ESTIMATING IRRIGATION WATER DEMAND WITH A MULTINOMIAL LOGIT SELECTIVITY MODEL

by

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ABSTRACT

Understanding irrigation water demand is vital to policy decisions concerning water scarcity. This thesis evaluates irrigation water-use responses to changes in prices, while accounting for cross-sectional characteristics of irrigators' resource settings. An irrigator's profit-maximizing decision is modeled in two stages. In the first stage, he decides which crop to plant, and in the second stage he decides how much water to apply given the crop choice.

This thesis employs an econometric modeling technique not previously used in the irrigation water demand literature, a multinomial logit selectivity model. This econometric technique allows the intensive (change in water use for each crop in the short run) and extensive (change in water use in the long run due to changes in crop-choice) margin effects to be computed in a simultaneous equation system. A multinomial logit selectivity model has applications to many resource issues in production agriculture where the two-stage decision process is common. The model is estimated from field-level data on water use and crop-choice for a 25-county region in western Kansas over the period 1991-2004.

Water use was found to be highly inelastic to the price of natural gas, but becomes more elastic as the price increases. The intensive margin effect was significant for natural gas price. The extensive margin effect only comprised half the total effect under high natural gas prices and was negligible for low prices. However, the extensive margin effect under high natural gas prices declined over time due to more efficient irrigation

systems and improved crop varieties. The intensive margin effect explained most of the water use response from changes in other variables, including corn price. An increase in corn price has a negligible extensive margin effect because corn is most often substituted with alfalfa, which has a similar water requirement.

Inelastic demand implies that policies aiming to conserve the Ogallala Aquifer by increasing the price of water will not accomplish their purpose and will affect irrigators' incomes. More effective policies would be voluntary or mandatory quantity restrictions. However, efficient restrictions would need to account for spatial variation in the rate of depletion and the remaining saturated thickness.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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CHAPTER 1 - INTRODUCTION

Water scarcity is a serious issue across the world, and understanding irrigation water demand plays an integral role in developing policies. In the past, water scarcity issues were addressed by expanding the supply of water by exploiting natural resources, such as through building dams or drilling deeper wells. However, this option is rapidly becoming infeasible and impractical as the convenient natural resources are exploited, so reasonable policies addressing water scarcity must focus on reducing the demand for water. In particular, obtaining irrigation water demand elasticity estimates is especially critical for evaluating the efficacy of raising prices to reduce consumption. If demand is inelastic, price increases will be ineffective at reducing water use and have an adverse effect on irrigators' incomes. The impacts that other factors, such as crop price and irrigation technology changes, have on water use have important policy implications also.

Irrigation water is vital to the western Kansas economy not only because it increases the productivity of the land, but because many businesses are needed to support the input-intensive crops produced. Increasing the productivity of the land not only adds value for irrigators, but it also provides feed for the cattle industry and inputs for the emerging ethanol industry. The Ogallala Aquifer, which is one of the most significant water resources in the United States and the primary source of water for western Kansas, is essentially a finite resource because there is very little recharge, making future water availability dependent on current usage.

Irrigated agriculture consumed 89 percent of water in Kansas in 1995. Most of the irrigation is confined to western Kansas, so this number is significantly larger for western Kansas communities. In addition, the source of 93 percent of this consumption was from groundwater supplies as opposed to surface water. Kansas ranked as the 14th largest consumer of water in the United States (Solley, Pierce, and Perlman).

The Department of Commerce and the U.S. Congress understood the importance of research to this issue, so they commissioned the High Plains Ogallala Regional Aquifer study, which was completed in 1982 (Peterson and Bernardo). For the Kansas portion of the Ogallala region, the study actually found that the depletion problem was not as dire as suspected at the time, projecting that over the next 40 years, irrigated acres would decrease due to increasing energy prices and limited water supply. Yields and real crop prices were expected to increase, but the overall effect was an expected reduction in annual water use due to reduced acres and improved irrigation efficiency (High Plains Study Council).

However, the trend in energy prices up to the present fell well below projections, and together with improved efficiencies and larger-than-expected increases in yields, this caused an increase in irrigated acres. Not only have the number of irrigated acres increased since 1982, but production of water-intensive crops such as alfalfa and corn on irrigated acres has increased. This has been in large part due to the unexpectedly large increases in corn yields. In spite of the increase in the acreages of water-intensive crops, water use has decreased since 1982, although not as much as the Ogallala Regional Aquifer study predicted (Peterson and Bernardo).

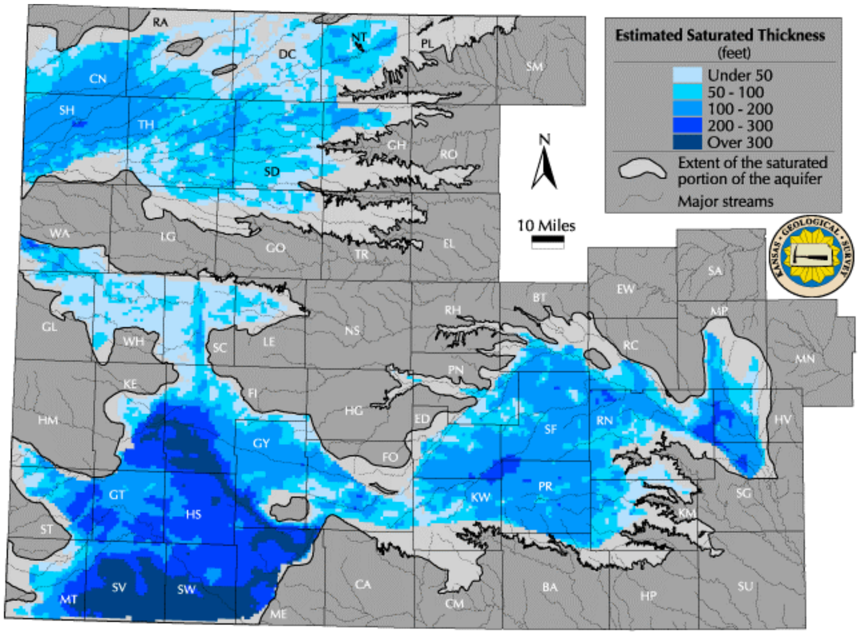
Figure 1.1 shows the current (1997-1999) estimated saturated thickness of the aquifer in Kansas. Southwest Kansas has the richest supply of water available with much of the region having a saturated thickness between 200 and 300 feet, and some areas having more than 300 feet. Meanwhile, much of northwest and south central Kansas has a saturated thickness of 100-200 feet.

Figure 1.2 and Figure 1.3 show the change in saturated thickness since the aquifer was first developed for irrigation use in absolute and relative measures, respectively. Even though southwest Kansas has the largest saturated thickness, a large amount of the aquifer has been depleted in that region, even in relative terms; many areas have witnessed a decline in saturated thickness exceeding 100 feet (or 30%).

West central Kansas had a very shallow saturated thickness even at the time of predevelopment, but a large fraction of the initial resource has now been depleted. Figure 1.3 shows that much of the region has seen 45-60% reductions in the original saturated thickness with some areas depleting more than 60% of the resource.

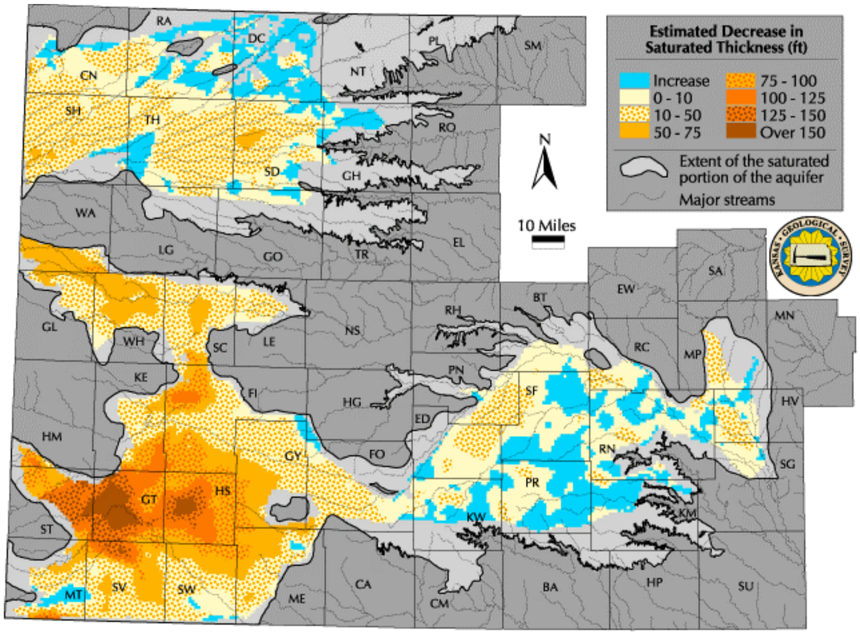
From these figures, it is evident that the supply of water will be an issue of increasing importance. Currently, the issue is of greatest urgency to west central Kansas, but the concern will spread. Even though southwest Kansas has large reserves, this region is quickly depleting the aquifer. This has led to an increasing interest in conserving the aquifer among policy makers and irrigators and warrants research to evaluate policy options.

Figure 1.1 Averaged 1997-1999 Saturated Thickness for the Ogallala Aquifer in Kansas



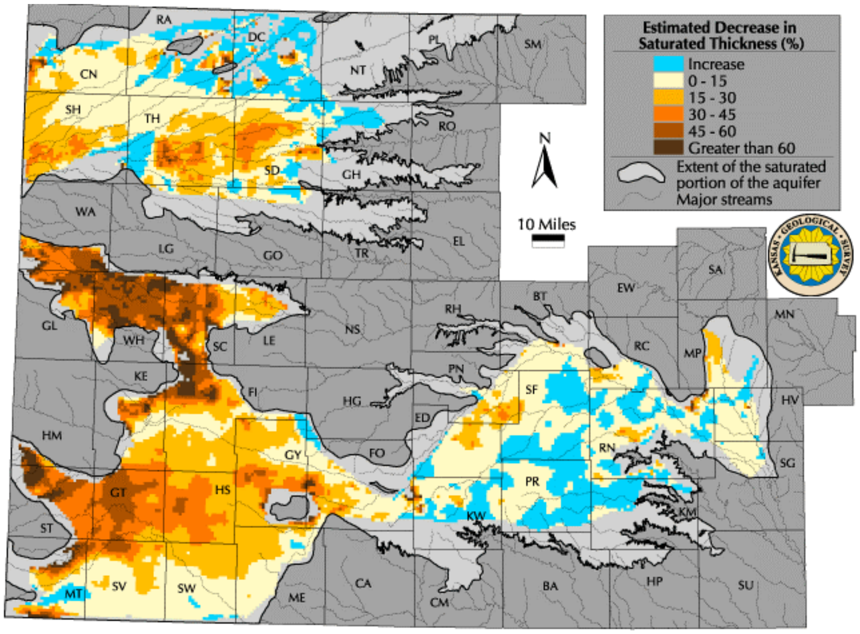
Source: Kansas Geological Survey

Figure 1.2 Change in Saturated Thickness for the Ogallala Aquifer in Kansas, Predevelopment to 1997-99



Source: Kansas Geological Survey

Figure 1.3 Percent Change in Saturated Thickness for the Ogallala Aquifer in Kansas, Predevelopment to 1997-99



Source: Kansas Geological Survey

This thesis does not attempt to answer whether or not conserving the Ogallala aquifer is the most desirable policy goal, but instead evaluates the efficacy of policies to conserve the aquifer, assuming conservation is a policy consensus. Because of the finite nature of the resource in Kansas, conserving for the future has an opportunity cost in terms of foregone production in the present. Whether this tradeoff can be justified in economic efficiency terms is debated in the literature.

As noted earlier, quantification of water demand is essential to evaluate alternative conservation policies. Research in estimating water demand has typically used programming models (Shumway; Howitt, Watson, and Adams; Bernardo et al.; Buller and Williams; Schaible), but more recently econometric methods (Nieswiadomy; Moore, Gollehon, and Carey (1994 a&b); Schoengold, Sunding, and Moreno) have also been applied.[1] Programming models directly model profit maximizing behavior in response to a particular set of prices, and then water price is varied to trace out a demand relationship. On the other hand, econometric studies infer the demand relationship from data that are assumed to be generated by a profit maximization process.

A limitation of previous research on water demand is that it has usually focused on future trends, which always depend on unknown variables, rather than trying to understand causes of past trends (Peterson and Bernardo). This research focuses on understanding the past behavior of farmers. Their response to changes in relevant factors will lead to policy implications for conserving the Ogallala.

This thesis uses econometric analysis to estimate demand for irrigation water for the Ogallala Aquifer in western Kansas. Farmers are viewed as multioutput producers who make a two-stage production decision annually, where the crop to plant is chosen in stage one and the amount of water to pump is decided in stage two. A multinomial logit model is used to estimate the stage one decision. Then a linear regression is estimated for water demand, accounting for selection bias due to crop-choice.

The overall goal of this study is to add to the discussion of the effect of water price (measured as the price of natural gas) on water demand. The three specific objectives to achieve this goal are to (1) estimate the total demand elasticity for irrigation water for groundwater irrigation in the Ogallala aquifer region of Kansas, (2) decompose marginal effects of water use with respect to prices into extensive and intensive marginal effects, and (3) identify and quantify other variables which impact the price responsiveness of irrigators.

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[1] Scheierling, Loomis, and Young and Koundouri give comprehensive lists of literature using programming and econometric models to estimate irrigation water demand

The first objective of this study is to estimate an overall elasticity of demand for irrigation water. Scheierling, Loomis, and Young recently performed a comprehensive review of the literature on irrigation water demand. Across the 24 studies they reviewed, they found a mean price elasticity of 0.48 (in absolute terms) and median elasticity of 0.16. But the standard deviation (0.53) was large and the elasticities ranged from 0.001 to 1.97. This shows the wide range of estimates and the need for further research with improved and updated data sources.

The second objective of this study is to decompose the demand response of irrigators into extensive and intensive marginal effects to better understand how irrigators respond to changes in natural gas prices. The extensive marginal effect is the change in water use due to changes in land allocation among various irrigated crops, while the intensive marginal effect reflects the short-run change in water use after cropping decisions have been made. The use of a multinomial logit selectivity model allows extensive and intensive margin effects to be computed in a simultaneous equation system. Research on many resource issues in agriculture involves this two stage modeling approach where crop-choice is the first stage and crop-specific input use is the second stage (Antle and Capalbo). Therefore, this research benefits the resource use literature because of the econometric technique employed.

The third objective of this study is to identify and quantify the impact other variables have on irrigation water demand. For example, a variable, such as irrigation technology, may have an impact on the price responsiveness of irrigators, so that irrigators with more efficient technologies are less price responsive and demand is more inelastic.

However, other marginal effects are also of interest, such as the effect of crop prices and irrigation technology on crop-choice and water demand. The direction and magnitude of these effects is of great value to policy makers.

While numerous studies have researched these issues, the results from this study will distinctly benefit the literature on irrigation water demand because of the unique data set and econometric techniques employed. The data for water use, crop-choice, irrigation technology, and well capacity are at the field-level. Previous studies were limited by more aggregate data. Furthermore, this study will provide information on the nature of irrigation water demand in response to recent energy price increases.

CHAPTER 2 - IRRIGATION WATER POLICY

Three possible motivations for conserving exhaustible aquifer resources such as the Ogallala are economic efficiency, equity, and as a moral principle. The goal of economic efficiency is for the water resource to "yield the greatest net benefit to society." Due to the common property attributes of the aquifer and because irrigators only pay what it costs them to extract the resource, irrigators do not incur external costs and the rate of depletion exceeds the economically efficient rate (Peterson, Marsh, and Williams).

Secondly, equity may motivate policy, where the goal is to assure that water is fairly distributed among users and preserves a fair amount for future generations. Thirdly, conservation policy is also motivated simply as a moral principle. This motivation does not account for costs and benefits, but recognizes a moral duty to preserve natural resources (Peterson, Marsh, and Williams).

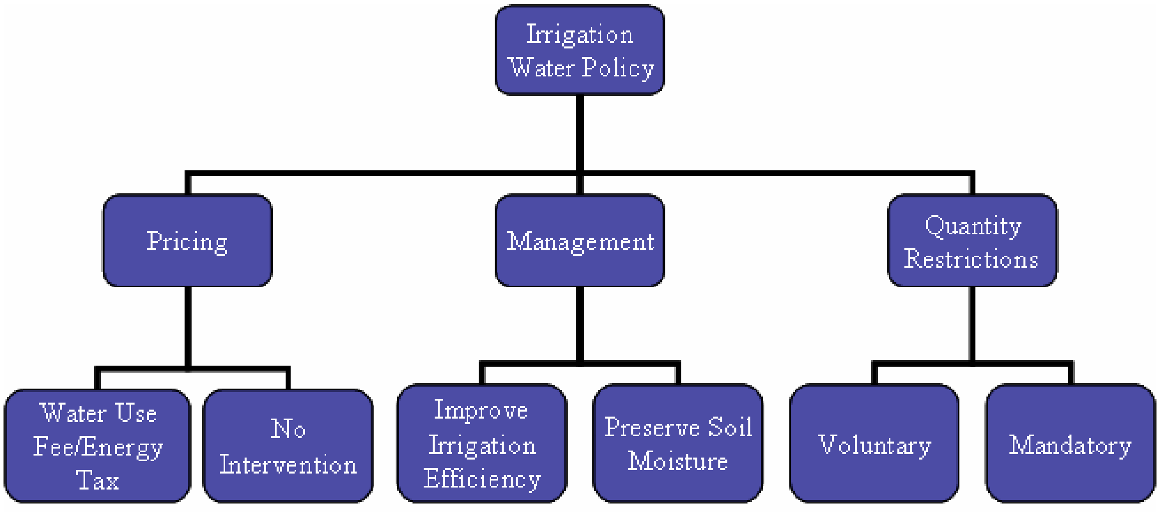
This thesis addresses policy options to conserve the aquifer, setting aside the question of whether or not conservation is a desirable policy goal. The motivations for conservation differ, but a general policy consensus has emerged to conserve the aquifer. Therefore, research is needed to evaluate the efficacy of different conservation policy options.

Policy to conserve irrigation water can be divided into three categories: pricing, management, or quantity restrictions (Figure 2.1). Two types of pricing policies are considered. First, policies could be implemented which increase the cost of using water, and therefore reduce its use. However, the reduction in water use depends on the elasticity of demand. This reduction in water use would be accomplished through either a unit tax on water use, or an energy tax that would effectively increase pumping costs. The second type of pricing policy is for the government not to intervene at all. At first this may not appear to be a pricing policy; however, implicitly it is a policy where the policy makers trust the market prices are sufficient to provide incentives that properly allocate water across users and throughout time.

There are also two ways to reduce water use through policies that encourage farmers to alter their management practices: increase efficiency (reduce the amount of irrigation water lost through evaporation, run-off, etc.), or preserve the existing soil moisture. One can improve the efficiency by converting to a more efficient irrigation technology or utilizing ET reports to improve application timing and minimize excess pumping. Secondly, a farmer can also improve soil moisture through capturing and retaining more precipitation. This is accomplished by reducing evaporation with more crop residue, reducing precipitation runoff by contour farming and preserving residue, controlling weed pressure, and growing less water intensive crops. Regulations to alter management practices are not well received by producers. Instead, this policy option has been implemented by funding research and extension and providing water conservation incentives, such as cost-share programs.

The third policy option is to impose quantity restrictions on water use. These restrictions are either voluntary or mandatory. Voluntary restrictions include some incentive for irrigators to reduce their water use and they could choose to either accept the incentive or continue irrigating. Mandatory restrictions are imposed on irrigators whether they agree to them or not, and may or may not include some compensation to the water user. A quantity restriction is either a partial restriction in water use or a complete restriction, where the irrigator may no longer pump water.

Figure 2.1 Irrigation Water Policy Options



A water market was first proposed as a policy option by Vernon Smith (1977). Implementing a water market is at the intersection of quantity restriction and pricing policies; implicitly, it may also have management impacts. The idea behind a water market is to issue water rights to irrigators with the sum of the allowed use affixed to the rights less than the current water use or at some predetermined goal, then allows users to trade their rights. Therefore, the government defined water rights, which act as property rights, restrict the total quantity of water consumed, but the water market also allows a market to determine a price for water. Theoretically, this market should result in the Pareto-optimal allocation of the resource, given the property right arrangements in place. The market should allocate water to the user who obtains the most value from the water, which will likely have the impact of giving incentives for improved management practices. Undoubtedly, hydrological characteristics of the aquifer in western Kansas present difficulties in determining initial water rights and trading those rights. Peterson, Marsh, and Williams illustrate that an advantage of a water market is that it considers all three motivations to conserve. The moral principle of conservation is addressed because there is a restriction on the total amount of water used. Equity is addressed through the quantity restriction also because water is conserved for future generations. The market for the rights distributes the water most efficiently across users as well.

2.1 KANSAS IRRIGATION WATER POLICY

In 1945, Kansas adopted the Kansas Water Appropriation Act. The Act stated that any user of water in the state must obtain an appropriation right, except for domestic users.[1] The Division of Water Resources (DWR) of the Kansas Department of Agriculture is charged with appropriating and enforcing the rights. In particular, enforcement and administration is designated to the Chief Engineer of the DWR. Water rights may be given for any beneficial purpose (Kansas Water Office).

Groundwater Management Districts (GMDs) were created by the state legislature in 1972 to manage water use at a local level as long as they complied with state regulations. The Kansas Water Office (KWO) was created in 1981. The KWO does not have any inherent power, but it is assigned with the responsibility of providing policy recommendations to the state legislature and governor and designing a state water management plan (Brenn).

The High Plains Ogallala Regional Aquifer Study in 1982 found that the depletion problem was not as dire as many suspected at the time. Their models projected that over

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[1] The Kansas Water Appropriations Act defines domestic use as “the use of water by any person or by a family unit or household for household purposes, or for the watering of livestock, poultry, farm and domestic animals used in operating a farm, and for the irrigation of lands not exceeding a total of two acres in area for the growing of gardens, orchards and lawns.”

the next 40 years, irrigated acres would decrease due to increasing energy prices and limited water supply. Yields and real crop prices were expected to increase, but the overall effect was an expected reduction in annual water use due to reduced acres and improved irrigation efficiency (High Plains Study Council).

Therefore, policies in Kansas focused on pricing and management strategies and were driven by the motivation for economic efficiency. The pricing strategy was to leave water use to market forces, because energy costs were expected to force water use to decline. Research and extension efforts focused on improving irrigation efficiency through improved irrigation technology and irrigation scheduling. Kansas also implemented a cost-share program to give incentives to irrigators to convert to more efficient irrigation systems through the State Conservation Commission. The National Resource Conservation Service's (NRCS) Environmental Quality Incentives Program (EQIP) also provides cost-share opportunities for irrigators to adopt better management practices and more efficient irrigation systems (National Resource Conservation Service 2005).

However, contrary to expectations, energy prices did not increase as much as projected, and together with improved efficiencies and larger increases in yields than expected, this caused irrigated acres to increase. Not only have the number of irrigated acres increased since 1982, but production of water-intensive crops such as alfalfa and corn on irrigated acres has increased. This has been in large part due to the increases in corn yields relative to other crop yields. However, in spite of the increase in acres of water-intensive crops, water use has decreased since 1982, but not as much as the Ogallala Regional Aquifer Study had predicted (Peterson and Bernardo).

Some of the most recent policies have shifted in focus, and more voluntary quantity restriction policies have been implemented. The Water Transition Assistance Program (Water TAP) is a voluntary water right buyout program adopted by the state legislature in 2006. After the water-right is purchased, the land may be dryland farmed. Particular regions with serious scarcity issues are targeted for this program. The Conservation Reserve Enhancement Program (CREP) is a voluntary water right buyout program, but the enrolled land must be planted with grass instead of dryland farmed as in Water TAP. CREP targets areas near rivers in particular, and eighty percent of the funding is provided by the federal government (Kansas Water Office). EQIP has also been used to convert irrigated cropland to less water intensive crop rotations or nonirrigated cropland.

CHAPTER 3 - LITERATURE REVIEW

The purpose of this chapter is to briefly summarize some of the previous work that applies to this thesis. Many articles that apply to specific areas of the thesis are cited throughout the text, so this chapter is meant only to give a broad overview. Studies evaluating irrigators' demand response to energy prices using econometric methods are reviewed, followed by those modeling the demand response with programming models. Emphasis is given to studies using econometric methods, since that is the method employed in this thesis. Finally, other relevant literature on irrigators' water use and crop-choice responses to variables other than energy prices are briefly discussed.

3.1 ECONOMETRIC DEMAND STUDIES

Nieswiadomy estimated demand for water in the High Plains of Texas using an econometric approach. Water use was specified as a function of crop prices, pumping cost, furrow cost, wage rate, and rainfall. Counties were used as observational units in the analysis. Nieswiadomy suggested a structural change in the market between 1972 and 1973. From 1957-1972 water price did not have a significant effect on demand, but from 1973-1980 there was an inverse relationship with an estimated elasticity of demand of -0.80. Peterson and Bernardo pointed out that a limitation of this study was the water-use data, which were inferred from county-level observations of water level changes over time.

In 1989, Ogg and Gollehon studied water demand with a linear regression using cross-sectional data. The 1984 FRIS (Farm and Ranch Irrigation Survey) dataset was used to obtain water use and variation in perceived prices due to different pumping costs. They estimated the demand equation with linear, log-log, and quadratic functional forms. The log-log functional form offered the most elastic demand estimate of -0.26, and was used throughout their analysis. The cost of pumping water was computed using survey data on water use and total irrigation energy costs. Therefore, a farmer's error in reporting water use not only affected the dependent variable in the model (water use), but also affected the independent variable (price of water). Ogg and Gollehon note that any error in the reported water use may be negatively correlated with the error term in the regression. To account for this possible bias, Ogg and Gollehon used instrumental variables, but the estimates were not greatly affected. The authors suggested that from the results of their research, the use of pricing policies alone to reduce the use of irrigation water would have an adverse effect on farmers' incomes with little reduction in water use.

