Irrigation Technology Adoption Under Factor Price Uncertainty: Groundwater-Irrigated Production in Nebraska, 1960 -- 2005

Jeff Savage
University of Illinois at Urbana-Champaign
Department of Agricultural and Consumer Economics
304 Mumford Hall, MC-710
1301 West Gregory Drive
Urbana, IL 61801
jsmith24@uiuc.edu

Nicholas Brozović
University of Illinois at Urbana-Champaign
Department of Agricultural and Consumer Economics
326 Mumford Hall, MC-710
1301 West Gregory Drive
Urbana, IL 61801
nbroz@uiuc.edu

Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2009 AAEA & ACCI Joint Annual Meeting, Milwaukee, WI, July 26-28, 2009.

Irrigation Technology Adoption Under Factor Price Uncertainty: Groundwater-Irrigated Production in Nebraska, 1960 – 2005

Abstract

The development of groundwater-irrigated production technologies, fed by water from the Ogallala Aquifer, facilitated the development of agriculture in the High Plains region of the United States that began during the 1960s. The current rate of pumping for irrigation in the region is causing the aquifer to be depleted in many areas, which is cause for concern from a socioeconomic and environmental standpoint. The goal of this paper is to assess the factors that affect the decision to adopt groundwater-irrigated production by farmers, in the presence of risk differentiated by heterogeneous farmland quality and groundwater depth. A binary choice model of adoption is estimated for Nebraska, from 1960 – 2005. The results suggest that farmers consider climate variability, revenue potential, and potential pumping costs in the investment decision.

Key words: Irrigation; Technology Adoption; Risk; Ogallala Aquifer

JEL classification: Q15;Q32;Q55

Introduction

The work presented in this paper is an attempt to understand a body of data: the population of farm plots in Nebraska that were converted from dryland production to groundwater-irrigated production during the time period 1960–2005. By focusing on the interaction between market prices and the land-quality augmenting capacity of groundwater-irrigated production for the plot, a dynamic model of technology adoption with uncertain returns to investment is developed to explain the shift from dryland wheat production to irrigated corn production by farmers in the High Plains region of Nebraska.

The High Plains Aquifer, or the Ogallala Aquifer, is a 174,000 square mile body of water that underlies portions of six states, from Texas to South Dakota, including 83% of Nebraska. Its 3.5 billion acre-feet of water currently irrigate one fifth of cropland currently under irrigated production in the United States, but intensive pumping and the aquifer's slow recharge rate have caused the water level of the aquifer to decline significantly in places (Torell, Libbin, and Miller 1990). The declining water level in many areas of the Ogallala Aquifer has become a major concern for policymakers and competitive water users. Irrigated corn production, which is grown on more irrigated acreage in the Great Plains than any other crop, appears to be at the core of the problem (Norwood 2000). Modern irrigation technology has the potential to improve the efficiency of applied water, so its adoption has been explored as one of many solutions to the problem.

The traditional net present value of investment states that adopting innovating production techniques should take place when the discounted expected value of the investment is equal to the expected discounted cost of the investment. When faced with volatile markets or weather shocks, the farmer's decision to invest in a new production technology—one that will improve yields and decrease production risk but increase their energy requirements, downside price risk and require substantial sunk capital costs—are adjusted to account for the perceived riskiness of the production technology. Risk introduces a "hurdle rate"—which requires the expected returns to investment be greater than the expected costs of investment—into the adoption decision. The observation that the rate of technological diffusion lags behind expectations based on the expected net present value of the investment has been well documented in agricultural production: Illinois corn producers' investment in site-specific technologies (Isik 2004); the switch to free-stall housing by Texas dairies despite increased milk production (Purvis et al. 1995); investment in modern irrigation equipment by California cotton producers (Carey and Zilberman 2002) . Carey and Zilberman (2002) find that the California droughts during the 1980s and early 1990s spurred much of the adoption of water-saving, capital intensive production technologies by California farmers. They hypothesize that prolonged shocks provide sufficient motivation for farmers to adopt modern agricultural production technologies that require substantial sunk costs.

Using plot-level, spatially referenced data on the climatic, agronomic, and hydrologic conditions and for every farm plot in Nebraska that drilled an irrigation well from 1960–2005, this paper develops a discrete choice model of the decision by the dryland farmer to adopt groundwater-irrigated production technology. Farmers are assumed to choose the production technology that maximizes their discounted expected profits, which are influenced by recent weather conditions, recent market trends in output prices and energy prices, the quality of their land, and their groundwater properties. Given the high sunk capital costs required for investment in groundwater-irrigated production, adoption is irreversible over the life of the equipment. Pumping costs are a significant portion of operating costs and vary by well depth and yield, so the effect of the interaction between changes in energy prices and plot pumping requirements is investigated. The significance of changes in potential profits due to changes in market prices and weather conditions on the adoption decision are analyzed in detail. The remainder of this paper is organized as follows: the following section summarizes related research; next, a conceptual model of groundwater-irrigated production technology adoption is developed; the data and estimation procedure are outlined; the results from econometric estimation are detailed; lastly, the paper concludes with a discussion of the implications of the analysis and suggested directions for future research.

