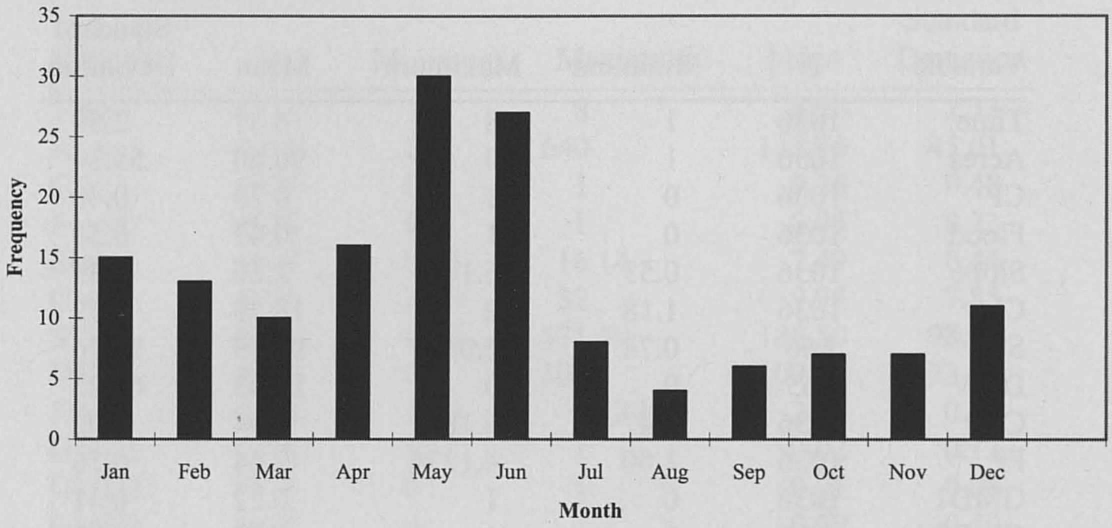


Figure B.2 Frequency of Cost Share Contract by Irrigated Acreage

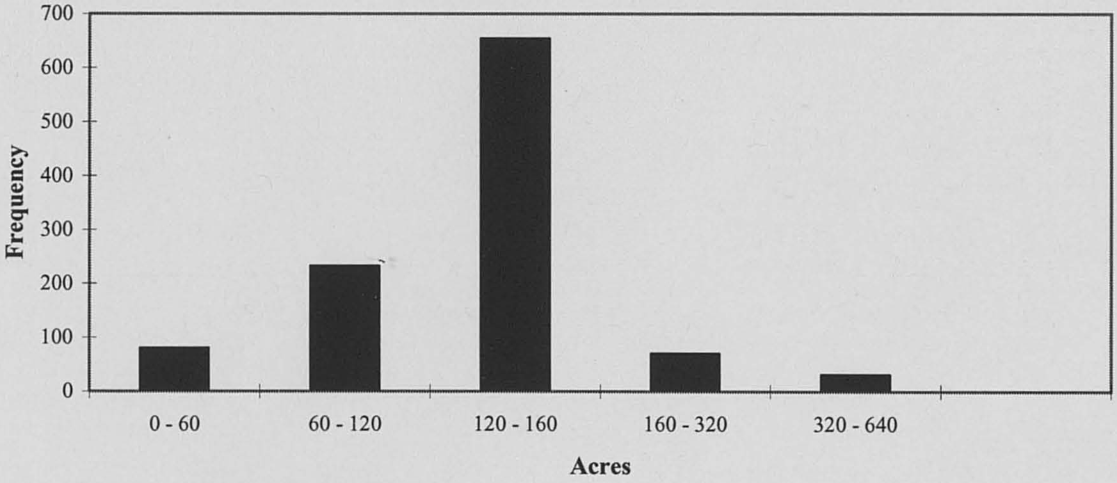


Figure B.3 Frequency of Center Pivot Conversion Cost Share Contract by Irrigated Acreage

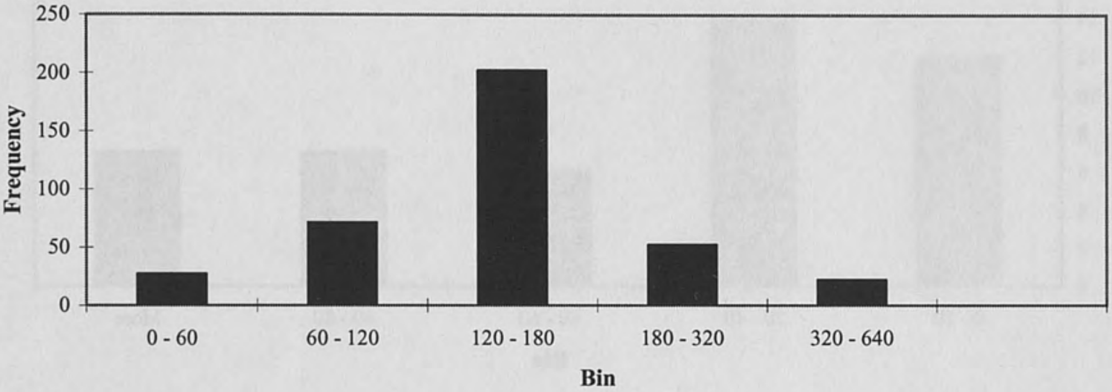


Figure B.4 Frequency of Drop Nozzle Conversion Cost Share Contract by Irrigated Acreage

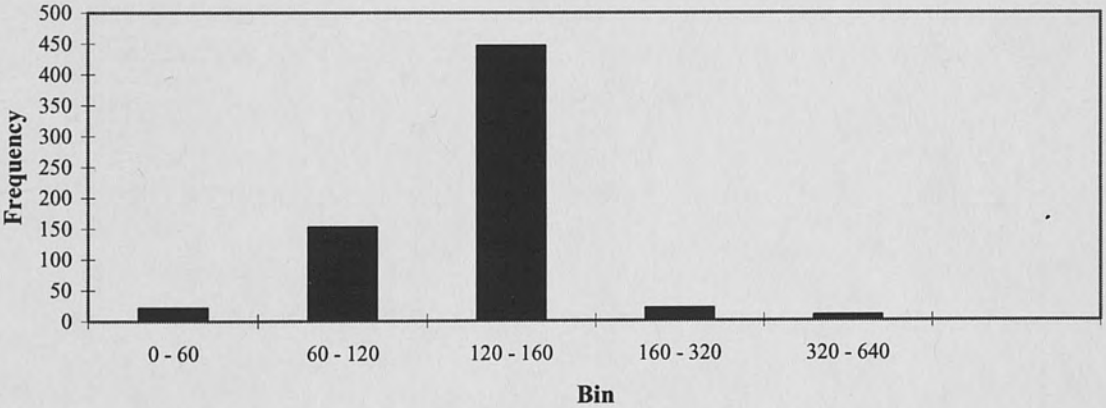


Figure B.5 Frequency of SDI Conversion Cost Share Contract by Irrigated Acreage