Moore, Gollehon, and Carey published two articles in 1994 that follow a very similar framework to that proposed in this thesis. The objectives of Moore, Gollehon, and Carey (1994b) were to examine factors affecting producers' decision on crop-choice, evaluate the extensive and intensive marginal effects of water price, and investigate any regional differences in water demand estimation. They evaluated irrigation farmers' crop-choice decisions between 5 crops in 4 different regions of the U.S. The 1984 and 1988 Farm and Ranch Irrigation Surveys (FRIS) were the primary sources of data.

The authors modeled crop-choice, land allocation, and supply functions as long-run decisions, while crop-level water use was a short-run decision. A binomial probit model was used to estimate each crop-choice equation. The land allocation and supply functions were estimated with Tobit models, and Heckman's model was used to estimate the water demand function.

The authors assumed that farmers' choices follow a variable input model, implying that water demand is a function of own-crop price, input prices, water price, own-crop acres, and a vector of other variables. Water price affects water demand both directly (at the intensive margin of use) and through a reallocation of crop acreage (at the extensive margin of use), because acreage is also a function of water price.

The authors found that regional differences were significant, so researchers should not model crop-choice or water demand across regions in a single model. The model also showed that, in general, the extensive margin effect was statistically significant, but the intensive margin effect was not. This indicates that producers respond to changes in water price through crop-choice, and after the crop-decision is made, producers do not alter their water use based on water price. When water price increases, producers decrease water use at the extensive margin through decreasing acres planted to water-intensive crops and vice versa for less water-intensive crops. The farm-level response to an increase in water price was negative in 3 of the 4 regions, and was highly inelastic in every region.

Moore, Gollehon, and Carey (1994a) was a follow-up to the previous article. In the previous article, the authors found that the variable input model did not explain water demand very well because farmers did not seem to respond to the price of water in the short-run. In this article, they proposed three models to explain producers' short-run decisions regarding irrigation water use. The first model was the variable input model explained previously. The second model was a fixed, allocatable input model. This model differed from the variable input model because water demand was not a function of water price. Instead, a farm-level water constraint was imposed on the model, which assumes that each farmer has a fixed amount of water on his farm to allocate to different crops. Therefore, water demanded by a particular crop was a function of all crop acreages and all crop prices, but not water price. The third model was a satisficing model, which assumed that production of a particular crop requires a fixed water-land ratio. In this model, once producers allocate their land, the only relevant factors affecting water consumption are the number of acres planted and weather.

They compared models with specification tests (F-tests) and prediction accuracy measures (mean absolute error, root mean square error, and mean absolute percentage error). Under the specification tests, the researchers found that the fixed, allocatable model was the best at explaining the dataset. The prediction accuracy measures were not conclusive, but also gave support that the fixed, allocatable input model was superior. In summary, Moore, Gollehon, and Carey (1994a) provided evidence that a fixed, allocatable input model should be used to evaluate producers' decisions regarding irrigation water use. A primary implication from this research is that producers do not respond to changes in water price in the short-run.

Schoengold, Sunding, and Moreno analyzed water demand for irrigators north of Los Angeles, CA. The choice of outputs is quite different from those in this thesis, but the data and methods have importance. They used panel data, which provided a richer dataset for analysis than the data used by Moore, Gollehon, and Carey. The variation in water price for Moore, Gollehon, and Carey was due to cross-sectional variation of depth-to-water and irrigation technology. Schoengold, Sunding, and Moreno utilized a

Tobit model to estimate the land allocation function, and an instrumental variables (IV) analysis to estimate water demand. The IV analysis accounted for the endogeneity of land allocation in the water demand function. Crop acreage and irrigation technologies were paired as a set of dependent variables to also account for the effect of a change in water price on irrigation technology choice.

Schoengold, Sunding, and Moreno estimated the direct and indirect effects water price has on water use. This is parallel to the intensive and extensive margin effects, respectively, discussed by Moore, Gollehon, and Carey. They computed direct elasticities of demand between -0.22 and -0.382, which were significant at the 1% level. The indirect elasticity of demand was -0.51; therefore, indirect effects accounted for 60% of total elasticity of demand. Compared to previous estimates, this estimated water demand as much more elastic and had a much larger share of the total effect coming from the direct effects. One limitation of this study is that precipitation was not accounted for in the water demand equation.

3.2 PROGRAMMING DEMAND STUDIES

Buller and Williams studied the effect of natural gas prices and commodity prices on the amount of water pumped by irrigators. They used a linear programming model for a representative farmer in western Kansas, which incorporated different irrigation schedules for each of the modeled crops as separate activities. Natural gas prices varied between $.50/Mcf to $9.00/Mcf to provide insight to the largest range of gas prices foreseeable. For each of the gas prices they also used low and high commodity prices.[1] Buller and Williams' results showed that irrigated corn acres began to sharply decline when natural gas prices exceeded $2.00/Mcf. They also found that water demand decreased with increases in natural gas prices, and that demand was more responsive to energy costs with low commodity prices.

Howitt, Watson, and Adams argued that linear programming models underestimate demand elasticities and proposed a quadratic programming model. They estimated elasticities using a statewide model of California agriculture. They estimated arc elasticities of -1.50 and -0.46 for water prices of $25-35/acre-foot and $35-45/acre-foot, respectively. Therefore, they found relatively elastic demands, but that water demand became less elastic and eventually inelastic as water price increased.

Schaible evaluated the efficacy of water-price policy reform in the Pacific Northwest. He argued that due to the high cost of increasing irrigated acreage and limits of infrastructure and policy, land and water should be evaluated as fixed, allocatable inputs. Schaible used a multistage, multi-output, normalized profit-maximization programming model approach. Scenarios were run where farmers were allowed to substitute groundwater for surface water and where farmers were restricted from substitution. Estimated demand elasticities were very inelastic, but elasticities were typically larger for alfalfa and small grains. He also evaluated changes in water use and net farm returns from an increase in surface water price by 10, 25, 50, and 75 percent. Generally, Schaible found that water-price policy reform would be an ineffective policy option at reducing water use and would have an adverse effect on farmers' incomes.

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[1] Low prices for wheat, corn, and sorghum were $2.44/bu, $1.96/bu, and $1.86/bu, respectively. High prices for wheat, corn, and sorghum were $3.86/bu, $2.60/bu, and $2.45/bu, respectively.

Schaible also recognized regional differences in water sources, crop production options, and water management institutions; therefore, he recommended region specific analysis of water-price policy.

3.3 OTHER RELEVANT STUDIES

Peterson and Ding studied the effect of irrigation efficiency on gross irrigation. They empirically estimated their model using corn yield data generated by an agronomic simulation model formulated for western Kansas. They also incorporated risk and well capacity into their model. They estimated a Just-Pope production function for corn where water impacts the mean and variance of yield. However, they found that variation in water use explained only a small proportion of yield risk.

Under all scenarios of risk and well capacities, gross irrigation decreased when the producer converted from flood to sprinkler or drip irrigation. Although per acre irrigation increased when converting from flood to sprinkler, the reduction in acres had an overall decreasing effect on gross irrigation.

Lichtenberg estimated the effect of land quality, crop prices, and irrigation system costs on crop-choice in western Nebraska from 1966-80. He estimated the effects with a log odds multinomial logit model using a quadratic specification. Lichtenberg recognized the high correlation of crop prices, so he only included futures corn price to explain output price for all crops; however, he did distinguish the price of hay. Lichtenberg found that land quality has a very significant effect on crop-choice and that there is typically a range of land quality each crop is planted on, which was captured with the quadratic term. As crop price increased, acreage of corn, soybeans, and small grains increased, while sorghum acres decreased.

Peterson and Bernardo reviewed the literature on crop and irrigation schedule selection. Three of the studies they reviewed are briefly summarized here. Hornbaker and Mapp found that the optimal irrigation schedule for LEPA (Low Energy Precision Application) technology resulted in less water use than high pressure and low pressure center pivot systems. Chenlaw, Featherstone, and Buller studied how crop allocation is affected by the amount of groundwater available for irrigation per year. They found that as the supply of water decreases, acres are shifted out of corn production into dryland sorghum, but corn and sorghum were the only crop alternatives provided. Llewelyn, Williams, and Diebel found a similar result that alfalfa was substituted for corn when water supply decreases. They also found that crop allocation can be responsive to different policy scenarios.

3.4 CONCLUSIONS

Moore, Gollehon, and Carey provided a useful framework for modeling a producer's decision-making process using econometric techniques. An advantage of econometric techniques is their grounding to detailed data on producers' actual responses to price changes in different situations. The challenge is to have data on enough other variables that account for differences in water use. The advantage of mathematical programming models is that they directly represent the responses of a theoretical optimizing decision-maker. However, they sometimes make predictions of land use at odds with observed data, most likely because some elements of the decision process cannot be represented in the model. Moore, Gollehon, and Carey found that farmers are not very responsive to water price in the short-run. However, their conclusion that a fixed, allocatable input model was best may not apply to the situation of groundwater irrigation in western Kansas. This assumption does not hold for most irrigation decisions in this region because a farm-level water constraint does not exist.

Schoengold, Sunding, and Moreno found a more elastic demand using econometric techniques. They also found a significant effect at the intensive margin of use, contrary to previous studies. One key advantage of their study was the use of panel data analysis.

The studies reviewed above produce varying estimates of water demand elasticities. Scheierling, Loomis, and Young studied demand elasticities of irrigation water using a meta-analysis. They included 24 studies from 1963 to 2004, resulting in 73 price elasticity estimates. They found a mean price elasticity of 0.48 (in absolute terms) and median elasticity of 0.16. But the standard deviation (0.53) was large and the elasticities ranged from 0.001 to 1.97. Price elasticity was the dependent variable in a weighted least squares regression that used characteristics of the empirical method and data to explain variations in elasticity estimates. They found that results from mathematical programming and econometric studies give more elastic results than those from field experiments. However, there did not appear to be much of a difference between mathematical programming and econometric studies. A higher price of water used in the model resulted in more elastic estimates. They also found that studies involving high-value crops, such as fruits and vegetables, yielded more inelastic demand elasticities. Allowing producers to change irrigation technology or scheduling in the study did not significantly affect estimates. Long run demand estimates were more elastic, but were not statistically different from short run demand estimates. Aggregate data, at the regional or state level, as opposed to field or farm-level data gave more inelastic estimates.

Results from Scheierling, Loomis, and Young suggest the need for further research to estimate the demand elasticity for irrigation water. A wide range of demand elasticities have been estimated, so policy analysis will need region-specific estimates and a range of methods to fully understand how producers may react to changes in water prices.

CHAPTER 4 - THEORETICAL MODEL

A profit maximizing theoretical framework is proposed to guide the empirical estimation of irrigation water demand. It is assumed that irrigation water is a variable, allocatable input, but the presence of nonallocatable inputs is recognized in the model. Nevertheless, due to the assumption that profit is linearly related to acreage, allocatable input demands are a function only of their own crop prices. Given the framework, a method for deriving the intensive and extensive marginal effects is shown. Finally, a proof is given, using duality theory, that the total extensive marginal effect is negative.

4.1 DERIVING INPUT DEMANDS

A producer seeks to maximize profit on each parcel of land in a multioutput setting.[1] The producer's decision is two-fold, involving choices about which crops (outputs) to grow as well as the optimal levels of crop inputs. The producer is constrained by the fact that the sum of acres allocated to each crop cannot exceed the total acres on the parcel of land. This implies land is a fixed allocatable input. The producer's constrained profit maximization problem can be formulated as

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[1] For purposes here, a parcel is defined as a field, or a contiguous area of land on which a single crop is normally grown. A limitation of this model is that farm-level constraints and attributes (such as other operations creating economies of scope) are not considered. However, for fields irrigated from the Ogallala, it is not unreasonable to assume that each field is regarded as a distinct production unit because water is seldom transported across fields. In any case, a field-level formulation is necessary to conform with the available data, as discussed in detail in chapter 6.

(4.1) $$\max_{\{L_j, w_j, z\}} \Pi = \sum_{j=1}^{J} L_j \left(p_j y_j - r_w \cdot w_j - r_z \cdot z \right)$$

Subject to:

$$\overline{L} = \sum_{j=1}^{J} L_j$$

where Π is the profit of the parcel of land, subscript j represents crops, where there are J crop choices, p is output price, y is output quantity per acre, r_w is an input price vector corresponding to w, w is a vector of allocatable inputs including quantity of water applied per acre, r_z is an input price vector corresponding to z, z is a vector of nonallocatable inputs, $\overline{L}$ is the number of acres in the parcel, and L_j is the number of acres allocated to crop j. Furthermore, it is assumed that yield is of the form

(4.2) $$y_j = f_j \left(w_j, z, \gamma, v \right)$$

where γ is a vector of exogenous characteristics of the parcel of land such as soil characteristics, hydrological characteristics, and weather conditions, which do not depend on crop choice, and v is a vector of unobservable variables such as producer preferences and management practices.

Irrigation water, which is included in the vector w, is viewed as an allocatable input. This is a disputed topic in the literature, with some arguing more recently that water is best regarded as a fixed allocatable input (Moore, Gollehon, and Carey 1994a). A fixed allocatable formulation makes sense in many farm-level surface water applications, where farmers have a fixed amount of water available to allocate among the crops on their farm. This formulation is also appropriate in groundwater studies where the farmer is constrained in the amount of water he can pump due to hydrological constraints. However, in western Kansas agriculture the water constraint would not be at the farm-level, but at the parcel-level because the constraint reflects the pumping capacity of the well servicing a particular parcel, not the available supply of water for the whole farm. This will become an increasingly appropriate formulation of the issue as the aquifer is depleted; an increase in multiple crops grown on individual parcels will be an indication of this occurring.

However, at this time most farmers in western Kansas are capable of pumping more water than is needed for any of the observed crops. Therefore their decision of how much water to pump is still affected by the price of water. Peterson and Ding found that if an irrigator in western Kansas has a well capacity of 500 gallons per minute (gpm) to irrigate a 160-acre field (the most common field size in western Kansas), then the well capacity is rarely constraining on the optimal quantity of irrigation of corn. Additionally, they demonstrate that legal limits on the amount of water a producer can pump are rarely constraining. In the sample data available, only 13 percent of the observations reported a well capacity less than 500 gpm.

The vector of allocatable inputs, *w*, also includes inputs such as fertilizer and insecticides, which require different usage depending on the crop-choice. Meanwhile, the vector of nonallocatable inputs, *z*, are inputs which are the same no matter which crop is grown, such as land rent and machinery.

The Lagrangian function (Λ) for problem (4.1) is

$$(4.3) \quad \Lambda = \sum_{j=1}^{J} L_j \left(p_j y_j - r_w \cdot w_j - r_z \cdot z \right) + \mu \left(\overline{L} - \sum_{j=1}^{J} L_j \right)$$

where μ is the Lagrange multiplier on the land constraint.

The First Order Conditions (FOCs) with respect to w_j, z, and μ are:

$$(4.4)\qquad \frac{\partial \Lambda}{\partial w_j} = L_j\left(p_j f_{wj} - r_w\right) = 0 \qquad \forall j = 1 \ldots J$$

$$(4.5)\qquad \frac{\partial \Lambda}{\partial z} = \sum L_j\left(p_j f_{zj} - r_z\right) = 0$$

$$(4.6)\qquad \frac{\partial \Lambda}{\partial \mu} = \overline{L} - \sum L_j = 0$$

where f_{wj} is the vector of first derivatives of f_j with respect to the elements of w, and f_{zj} is the vector of first derivatives of f_j with respect to the elements of z. Because profit is linearly related to land allocation, the optimal condition for L_j takes a binary form. The derivative of Π with respect to L_j is a constant, $p_j y_j - r_w \cdot w_j - r_z \cdot z$, which is simply the profit per acre of crop j. Let π_j denote the profit per acre of crop j. In this model, π_j is assumed constant within each parcel of land, reflecting negligible within-field variation in soil characteristics. The optimal land allocation, L_j^*, can be written

$$(4.7)\qquad L_j^* = \begin{cases} \overline{L} & , \text{ if } \pi_j \geq \pi_k \quad \forall k = 1 \ldots J \\ 0 & , \text{ otherwise} \end{cases}$$

Let $j*$ denote the most profitable crop, so that $L_{j*}^* = \overline{L}$. Substituting (4.7) into equation (4.5) gives $p_j f_{zj*} = r_z$, which is the condition that the values of marginal products of the inputs in z on crop $j*$ are equal to the corresponding prices of those inputs, r_z. Substituting (4.7) into equation (4.4) produces a similar result.

These equations can then be solved for the factor demands on the optimally chosen crop, j*:

$$(4.8)\qquad w_{j*}^* = w_{j*}\left(p_{j*}, r_w, r_z, \gamma, v\right) = w_{j*}\left(x_{j*}, v\right)$$

(4.9) $z^* = z\left(p_{j*}, r_w, r_z, \gamma, v\right) = z\left(x_{j*}, v\right)$

That is, factor demands are only defined for the crop actually selected. Substituting the optimal factor demands into π_j gives the indirect profit per acre function for this crop.

(4.10) $\pi^*_{j*} = \pi_{j*}\left(p_{j*}, r_w, r_z, \gamma, v\right) = \pi_{j*}\left(x_{j*}, v\right)$

For simplicity of notation, x_j, is the vector of output price of crop *j*, input prices, and other characteristics embodied in γ.

One important result is that factor demands for a crop are a function only of its own output price. Typically in a multioutput profit maximization problem with allocatable and nonallocatable factors, factor demands are a function of all output prices because the production functions are linked by the nonallocatable factor (Beattie and Taylor). However, the results differ here because of the presence of corner solutions for land allocation on a parcel of land.

The factor demands are actually the same for this model as the variable input model. The difference is that this model acknowledges the presence of nonallocatable inputs. However, due to the evaluation of the issue at the parcel-level and resulting corner solutions for land allocation, the model yields the same factor demands. If the model were evaluated at the farm-level, factor demands would be a function of all output prices.

4.2 DERIVING INTENSIVE AND EXTENSIVE MARGINAL EFFECTS

Therefore, an irrigator's decision problem is most usefully regarded as a two-staged problem, where the crop (a discrete variable) is chosen in the first stage, and water applied to this crop (a continuous variable) is chosen in the second stage.

In stage one, crop *j* is optimally chosen ($j = j^*$) if

(4.11) $\pi_j \geq \pi_k \qquad \forall k = 1 \ldots J$.

From the perspective of an outside observer, to whom the elements of *v* are random variables, there is no certainty that a particular crop will be grown given the vector of observed variables, *x*. Rather, crop choices must be represented probabilistically. The probability that crop *j* is chosen is the probability that condition (4.11) holds, which can be represented with a probability mass function. More formally, this is written

(4.12) $\text{Prob}(j = j^*) = \delta_j(x) \qquad \forall j = 1 \ldots J$

where δ is the probability mass function of crop *j*, and *x* is a vector containing all the elements in the x_j's. Therefore, the ex ante version of equation (4.7) is

(4.13) $L_j^* = \delta_j(x)\overline{L}$

Total water use on a parcel of land, *W*, is

(4.14) $W = \sum L_j^* w_j^*$

To find how total water use changes as an exogenous variable, θ, changes, the function *W* is differentiated with respect to θ. This is complicated by the fact that L_j^* as defined in equation (4.7) is not a differentiable function. However, L_j^* as defined in equation (4.13) is a differentiable function. Substituting equation (4.13) into equation (4.14) gives

(4.15) $W = \sum \delta_j(x)\overline{L}w_j^* = \overline{L}\sum \delta_j(x)w_j^*$, and

differentiating with respect to θ gives

(4.16) $\dfrac{\partial W}{\partial \theta} = \overline{L}\sum\left(\delta_j \dfrac{\partial w_j}{\partial \theta} + \dfrac{\partial \delta_j}{\partial \theta} w_j\right) \qquad \theta \in x_j \quad \forall j = 1 \ldots J$.

However, it may be more appropriate for interpretation to obtain the effect of a change in an exogenous variable on the water use per acre, $w = W/\overline{L}$.

$$(4.17) \quad \frac{\partial w}{\partial \theta} = \sum \left(\delta_j \frac{\partial w_j}{\partial \theta} + \frac{\partial \delta_j}{\partial \theta} w_j \right) \qquad \theta \in x_j \quad \forall\, j = 1 \ldots J$$

The first term on the right hand side of equation (4.17) is the change at the intensive margin and the second term is the (ex ante) change at the extensive margin. When θ is the price of water, the intensive margin change is the short-run, direct effect on water use from an increase in the price of water after crop selections have been made. A change in water use at the intensive margin results from improved irrigation management practices or perhaps simply reducing the amount of water applied to the crop. The intensive margin effect should be negative for each crop by the law of demand.

The extensive margin effect is the long-run response of water use from changing cropping patterns. The extensive margin effect is the change in probability of planting a crop from a change in water price, weighted by the amount of water applied to the crop. The extensive margin effect will be positive for some crops and negative for others, which is evident because the marginal probabilities must sum to zero. However, the sum of the extensive marginal effects across all crops need not equal zero because of the weighting by water use. It is possible for the water use on a given crop to increase if the sum of the intensive and extensive margin effects is positive. However, the assumptions of convexity of the profit function in input prices requires that the overall impact of an increase in water price decreases water use, that is $\frac{\partial w}{\partial r} < 0$. Moreover, as proven for the two-crop case in the section below, the overall extensive margin effect will be negative:

$$\sum \frac{\partial \delta_j}{\partial \theta} w_j < 0 .$$

4.3 PROOF THAT THE EXTENSIVE MARGINAL EFFECT IS NEGATIVE

It can be proven simply by contradiction in the two output case with a single allocatable input, *w*, that the total extensive marginal effect is negative. Assume that crop 1 is more water intensive than crop 2. This means the per acre water allocation to crop 1 is greater than the per acre allocation to crop 2, $w_1^* > w_2^*$. Also assume that crop 2 is initially more profitable than crop 1, $\pi_2^* > \pi_1^*$; the solution to the land allocation is then $L_2^* = \overline{L}$ and $L_1^* = 0$.

Under the maintained assumption that $f_1(w_1)$ and $f_2(w_2)$ are concave functions, if input price increases and the same crop is chosen then input use must decrease (the intensive margin effect is negative). Therefore, for input use to increase with an increase in input price, *r*, the first condition is that crop-choice must change from crop 2 to crop 1. The reduction in profit of crop 2 from an increase in *r* must be larger (more negative) than the reduction in crop 1. Furthermore, the difference in reduction of profits must be greater than the original difference in profits, thus making crop 1 more profitable than crop 2. Mathematically, this condition is written $\frac{\partial \pi_1^*}{\partial r} - \frac{\partial \pi_2^*}{\partial r} > \pi_2^* - \pi_1^* > 0$.

The second condition is that the new input use on crop 1 must exceed the original input use on crop 2. The original optimal water allocation plus the reduction in input use from an increase in *r* must be greater than the original input use on crop 2. This is written

$w_1^* + \frac{\partial w_1^*}{\partial r} > w_2^*$. If either of these two conditions is proven to not hold then $\frac{\partial w}{\partial r} < 0$ must hold.

An application of Hotelling's Lemma proves quickly that $\frac{\partial \pi_1^*}{\partial r} > \frac{\partial \pi_2^*}{\partial r}$ is not possible, given the assumptions.

(4.18) $$\frac{\partial \pi_1^*}{\partial r} = -w_1^* > -w_2^* = \frac{\partial \pi_2^*}{\partial r}$$

(4.19) $$\Rightarrow w_1^* < w_2^*$$

The conclusion in equation (4.19) contradicts the initial assumption that $w_1^* > w_2^*$. Therefore, $\frac{\partial \pi_1^*}{\partial r} > \frac{\partial \pi_2^*}{\partial r}$ is not possible, and therefore the conclusion is that $\frac{\partial w}{\partial r} < 0$.

Therefore, the overall value of the extensive margin effect summed across all crops is negative. An important implication of this result is that if the extensive margin effect is not accounted for in research, then demand response will be underestimated (in absolute terms). That is

(4.20) $$\left|\frac{\partial w}{\partial r}\right| > \left|\sum\left(\delta_j \frac{\partial w_j}{\partial r}\right)\right|$$

CHAPTER 5 - EMPIRICAL MODEL

A multinomial logit selectivity model is proposed to estimate irrigation water demand. The multinomial logit model is used to estimate the crop-choice decision in stage one of the problem. The use of the multinomial logit model is defended, and methods of evaluating the model are discussed. Then, accounting for selectivity, a modified ordinary least squares regression model to estimate irrigation water demand is presented. Finally, the method of computing the intensive and extensive marginal effects is explained.

5.1 EMPIRICAL ESTIMATION OF CROP-CHOICE

The theoretical chapter demonstrated that the crop-choice decision in stage one is best represented as a discrete choice probability, where the probability of planting crop j depends on a vector, x, of independent variables. The elements of x include all crop prices, input prices, energy prices, and location specific factors. These same variables affect the water-use decisions in stage two, but the exact definitions of the variables will differ because of the sequential timing of the decisions. For example, the expected value of energy prices during the irrigation season, formulated when the crop-choice is made, is the relevant measure in stage one, while the observed within-season energy price is the appropriate measure corresponding to stage two. For this reason, the empirical specification makes a distinction between the independent variables in the two stages, where $\tilde{x}$, which contains expected prices and expected climate conditions, denotes the independent variables in stage one, and x denotes the regressor vector in stage two.

For estimation purposes, the crop choice decision is modeled with the multinomial logit model, where the probability function in equation (4.12) is specified as (Greene 1993)

$$(5.1) \quad \delta_{ij} = \frac{e^{\alpha'_j \tilde{x}_i}}{\sum_{k=0}^{J-1} e^{\alpha'_k \tilde{x}_i}} \qquad \forall\, j = 0 \ldots J-1$$

where α_j is a vector of parameters to be estimated and *i* denotes each individual parcel of land. A standard normalization in the multinomial logit model is $\alpha_0 = 0$. Therefore, when j=0, the probability in (5.1) simplifies to

$$(5.2) \quad \delta_{i0} = \frac{1}{\sum_{k=0}^{J-1} e^{\alpha'_k \tilde{x}_i}}$$

(Note that *j* starts at 0 instead of 1 in the notation above for estimation purposes.)