Previous Studies

Empirical research on technology adoption by agricultural producers is found in applied economics. A brief review of the results and techniques used in applications to the Ogallala Aquifer is presented. Then, the general modeling techniques and results obtained by econometric analysis—particularly as it applies to the effects of risk and uncertainty on the adoption decision—are reviewed.

The economic literature of technology adoption generally analyzes the adoption decision in the context of socioeconmic, demographic, and structural factors, or the rate of diffusion of innovation through time.[1] Among the various variables of producer attributes, market characteristics, and land quality constraints that have been studied in the context of adoption, risk has been recognized as a major factor in the adoption decision (Feder, Just, and Zilberman 1985). Uncertainty related to technology adoption in agriculture takes two forms: first, the perceived riskiness of future farm profitability under the new production technology and second, uncertainty in production and prices related to the dynamic setting of farm optimization decisions.

The effect of risk on investment in agricultural production technology at the farm level is explored empirically in a variety of frameworks, including expected utility maximization by risk-averse and downside risk averse producers (Koundouri, Nauges, and Tzouvelekas (2006); Kim and Chavas (2003); Antle (1983a)) and the role of learning in updating producers' expectations of future yields under a new technology (Foster and Rosenzweig (2004); Cameron (1999); Foltz (2003); Besley and Case (1993)). These farm-level adoption studies estimate empirical models of adoption using cross-sectional data and panel data with few time periods. The importance of heterogeneous producer attributes, such as farmer education levels or past farm profitability, and land quality attributes, such as soil type, are considered in the context of the decision to adopt new production innovations. One shortcoming of empirical applications to technology adoption in agriculture is the dearth of available farm-level data across time, which restricts the researcher to framing dynamic problems in a static setting. Many studies estimate models using cross-sectional data, which may provide biased estimates of an inherently dynamic process (Cameron 1999).

Koundouri, Nauges, and Tzouvelekas (2006) exploit the limits of cross-sectional data in their analysis of the effect of production risk on profits by estimating exogenous profit moments using an approach developed by Antle (1983b). Koundouri, Nauges, and Tzouvelekas

(2006) find the probability of adopting water-saving irrigation technology increases for farmers with higher variance of profit and for farmers that face the risk of extreme outcomes. Farmers were surveyed regarding their profits, production techniques, farm characteristics, and farmer characteristics at the time the adoption decision was made but before production using the modern technology began. Profit moments are calculated using the sample profit distribution. A binary probit is used to estimate the adoption decision as a function of the profit moments, farm characteristics, and household characteristics. Farmer education levels and the number of extension visits were statistically higher among adopters of efficient irrigation technology than among nonadopters .

The use of profit moments to approximate risk builds off the work of Sandmo (1971) and Just and Pope (1979), which utilize a mean-variance approximation of producer utility in profit. In these analyses, the estimation of utility functions of farm profits or farm production is necessary. In order to incorporate Arrow-Pratt measures of risk aversion and downside risk aversion. Antle (1983b) builds the linear moment model (LMM), a flexible model based on the probability distribution of output. Since output distributions are functions of their moments, the stochastic structure of the production process can be inferred.

The groundwater-saving potential of shifting production to alternative production technologies in regions fed by the Ogallala has been the focus of applied engineering research. Norwood (2000) finds limited-irrigated corn yields to be superior to dryland corn yields when water is scarce. O'Brien et al. (2001) find the net returns of center pivot irrigation to be higher than the net returns of furrow irrigation, a much less efficient technique. Peterson and Ding (2005) use a risk programming model to quantify the effect of irrigation efficiency on irrigation water use in the Great Plains. They find that the shift from flood irrigation to higher efficiency techniques are associated with reduced water use.

One study of particular interest is Lichtenberg (1989), which analyzes cropping patterns in the northern High Plains of Nebraska during the period from 1966–1980. Lichtenberg (1989) finds support for the hypothesis that center pivot irrigation technology augments land-quality by supplementing scarce water resources and labor with energy and capital. This study examines the influence that land quality and center pivot technology adoption have on cropping patterns for six crop categories: irrigated corn, dryland corn, wheat, sorghum, soybeans, and small grains. County averaged, time-series data on crop allocation, water-holding capacity of the topsoil, the capital cost of a center pivot assuming a well depth of 200 feet, and crop prices, are used to estimate a multinomial logit of cropland allocation. The results suggest that land quality is a major determinant of crop choice and that center pivot technology fueled the shift in allocations from dryland wheat to irrigated corn during the time period. These results motivate the approach taken in this paper and Lichtenberg (1989) also illustrates the data limitations of past empirical work in the technology adoption literature in agriculture: the data used to estimate the econometric model are county-level averages and there is no data on well depth. By incorporating data on a much finer scale, the results of our research have the potential to offer more information on the determinants of agricultural groundwater use in Nebraska.