Intuitively, the probability function should be homogenous of degree 0 in prices, so that if all prices double, the probability of planting each crop would remain the same. To force this property on the function, prices are normalized. Quadratic terms of prices are also included in the estimation to allow for nonlinear price responses. The quadratic price terms are simply squared normalized prices. This specification is homogenous of degree 0 as demonstrated in equation (5.3), where for simplicity *x* is taken to include only output prices, *p*, and input prices r_w, along with their squares, *t* is some constant, and *r* is an input price (excluded from r_w) used to normalize all prices.

$$(5.3) \quad \delta_j\left(\frac{p}{r}, \frac{r_w}{r}, \frac{p^2}{r^2}, \frac{r_w{}^2}{r^2}\right) = \delta_j\left(\frac{tp}{tr}, \frac{tr_w}{tr}, \frac{(tp)^2}{(tr)^2}, \frac{(tr_w)^2}{(tr)^2}\right)$$

The method of maximum likelihood is used to estimate the parameters of the multinomial logit model. The maximum likelihood method chooses a set of parameters to maximize the likelihood that the actual choices, represented in the dependent variable, would actually occur given the set of independent variables facing the producer (Pindyck and Rubinfeld). The joint probability or likelihood (*L*) for *J* choices is

$$(5.4) \qquad L = \prod_{i=1}^{n} \prod_{j=0}^{J-1} d_{ij} \delta_{ij}$$

for each parcel of land *i* with a total of *n* parcels, and where *d* is a binary variable equal to 1 if crop *j* was planted on parcel *i* and 0 otherwise. Taking the log of this equation yields the log likelihood function

$$(5.5) \qquad \ln L = \sum_{i=1}^{n} \sum_{j=0}^{J-1} d_{ij} \delta_{ij}$$

The log likelihood function yields a more tractable expression to optimize, and the points of maximization for the two functions are equivalent, so the log likelihood is preferred for estimation purposes. A typical optimization algorithm to find coefficients that maximize the value of ln *L* is Newton's method (Greene 1993). The maximum likelihood estimator is consistent, asymptotically normally distributed, and asymptotically efficient (Greene 1993).

As noted above, the coefficients for the equation when j=0 are normalized to all equal 0. This normalization, which accounts for the property that the probabilities for a set of independent variables must sum to 1, allows the model to only estimate *J*-1 equations rather than *J* equations. Another alternative would be to estimate all *J* equations and then restrict the *J* sets of coefficients so that the probabilities sum to 1. However, the $\alpha_0 = 0$ normalization saves computational time. This application of the multinomial logit model is similar to that of Lichtenberg as described in the literature review.

5.1.1 Marginal Effects

The coefficients of the independent variables estimated by the logit model do not have a straightforward interpretation like the slope coefficients of the OLS (Ordinary Least Squares) regression model. Therefore, to find the marginal effect of changes in independent variables, the following equation must be used (Greene 1993):

$$(5.6) \qquad \frac{\partial \delta_j}{\partial \tilde{x}} = \delta_j \left[\alpha_j - \sum_{k=1}^{J} \delta_k \alpha_k \right] \qquad \forall\, j = 0 \ldots J-1$$

When *j*=0 then the marginal effect is

$$(5.7) \qquad \frac{\partial \delta_0}{\partial \tilde{x}} = -\delta_0 \sum_{k=1}^{J} \delta_k \alpha_k$$

The marginal effect $\partial \delta_j / \partial \tilde{x}$ is interpreted as the change in the probability of outcome *j* resulting from a one-unit increase in $\tilde{x}$, given the set of values of the independent variables. The marginal effects depend on the probabilities, which depend nonlinearly on all independent variables, implying that the marginal effects are not constant. To facilitate comparison across regressors, the probabilities and marginal effects are often computed at the means of the independent variables. However, it is also of interest to vary the independent variables and examine how the probabilities and marginal effects change.

The marginal effects are further complicated by the fact that the characteristics in $\tilde{x}$ include quadratic terms. To compute marginal effects, the term $\alpha_j \tilde{x}$ in equations (5.1) and (5.2) can be represented more generally as some function $q_j(\cdot)$. Then it can be shown that more general forms of equations (5.6) and (5.7) are

$$(5.8) \qquad \frac{\partial \delta_j}{\partial \tilde{x}} = \delta_j \left[\frac{\partial q_j}{\partial \tilde{x}} - \sum_{k=1}^{J} \delta_k \frac{\partial q_k}{\partial \tilde{x}} \right] \qquad \text{for } j=1 \ldots J\text{-}1$$

and when j=0 the marginal effect is

(5.9) $$\frac{\partial \delta_0}{\partial \tilde{x}} = -\delta_0 \sum_{k=1}^{J} \delta_k \frac{\partial q_k}{\partial \tilde{x}}$$

Elasticities, ω, for the crop-choice are computed as

(5.10) $$\omega = \frac{\partial \delta_j}{\partial \tilde{x}} \tilde{x}$$

where $\tilde{x}$ is the value of the independent variable at which the probability is computed.

5.1.2 Hypothesis Testing

To test if an individual independent variable is significantly impacting the log likelihood function, the standard t-test is applied just as in the Ordinary Least Squares (OLS) regression models (Greene 1993). The null hypothesis of the test is that the single coefficient is equal to zero. If the null hypothesis is rejected, then the coefficient is statistically significantly different from zero.

There are three key statistics that measure whether multiple independent variables are significantly making an impact on the log likelihood function: the likelihood ratio (LR) statistic, the Lagrange multiplier (LM) statistic, and the Wald test. These three tests are asymptotically equivalent, so if the sample size is sufficiently large they will all yield the same statistic with the same result. However, the tests could potentially yield different results if the sample size is small. The Wald test will always give the largest test statistic and the LM statistic will always be the smallest. Therefore, if the test is rejected for the LM statistic then the test is rejected for the LR and Wald tests also (Pindyck and Rubinfeld).

The LR, LM, and Wald tests are analogous to the F-test in the OLS regression. These three statistics test the null hypothesis that all the coefficients in the logit model are jointly equal to zero. If the null hypothesis is rejected then at least one of the coefficients is not equal to zero. If the model fails to reject the null hypothesis then the model is poorly specified as the independent variables are not making a significant difference in likelihood. The three tests can also be used to test if a subset of coefficients in the model is jointly equal to zero. The test statistics are distributed according to the chi-squared distribution with degrees of freedom equal to the number of restrictions being tested (Greene 1993).

5.1.3 Goodness of Fit Measures

Three common measures have been proposed to indicate the goodness of fit of a multinomial model. However, the statistics do not have a precise interpretation like the OLS R^2 measure. Nonetheless, they do provide some insight into the model's predictive capacity and are especially helpful when comparing across models. The three measures are the count R^2, McFadden's R^2, and the pseudo R^2. Each of the statistics is bounded between 0 and 1, similar to the OLS R^2 (Maddala).

The simplest measure is the count R^2. It is defined simply as

$$(5.11) \quad \text{count } R^2 = \frac{\text{number of correct predictions}}{\text{total number of observations}}$$

However, Train discourages the use of this statistic. Train states, "This statistic incorporates a notion that is opposed to the meaning of probabilities" (p. 73). The count R^2 assumes that the decision-maker chooses the option with the highest probability. Probability, by definition though, is the proportion of outcomes for a given alternative with numerous repetitions of a situation. Even if an alternative has a very low probability, given enough repetitions we would still expect to see the outcome (Train).

McFadden's R^2, also known as the likelihood ratio index (LRI), is

$$\text{(5.12)} \quad \text{McFadden's } R^2 = 1 - \frac{\ln L_U}{\ln L_R}$$

where ln L_U and ln L_R are the maximum values of the log-likelihood functions in the unrestricted and restricted models, respectively. Here, the restricted model is the null model where all coefficients are equal to zero. Unlike the OLS R^2, McFadden's R^2 cannot equal 1, so an extremely large value may be an indication of a misspecified model rather than a perfect fit (Greene 1993).

Cragg and Uhler propose a pseudo R^2 (Maddala).

$$\text{(5.13)} \quad \text{pseudo } R^2 = \frac{L_U^{2/n} - L_R^{2/n}}{\left(1 - L_R^{2/n}\right) L_U^{2/n}}$$

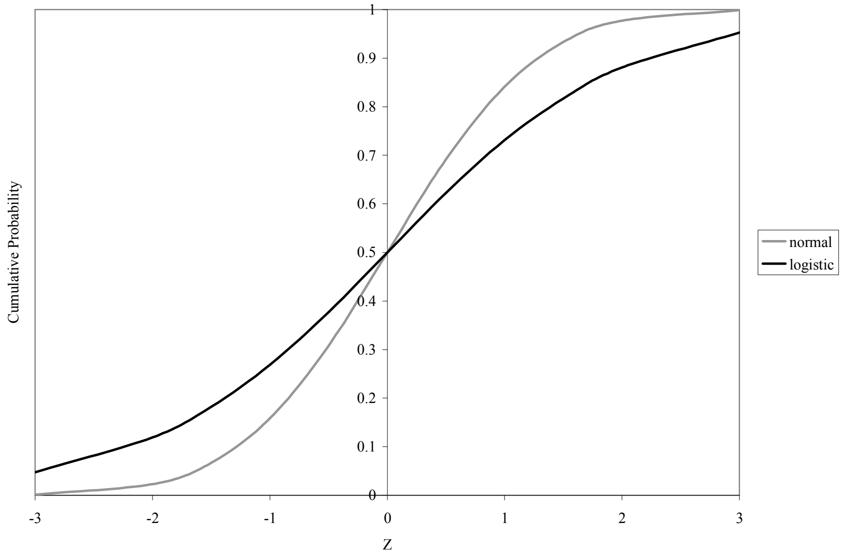
The pseudo R^2 is derived as an analogous measure of the R^2 for maximum likelihood estimation of a continuous dependent variable regression and can equal values from 0 to 1 (Maddala).

5.1.4 Logit versus Probit

The logit model is based on the cumulative logistic probability function. An alternative specification is the probit model, which is based on the cumulative normal distribution. These models are easiest to compare in the case when there are only two discrete choices (i.e., j=0,1). Figure 5.1 shows the differences in the cumulative probability distributions of choosing j=1 over j=0. The x-axis is labeled Z, which is the value of the vector of estimated coefficients multiplied by the vector of independent variables, $\alpha'_j x_i$. Z is then transformed by equation (5.1) into a cumulative probability according to the logistic probability function. So even though the parameters to be estimated, α_1, are linear coefficents on the $\tilde{x}_i$'s, the probabilities are not linearly related to the independent variables as demonstrated in Figure 5.1 (Pindyck and Rubinfeld).

Figure 5.1 shows that the probability is most sensitive to changes in Z when the probability is near half. Conversely, when the model yields high or low probability predictions for the independent variables, then the model is less sensitive to changes in variables.

Figure 5.1 Cumulative Probability Densities of Normal and Logistic Functions



Source: Pindyck and Rubinfeld

The differences in the probit and logit models are evident from Figure 5.1 because of the distributions on which they base their estimations. The cumulative logistic probability is more sensitive to changes in the independent variables when probabilities are very high or low compared to the normal distribution. On the other hand, the cumulative normal distribution is more sensitive to changes in independent variables when the probability is close to half.

A series of simple, binomial probit models could be used to estimate farmers' decisions to plant each crop individually as used in Moore, Gollehon, and Carey (1994b). However, it is a closer representation to model a farmer's decision as one of choosing which crop to plant from among several alternatives, rather than choosing whether or not to plant each particular crop. Furthermore, the sum of the probability of planting each crop is not constrained to equal one when using binomial probit models for each crop. With the multinomial logit model, the sum of probabilities across all crops equals one and the sum of marginal effects across crops equals zero. This property of the multinomial logit model is an appropriate constraint for decision-behavior and is convenient for calculating intensive and extensive marginal effects.

Multivariate probit models are used to estimate models with numerous decisions, but each decision has only two alternatives. However, the multinomial logit model is used to estimate a model of one decision with more than two alternatives (Greene 1993). Given the issue of this paper, clearly the multinomial logit model is the appropriate choice. Each farmer makes a single decision of which crop to plant, and that decision is among all the possible crops.

5.1.5 Assumption of Independence of Irrelevant Alternatives

The multinomial logit model assumes the "independence of irrelevant alternatives," which is clearly a limitation in modeling farmers' behavior. Wu and Babcock state, "This assumption states that the relative choice probabilities for any two alternatives are independent of the other choices available. This is a convenient property with regards to estimation, but it is often an unappealing restriction to place on farmer behavior" (p. 496). In spite of alternative discrete choice specifications that relax this assumption, the multinomial logit model is used due to current econometric limitations with selectivity models (Wu and Babcock).

5.1.6 Multinomial versus Conditional

Another possible specification for estimation is the conditional logit model. The probability function for the conditional logit model is (Greene 1993)

$$(5.14)\quad \delta_j = \frac{e^{\alpha'\tilde{x}_j}}{\sum_j e^{\alpha'\tilde{x}_j}}$$

The conditional logit model is appropriate when the independent variables are choice specific, rather than individual specific (Greene 1993), hence the regressors are indexed by j instead of i. In the conditional logit model the independent variables are specifically related to the particular choice. The observed independent variables may differ across individuals, but only to the extent to which they are embodied in the individuals' choices. Individual-specific variables that do not vary with the choice made are not included. Here, only one vector of coefficients is estimated, α, which relates the attributes of given choice, $\tilde{x}_j$, to the probability that it is selected.

In the context of crop decisions, the conditional logit model would be appropriate if the independent variables were variables like input use and output measures, which are specific to the crop. However, in the modeling framework described above, the multinomial logit model is the proper choice because the independent variables are specific to the individual. Each individual has his/her own soil and climate characteristics on which they base their decision.

It is more difficult to decipher if the vector of crop and input prices is crop-specific or individual-specific. All individuals do face the same price vectors each year.

However, there is not a single measure for crop price that varies across choices as would be the case for a conditional logit framework. Instead, individuals face all crop prices and these prices affect the decision to plant each crop. The price of corn affects the probability of whether a farmer chooses to produce alfalfa or not. Input prices are the same across all crop decisions, so that the farmer will pay the same amount per unit of water whether he/she plants corn or soybeans. Conversely, if water usage of the crop were the independent variable then the farmer would face a different amount of water use for each crop and a conditional logit model would be more appropriate.

5.2 EMPIRICAL ESTIMATION OF WATER DEMAND

The estimation of optimal water use for a given crop is specified as

$$w_j = g_j(x_j; \beta_j) + \eta_j(v) \tag{5.15}$$

where β_j is a vector of parameters to be estimated and η_j is regarded as a random disturbance. The function $g_j(\cdot)$ is linear in normalized prices assuming a quadratic production function as supported by the literature (Schoengold, Sunding, and Moreno). Normalizing prices gives the appropriate theoretical property that input demand is homogenous of degree 0.

Estimation of equation (5.15) is complicated by a sample selection problem. This problem arises because the sample to estimate β_j consists only of observations where crop j was chosen. If η_j and ε_j are correlated, OLS estimation of (5.15) will produce biased estimates of β_j because $E[\eta_j] \neq 0$. Intuitively, the problem is that the observations for crop j were likely generated by farmers who, for unobservable reasons, prefer that crop over alternatives (implying ε_j is large for these individuals). In the case where η_j is positively correlated with ε_j, the observed values of w_j will be larger, on average, than those in a purely random sample. Lee (1983) showed that

$$(5.16)\quad E[\eta_j] = -\rho_j\sigma_j \frac{\phi\left(\Phi^{-1}(\delta_j)\right)}{\delta_j}$$

where ρ_j is the correlation coefficient between η_j and a particular transformation of ε_j, σ_j is the variance of η_j, $\phi(\cdot)$ is the standard normal p.d.f., and $\Phi^{-1}(\cdot)$ is the inverse of the standard normal c.d.f.

Lee proposed a method to correct for sample selection by including an extra term in equation (5.15). The new term is derived from the predicted probabilities of the discrete choice model, and is constructed to ensure that the expected residual of the estimated equation is indeed zero. In particular, let $\hat{\alpha}_j$ be the estimated coefficients from equation (5.1). The predicted probability that crop *j* was chosen, $\hat{\delta}_j$, can then be obtained by inserting these coefficients into equation (5.1) and a new variable, λ_j, is constructed as $\lambda_j = \phi\left(\Phi^{-1}(\hat{\delta}_j)\right)/\hat{\delta}_j$. Unbiased estimates of β_j are obtained by applying OLS to the equation

$$(5.17)\quad w_j = g_j(x_j;\beta_j) + \kappa_j\lambda_j + e_j$$

where $E[e_j] = 0$ and κ_j is an additional coefficient to be estimated. Rejecting the null hypothesis $\kappa_j = 0$ indicates the presence of sample selectivity. For valid inferences to be made, however, the estimated standard errors of all parameters must be corrected. The correction procedure is described by Greene (1993) and Wu and Babcock.

Wu and Babcock also explain that selectivity models can suffer from a lack of robustness and multicollinearity if the variables in the multinomial logit model are the same as the variables in the linear regression. However, as noted above, the regressors in the two stages differ in their definitions. The multicollinearity and robustness issues are addressed in assessing the model performance in chapter 7.

5.2.1 Intensive and Extensive Marginal Effects

Moore, Gollehon, and Carey (1994b) were the first to econometrically estimate the intensive and extensive margin effects of water use. Schoengold, Sunding, and Moreno also estimated these effects. Both of these articles estimated a land allocation function with acres as a continuous function of water price, and a water demand function with water use as a function of acres and water price. This allowed for fairly straightforward estimation of the effects. However, as explained earlier, this data set does not allow for the estimation of a continuous land allocation function, so the intensive and extensive margin effects are defined slightly differently.

From equation (4.15)

$$(5.18)\quad w = \sum \delta_j w_j$$

where $\delta_j(x)$ takes on the specific functional form of the probability assumed in the multinomial logit model expressed in equation (5.1).

Differentiating *w* with respect to the price of water gives

$$(5.19)\quad \frac{\partial w}{\partial r_w} = \sum \left(\delta_j \frac{\partial w_j}{\partial r_w} + \frac{\partial \delta_j}{\partial r_w} w_j \right)$$

where the first term in the sum is the intensive margin effect and the second term is the extensive margin effect. The marginal effect of water price on the probability of planting crop *j* takes the form as given in equations (5.6) and (5.7). Intensive and extensive marginal effects for other variables, which are included in both the crop-choice and water use models, are analogously defined.

Because a multinomial logit selectivity model is used, the intensive and extensive marginal effects are calculated from a simultaneous equation system. Estimating crop-choice with the multinomial logit model provides convenient constraints for calculating the intensive and extensive marginal effects; the sum of probabilities across all crops equals one and the sum of marginal probabilities equals zero. Moore, Gollehon, and Carey (1994b) did not calculate marginal effects in a simultaneous equation system. Intensive marginal effects were derived from a water demand model estimated with the Heckman selectivity model and extensive marginal effects were calculated from a separate land allocation model estimated with the Tobit model. While their procedure produces unbiased estimates because their equations are diagonally recursive, there is a statistical efficiency gain from simultaneous estimation.

CHAPTER 6 - DATA

This chapter discusses the data used to estimate the model described in the previous chapter. The data are from a 25 county region in western Kansas that pumps groundwater from the Ogallala Aquifer. The uniqueness of these data is that they are at the parcel-level, which allows for more accurate estimation of the model. Furthermore, the data span 14 years (1991-2004), and during this time natural gas prices greatly increased. The left-hand side variable for crop-choice in the multinomial logit model is obtained from WIMAS (Water Information Management and Analysis System). Right-hand side variables in the logit model include: normalized expected alfalfa, corn, and natural gas prices; average precipitation and evapotranspiration from the Kansas Weather Library; land classification and permeability from NRCS (Natural Resource Conservation Service); irrigation technology dummy variables and well capacity from WIMAS; and a time trend. The left-hand side variables for water use per acre in the water demand regressions are from WIMAS. Right-hand side variables in the water use regressions include: normalized own crop and natural gas prices; precipitation and evapotranspiration from the Kansas Weather Library; permeability from NRCS; and irrigation technology dummy variables and well capacity from WIMAS. All prices are normalized by an Index of Prices Paid by Farmers obtained from NASS (National Agricultural Statistics Service).

6.1 WIMAS (WATER INFORMATION MANAGEMENT AND ANALYSIS SYSTEM)

The WIMAS dataset is obtained from the Kansas Water Office (KWO). The data are from annual reports that all water-right holders are required to submit to the Kansas Department of Agriculture-Division of Water Resources. The WIMAS dataset provides parcel-level data on the quantity of water pumped (in acre feet), number of acres irrigated, crop-choice, well capacity, and irrigation technology. A parcel, or field, is defined as the area irrigated by a single well, also referred to as a point of diversion in the WIMAS dataset. For analysis, total water use was converted to acre-inches and then divided by the total number of acres irrigated in each parcel, so water use is measured in acre-inches per acre. The well capacity is the pumping or flow rate (gallons per minute) reported by users. If well capacity was not reported in some years, yet it was reported in a previous year, it was assumed that well capacity was equal to the previous year.

Beginning in 1988, strengthened enforcement resulted in more farmers reporting their water use and improved the accuracy of the data, yet the type of irrigation technology was not requested on the report until 1991. Therefore, the dataset used in this analysis is from 1991 to 2004. Only observations for the following irrigation technologies were included in the analysis: flood, standard center pivot, and center pivot with low drop nozzles.[1] These are by far the most common technologies, so removing

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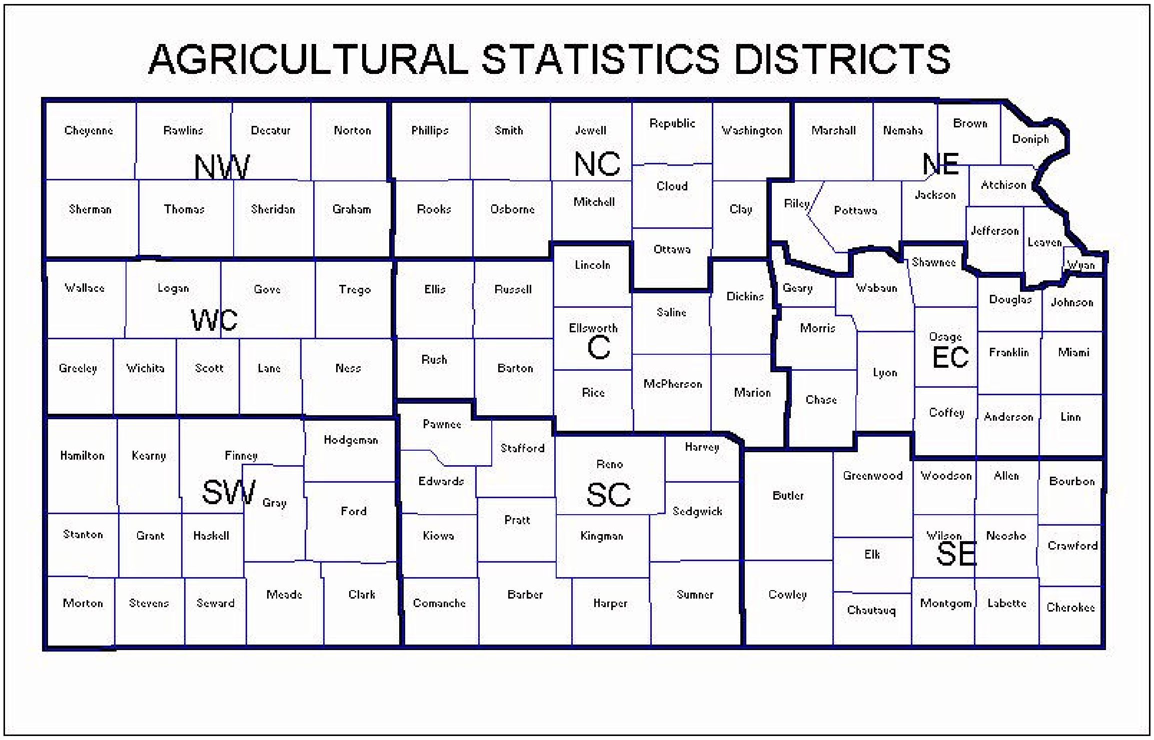
[1] Flood irrigation uses gravity to deliver water to the crops through ditches in the field rows. Center pivot with low drop nozzles is also commonly referred to as the Low Energy Precision Application (LEPA) system.

observations from WIMAS for irrigation systems other than these three types only resulted in only a 1.5% reduction in observations. Additionally only observations with alfalfa, corn, sorghum, or soybeans grown on the entire field are used in the analysis. If fields were split between crops, there were no data on the portion of the field devoted to each crop. So the difficulties with inadequate data are avoided by simply removing observations with multiple crops planted on a single field. Wheat is another crop sometimes grown on irrigated parcels, but it is excluded because of the difficulties of identifying its water application, since application occurs over two irrigation periods in separate years to produce one crop. Furthermore, cropping practices vary between wheat and row crops, which could bias results. So to avoid the difficulties wheat presents, all observations are deleted, which decreased the number of observations by 5.3%.

The data are further limited to only groundwater use and only counties in the northwest (NW), west central (WC), southwest (SW), and south central (SC) agricultural districts as defined by KASS (Figure 6.1). Barton County, although not in any of these districts, is also included in the analysis. This region includes the major area overlaying the Ogallala Aquifer.

Figure 6.1 Kansas Agricultural Statistics Districts Map



Source: KASS, available at http://www.nass.usda.gov/ks/distmap.htm

6.2 OUTPUT PRICES

Two distinct measures of output prices are used in the two-stage regression model. Stage one requires expected crop prices formulated when crop decisions are made, while stage two requires within-season expectations of crop prices. The crop-choice expectations were taken from futures price data obtained from the Commodity Research Bureau, Inc. This series is the monthly average price of the December contract in February for corn. For soybeans, the November contract price in February is used. There is no expected price for sorghum, since there is no sorghum futures price. This is not an issue, however, because expected sorghum and corn prices are likely to be highly correlated. The three year average basis for Scott City is then added to this price. Since alfalfa does not have a futures contract, the previous three year average price is calculated from NASS (National Agricultural Statistics Service) price series data.[2]

The series of actual crop prices used in the water demand model is from NASS. The series is a marketing year average state-level price as reported in the publication *Agricultural Prices*. While this price is inconsistent with the Scott City expected price since it is state-level, this should not be an issue because the data is used in separate regressions and only relative price changes are relevant for regression. Prices for alfalfa, corn, sorghum, and soybeans are dollars per ton ($/ton), dollars per bushel ($/bu), dollars per hundred pounds ($/cwt), and dollars per bushel ($/bu), respectively.

6.3 INPUT PRICES

Natural gas prices were also collected from the Commodity Research Bureau, Inc. The expected natural gas price is the average of the average monthly prices of the June and July contracts in February. Prices for the water demand model are the average prices of the June and July nearby futures contracts. Farmers are not likely to respond to a price change in August since they are nearly done irrigating and will finish the season with the current irrigation schedule. Prices are reported as dollars per thousand cubic feet ($/Mcf). Natural gas price is used because natural gas is the most common source of energy for irrigation in Kansas. According to the 1998 Farm and Ranch Irrigation Survey

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[2] Because the alfalfa data series only started in 1989, the expected price for 1991 is only a two year average.

(FRIS), natural gas was the energy source of 60.4% of wells in Kansas. Electricity and diesel fuel are the energy source for 21.1% and 13.7% of wells in Kansas, respectively.

The Index of Prices Paid by Farmers (1990-92=100) including production items, interest, taxes, and wage rates computed by NASS is used to account for prices of non-water inputs. The index is used to normalize prices; therefore, the index does not have a coefficient in the regression equations. The index was scaled by dividing it by 100. This scaled index was used to normalize prices.

6.4 SOIL CHARACTERISTICS

Variables describing the soil characteristics were obtained from the Natural Resource Conservation Service (NRCS), State Soil Geographic (STATSGO) dataset. These data were compiled by Golden and Peterson (2006), who assigned the data PLSS (Public Land Survey System) section identification using ArcGIS. The characteristics were then merged to the WIMAS dataset at the PLSS section-level. The relevant variables used in this model are average land classification, and average permeability of the root profile.

The NRCS defines the land capability classification as “a system of grouping soils primarily on the basis of their capability to produce common cultivated crops and pasture plants without deteriorating over a long period of time” (National Resource Conservation Service 2007). Soils with a low capability classification have fewer limitations to produce crops. A land classification of 6 or higher indicates that the soil has limitations which make it “generally unsuitable for cultivation.” The permeability of the soil measures the rate water flows down through the soil. A higher permeability indicates that water moves more quickly through the soil, which is the case for sandier soils.

6.5 WEATHER

Climate and weather data were obtained from the Kansas Weather Library. Weather data were merged to observations by the agricultural statistics districts (refer back to Figure 6.1). Weather observations for the northwest, west central, southwest, and south central districts were taken from the Colby, Tribune, Garden City, and St. John weather stations, respectively. Barton County is also included in the analysis and is matched with weather observations from the south central district.

Climate variables (expected weather conditions) include average precipitation and average ET (evapotranspiration) during the sample period. Average precipitation is the average annual precipitation from 1991 to 2004, and average ET is the average cumulative ET from May through August from 1991 to 2004. ET is the amount of water lost into the air through both evaporation and transpiration, which depends on solar radiation, temperature, wind, and humidity. For this dataset calculation of ET is alfalfa-based. The units of both precipitation and ET are inches.

Weather variables (used in the water demand model) are computed for each year, and include two precipitation variables and an ET variable. The two precipitation variables are the cumulative precipitation for January through April and the cumulative precipitation for May through August. The variable for ET is the cumulative ET from May through August.

6.6 TIME TREND

A time trend is also included in the crop-choice model. This variable is intended to capture the effect of improved technologies in corn and soybeans that have made them more appealing to plant. Improved hybrids in corn and soybeans have increased yields, and the Glyphosate resistant technology in soybeans has made them an appealing crop to include in a rotation to relieve weed pressure. The time trend variable is simply the year minus 1990.

Figure 6.2 shows the trend in irrigated acreage for four of the major crops grown in Kansas (irrigated alfalfa acreage data was not available) from 1985 to 2005. In 1985, corn, sorghum, and wheat were all grown on about the same number of acres. This quickly changed, however, as corn acreage increased rapidly and both wheat and sorghum acres decreased. Soybean acreage has remained steady, although in 1997 acreage began to increase. Corn yields have steadily increased, while wheat and sorghum yields have fluctuated around relatively constant means, as shown in Figure 6.3 through Figure 6.6.[3] The slight improvement in soybean yields, along with the advent of Glyphosate resistant technology, likely contributed to the increase in the acreage of soybeans.

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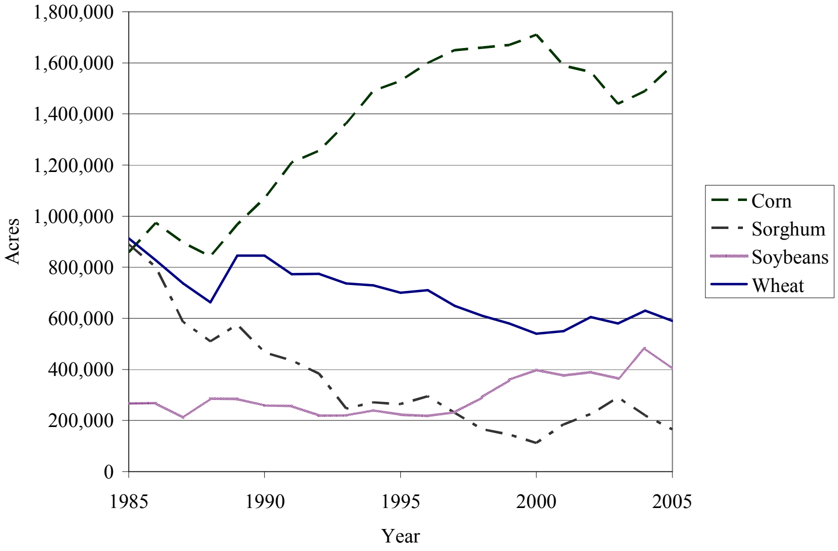
[3] Yield data were obtained from Kansas Agricultural Statistics Service.

Figure 6.2 Irrigated Acreage in Kansas by Crop



Source: Kansas Agricultural Statistics Service (KASS)

Figure 6.3 Average Irrigated Corn Yield

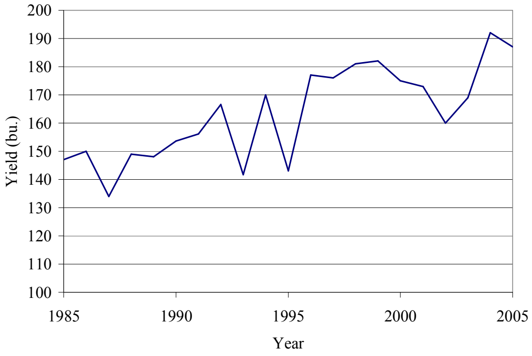


Figure 6.4 Average Irrigated Soybean Yield

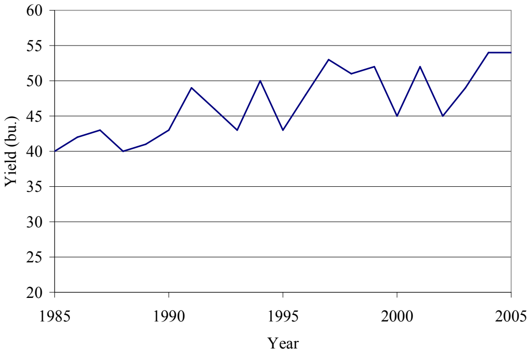


Figure 6.5 Average Irrigated Sorghum Yield

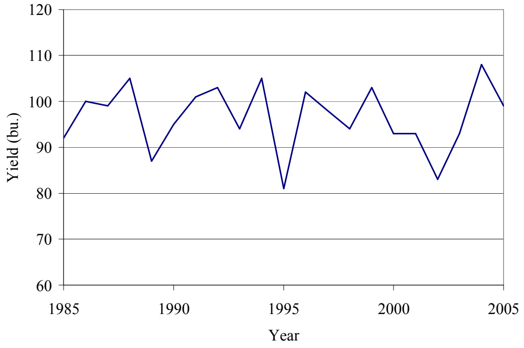
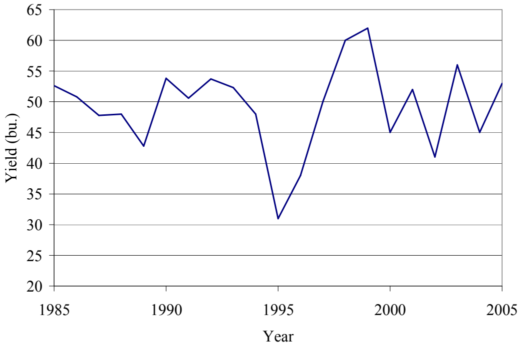


Figure 6.6 Average Irrigated Wheat Yield



The time trend could be capturing effects other than hybrid improvements in corn and soybeans, such as changes in policies or other input costs. It is possible that the time trend could be collinear with other variables already included in the model. For example, irrigation technology choice has a trend over time (Table 6.4), and natural gas price has increased over time (Figure 6.12).

6.7 DATA LIMITATIONS

Parcel-level data provides many advantages, but also has limitations. Crop-choice decisions are field specific, but there are also farm-level aspects to the decision. For example, if an operator has equipment for a specific crop, such as alfalfa, then he will be more likely to plant that crop on his fields. So a limitation of this data is that there are no operator characteristics.

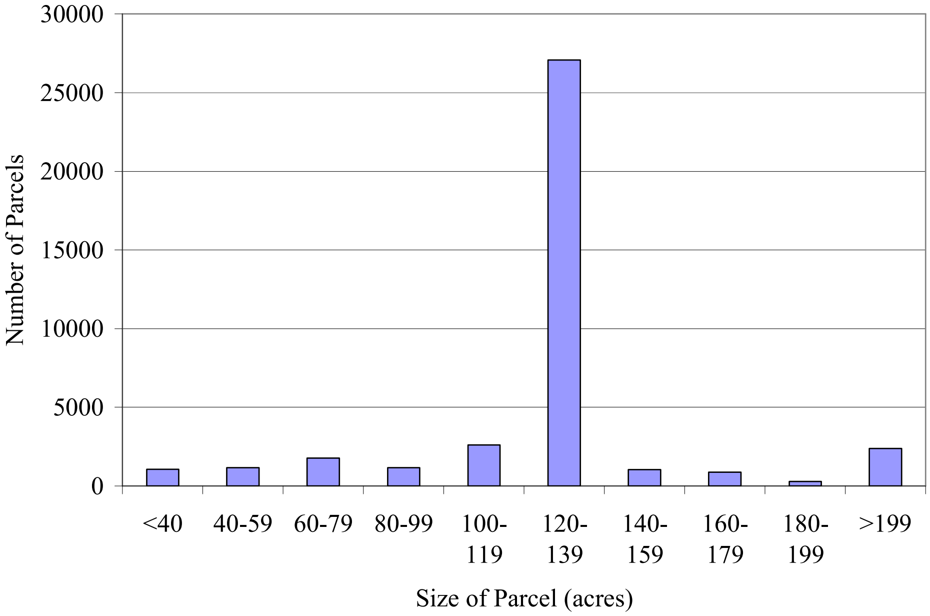
Crop rotations are not accounted for either. There are no data on the crop planted in the previous year for many of the observations, so a lag term to account for crop rotations is not possible. Continuous corn appears to be the most popular crop rotation in the sample, as 70.49% of acres are planted to corn (Table 6.1). If a corn-soybean rotation were more common, as it is in other regions of the United States, accounting for crop-rotations would be more important.

6.8 DESCRIPTIVE STATISTICS

The resulting dataset has 5,075 unique parcels of land over 14 years resulting in a total of 39,457 observations. Therefore, not every parcel of land has observations for all 14 years in the series. There were observations in 25 counties in western Kansas, with observations in each Groundwater Management District (GMD).

Parcels between 120 and 139 acres compose the majority (68.6%) of the sample observations (Figure 6.7). This is the most popular size because it is the typical area irrigated by a center pivot on a quarter-section (160 acre) field. The minimum parcel size in the sample is 11 acres and the maximum parcel size is 680 acres.

Figure 6.7 Histogram of Parcel Size



Corn was by far the most commonly grown crop in the sample, with an average of 70.49% of acres planted to corn over the data period (Table 6.1). The percent of acres planted to corn reached its peak in 1996, stayed relatively constant for the next four years, then after 2000 trended downwards. Sorghum acres dropped drastically after 1992 and made up less than 2% of acres planted from 1998-2001. In 1991, only 6.24% of acres were planted to soybeans, but acreage continued to increase, representing 16.16% of acres in the sample in 2004. Alfalfa acreage remained fairly steady over the sample period, accounting for an average of 16.94% of acres.

Table 6.1 Percent of Acres Planted to each Crop by Year

Year	Alfalfa	Corn	Sorghum	Soybeans
1991	20.20%	63.15%	10.41%	6.24%
1992	18.21%	67.04%	9.24%	5.51%
1993	17.74%	73.06%	4.45%	4.75%
1994	18.53%	72.45%	3.72%	5.30%
1995	18.55%	71.85%	4.54%	5.06%
1996	15.26%	76.68%	3.46%	4.60%
1997	15.85%	73.31%	3.23%	7.61%
1998	16.08%	72.90%	1.78%	9.23%
1999	15.09%	72.70%	1.94%	10.27%
2000	12.86%	74.54%	1.16%	11.44%
2001	15.94%	70.66%	1.89%	11.51%
2002	18.33%	67.49%	2.27%	11.90%
2003	19.39%	64.24%	4.80%	11.57%
2004	17.27%	64.14%	2.43%	16.16%
Total	16.94%	70.49%	3.73%	8.84%

Alfalfa is the most water intensive crop with an average of 18.51 inches of water applied per acre in the sample, but also has the largest standard deviation of water use

(Table 6.2). Corn is the second most water intensive crop, followed by soybeans and sorghum. An average of only 11.39 inches of water was applied to sorghum.

Table 6.2 Descriptive Statistics of Annual Water Use per Acre (inches) by Crop

Crop	Mean	Standard Deviation
Alfalfa	18.51	7.49
Corn	15.88	6.04
Sorghum	11.39	6.59
Soybeans	14.01	5.25

When farmers in the sample had flood irrigation technology, they tended to plant more sorghum and less alfalfa and soybeans. On parcels using flood irrigation, 16.16% of the acres were planted to sorghum (Table 6.3). Crop choices were similar under the two center pivot technologies, although generally less sorghum was grown under the more efficient technology, center pivot with low drops. Standard center pivot was the most popular irrigation system, used on 49.50% of acres in the sample, while flood irrigation was only used on 6.30% of the observations.

Table 6.3 Percent of Acres Planted with each Irrigation System

	Alfalfa	Corn	Sorghum	Soybeans	Total
Flood	6.67%	71.61%	16.16%	5.56%	6.30%
Standard Center Pivot	19.27%	69.72%	3.75%	7.26%	49.50%
Center Pivot with Low Drops	15.80%	71.19%	1.94%	11.08%	44.20%

However, the number of acres under standard center pivot decreased drastically during the sample period from 87.34% of acres to 9.69% of acres, while center pivot with low drop nozzles increased over the period from 0.43% of acres to 88.12% of acres (Table 6.4). Even though standard center pivot was the most common system in the entire sample, currently center pivot with low drops is by far the most popular system. The percent of acres under flood irrigation steadily decreased from 12.23% to 2.18% from 1991 to 2004.

Table 6.4 Percent of Acres Under Each Irrigation System by Year

Year	Flood	Standard Center Pivot	Center Pivot with Low Drops
1991	12.23%	87.34%	0.43%
1992	10.92%	83.73%	5.35%
1993	9.53%	82.51%	7.96%
1994	9.67%	81.57%	8.76%
1995	8.54%	83.56%	7.89%
1996	7.76%	84.70%	7.54%
1997	7.00%	58.29%	34.71%
1998	5.52%	44.92%	49.57%
1999	4.63%	38.06%	57.31%
2000	4.33%	25.95%	69.72%
2001	3.72%	18.30%	77.97%
2002	2.84%	11.64%	85.52%
2003	2.61%	10.57%	86.82%
2004	2.18%	9.69%	88.12%
Total	6.30%	49.50%	44.20%

The average well capacity is similar for each of the crops, except the average well capacity when sorghum is planted is about 200 gpm less than the other three crops (Table 6.5). Sorghum also has the largest standard deviation of well capacity, however. The overall average well capacity in the sample is 740.3 gpm, with a large standard deviation of 255.8 gpm.

Table 6.5 Descriptive Statistics of Well Capacity (gpm) by Crop

Crop	Mean	Standard Deviation
Alfalfa	770.7	204.0
Corn	741.6	264.9
Sorghum	564.3	302.7
Soybeans	764.5	202.3
Total	740.3	255.8

High correlation among prices could lead to multicollinearity among model regressors, creating estimation difficulties. Table 6.6 shows the correlation matrix for the expected price series. The price of sorghum is not included in the analysis because there is no expected price for sorghum as noted previously. Expected corn and soybean prices are highly correlated (94.0%), so including both variables in the model would likely result in multicollinearity issues. Therefore, only the expected alfalfa and corn prices are included in the multinomial logit model.

Table 6.6 Correlation Matrix of Expected Crop Prices

	Alfalfa	Corn	Soybeans
Alfalfa	1		
Corn	0.113	1	
Soybeans	-0.070	0.940	1

Although the price trends in the expected price series and the NASS price series are similar, there are differences, which make it important to use the expected price series in the crop-choice model (Figure 6.8 and Figure 6.9). In particular, the expected price series tends to lag the NASS price series. The alfalfa NASS price series dropped quickly in 1998 and 2003, but alfalfa prices were high in 1996-1997 and 2001-2002. Corn price remained relatively constant with a spike in price in 1995 and another increase in 2002.

Currently, corn prices are over $4/bu in many areas of western Kansas. Unfortunately, the corn price in the sample period came nowhere near $4/bu, so the model does not have data to examine how farmers respond at such a high price. Indeed, corn prices only exceeded $3/bu once during the sample period.

Figure 6.8 Alfalfa Price Series

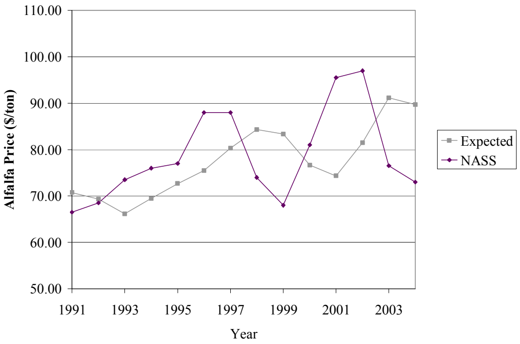
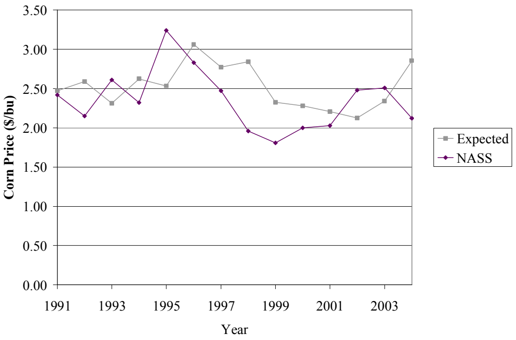
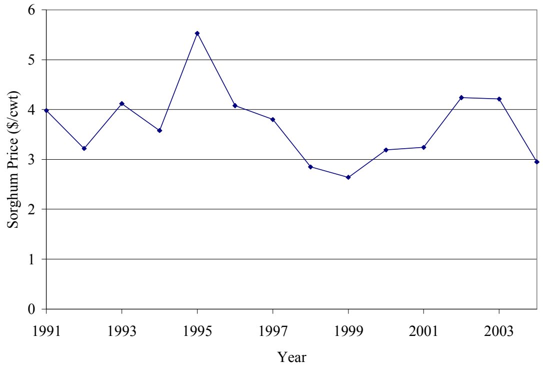


Figure 6.9 Corn Price Series



Expected sorghum and soybean prices are not included in the model, for reasons explained earlier. Therefore, Figure 6.10 and Figure 6.11 only show the NASS price series for sorghum and soybean prices. The trends in sorghum and soybean prices are similar to the trend in the NASS price series for corn with high prices around 1995, 1996, 2002, and 2003 and low prices in the late 1990s.

Figure 6.10 Sorghum Price Series **Figure 6.11 Soybean Price Series**



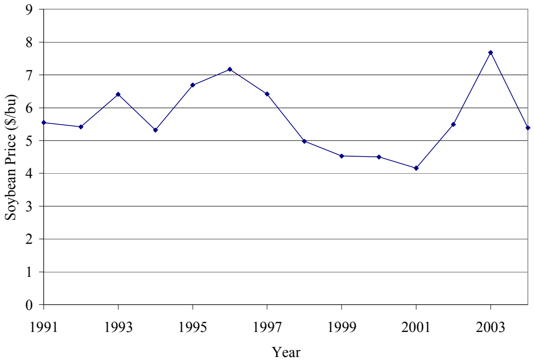
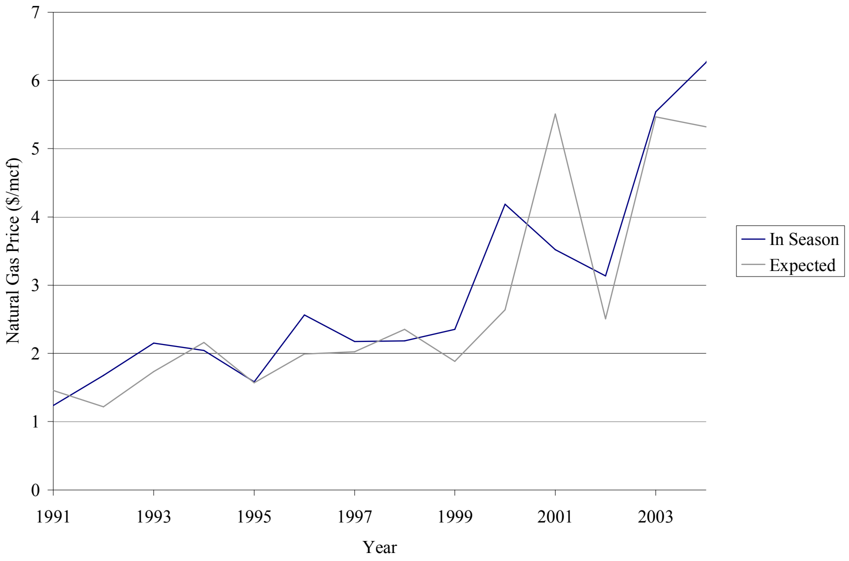


Figure 6.12 shows both the expected and in-season natural gas price series throughout the sample period. The price of natural gas increased greatly during the period. In 1991, the in-season price of natural gas was $1.24/Mcf and by 2004 the price had increased five fold to $6.26/Mcf.

Figure 6.12 Price of Natural Gas ($/Mcf) 1991-2004



The percent of acres planted to each crop and the well capacity at the county and GMD-level are given in Table 6.7. A set of descriptive statistics for selected variables is given in Table 6.8. The set of descriptive statistics for normalized prices is given in Table 6.9. These are important statistics because marginal effects are only computed within the range of the data, and normalized prices, not actual prices, are used in estimating the model.

Table 6.7 Percent Acres Planted to Each Crop and Well Capacity by County and GMD

		Percent of Acres Planted				Well Capacity
County	GMD	Alfalfa	Corn	Sorghum	Soybeans	(gpm)
Cheyenne	4	6%	84%	2%	8%	584
Decatur	4	5%	88%	3%	4%	423
Rawlins	4	2%	83%	10%	5%	428
Sheridan	4	2%	90%	4%	5%	532
Sherman	4	4%	89%	4%	4%	598
Thomas	4	1%	90%	3%	6%	577
Average	*4*	*3%*	*89%*	*4%*	*5%*	*562*
Scott	1	1%	65%	32%	1%	271
Wallace	1	3%	91%	5%	1%	613
Wichita	1	9%	70%	18%	2%	289
Average	*1*	*4%*	*79%*	*16%*	*1%*	*411*
Finney	3	43%	51%	2%	4%	781
Ford	3	11%	73%	10%	7%	710
Grant	3	28%	68%	3%	1%	871
Kearny	3	51%	47%	1%	1%	792
Meade	3	7%	83%	6%	3%	973
Morton	3	20%	64%	16%	0%	651
Seward	3	25%	68%	5%	2%	913
Stanton	3	2%	91%	7%	0%	685
Stevens	3	13%	85%	1%	1%	1126
Average	*3*	*31%*	*63%*	*3%*	*3%*	*823*
Barton	5	19%	57%	8%	16%	783
Edwards	5	19%	63%	2%	15%	823
Kiowa	5	13%	64%	3%	20%	862
Pawnee	5	20%	54%	5%	21%	727
Pratt	5	6%	78%	2%	14%	870
Reno	2 & 5	2%	61%	8%	29%	810
Stafford	5	10%	71%	2%	17%	833
Average	*2 & 5*	*13%*	*66%*	*3%*	*17%*	*823*
Total		17%	70%	4%	9%	740

Table 6.8 Descriptive Statistics of Selected Variables

Variable	Mean	Standard Deviation	Minimum	Maximum
Expected Price Series				
Alfalfa Price	77.83	7.31	66.17	91.17
Corn Price	2.52	0.27	2.13	3.06
NASS Price Series				
Alfalfa Price	79.15	9.55	66.50	97.00
Corn Price	2.34	0.37	1.81	3.24
Sorghum Price	3.66	0.72	2.64	5.53
Soybean Price	5.66	1.02	4.16	7.68
Input Prices				
Expected Natural Gas Price	2.72	1.46	1.22	5.51
In Season Natural Gas Price	2.93	1.42	1.24	6.26
Index of Prices Paid	114.49	8.97	100	132
Acres in Parcel	128.1	48.9	11	1545
Climate/Weather				
Average Annual Precipitation	21.04	1.99	15.31	23.08
Average May-Aug Cumulative ET	37.60	1.77	35.43	39.44
Jan-April Precipitation	4.47	1.93	0.69	9.26
May-Aug Precipitation	12.61	4.34	3.22	22.77
May-Aug Cumulative ET	37.62	5.73	28.42	56.25
Soil Characteristics				
Average Land Classification	3.32	1.29	1.67	6
Average Permeability in Root Profile	4.93	4.36	0.48	13
Hydrological				
Well Capacity	740.26	255.78	30	3000

Table 6.9 Descriptive Statistics of Normalized Prices

Variable	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Normalized Expected Price Series				
Alfalfa Price	67.99	3.67	60.93	73.98
Corn Price	2.22	0.29	1.76	2.66
Normalized NASS Price Series				
Alfalfa Price	69.22	7.01	55.30	80.17
Corn Price	2.06	0.40	1.60	3.00
Sorghum Price	3.23	0.74	2.23	5.12
Soybean Price	4.98	0.95	3.41	6.23
Normalized Input Prices				
Expected Natural Gas Price	2.31	1.07	1.21	4.52
In Season Natural Gas Price	2.49	1.01	1.24	4.75

CHAPTER 7 - RESULTS

The results of estimating the multinomial logit selectivity model with the data described previously are presented in this chapter. Hypothesis tests confirm that the variable, allocatable input specification for irrigation water is appropriate. Water use is decreasing in natural gas price and the marginal effects are decomposed into intensive and extensive marginal effects. The extensive marginal effect is negligible at low natural gas prices, but increases with high prices. The intensive marginal effect is significant; and even when natural gas price is high, the intensive marginal effect comprises more than half of the total marginal effect. Water use on corn is the least responsive of all the crops to changes in natural gas price in the short-run. More efficient irrigation technology and other technological improvement, represented with a time variable, reduce the magnitude of the marginal effect of natural gas price. Corn and alfalfa are estimated to be economically competing outputs, and since they are both water intensive crops, corn and alfalfa prices have a negligible extensive marginal effect. Over the sample range, the magnitude of the effect of well capacity on water use is the largest of all the variables.

7.1 MODEL ESTIMATION AND EVALUATION

The results of the multinomial logit model for crop-choice are given in Table 7.1 where the coefficients correspond to the vector α_j as defined in the model chapter. The coefficients of this model do not have a direct interpretation, as noted in chapter 5, and the sign of the coefficients may not correspond to that of the marginal effects. The coefficients for the crop-choice of alfalfa are equal to zero, which is a normalization for estimation purposes.

The significance of the coefficients, however, is important to evaluate. Nearly all the coefficients in the model are statistically significant at the 10% level, and frequently significant at the 1% level. The coefficients on natural gas price and its squared term are not significant in two of the equations; however, they are significant in the sorghum equation at the 1% level. A Wald test was run with the restricted model excluding the two natural gas price terms from the logit model. The test statistic is 250, compared to a critical Chi-squared value of 16.81 (1% significance level), indicating that the two variables have a very statistically significant impact in the model. The test statistic for excluding the two terms from only the corn equation is 64.67 compared to the critical value of 9.21, while excluding the natural gas price squared terms from the model yields a test statistic of 34.15 compared to the critical value of 11.34. Each of these tests demonstrates that natural gas price and its squared term do make a statistically significant impact in crop-choice, and are therefore included in the model.

Table 7.1 Multinomial Logit Model Parameter Estimates

	Corn			Sorghum			Soybeans		
Variable	Coefficient	St. Error	t-statistic	Coefficient	St. Error	t-statistic	Coefficient	St. Error	t-statistic
Constant	67.606 **	5.488	12.318	-49.744 **	12.143	-4.096	66.116 **	7.725	8.558
Normalized Prices									
Alfalfa	-1.008 **	0.158	-6.385	2.644 **	0.355	7.459	-1.086 **	0.223	-4.866
Alfalfa Squared	0.007 **	0.001	6.209	-0.019 **	0.003	-7.357	0.008 **	0.002	4.791
Corn	3.056 **	1.053	2.901	-6.585 **	2.137	-3.081	6.650 **	1.531	4.345
Corn Squared	-0.580 *	0.236	-2.461	1.447 **	0.474	3.050	-1.456 **	0.347	-4.197
Natural Gas	-0.187	0.181	-1.031	-1.228 **	0.328	-3.744	0.015	0.290	0.052
Natural Gas Squared	-0.002	0.028	-0.060	0.257 **	0.051	5.028	-0.030	0.045	-0.675
Climate									
Average Precipitation	-0.675 **	0.027	-25.370	-0.616 **	0.031	-20.112	-0.380 **	0.036	-10.655
Average ET	-0.521 **	0.019	-28.103	-0.502 **	0.028	-17.670	-0.747 **	0.029	-25.694
Soil Characteristics									
Land Classification	-0.271 **	0.027	-10.174	-0.385 **	0.046	-8.433	-0.272 **	0.040	-6.728
Permeability	-0.063 **	0.008	-7.879	-0.091 **	0.015	-6.062	-0.072 **	0.012	-6.196
Other									
Flood	-0.145 *	0.078	-1.869	1.640 **	0.109	15.039	-0.142	0.107	-1.336
Std. Center Pivot	-0.179 **	0.042	-4.255	0.357 **	0.091	3.917	-0.283 **	0.061	-4.682
Well Capacity	0.0013 **	0.0001	16.721	-0.0008 **	0.0001	-5.817	0.0004 **	0.0001	3.549
Time Trend	0.052 **	0.010	5.062	-0.098 **	0.018	-5.414	0.125 **	0.016	7.627

* and ** indicate significance at the 10% and 1% levels, respectively.

The goodness of fit measures are given in Table 7.2. The likelihood ratio test statistic is very large, indicating that the variables in the model help explain irrigators' crop-choices much better than simply defining irrigators' crop-choices with the average probability of planting each crop in the sample. The pseudo R^2 and McFadden's R^2 also give an indication of fit. These numbers are low, but should not be compared to statistics from different models and cannot be interpreted as the R^2 in OLS. However, these two measures can be used to compare the fit of different specifications for the same model. Choosing the crop with the highest probability for each observation, the model accurately predicts 70% of the crop-choice decisions.

Table 7.2 Logit Goodness of Fit Measures

Likelihood ratio test statistic	10240
Pseudo R^2	0.14
McFadden's R^2	0.14
Count R^2	0.70

Table 7.3 gives a more detailed description of the crop-choice prediction accuracy of the model. The model frequently predicts corn (92% of the time) and never predicts soybeans. However, this does not indicate a problem with the model. As discussed in chapter 5, Train warns against relying too heavily on this result, because it counters the very idea of probabilities. Soybeans may always have a lower probability of being grown than corn; nevertheless, a probability states that with enough repetitions, soybeans will be planted. However, under the assumption that the crop with the highest probability is planted, soybeans will never be predicted. The model may have difficulty correctly predicting soybeans because the decision to plant soybeans may be due to idiosyncratic factors. Glyphosate resistance makes soybeans an appealing crop to rotate with corn to relieve weed pressure, which will arise at periodic but unpredictable intervals on different parcels.

Table 7.3 Frequencies of Actual and Predicted Outcomes

	Predicted				
Actual	Alfalfa	Corn	Sorghum	Soybeans	Total
Alfalfa	1561	4933	13	0	6507 (16.5%)*
Corn	1312	26063	74	0	27449 (69.6%)
Sorghum	27	1712	105	0	1844 (4.7%)
Soybeans	81	3567	9	0	3657 (9.3%)
Total	2981 (7.6%)	36275 (91.9%)	201 (0.5%)	0 (0.0%)	39457

* The percent of total observations are in parentheses.

Table 7.4 reports the marginal effects, of all variables except prices on the probability of planting each of the crops, averaged across all observations. As an example of how to interpret the marginal effect of a dummy variable, if the parcel of land has flood irrigation technology, then the farmer is 7.17% less likely to plant corn compared to the center pivot with low drops system (the omitted base group). Prices are excluded at this point because they have squared terms that complicate the marginal effects; they are fully described in later sections. Most of the variables have a very statistically significant effect in explaining crop-choice.

Table 7.4 Marginal Effects on Crop-Choice Averaged Across Observations

	Alfalfa	Corn	Sorghum	Soybeans
Climate				
Average Precipitation	0.0748 **	-0.0874 **	-0.0018 **	0.0144 **
Average ET	0.0635 **	-0.0384 **	-0.0010	-0.0241 **
Soil Characteristics				
Land Classification	0.0321 **	-0.0232 **	-0.0059 **	-0.0031
Permeability	0.0076 **	-0.0048 **	-0.0014 **	-0.0014 *
Other				
Flood	0.0083	-0.0717 **	0.0705 **	-0.0071
Std. Center Pivot	0.0196 **	-0.0284 **	0.0208 **	-0.0120 **
Well Capacity	-0.0001 **	0.0003 **	-0.0001 **	-0.0000 **
Time Trend	-0.0062 **	0.0054 **	-0.0059 **	0.0068 **

* and ** indicate significance at the 10% and 1% levels, respectively.

The results from the OLS regressions for water use for each crop, accounting for selectivity, are given in Table 7.5. The results show estimates from four different regressions, where water use per acre (inches) is the dependent variable. Previous research has used total water use as the dependent variable and included acres as one of the independent variables. The number of acres explains a large share of the variation in water use, so the R^2 may be very large for those models. However, this variable simply captures the obvious relationship that larger irrigated parcels consume more water. Evaluating water use per acre allows for consistent comparisons of water use across parcels of various sizes.

Table 7.5 Parameter Estimates for Water Use OLS Regressions

Variable	Alfalfa	Corn	Sorghum	Soybeans
Constant	35.87 **	2.78 **	13.71 **	-2.37 *
	(1.404)	(0.416)	(2.253)	(1.008)
Normalized Prices				
Own Price	-0.055 **	1.531 **	0.497 *	-1.045 **
	(0.011)	(0.105)	(0.260)	(0.107)
Natural Gas	-0.675 **	-0.182 **	-0.788 **	-0.440 **
	(0.092)	(0.047)	(0.234)	(0.093)
Climate				
Precipitation (Jan-April)	-0.843 **	-0.650 **	-0.324 **	0.106 *
	(0.040)	(0.019)	(0.094)	(0.053)
Precipitation (May-Aug)	-0.346 **	-0.329 **	-0.312 **	-0.236 **
	(0.019)	(0.009)	(0.044)	(0.024)
ET	0.161 **	0.258 **	0.170 **	0.329 **
	(0.015)	(0.007)	(0.033)	(0.021)
Soil Characteristics				
Permeability	-0.398 **	0.139 **	0.325 **	0.228 **
	(0.024)	(0.014)	(0.058)	(0.021)
Other				
Flood	-0.583 *	2.379 **	-2.277 **	1.327 **
	(0.333)	(0.135)	(0.671)	(0.338)
Std. Center Pivot	-0.905 **	0.001	-0.853 *	-0.265
	(0.163)	(0.085)	(0.483)	(0.196)
Well Capacity	0.0084 **	0.0093 **	0.0113 **	0.0142 **
	(0.001)	(0.000)	(0.002)	(0.001)
Well Capacity Squared	-1.27E-06 *	-2.35E-06 **	-2.45E-06 *	-6.02E-06 **
	(0.000)	(0.000)	(0.000)	(0.000)
λ	-9.259 **	3.075 **	-4.628 **	2.667 **
	(0.261)	(0.287)	(0.685)	(0.294)
Adjusted R^2	0.31	0.22	0.14	0.28

* and ** indicate significance at the 10% and 1% levels, respectively.
Standard Errors are in parentheses.

Most of the variables in the regressions are significant, frequently at the 1% level. Most of the signs of the coefficients match expectations, although a few are counterintuitive. For example, it is expected that alfalfa and soybean water use would increase as their prices increase, but the signs of the coefficients are negative. The coefficients on precipitation should all be negative, but the coefficient on January-April precipitation is positive for soybeans.

The variables included in the model explain 31% of the variation in water use per acre when alfalfa is planted. However, only 14% of the variation is explained by the variables when sorghum is planted. The coefficients on λ are significant in each of the regressions, indicating that if selectivity were not accounted for, the results would be biased.

The coefficients on natural gas price are significant in each of the regressions, which give evidence that the variable, allocatable input specification is appropriate. A squared term for well capacity is included in the regression because water use is expected to increases as well capacity increases but at a decreasing rate. In other words, there is not expected to be as large a difference in water use between parcels with very large well capacities. Technological improvements in hybrids are not thought to have had a significant impact on water use, so a time trend is not included in the regressions.

The marginal effects of the variables in the water use regressions are the effects at the intensive margin. The effect of actual prices on short-run water use is of interest, but the prices in the regression are normalized by the index of prices paid for inputs. Therefore, the marginal effect of each price at the data means is computed by dividing the coefficient on the normalized price by the mean value of the index. The marginal effects at the mean index of prices paid are reported in Table 7.6.

Table 7.6 Marginal Effects of Prices in Water Use Regressions

	Alfalfa	Corn	Sorghum	Soybeans
Own Price	-0.048	1.338	0.434	-0.912
Natural Gas Price	-0.589	-0.159	-0.688	-0.385

In the empirical model chapter (chapter 5) it was stated that multinomial logit selectivity models can suffer from multicollinearity and a lack of robustness if the variables in the multinomial logit model and the linear regressions are the same. However, this model specification should have enough difference in the variables in the two models to prevent such issues. The variables for average land classification and the time trend are used in the multinomial logit but not in the water demand equations. The squared term for well capacity is used only in the water demand equations and not crop-choice, whereas squared price terms are only used in the crop-choice model. Only the own-crop price is used in each of the water demand equations; however, alfalfa and corn price are both used in the crop-choice equation. In addition, expected prices and weather variables are used in the crop-choice model, and actual prices and weather variables are used in the water demand equation.

7.2 IMPACT OF VARIABLES ON CROP-CHOICE AND WATER USE

In the subsequent sections, the effects of each variable on crop-choice and short-run water use are discussed. The crop-choice probabilities and marginal effects are computed at the means of the independent variables, unless otherwise noted. For example, the statement "when natural gas price is $5/Mcf, the marginal effect (or probability)…" means that the marginal effect is computed when natural gas price equals $5/Mcf and all other variables are held at their means. The marginal effects of prices are adjusted for normalization as described in the previous section, so they can be interpreted as a marginal effect of the actual price rather than the normalized price. The marginal effect on probabilities is also reported as an average across individual observations (Table 7.4).

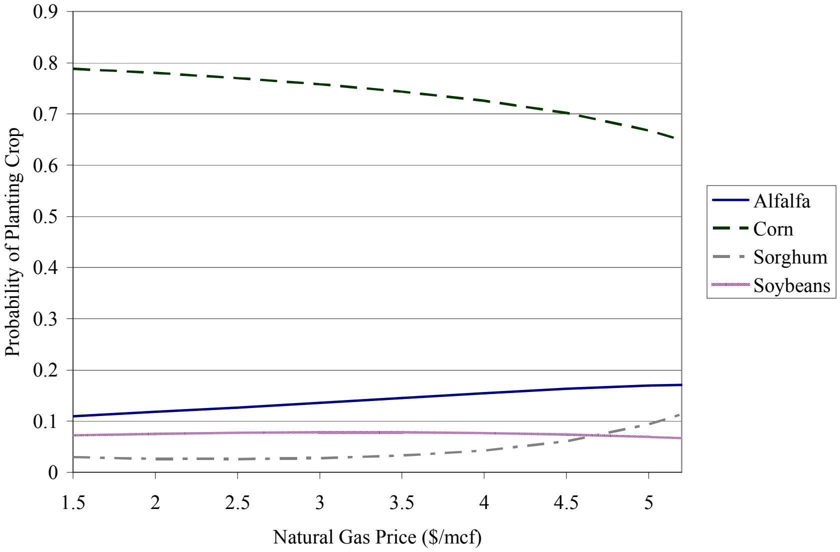
The impact of variables on expected water use is also discussed. For the purposes of this thesis, expected water use is defined as the sumproduct of the probability of planting each crop and its respective water use. The expected water use is represented in the model chapter in equation (5.18). In the discussions that follow, expected water use is graphed to show how water use responds to changes in variables. The total marginal effect of water use in equation (5.19) is not constant across all values of the variables because the marginal effect on probabilities is not constant; therefore, the effect of some variables on expected water use is best shown graphically.

7.2.1 Impact of Natural Gas Price

The impact of natural gas price on water use is analyzed first by evaluating its impact on the 1st stage decision, crop-choice. Then the 2nd stage, short-run impacts are analyzed from the results of the water use demand regressions for each crop. Finally, the effects are presented as extensive and intensive marginal effects. Important interactions on the effect of natural gas price with irrigation systems, technological improvements, and well capacity are also discussed.

Focusing first on the impact of natural gas price on crop-choice, Figure 7.1 reveals that the probability of planting corn is the most responsive of the crops. As natural gas price increases, the marginal probability becomes more negative. When natural gas is \$1.50/Mcf, a \$1/Mcf increase in natural gas reduces the probability of planting corn by 1.33%; however, when natural gas is \$5.00/Mcf, a \$1/Mcf increase in natural gas reduces the probability of planting corn by 8.47%. As natural gas price changes from \$1.50/Mcf to \$5.20/Mcf, the probability of planting corn decreases 13.9%.

Figure 7.1 Probability of Planting Each Crop as Natural Gas Price Changes



The probability of planting alfalfa is fairly unresponsive to natural gas prices, but increases slightly at a decreasing rate. When natural gas price is \$5.00/Mcf, a \$1/Mcf increase in natural gas only increases the probability of planting alfalfa by 0.83%.

The probability of planting soybeans is unresponsive to changes in natural gas prices across the whole range of prices. Likewise, the probability of planting sorghum is unresponsive to changes in natural gas price, until natural gas reaches $3.50/Mcf. As natural gas price changes from $3.50/Mcf to $5.20/Mcf, the probability of planting sorghum increases 8.1%. This result arises because much of the acreage substitution in response to natural gas price increases occurs between corn and sorghum.

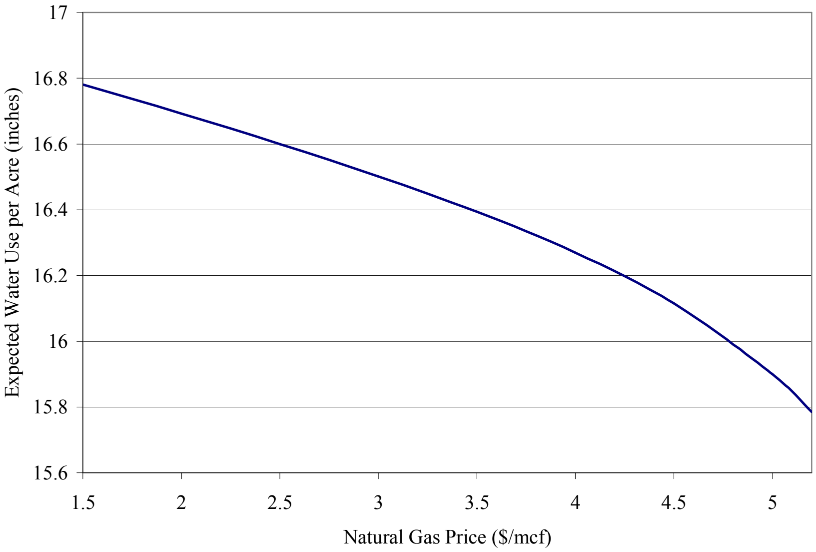
Next turning to the impact on short-run water use, the values in Table 7.6 indicate that as natural gas increases $1/Mcf, water use decreases 0.589, 0.159, 0.688, and 0.385 inches given the irrigator plants alfalfa, corn, sorghum, or soybeans, respectively. Alfalfa and sorghum have the largest short-run response and corn has by far the smallest. The small response of corn water use in the short-run is probably because corn yield is very sensitive to water shortages, especially in certain stages of crop growth. If a farmer were to reduce water use on corn a little, he may lose the entire crop or at least have major yield loss. On the other hand, alfalfa and sorghum yields are not as sensitive to water use. If a farmer chooses to reduce water to alfalfa, he may lose a cutting or his cutting may be smaller, but he will not run the risk of losing the entire crop for the year. Sorghum is much more drought tolerant than corn, so reducing water use is not as risky.

Irrigators may reduce water use in the short-run by either improving management practices to conserve water or simply pumping less. Farmers may improve their management practices by more intensive supervision of water application and only pumping when necessary. In terms of price response, if natural gas is cheap, farmers may keep pumping to reduce risk because doing so is not that costly; but when the cost to pump increases, they manage the water more intensively and bear more risk. Farmers may also be responding by simply applying less water to crops, thereby reducing yields.

Given responses of the various crops to water stress, this is a more likely scenario in alfalfa and sorghum production, but less likely on corn, where reduced water use is probably more economic to obtain from improved management. Reduced water use on soybeans could be a combination of the two scenarios.

Finally, Figure 7.2 shows that the overall impact of natural gas price is to decrease expected water use. The relationship is fairly linear until natural gas reaches $3.50/Mcf. Below $3.50/Mcf, the reduction in water use is all due to changes in short-run water use, but as natural gas price increases above $3.50/Mcf, water use also decreases due to shifts in planted acres from corn to sorghum. This causes expected water use to begin decreasing at an increasing rate and gives curvature to the relationship. However, the overall effect of natural gas increasing from $1.50/Mcf to $5.20/Mcf only decreases water use per acre by 1 inch.

Figure 7.2 Expected Water Use as Natural Gas Price Changes



Calculations of special interest in the literature are the intensive and extensive marginal effects. These are calculated with equation (5.19), as defined in the empirical model chapter. Due to the nonlinearities in the crop-choice model, the marginal effects are not the same at every price and the varying impact of the natural gas price on water use is best understood by evaluating these effects at different prices and exploring the interaction with other variables.

The intensive marginal effect summed across crops increases only slightly as natural gas price increases (Table 7.7). The increase in the intensive margin effect is because the probability of growing corn decreases[1] at higher natural gas prices and corn water use is the least responsive to natural gas price of all the crops. When natural gas price is \$5/Mcf, the intensive marginal effect on water use is -0.297 inches. Or, in elasticity terms, when natural gas price is \$5/Mcf, as the natural gas price increases 1%, water use decreases 0.09% at the intensive margin.

The extensive marginal effect is positive, but nearly zero, at low natural gas prices, but becomes negative as natural gas price increases (Table 7.7). The positive extensive marginal effect at low natural gas prices is an unexpected result, as a proof was given in chapter 4 that the extensive margin effect is negative. However, the proof was only for 2 crops and the most profitable crop was planted with probability one. In the empirical model, there are 4 crops and the probabilities are smooth curves with no

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[1] The intensive margin effect depends on the probability of growing the crop because it is the marginal effect from the water demand regression weighted by the probability of growing the crop (Equation (5.19)). The intensive margin effect summed across crops is not the sum of the marginal effects of the water demand regressions.

certainty that a particular crop will be planted. So the same result from the proof in chapter 4 may not necessarily hold. Empirically, the extensive margin effect is positive because the probability of planting alfalfa increases, and alfalfa consumes a large amount of water. When natural gas is \$5/Mcf, as natural gas price increases 1%, water use decreases 0.07% at the extensive margin. Therefore, when natural gas is \$5/Mcf, the intensive and extensive marginal effects are nearly equal; about half the reduction in water use is through short-run adjustment and half is through changing to less water intensive crops.

Irrigation water use is very inelastic at all price levels, but becomes more elastic as natural gas price increases. An estimate of the elasticity of water when natural gas price is \$5/Mcf and all other variables are at their means is -0.1645.

Table 7.7 Intensive and Extensive Marginal Effects at Different Natural Gas Prices

	Marginal Effect			Elasticity		
Natural Gas Price (\$/mcf)	Intensive	Extensive	Total	Intensive	Extensive	Total
2	-0.241	0.060	-0.181	-0.0288	0.0072	-0.0217
3.5	-0.256	0.028	-0.228	-0.0547	0.0060	-0.0488
5	-0.297	-0.226	-0.523	-0.0934	-0.0711	-0.1645

Table 7.8 decomposes the marginal effects by crop when natural gas is \$5/Mcf (the last line of Table 7.7). The change at the intensive margin is greatest from corn, which is only because the probability of planting corn is so high. Even though water use on sorghum and alfalfa decrease the most from increasing natural gas prices, the probabilities of planting these crops are relatively low.

The extensive margin effect is negative for corn and soybeans because the marginal probability of planting these crops is negative. The largest negative effect at the extensive margin is from corn. However, the increase in water use on sorghum due to increased acres nearly cancels the effect of decreased corn acreage. Similarly, the marginal effects of more alfalfa and fewer soybeans negate each other. The overall extensive margin effect is negative when summed across all crops due to an increase in the probability of planting a less water intensive crop, sorghum.

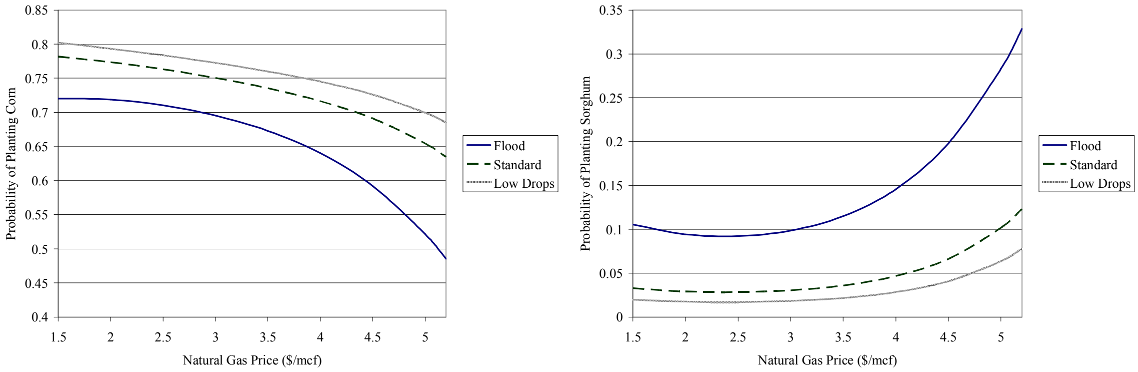
Table 7.8 Marginal Effects by Crop when Natural Gas is $5/Mcf

	Marginal Effect			Elasticity		
Crop	Intensive	Extensive	Total	Intensive	Extensive	Total
Alfalfa	-0.100	0.153	0.053	-0.0314	0.0482	0.0168
Corn	-0.106	-1.353	-1.459	-0.0334	-0.4253	-0.4587
Sorghum	-0.064	1.127	1.063	-0.0203	0.3544	0.3341
Soybeans	-0.027	-0.154	-0.180	-0.0084	-0.0484	-0.0568
Total	-0.297	-0.226	-0.523	-0.0934	-0.0711	-0.1645

7.2.1.1. Interaction of Natural Gas Price Impact with Irrigation Systems

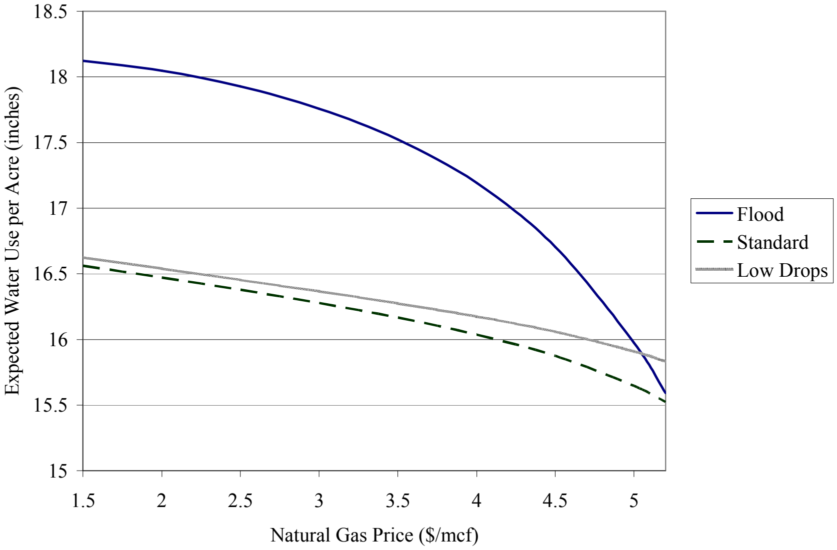
The irrigation system used has some very interesting impacts on the marginal effect of natural gas price on water use. Farmers using flood irrigation are more likely to switch crops from corn to sorghum than farmers using center pivot irrigation technology (Figure 7.3).

Figure 7.3 Probability of Planting Corn or Sorghum under Different Systems as Natural Gas Price Increases



Even though expected water use is greater under flood irrigation, natural gas price response is much larger also (Figure 7.4). Expected water use is 1.5 inches greater under flood irrigation than center pivot irrigation when natural gas price is $1.50/Mcf; however, when natural gas increases to above $5.00/Mcf, expected water use is nearly identical across systems. The natural gas price response is very similar for standard center pivot and center pivot with low drops, although the more efficient technology, center pivot with low drops, is slightly less responsive to changes in natural gas prices. Expected water use decreases more quickly with flood irrigation because flood irrigators are more likely to switch from corn to sorghum.

Figure 7.4 Expected Water Use under Different Systems as Natural Gas Price Changes



The intensive and extensive marginal effects with different irrigation systems, when natural gas is $5/Mcf, are shown in Table 7.9. As reflected in the slopes of the curves in Figure 7.4, irrigators with more efficient irrigation systems are less responsive to natural gas prices. Table 7.9 shows that this response gap comes from differences at both the intensive and extensive margins. The intensive marginal effect is lower for more efficient irrigation technologies because more corn is grown under these technologies, and corn is the least responsive crop to natural gas price. The extensive marginal effect is also smaller for more efficient technologies because the marginal probability of planting corn is not as negative. The difference in the extensive margin effects is especially large. The overall elasticity of water use under flood irrigation is -0.55, but under center pivot irrigation with low drops is only -0.11.

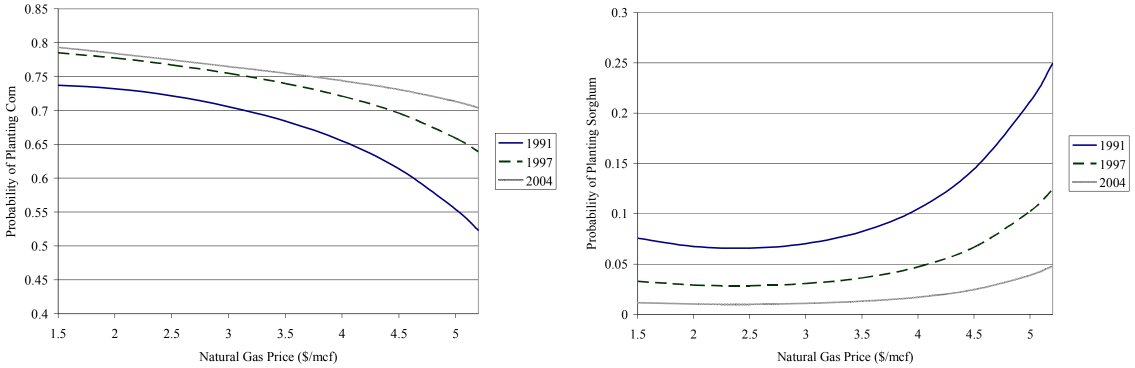
Table 7.9 Marginal Effects by Irrigation System when Natural Gas is $5/Mcf

	Marginal Effect			Elasticity		
Irrigation System	Intensive	Extensive	Total	Intensive	Extensive	Total
Flood	-0.3811	-1.3911	-1.7722	-0.1193	-0.4354	-0.5547
Standard	-0.3045	-0.2505	-0.5550	-0.0973	-0.0801	-0.1774
Low Drops	-0.2789	-0.0747	-0.3536	-0.0876	-0.0235	-0.1111

7.2.1.2. Interaction of Natural Gas Price Impact with Time Trend

Another interaction of importance is the effect technological improvement (primarily through improved yields of corn and soybeans) has on the response of water to natural gas price increases.[1] Yield improvement in corn has reduced the marginal effect of natural gas price on the probability of planting corn. Irrigators are also less likely to switch to sorghum production (Figure 7.5). Improved hybrids have made corn more profitable, so it takes a larger increase in the natural gas price to give enough incentive for farmers to switch out of corn production.

Figure 7.5 Probability of Planting Corn or Sorghum for Different Years as Natural Gas Price Increases



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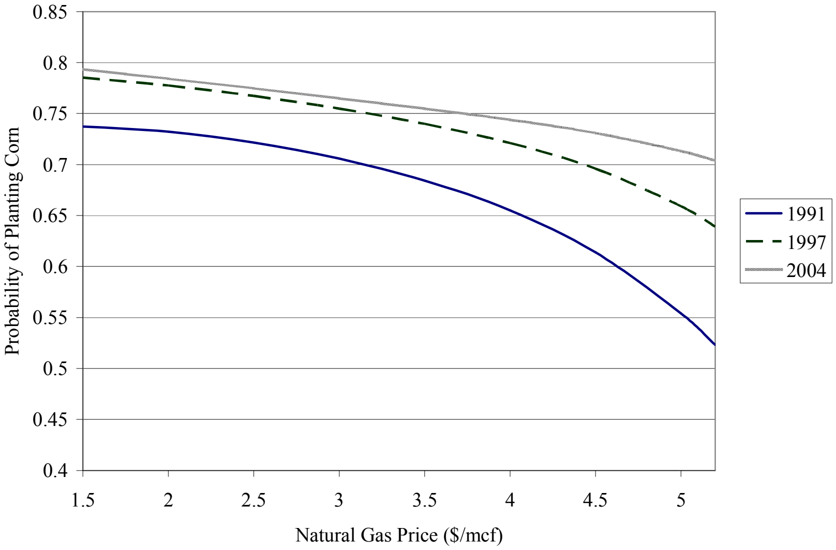
[1] Due to lack of reliable, exogenous measures of hybrid improvements, this was measured in the model by a time trend variable as a proxy. However, the time trend could also be capturing effects other than hybrid improvements as discussed in section 6.6.

Therefore, technological improvement has reduced the response of irrigators to changes in natural gas price (Figure 7.6). With the technology of 1991, expected water use decreases 1.43 inches when natural gas price increases from \$1.50/Mcf to \$5.20/Mcf, whereas water use only decreases 0.82 inches with the technology of 2004.

Figure 7.6 Expected Water Use for Different Years as Natural Gas Price Changes



New technology has reduced the water demand responsiveness mainly due to a large reduction in the extensive marginal effect. Figure 7.7 shows the absolute value of the extensive marginal effect with the technology of different years in the sample. Improved technology has made the probability of planting corn less responsive to price changes as discussed earlier, therefore decreasing the extensive marginal effect. When natural gas is \$5/Mcf, an additional \$1/Mcf increase would cause water use to decrease 0.55 inches through changes in crop-choice with the technology of year 1991, but only 0.05 inches with the technology of 2004 (Table 7.10). The intensive margin effect also decreases with improved technology, because the probabilities of planting corn and soybeans, which are the least responsive crops at the intensive margin, increase, and the probabilities of planting alfalfa and sorghum decrease. The elasticity of total water use when natural gas is $5/Mcf with the technology of year 1991 is -0.29, and with the technology of year 2004 is -0.10 (Table 7.10).

Figure 7.7 Extensive Marginal Effect when Natural Gas is $5/Mcf as Time Changes

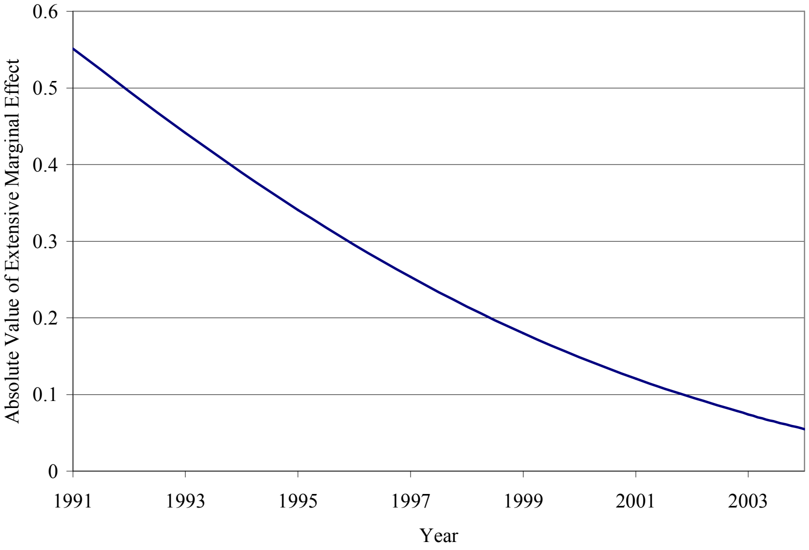


Table 7.10 Marginal Effects by Year when Natural Gas is $5/Mcf

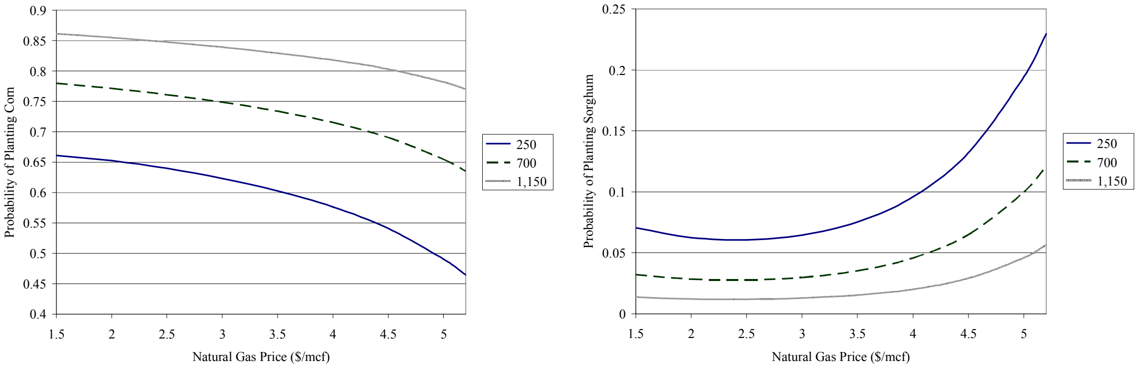
	Marginal Effect			Elasticity		
Time	Intensive	Extensive	Total	Intensive	Extensive	Total
1	-0.3644	-0.5512	-0.9156	-0.1161	-0.1756	-0.2917
14	-0.2621	-0.0549	-0.3170	-0.0827	-0.0173	-0.1000

7.2.1.3. Interaction of Natural Gas Price Impact with Well Capacity

Well capacity also has an interaction with the effect of natural gas price. This is primarily due to larger shifts from corn to sorghum at low well capacities (Figure 7.8).

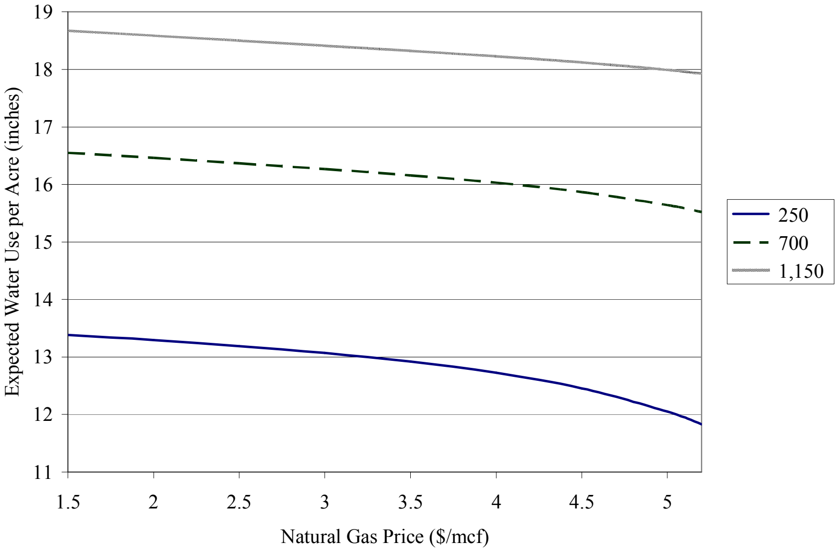
As Figure 7.8 shows, when natural gas price increases, the irrigators' probability of growing corn decreases faster and the probability of growing sorghum increases faster at a low well capacity. At a natural gas price of $5.00/Mcf and a well capacity of 1,150 gpm, expected water use is 17.97 and 15.54 inches for corn and sorghum, respectively. When well capacity decreases to 250 gpm, expected water use is 12.54 inches and 8.46 inches for corn and sorghum, respectively. So, the marginal effect of well capacity is more negative for short-run water use on sorghum than corn. Therefore, with a larger discrepancy in water use between corn and sorghum at low well capacities, the irrigator can reduce costs more by shifting to sorghum at a low well capacity.

Figure 7.8 Probability of Planting Corn or Sorghum for Well Capacities (gpm) as Natural Gas Price Increases



At low well capacities the response in expected water use to energy prices is larger (Figure 7.9). When the well capacity is 250 gpm, expected water use decreases 1.55 inches per acre as natural gas increases from $1.50/Mcf to $5.20/Mcf. However, when well capacity is 1,150 gpm, expected water use only decreases 0.75 inches per acre as natural gas increases from $1.50/Mcf to $5.20/Mcf. This is a surprising result, because it may be assumed that irrigators with a low well capacity will pump all they can with their limited capabilities, and therefore would not be as responsive to price changes. However, this result arises because farmers at low well capacities are more likely to substitute land into a less water intensive crop, namely sorghum.

Figure 7.9 Expected Water Use for Well Capacities as Natural Gas Price Changes



As the well capacity increases, the extensive margin effect (in absolute terms) decreases at a decreasing rate (Figure 7.10). The intensive marginal effect decreases slightly as well capacity increases; the intensive marginal effect is -0.38 and -0.24 for well capacities of 250 gpm and 1,150 gpm, respectively (Table 7.11). When the well capacity is 250 gpm, the extensive marginal effect is nearly twice the size of the intensive marginal effect. But as well capacity increases to 1,150 gpm, the extensive margin effect is less than ¼ the size of the intensive margin effect. The extensive margin effect is larger at smaller well capacities because of an increased probability of switching from corn to sorghum as explained previously in the section about the interaction of natural gas price and well capacity. The intensive margin effect also decreases as well capacity increases because of an increased probability of growing sorghum. The elasticity of total water use when natural gas is \$5/Mcf with a well capacity of 250 gpm is -0.41, and with a well capacity of 1,150 gpm is only -0.08 (Table 7.11).

Figure 7.10 Extensive Marginal Effect when Natural Gas is \$5/Mcf as Well Capacity Changes

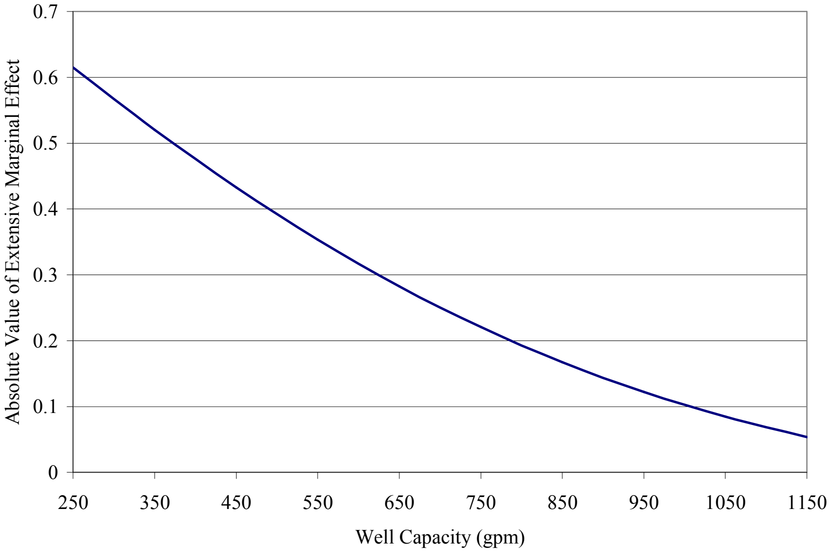


Table 7.11 Marginal Effects by Well Capacity when Natural Gas is \$5/Mcf

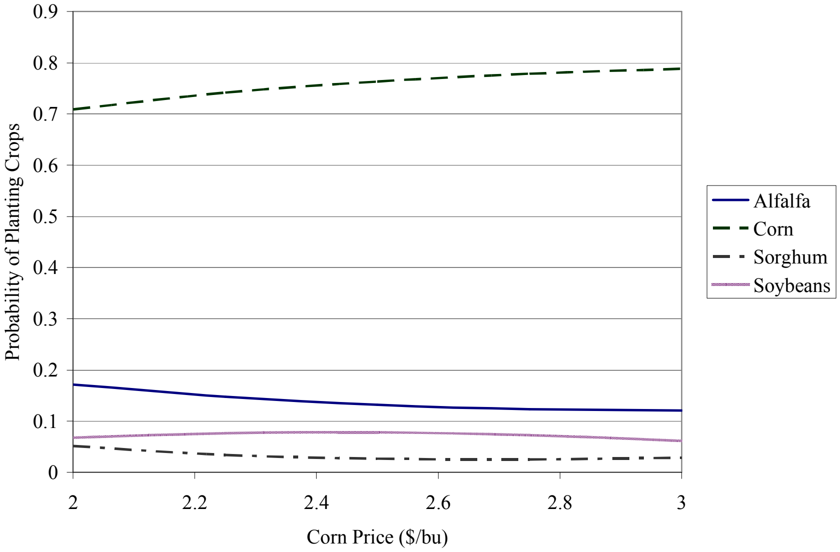
	Marginal Effect			Elasticity		
Well Capacity	Intensive	Extensive	Total	Intensive	Extensive	Total
250	-0.3814	-0.6152	-0.9965	-0.1582	-0.2552	-0.4135
1150	-0.2458	-0.0536	-0.2994	-0.0683	-0.0149	-0.0832

7.2.2 Impact of Crop Prices

Unfortunately, due to limitations of the sample, the effect of corn price is only evaluated between \$2/bu and \$3/bu. Due to increased demand for ethanol, corn prices have recently exceeded \$4/bu in western Kansas. The impact of these price levels on water use is an important question; however, this thesis does not attempt to simulate out of sample. The extensive marginal effect was found to be negligible for corn price because an increase in corn price increases the probability of planting corn but also decreases the probability of planting alfalfa (both crops consume large amounts of water). The short-run change in water use is constant for different corn prices. So even though there are no data on corn prices outside the sample, it is noteworthy that the effect of corn price is fairly constant over the prices within the sample due to a negligible extensive margin effect.

An increase in corn price increases the probability of planting corn at a decreasing rate, as expected (Figure 7.11). The marginal effect decreases and almost becomes zero as corn price approaches $3/bu. Based on this relationship, one might expect that including observations with corn price exceeding $4/bu would extend the effect of corn price, so that the probability would continue increasing, but at an ever decreasing rate. Corn and alfalfa were estimated to be economically competing outputs, but the corn price appears to have little effect on the probability of planting sorghum or soybeans.

Figure 7.11 Impact of Corn Price on the Probability of Planting each Crop



As corn price increases, the expected water use also increases, as shown in Figure 7.12. However, this is only due to the increased water use on corn, as the effect at the extensive margin is negligible. Increasing corn price by $1/bu, increases water use by 1.338 inches on corn planted (Table 7.6). When corn is worth more, apparently irrigators will increase water use to improve yields, which are more valuable. Conversely, the extensive margin effect, albeit small, is actually negative. The intuition for this is more subtle: Alfalfa production uses more water than corn per acre, and a decrease in the probability of planting alfalfa more than offsets the increased water use from the extra corn acreage. The intensive and extensive marginal effects at the data means are reported in Table 7.12.

Figure 7.12 Impact of Corn Price on Expected Water Use

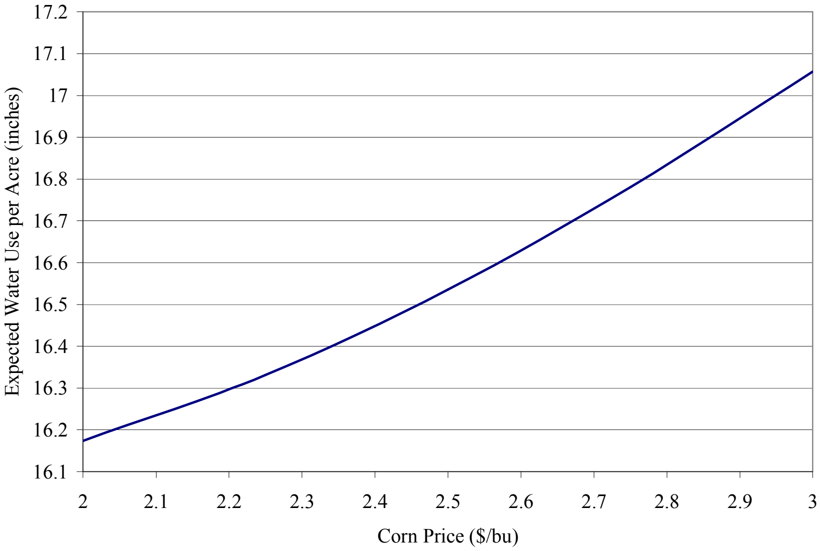


Table 7.12 Intensive and Extensive Marginal Effects for Corn Price

Marginal Effect			Elasticity		
Intensive	Extensive	Total	Intensive	Extensive	Total
1.172	-0.103	1.069	0.179	-0.016	0.163

Farmers using more efficient irrigation systems are more responsive to corn price in their crop-choice. The marginal probability of planting corn becomes negligible at high corn prices with flood irrigation, but remains positive with more efficient systems (Figure 7.13). A similar effect on the marginal probability of planting corn has occurred because of technological improvement (Figure 7.14).

Figure 7.13 Probability of Planting Corn under Different Systems as Corn Price Increases

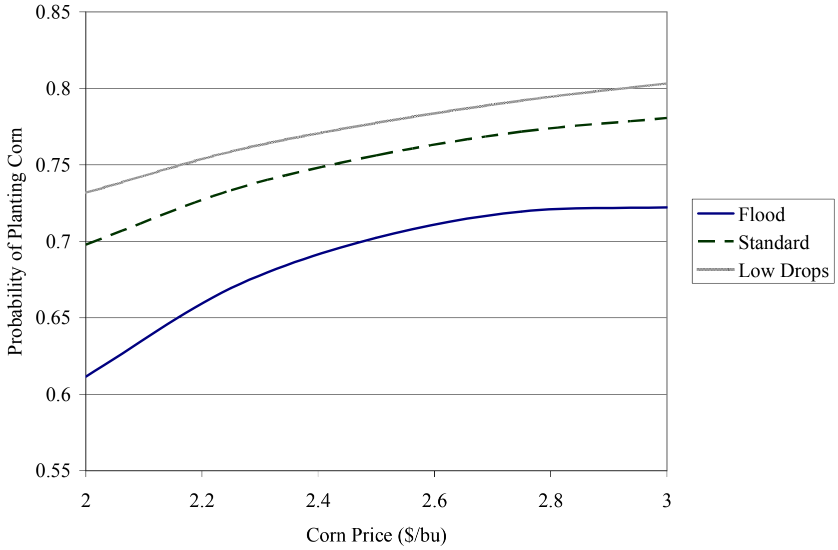
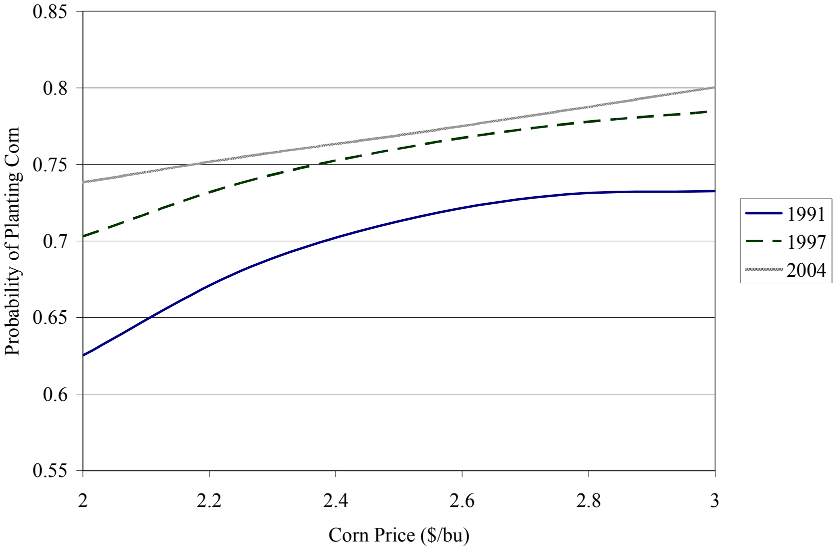


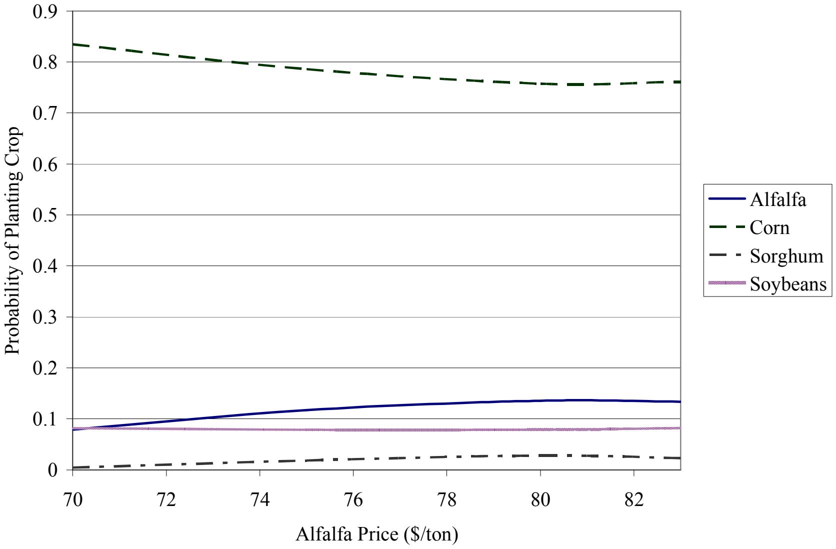
Figure 7.14 Probability of Planting Corn for Different Years as Corn Price Increases



Even though technology has some interesting interactions with the impact of corn price on the probability of planting corn, because the extensive marginal effect is negligible, the interaction has little importance on expected water use. Corn production replaces alfalfa production as corn price increases, and this effect results in very little change in the shape of the expected water use relationship in Figure 7.12.

As alfalfa price increases, the probability of planting alfalfa increases as expected (Figure 7.15). At high prices the marginal probability is negligible, however. The marginal probability of planting corn increases as the alfalfa price increases, demonstrating again that alfalfa and corn are economically competing outputs. Alfalfa price has a negligible effect on the probability of planting sorghum and soybeans. The short-run marginal effect of an increase in alfalfa price is negative according to the water use regression. This result is contrary to the expected effect of alfalfa price, but is a relatively small effect. If the alfalfa price increased $10/ton, the model predicts water use on alfalfa to only decrease 0.48 inches (Table 7.6).

Figure 7.15 Impact of Alfalfa Price on the Probability of Planting each Crop



Short-run water use for sorghum increases 0.434 inches as sorghum price increases $1/cwt (Table 7.6). This is a fairly large effect considering sorghum prices ranged from $2.64/cwt to $5.53/cwt. Nevertheless, the intensive margin effect of sorghum is relatively unimportant because yield increases over the years have drastically reduced the probability of planting sorghum. The marginal effect of soybean price on soybean water use is negative and quite large in magnitude, which is contrary to intuition (Table 7.6).

7.2.3 Impact of Climate/Weather Conditions

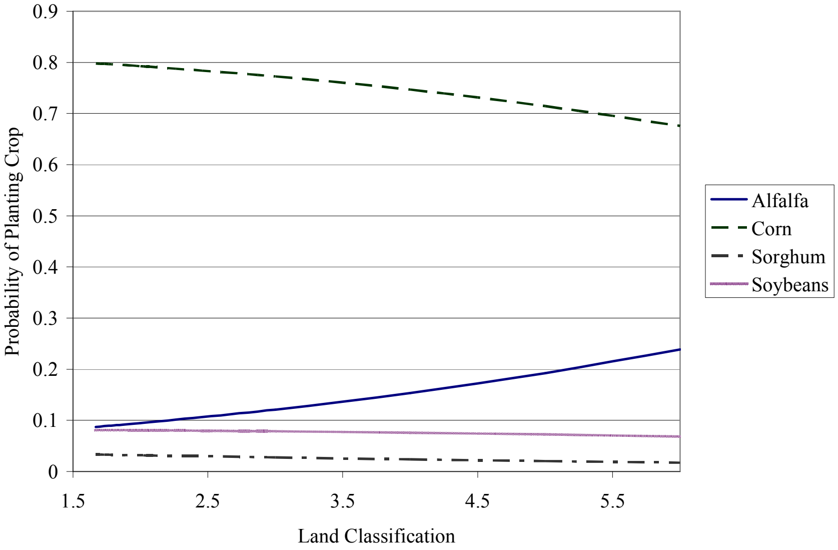
As precipitation increases, the amount of water pumped decreases. For an extra inch of rain in January through April, water use decreases 0.65 inches when corn is planted (Table 7.5). All of the coefficients on the precipitation variables are less than one, so precipitation and irrigation water use are not perfect substitutes as one may expect. January through April precipitation has a larger marginal effect than May through August precipitation in reducing water use in alfalfa, corn, and sorghum. Perhaps, if farmers feel they have sufficient soil moisture at the start of the crop season, they do not pump as much during the season, for example by delaying the start date of irrigation. Conversely, early irrigations are essential for initial crop growth in years with a dry winter and spring. Apparently this spring rain makes a large difference in water use. The January through April precipitation coefficient is positive, but not as significant for soybeans. This coefficient is contrary to expectations, but may have been obtained because soybeans have a later planting date than corn.

Evapotranspiration (ET) also has a significant effect on irrigation water use. As ET increases, water use must also increase. For corn, for example, as cumulative ET increases one inch, water use increases 0.258 inches.

7.2.4 Impact of Soil Characteristics

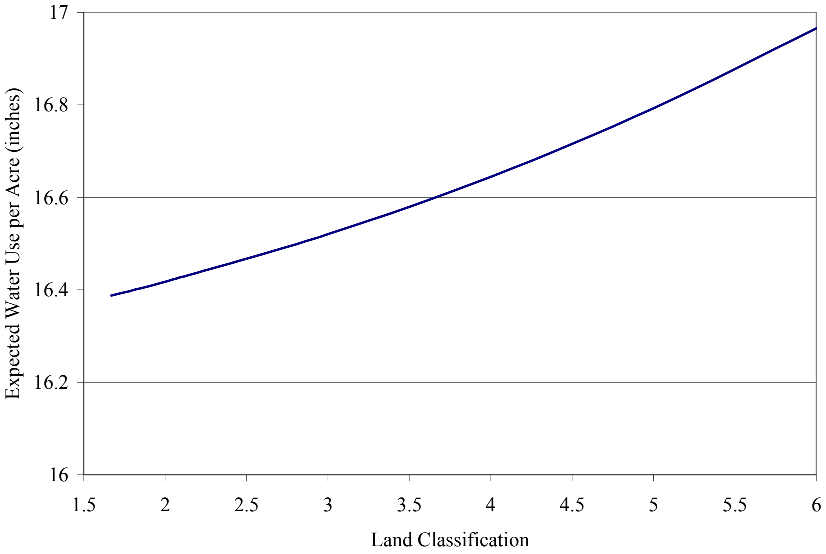
As the land classification improves (gets smaller) the probability of planting corn and sorghum increase. The probability of planting corn increases 2.32% as the land classification decreases 1 rank, averaged across all observations (Table 7.4). The marginal effect of land classification on the probability of planting soybeans is insignificant. Conversely, the probability of planting alfalfa is larger on a poorer land classification; the probability increases 3.21% as land classification increases 1 rank. The effects of land classification on the probabilities of planting different crops, at the means of the other independent variables, are shown in Figure 7.16.

Figure 7.16 Impact of Land Classification on the Probability of Planting Each Crop



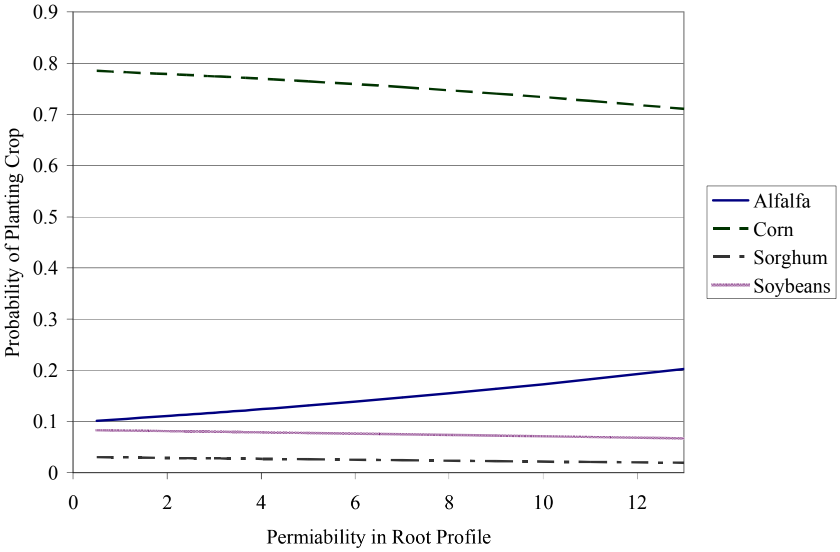
Expected water use decreases as the land classification improves because of this shift in crop-choice. There is essentially a trade-off between corn and alfalfa as land classification changes, and alfalfa uses more water than corn. The change in water use is relatively small as it only decreases 0.58 inches when land classification improves from 6 to 1.67 (Figure 7.17).

Figure 7.17 Impact of Land Classification on Expected Water Use



The effect of soil permeability on crop-choice is similar to the effect of land classification. As the permeability of the soil increases, the probability of planting corn decreases and the probability of planting alfalfa increases (Figure 7.18). For a one unit increase in permeability, the probability of planting alfalfa increases 0.76% (Table 7.4). The effects of soil characteristics on crop-choice may be a result of the preference of farmers to raise alfalfa in sandy creek bottoms that have poor soil characteristics.

Figure 7.18 Impact of Permeability on the Probability of Planting Each Crop



In the short-run, as the permeability of the soil increases, water use increases in three of the crops, as expected (Table 7.5). However, water use decreases, and the coefficient is significant, for alfalfa. Permeability is not expected to have a large influence on water application to alfalfa because alfalfa has a very deep root profile making it more likely to capture water percolating through the soil. Nevertheless, this does not explain a negative coefficient in the model. The probability of planting alfalfa increases as the permeability increases, so these results may be confounded and the selectivity variable is not able to account for it.

The magnitudes of the coefficients on permeability are quite large. Average permeability ranged from 0.48 to 13 in the data, so if permeability increases 10, water use increases 1.39 inches, 3.25 inches, and 2.28 inches for corn, sorghum, and soybeans, respectively.

Overall, expected water use increases as permeability increases, both because of increased use for corn, sorghum, and soybeans, and because of a crop-choice shift to alfalfa from corn. However, the unanticipated result that water use on alfalfa decreases as permeability increases reduces the overall effect of permeability on expected water use.

7.2.5 Impact of Irrigation System

The probability of planting corn is greater for irrigators using more efficient irrigation systems, while the probability of planting sorghum is smaller. Irrigators using flood irrigation are 7.17% less likely to plant corn than those with a center pivot with low drop nozzles, but are 7.05% more likely to plant sorghum (Table 7.4). There is not a significant difference in the probability of planting alfalfa or soybeans. Irrigators using a standard center pivot are 1.96% more likely to plant alfalfa, 2.84% less likely to plant corn, 2.08% more likely to plant sorghum, and 1.20% less likely to plant soybeans than irrigators with a center pivot with low drops.

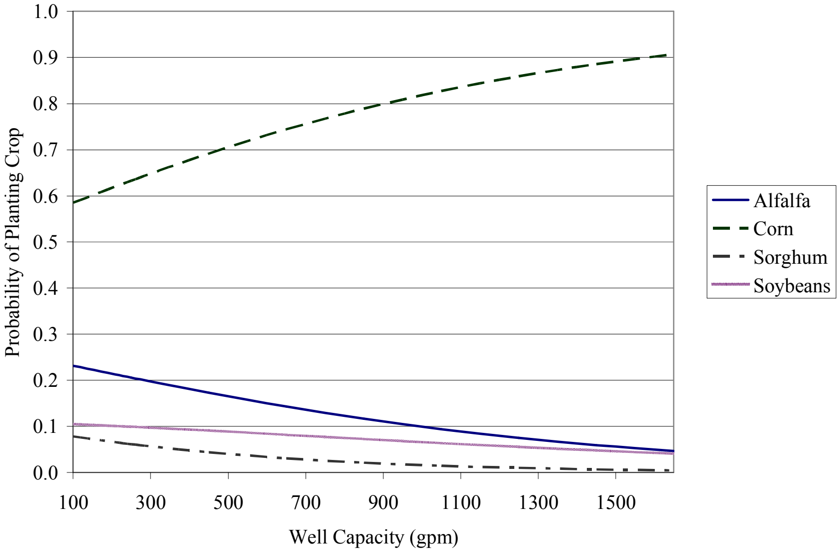
Even though irrigators who use flood irrigation are less likely to plant corn, they apply 2.38 inches more than irrigators with low drops when they do grow corn (Table 7.5). Flood irrigators without limited water may plant corn and because of the inefficiency of the system, apply a lot more water than irrigators with more efficient systems. However, flood irrigators apply 2.28 inches less on sorghum compared to irrigators with low drops. Irrigators who plant sorghum on flood irrigation may have a very limited irrigation schedule, essentially growing dryland sorghum and only using the flood irrigation in dry periods, as opposed to irrigators with center pivot technology who irrigate sorghum to get the best yield possible. This effect would result in less water applied to sorghum on flood irrigation compared to center pivot technology. However, this result may also be an acreage effect. Farmers, who are irrigating 160 acres with flood irrigation as opposed to 126 acres with a center pivot, apply less water per acre. Flood irrigators apply 1.33 inches more on soybeans and 0.58 inches less on alfalfa than irrigators with lows drops. Overall, there is little difference in water application between standard center pivot and center pivot with low drops, although irrigators with low drops seem to apply less on alfalfa and sorghum.

Accounting for crop-choice changes and differences in water use, expected water use for flood irrigation is 1.44 inches more than for center pivot with low drops. There is a negligible difference in expected water use between the two center pivot technologies.

7.2.6 Impact of Well Capacity

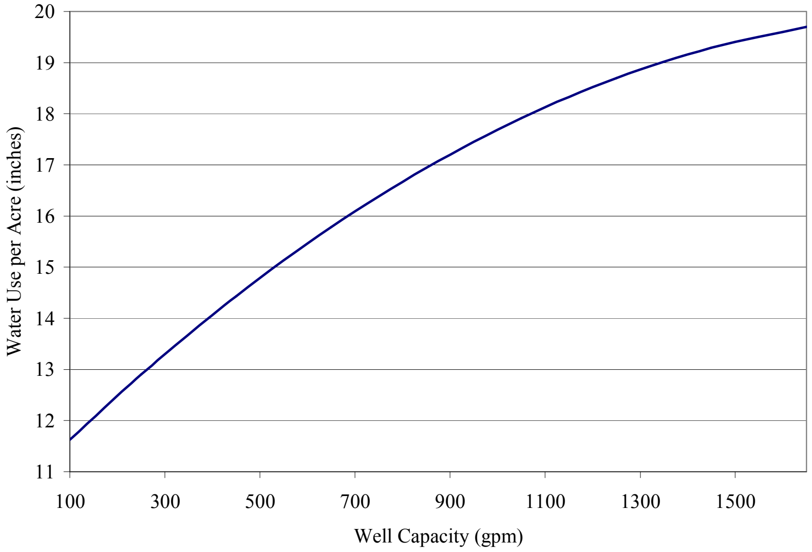
As well capacity increases, the probability of planting corn increases, and the probability of planting all other crops decreases (Table 7.4). Corn production is very sensitive to water needs at certain growth stages, so irrigators have to be able to meet those demands by pumping water fast. Other crops are not as sensitive to water deficits in short time periods during the season. The probability of planting corn increases 3% as well capacity increases 100 gpm, averaged across all observations. The effect on the probability of each crop at the means of the independent variables is presented in Figure 7.19.

Figure 7.19 Impact of Well Capacity on the Probability of Planting Each Crop



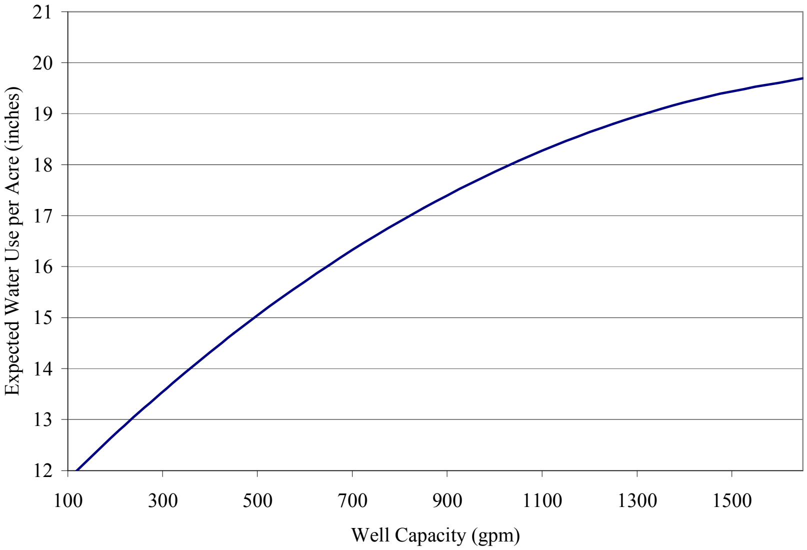
Water use on each crop is increasing in well capacity at a decreasing rate, as expected. The impact of well capacity on corn water use is of particular importance considering the increase in probability of planting the crop. Figure 7.20 shows that the effect on corn water use is very large. Water use is 5.43 inches more on parcels with a well capacity of 1,150 gpm than parcels with a well capacity of only 250 gpm.

Figure 7.20 Impact of Well Capacity on Water Use for Corn



Of all the variables affecting water use that are evaluated in this model, the well capacity has the largest effect. The overall impact on expected water use, accounting for changes in crop-choice and water use, is shown in Figure 7.21. Expected water use is 5.32 inches more on parcels with a well capacity of 1,150 gpm versus parcels with a well capacity of only 250 gpm.

Figure 7.21 Impact of Well Capacity on Overall Expected Water Use



The increase in water use is essentially all from changes in water use at the intensive margin. Table 7.13 reports the intensive and extensive marginal effects for well capacity on water use. The extensive marginal effect is actually negative, mostly due to the decrease in the probability of growing alfalfa. As well capacity increases 100%, which is common between parcels, water use increases 25.36%.

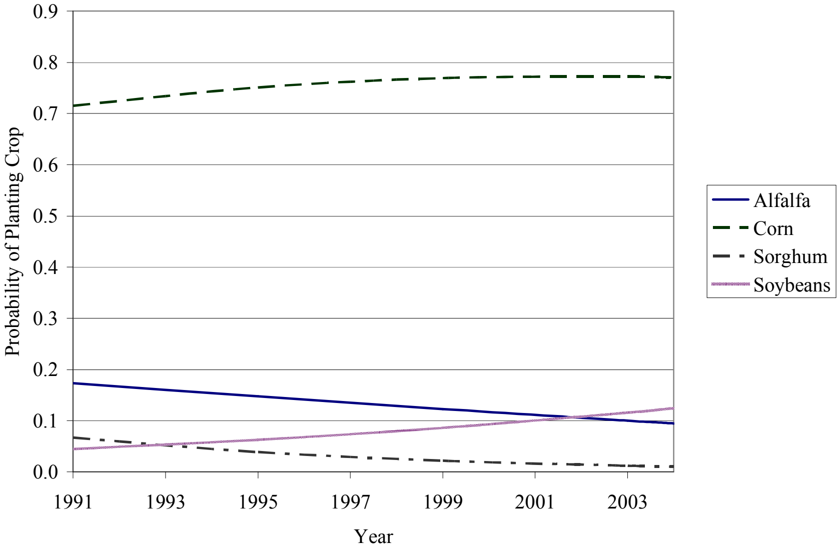
Table 7.13 Intensive and Extensive Marginal Effects for Well Capacity

Marginal Effect			Elasticity		
Intensive	Extensive	Total	Intensive	Extensive	Total
0.00593	-0.00026	0.00567	0.2652	-0.0116	0.2536

7.2.7 Impact of Technological Improvements

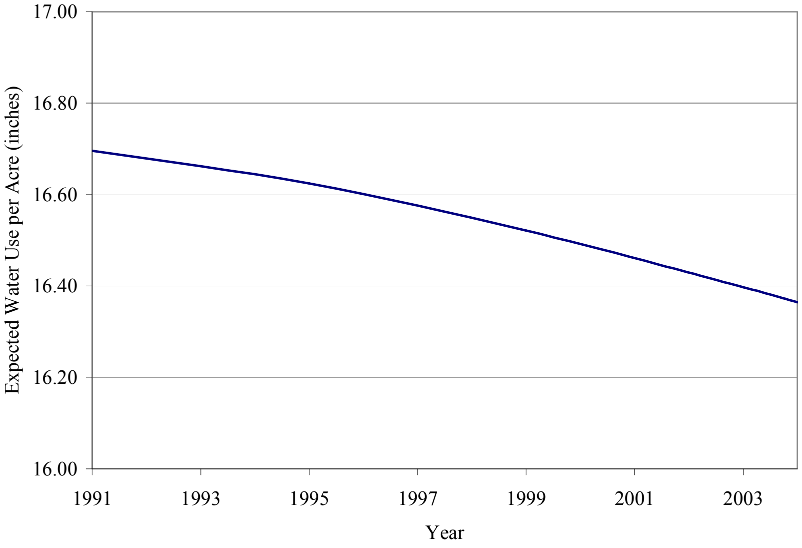
Technological improvements have increased the probability of planting corn and soybeans, and decreased the probability of planting alfalfa and sorghum (Figure 7.22). This is likely because of relative yield improvements in both corn and soybeans. Additionally, extensive biotechnological improvements in these crops have made them especially appealing for weed and pest management.

Figure 7.22 Impact of Technological Improvement on Probability of Planting Each Crop



The impact on overall expected water use is actually negative because the decreased water use from the decrease in the probability of growing alfalfa more than offsets the effect of the increase in probability of growing soybeans and corn. However, the effect is relatively small; expected water use is only 0.33 inches less with the technology of 2004 versus 1991 (Figure 7.23).

Figure 7.23 Impact of Technological Improvement on Expected Water Use



CHAPTER 8 - CONCLUSIONS AND IMPLICATIONS

Understanding irrigation water demand is vital to policy making decisions to conserve the Ogallala Aquifer. Previous research has demonstrated the need for regional studies of water demand, and a wide variety of elasticity estimates warrant a need for further research. Water use was modeled as a two-stage decision: the first stage is a crop-choice decision, and in the second stage water use is determined given the crop-choice. Irrigation water was modeled as a variable, allocatable input, but the presence of nonallocatable inputs is recognized. Nevertheless, it is shown that if the decision is modeled at the parcel-level, with the assumption of a homogenous parcel, the presence of nonallocatable inputs does not require water demand to be a function of all output prices. This thesis employed an econometric modeling technique not yet used in the irrigation water demand literature, a multinomial logit selectivity model. The response of water use to different variables, the response to natural gas price being especially of interest, was decomposed into intensive and extensive marginal effects.

The model was estimated from a unique dataset on spatially referenced, field-level water use. Data on crop-choice, water use, acres, irrigation system, and well capacity were obtained at the parcel-level from water use reports that irrigators are required to submit. Data were used from 1991-2004, a period in which irrigators encountered energy prices that increased fivefold.

The results showed that water demand is very inelastic; however, the elasticity increases in absolute value as natural gas price increases. When natural gas price is high, \$5/Mcf, the elasticity is -0.16, and the marginal effect from an additional increase of natural gas by \$1/Mcf is a 0.52 inch decrease in water use per acre. The extensive margin effect only comprises half the total effect when natural gas price is high, but is negligible when natural gas price is lower. However, even when natural gas prices are high, more efficient irrigation systems and technological advances over time have dampened the extensive margin effect. Interestingly, irrigators with a lower well capacity are actually more responsive to natural gas price because they are more likely to switch from corn to sorghum. Farmers' risk of not providing sufficient water for corn is larger with smaller well capacities, so when natural gas price is high, the return may no longer justify the risk.

The estimated elasticity of water use with respect to corn price was 0.16, with all of the impact coming from the intensive margin effect. Since the change in water use is nearly all at the intensive margin, the marginal effect of an increase in water price remains nearly constant across corn prices within the sample data. Interestingly, the effect of a 1% increase in corn price offsets the effect of a 1% increase in natural gas price, when natural gas is \$5/Mcf. The effect of an increase in corn price on the extensive margin effect is negligible because corn and alfalfa were found to be economically competing outputs. The results showed that irrigators using flood irrigation versus center pivot apply more water to corn and less water to sorghum, but flood irrigators are more likely to choose sorghum and less likely to choose corn. Overall, expected water use is 1.44 inches more for flood irrigators than irrigators with center pivot with low drop nozzles. The difference in water use and crop-choice between standard center pivot and center pivot with low drops is minimal. The well capacity has a large impact on water use, but the effect is all at the intensive margin. Expected water use is 5.32 inches more on parcels with a well capacity of 1,150 gpm than parcels with a well capacity of only 250 gpm. Technological improvements in corn and soybeans have actually slightly decreased water use because of a reduction in alfalfa acreage and an increase in soybean acreage.

8.1 RESEARCH IMPLICATIONS

This thesis has several implications for research, both theoretical and empirical. There are also limitations to the methods used in this thesis which are recognized and evaluated as opportunities for further research.

The theory section of this thesis has some important implications for irrigation groundwater demand research. First, the fixed, allocatable input model does not make logical sense for groundwater irrigation in settings such as the Ogallala region, unless there is an effective constraint on water use. If there is an effective water constraint, and given the hydrological characteristics of groundwater, the water constraint should be modeled at the parcel-level rather than the farm-level.

If water is not effectively constrained, water should be modeled as an allocatable input, but the model should also account for nonallocatable inputs. The second implication for research is that the proper factor demands for this type of model depend on whether the problem is analyzed at the parcel or farm-level. If modeled at the parcel-level, factor demands are only a function of own-crop price. However, if modeled at the farm-level, factor demands are a function of all crop prices due to the linkage of demands through the nonallocatable inputs.

The third theoretical research implication is that if the extensive margin effect is not accounted for, input demand is underestimated. This concept has been accepted in the literature, but it is believed that a formal proof had not been shown previous to this thesis.

Empirically, the model does find that accounting for selectivity in water demand is important, as the λ value was significant at the 1% level in each of the OLS regressions for water use. If selection bias had not been accounted for with the addition of the λ term in each of the water use regressions, the parameter estimates would have been biased. Natural gas price is significant in the multinomial logit model and the water use regressions, providing empirical support for modeling water as a variable, allocatable input as developed in the theoretical model.

A limitation of this model is that observations with wheat and multiple crops planted on the parcel were excluded from the analysis. These observations were excluded because of complications with water use and soil data. Water use on wheat cannot be reliably obtained from the dataset, because water is applied in two calendar years for the one crop, and a second crop is often grown before wheat in the first year of this cycle. When multiple crops are planted, the data do not specify the number of acres planted to each crop, so that water use for each crop is not available. To improve analysis of water use, the DWR would need to revise their survey so the number of acres for each crop and water use on each crop is indicated by the farmer. These data will become increasingly important if farmers plant more parcels to multiple crops to meet water constraints, especially as irrigation technology allows irrigators to do so with greater ease. The exclusion of wheat and multiple crops may have biased the extensive marginal effect. In particular, if wheat is substituted with corn, the extensive margin effect for natural gas and corn price may be larger than estimated in this thesis.

Another limitation is the assumption of the independence of irrelevant alternatives imposed by the multinomial logit model. However, the multinomial logit model was the best option available because econometric techniques have not been developed to account for selection bias with other discrete dependent variable models.

Given these two limitations of the model, an opportunity for further research is to model crop-choice decisions (i.e., focus only of the first stage) with a discrete choice model that relaxes the assumption of the independence of irrelevant alternatives. Additionally, wheat and multiple crop-choices could be included in the analysis, because the need to quantify water use is circumvented. If all crop-choices were included, the data set also would be balanced for panel data analysis. Therefore, a panel data analysis of crop-choice with a nested logit model or a random parameters logit is highly relevant to confirm or refute the results of the crop-choice model in this thesis. The extensive margin effect is negligible for most variables in this thesis mostly because alfalfa and corn are substituted; if instead for example, wheat and corn are substituted, the extensive margin effect could be larger than estimated.

Another important opportunity for further research is to investigate how farmers may respond to different quantity restriction scenarios. Policy makers will need information on the impact of quantity restrictions on both production decisions and the welfare of irrigators. Various methods of imposing the quantity restrictions should be investigated to provide the most complete information to policy makers.

8.2 POLICY IMPLICATIONS

The findings of this thesis suggest that policies aiming to conserve water in the Ogallala Aquifer which fit under the "pricing" category will not accomplish their purpose and may cause great economic harm. The elasticity of demand for irrigation water with respect to natural gas price is very low. Additionally, the current trends in production agriculture, such as improved irrigation technology and improved corn and soybean hybrids, are making water demand even more inelastic. An inelastic demand means that irrigators will not decrease their water use much with increases in natural gas prices, but they will suffer large losses in income.

Researchers' projections in the 1980s that market forces would eliminate irrigation water use before the aquifer depleted seemed reasonable at the time. However, prices did not rise as fast as expected and technology has trumped the impact of recent energy price increases. Furthermore, recent increases in the corn price will increase water use. Policies could restrict water use through either voluntary or mandatory quantity restrictions. The conditions of the aquifer, shown in the introduction, strongly suggest that efficient restriction policies are not "one size fits all." To attain efficiency, restrictions would need to account for both the rate of depletion and the remaining saturated thickness. This logic is embedded to some degree in the targeted efforts of the WaterTAP and CREP policies. The impact of these policies on water use will determine the scope of future restrictions.

Converting from flood to center pivot irrigation was found to reduce water use per irrigated acre. Assuming that irrigators are not allowed to change irrigated acreage in response to a technology upgrade, subsidies to replace flood systems with more modern equipment would contribute to water conservation. However, there does not appear to be a very large difference in water use between standard center pivot and center pivot with low drop nozzle technologies. Sufficient evidence exists that low drop nozzles are more efficient than the standard center pivot, but without quantity restrictions the adoption of more efficient technologies within center pivots will not reduce gross consumption of irrigation water. Unfortunately, this thesis does not model changes in acreage due to irrigation technology choices, so the results cannot speak to the question of how irrigation technologies would affect water use if acreage changes were not controlled.

Policies which encourage improved management practices may include research subsidies or cost-share programs with irrigators to encourage adoption of efficient technologies and practices. However, more efficient irrigation systems reduce the price responsiveness of irrigators. Therefore, the results demonstrate that these management policies actually reduce the effectiveness of pricing policies.

One policy approach receiving little attention among policy makers to date is implementing water markets as a method of distributing restricted water rights. A water market incorporates all three types of water policies and has the ability to comply with all three motivations to conserve water. The government would issue water rights periodically (yearly or every 5 years) and would only give a right if the irrigator has the capability to pump the amount of water in the right. The appropriation should consider both the rate of depletion in that region and the remaining saturated thickness. Due to the hydrology of the aquifer, trading must consider a spatial constraint. Water trading in the Western United States has typically shifted water from farming practices to urban uses, and rural communities' economies have suffered as a spillover effect of the policies (Gollehon). Policy makers could resolve this issue by only allowing trading among agricultural producers. Transferring water from western Kansas to urban areas may not even be feasible due to transportation costs. However, selling or leasing water rights to industries may help rural communities. Perhaps if water rights were available for industries, it would attract new industries to locate in rural western Kansas. These industries may likely provide more jobs to the local economy than irrigated agriculture, and also use less water. Obtaining the most value from the water in the Ogallala is to the greatest advantage of rural communities in western Kansas.

Initially distributing the water rights is the most difficult step to implementing the market. However, once rights are distributed, the most efficient irrigators who could obtain the highest value from the right would buy the rights from less efficient irrigators. The gross quantity restriction would encourage adoption of efficient technologies and conservation management practices, yet constrain the adoption of these practices from having the reverse effect of increasing water use.

Before implementing such a policy, researchers must investigate several issues. It is vital to understand the hydrology of the aquifer, which would determine the spatial constraint of trading. Economists also need to investigate how farmers would likely respond in a water market. Would irrigators actually trade? Are there any unexpected consequences or externalities? This research requires an interdisciplinary understanding of the issues, and models that incorporate biophysical processes as well as economic markets. Research must also attempt to quantify the expected effects on farmer profits and the economies of the local communities.

Effective irrigation water policy is essential to conserve the Ogallala Aquifer, to sustain production agriculture's revenues, to stimulate rural communities' economies, to minimize the cost to the taxpayer, and to meet the growing food and energy demands of the world. These interests are competing, but need not be mutually exclusive in developing policy. Policy makers face difficult decisions that they have avoided in the past. Research is one of the keys to informing policy makers as they formulate effective policy.

CHAPTER 9 - REFERENCES

Antle, J.M., and S.M. Capalbo. "Econometric-Process Models for Integrated Assessment of Agricultural Production Systems." *American Journal of Agricultural Economics*. 83 (2001): 389-401.

Beattie, B.R., and C.R. Taylor. *The Economics of Production*. Reprint. Originally published: New York: John Wiley & Sons, Inc., 1985.

Bernardo, D.J., K. Whittlesey, K.E. Saxton, and D.L. Bassett. "An Irrigated Model for Management of Limited Water Supplies." *Western Journal of Agricultural Economics*. 12 (1987): 164-173.

Brenn, D. "Understanding Kansas Water Law, Policy, and Planning." Presentation to "Water and Society" class. Kansas State University. October 6, 2006.

Buller, O.H., and J.R. Williams. "Effects of Energy and Commodity Prices on Irrigation in the High Plains." Report of Progress No. 611, Kansas State University Agricultural Experiment Station, December 1990.

Chenlaw, D., A.M. Featherstone, and O.H. Buller. "Groundwater Allocation in Irrigated Crop Production." *Journal of Production Agriculture*. 2 (1989): 37-41.

Commodity Research Bureau, Inc. "Historical Market Data." CRB PowerGen Synthetic Data Generator. Version 5.0.3. Chicago: June 2006.

Dumler, T.J., and D.H. Rogers. "Irrigation Capital Requirements and Energy Costs." Department of Agricultural Economics MF-836, Kansas State University, 2004.

Farm and Ranch Irrigation Survey (1998), National Agricultural Statistics Service, U.S. Department of Agriculture (1999). Available at http://www.ers.usda.gov/Data/WesternIrrigation/ShowTables.asp?tabList=4

Gisser, M. "Groundwater: Focusing on the Real Issue." *Journal of Political Economy*. 91 (1983): 1001-1027.

Golden B.B., and J.M. Peterson. "Evaluation of Water Conservation from More Efficient Irrigation Systems." Staff Paper 06-03, Department of Agricultural Economics, Kansas State University, June 2006.

Gollehon, N.R. "Water Markets: Implications for Rural Areas of the West." *Rural Development Perspectives*. 2 (1999): 57-63.

Greene, W. *Econometric Analysis,* 2nd ed. New York: Macmillan Co., 1993.

Greene, W. *LIMDEP User's Manual and Reference Guide, Version 8.0.* Plainview NY: Econometric Software, Inc., 2002.

High Plains Study Council. "A Summary of Results of the Ogallala Aquifer Regional Study, with Recommendations to the Secretary of Commerce and Congress." December 1982.

Hornbaker, R.H. and H.P. Mapp. "A Dynamic Analysis of Water Savings from Advanced Irrigation Technologies." *Western Journal of Agricultural Economics*. 13 (1988): 307-15.

Howitt, R.E., W.D. Watson, R.M. Adams. "A Reevaluation of Price Elasticities for Irrigation Water." *Water Resources Research* 16 (1980): 623-628.

Kansas Agricultural Statistics Service (KASS). Available at www.nass.gov/ks/

Kansas Geological Survey (KGS). "An Atlas of the Kansas High Plains Aquifer." December 2000. Available at http://www.kgs.ku.edu/HighPlains/atlas/

Kansas Geological Survey (KGS). "High Plains Aquifer Section-Level Database." Available at http://hercules.kgs.ku.edu/geohydro/section_data/hp_step1.cfm

Kansas Water Office. "Water Appropriation Act." Fact Sheet No. 25. January 2001. Available at http://www.kwo.org/Reports%20&%20Publications/Fact%20Sheets/No_25_Water_Appropriation_Act.pdf

Kastens, T.L., K.C. Dhuyvetter, and R. Jones. "Prices for Crop and Livestock Cost-Return Budgets." Department of Agricultural Economics MF-1013, Kansas State University, 1999-2003.

Koundouri, P. "Current Issues in the Economics of Groundwater Resource Management." *Journal of Economic Surveys* 18 (2004):703-740.

Langemeier, L.N. and M.R. Langemeier. "Prices for Crop and Livestock Cost-Return Budgets." Department of Agricultural Economics MF-1013, Kansas State University, 1991-1994.

Langemeier, L.N., T.L. Kastens, and R. Jones. "Prices for Crop and Livestock Cost-Return Budgets." Department of Agricultural Economics MF-1013, Kansas State University, 1996-1998.

Langemeier, L.N. and R. Jones. "Prices for Crop and Livestock Cost-Return Budgets." Department of Agricultural Economics MF-1013, Kansas State University, 1995.

Lee, L.-F. "Generalized Econometric Models with Selectivity." *Econometrica* 51(March 1983): 507-12.

Lichtenberg, E. "Land Quality, Irrigation Development, and Cropping Patterns in the Northern High Plains." *American Journal of Agricultural Economics* 71 (1989): 187-194.

Llewelyn, R.V., J.R. Williams, and P.L. Diebel. "The Economic Impacts of Water Supply Reductions: Economically Optimal Cropping Practices on the Upper Arkansas River Under Varying Policy Conditions." Kansas Water Resources Research Institute Report 313, June 1996.

Maddala, C.S. *Introduction to Econometrics*, 3rd ed. New York: John Wiley & Sons, Ltd, 2001.

Moore, M.R., N.R. Gollehon, and M.B. Carey. "Alternative Models of Input Allocation in Multicrop Systems: Irrigation Water in the Central Plains, United States." *Agricultural Economics* 11 (1994a): 143-158.

Moore, M.R., N.R. Gollehon, and M.B. Carey. "Multicrop Production Decisions in Western Irrigated Agriculture: The Role of Water Price." *American Journal of Agricultural Economics* 76 (1994b): 859-874.

National Resource Conservation Service. "Farm Bill 2002: EQIP/Ground and Surface Water Conservation." Fact Sheet. October 2005. Available at http://www.nrcs.usda.gov/PROGRAMS/eqip/eqip_gswc_fs101305.pdf

National Resource Conservation Service. "Ecological and Interpretative Groups" *National Soil Survey Handbook.* Part 622. Last Modified: April 2007. Available at http://soils.usda.gov/technical/handbook/contents/part622.html

Nieswiadomy, M. "The Demand for Irrigation Water in the High Plains of Texas, 1957-80." *American Journal of Agricultural Economics*. 67 (1985): 619-26.

Ogg, C.W., and N.R. Gollehon. “Western Irrigation Response to Pumping Costs: A Water Demand Analysis Using Climatic Regions.” *Water Resources Research* 25 (1989): 767-773.

Peterson, J.M., and D.J. Bernardo. “A Review of Economic Analyses of Water Policies and Irrigation Issues in the High Plains: 1980-2000.” Research Report 36, Department of Agricultural Economics, Kansas State University, June 2003.

Peterson, J.M., and Y. Ding. “Economic Adjustments to Groundwater Depletion in the High Plains: Do Water-Saving Irrigation Systems Save Water?” *American Journal of Agricultural Economics* 87 (2005): 147-259.

Peterson, J.M., T.L. Marsh, and J.R. Williams. “Conserving the Ogallala Aquifer: Efficiency, Equity, and Moral Motives.” *Choices* 1 (2003): 15-18.

Pindyck, R.S., and D.L. Rubinfeld. *Econometric Models and Economic Forecasts*, 4th ed. Boston MA: Irwin/McGraw-Hill, 1998.

Rogers, D.H., and M. Alam. “Comparing Irrigation Energy Costs.” Irrigation Management Series. MF-2360, Kansas State University, 1999.

Schaible, G.D. “Water Conservation Policy Analysis: An Interregional, Multi-Output, Primal-Dual Optimization Approach.” *American Journal of Agricultural Economics* 79 (1997): 163-177.

Scheierling, S.M., J.B. Loomis, and R.A. Young. “Irrigation Water Demand: A Meta-analysis of Price Elasticities.” *Water Resources Research* 42 (2006): W01411.

Schoengold, K., D.L. Sunding, and G. Moreno. “Panel Estimation of an Agricultural Water Demand Function.” Working paper, Department of Agricultural and Resource Economics, University of California, Berkeley, 2005.

Shumway, C.R. “Derived Demand for Irrigation Water: The California Aqueduct.” *Southern Journal of Agricultural Economics* 2 (1973): 201-25.

Smith, V. L. "Water Deeds: A Proposed Solution to the Water Valuation Problem." *Arizona Rev.* 26 (January 1977):7-10.

Solley, W.B., R.R. Pierce, and H.A. Perlman (1998). *Estimated Use of Water in the United States in 1995*. U.S. Geological Survey, U.S. Department of the Interior. Circular 1200.

Tierney, W.I. Jr. and J.R. Mintert. “Prices for Forward Planning.” Department of Agricultural Economics MF-525, Kansas State University, 1990.

Train, K.E. *Discrete Choice Methods with Simulation*. Cambridge University Press, 2003.

United States Department of Agriculture. National Agricultural Statistics Service. *Agricultural Prices.* July 1997-2005. Available at http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1003

Williams, J.R., R.V. Llewelyn, D. DeLano, and I. Thangavelu. “Irrigation Cost Estimation Procedures Used in the Irrigation Economics Evaluation System (IEES).” Research Report 23, Department of Agricultural Economics, Kansas State University, 1996.

Wu, J. and B.A. Babcock. “The Choice of Tillage, Rotation, and Soil Testing Practices: Economic and Environmental Implications.” *American Journal of Agricultural Economics* 80 (1998): 494-511.

Appendix 1 – Alternative Model Specifications

Two alternative model specifications were considered. First, the model was estimated using the pumping cost, which varies across parcels with the same energy price because of differences in depth to water, instead of the natural gas price. Secondly, the model was estimated with an alternative expected price series. The data used in these models is first discussed then the differences in the results from the base model are discussed.

Pumping Cost versus Natural Gas Price

Due to differences in the depth to water, each parcel has a unique cost of pumping water. It makes intuitive sense that farmers with higher costs of pumping water would pump less, and that the model should account for this. Indeed this is the method Moore, Gollehon, and Carey (1994b) utilized to evaluate the effect of water price on water use. They only have two years of data, so the variation in depth to water causes most of the variation in water price in their study.

Water price (*WTRP)* is represented as the cost of pumping one acre foot of water. The formula (Rogers and Alam) to compute the pumping cost is

$$WTRP = NTGP(0.0223(lift + 2.31PSI))$$

where *NTGP* is the price of natural gas (\$/Mcf), *lift* is the distance from the water level to the well outlet (feet), and *PSI* is the pressure at the pump (pounds/square inch). The constant 0.0223 is the natural gas (Mcf) use required to lift 1 acre-foot of water 1 foot in height. The constant 2.31 (feet/psi) is a conversion factor. This formula assumes irrigation pumps are 75% efficient (not the same as application efficiency), and 100% of Nebraska Pumping Plant Criteria efficiency rating (Dumler and Rogers). The three year average depth to water in 2001 is used for *lift*. The pressures for flood, standard center pivot, and center pivot with low drop nozzles are assumed to be 10, 35, and 20 psi, respectively (Williams et al.).

Hydrology data are from the Kansas Geological Survey's "High Plains Aquifer Section-Level Database."[1] Data on depth to water and saturated thickness are available at the section-level. Depth to water and saturated thickness are the 2001 three year average, reported in feet. So each parcel has the same depth to water data for the whole period because data across time is neither readily available nor reliable. The Section-Level Database only reports average depth to water for three years (1998, 2001, and 2004). Furthermore, the differences between these time periods are not meaningful estimates because of inherent measurement uncertainty of water depths, which varies with barometric pressure and other changeable factors.

When pumping cost is used in the model instead of the natural gas price, the signs of the coefficients are opposite the expected signs. The probability of planting corn increases as the pumping cost increases, and the probability of planting the other three crops decreases. The marginal effects of pumping cost in the water use regressions are positive in all of the crops, except soybeans, which is contradictory to the law of demand.

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[1] To access the Section-Level Database online: http://hercules.kgs.ku.edu/geohydro/section_data/hp_step1.cfm

Indeed, this is similar to the results Moore, Gollehon, and Carey (1994b) obtained in the Central Plains region of their study.

The reason this result is obtained is likely because depth to water is confounded with other variables affecting crop-choice and water use. When the base model with natural gas price is run with an extra variable for the depth to water, the probability of planting corn increases as the depth to water increases, and water use increases as the depth to water increases for each of the crops. In Kansas, many of the areas that have a large depth to water are also some of the best places to grow corn and may have other conditions which make them conducive to pump large amounts of water. For example, GMD 3 has the largest average depth to water, yet it also has the largest average saturated thickness and well capacity of any of the GMDs (Figure 9.1). Well capacity should capture part of this effect, but apparently is not sufficient.

Figure 9.1 Percent Acres Planted to Each Crop and Average Hydrological Characteristics by County and GMD

		Percent of Acres Planted						
County	GMD	Alfalfa	Corn	Sorghum	Soybeans	Depth to Water in 2001 (ft)	Saturated Thickness in 2001 (ft)	Well Capacity (gpm)
Cheyenne	4	6%	84%	2%	8%	173	102	584
Decatur	4	5%	88%	3%	4%	49	42	423
Rawlins	4	2%	83%	10%	5%	152	92	428
Sheridan	4	2%	90%	4%	5%	134	81	532
Sherman	4	4%	89%	4%	4%	151	123	598
Thomas	4	1%	90%	3%	6%	131	97	577
Average	*4*	*3%*	*89%*	*4%*	*5%*	*139*	*98*	*562*
Scott	1	1%	65%	32%	1%	124	46	271
Wallace	1	3%	91%	5%	1%	155	80	613
Wichita	1	9%	70%	18%	2%	135	37	289
Average	*1*	*4%*	*79%*	*16%*	*1%*	*139*	*57*	*411*
Finney	3	43%	51%	2%	4%	148	261	781
Ford	3	11%	73%	10%	7%	100	96	710
Grant	3	28%	68%	3%	1%	244	171	871
Kearny	3	51%	47%	1%	1%	152	237	792
Meade	3	7%	83%	6%	3%	140	309	973
Morton	3	20%	64%	16%	0%	149	207	651
Seward	3	25%	68%	5%	2%	177	310	913
Stanton	3	2%	91%	7%	0%	206	173	685
Stevens	3	13%	85%	1%	1%	185	351	1126
Average	*3*	*31%*	*63%*	*3%*	*3%*	*152*	*239*	*823*
Barton	5	19%	57%	8%	16%	17	107	783
Edwards	5	19%	63%	2%	15%	33	125	823
Kiowa	5	13%	64%	3%	20%	60	126	862
Pawnee	5	20%	54%	5%	21%	31	85	727
Pratt	5	6%	78%	2%	14%	45	157	870
Reno	2 & 5	2%	61%	8%	29%	23	125	810
Stafford	5	10%	71%	2%	17%	22	137	833
Average	*2 & 5*	*13%*	*66%*	*3%*	*17%*	*34*	*128*	*823*
Total		17%	70%	4%	9%	103	153	740

Using the natural gas price has another advantage. The primary research objective is to understand how farmers have responded in their water use to energy price increases, not how farmers differ in water use due to cross-sectional differences in pumping costs. The natural gas price, which changes for each farmer each year, is more conducive for evaluating the question rather than the pumping cost.

Alternative Expected Price Series

It is very difficult and controversial to determine what prices farmers use as expected prices, so it is insightful to run the analysis with a couple different series and determine how sensitive the model is. An alternative series of expected output prices is from reports published in the *Kansas Farm Management and Marketing Handbook* (Tierney, W.I. Jr. and J.R. Mintert; Langemeier, L.N. and M.R. Langemeier; Langemeier, L.N. and R. Jones; Langemeier, L.N., T.L. Kastens, and R. Jones; and Kastens, T.L., K.C. Dhuyvetter, and R. Jones). From here after this price series is called the "K-State" price series and the expected price series used in the base model used in the thesis is called the "Futures" price series. Every October Kansas State University publishes expected harvest prices for the next year. This is published before many producers make their row crop decision, but is timely for those considering wheat as a crop alternative. The K-State price series is defendable from the standpoint that some farmers literally see these prices as expected prices for the next year.

One issue with the use of this data is that the methodology of computing expected prices changed in 1996 (expected price for 1997). In addition, corn, sorghum, and soybean prices were reported at the state-level from 1990-95, but after the change in methodology the prices were reported at the regional-level within the state. The series used in this analysis is the price reported for Scott City, KS. Therefore, for consistency, the previous 3-year average basis for Scott City was added to the state-level price reported as expected prices for 1991-96. The expected price of alfalfa was only reported at state-level the entire period, so it does not need adjusting.

The goodness of fit measures are nearly identical using either price series, so they do not indicate a clear choice. Additionally, the water use regressions are nearly identical, and variables other than prices have similar effects on crop-choice. There are some differences in the marginal effects of prices on crop-choice though. In general, crop-choice is more responsive to changes in the natural gas price with the Futures prices series. The marginal effect of natural gas price on the probability of planting alfalfa becomes negative at high natural gas prices using the K-State prices, where it is always positive with the Futures series. However, the probability of planting corn always decreases with increases in the natural gas price using the Futures price series, but at low natural gas prices the marginal effect is positive for the K-State series, and is generally a very small effect across all natural gas prices. It is interesting that changing the crop price series changes the effect natural gas price on crop-choice. The signs of the marginal effects on crop-choice from crop prices are nearly identical, although magnitudes of the marginal effects vary slightly.

Theory indicates that both alfalfa and corn probabilities should decrease with increases in natural gas prices since they are the two most water intensive crops.[2] When evaluated at high natural gas prices, the K-State price series gives the expected signs for these marginal effects. However, at the mean natural gas price, the marginal effect of natural gas price on the probability of planting alfalfa and corn is positive. Moreover, when evaluating the effect of natural gas price on the probability of planting corn, the

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[2] Refer to section 4.3 of this thesis for a proof.

effect using the Futures price series fits intuition better. Therefore, the Futures price series is used in the model estimation.