Conceptual Model

We consider a farmer currently operating a plot using dryland production. The farmer has a discrete choice between using two technologies: dryland production and groundwater-irrigated production. Irrigated production involves drilling a groundwater well and installing a pump and some sprinkler technology, such as a center pivot. Irrigation technology is considered land quality-augmenting in the sense defined by Caswell and Zilberman: by substituting capital and energy for the water absorption capabilities and the water-holding capacity of the soil, it enhances the ability of lower quality land to provide water and nutrients for crops, thereby reducing the productivity differentials between lower and higher qualities of land (Caswell and Zilberman 1986). In regions that rely on intermittent rainfall patterns, the switch to groundwater irrigation can act as a hedge against downside production risk caused by inadequate precipitation during the growing season.

The decision to irrigate can invite other sources of risk into the production process though: the electric/gas power requirement for operating the irrigation equipment is a substantial portion of total variable operating costs, compared to the energy requirements of dryland production (Gonzalez-Alvarez, Keeler, and Mullen 2006). Farm pumping requirements are determined by well depth and well yield. The potential returns of investing in irrigated production over dryland production depend on heterogenous groundwater and land quality characteristics, and therefore vary across heterogeneous farms.

The returns from both production technologies are stochastic due to uncertainty about prices, water costs, and climate conditions. Output prices and energy prices are assumed to be changing over time, and the farmer has expectations regarding the trend of prices through time. Severe weather hazards are difficult to predict, but the farmer forms realistic expectations regarding weather patterns based on recent trends. The returns from investment in irrigated production are given by the difference in the net present value of expected profits from irrigated production over dryland production, which are determined by output prices, relative yields, water costs, and climate conditions. The farmer will switch from dryland production to irrigated production if the expected value of adoption is positive, which we observe when the farmer registers the well. Otherwise, the farmer delays the investment decision until the expected value becomes positive at a later time, in light of new trends in prices, production costs, or increased weather volatility. If the farmer does not expect irrigated production to have higher profits during the period of analysis, the adoption decision is not observed. With data currently available only for the population of farmers in Nebraska that adopted groundwater irrigation technology during the study period, analysis is restricted to this population.[2] In order to derive results regarding the impact uncertainty plays on the adoption decsision, several simplying assumptions are made regarding the farm's investment decisionmaking process. It is assumed that the farm operates in perfectly competitive factor and output markets, so farm yield effects do not inluence market prices for inputs or output. Also, existing capital stock does not significantly affect the magnitude of uncertainty in the investment decision.

Farm Production and Profits

Farmers utilize a vector of conventional inputs $\boldsymbol{x}$ and irrigation water x_w to produce a single output q through a technology described by a well-behaved (i.e. continuous and twice differentiable) production function $f(\cdot)$. Additionally, assume the production function has nonjoint marginal products, so the decision to adopt is not influenced by changes in variable inputs such as fertilizer or seed costs, which are not explicitly modeled.[3] Let p denote output price and $\boldsymbol{r}$ the corresponding vector of input prices. The farmer is assumed to incur production risk and price risk as farm profits are affected by climatic conditions and market conditions. Groundwater-irrigated production is assumed to be associated with higher yields and higher production costs. Profit gains associated with groundwater extraction and application depend on heterogeneous farm characteristics $\boldsymbol{\alpha}$, including field size, land quality, and groundwater depth. The production function is written as $q = f(\boldsymbol{\alpha}, x_w, \boldsymbol{x})$. Groundwater-irrigated water costs are given by $r_w h(\boldsymbol{\alpha}) x_w$, where $h(\boldsymbol{\alpha})$ is a non-decreasing function of depth to groundwater and evapotranspiration requirements.

The farmer's problem is to maximize the net present value of expected profit,

$$(1) \quad \max_{\boldsymbol{x}, x_w} E\left[\sum_{t=0}^{T} \rho^t \pi\right] = \max_{\boldsymbol{x}, x_w} \sum_{t=0}^{T} \rho^t E\left[p f(\boldsymbol{\alpha}, x_w, \boldsymbol{x}) - r_w h(\boldsymbol{\alpha}) x_w - \boldsymbol{r}\boldsymbol{x}\right]$$

where T is the life of the irrigation equipment and ρ is the farmer's discount rate. The farmer's decision to adopt groundwater-irrigated production technology is modeled as a binary choice. The farmer can choose to adopt (y = 1) or continue dryland production (y = 0). The farmer maximizes expected value by considering the difference in reduced-form expected profit,

$$E[V] = \sum_{t=0}^{T} \rho^t E\left[p(q^1 - q^0) - r_w h(\boldsymbol{\alpha}) x_w^1 - 0 - \boldsymbol{r}\boldsymbol{x}^1 - \boldsymbol{r}\boldsymbol{x}^0\right]$$

$$E[V] = \sum_{t=0}^{T} \rho^t E\left[p(q^1 - q^0) - r_w h(\boldsymbol{\alpha}) x_w^1\right] \quad (2)$$

If $E[V] > 0$, then the farmer invests in groundwater-irrigated production and the adoption decision (y = 1) is observed. If the expected value of adoption in the current period is negative, but positive in a future time period, then the decision (y = 0) is observed. Farmers with potentially high pumping costs may choose to delay investment until real energy prices are lower or the revenue gains from switching to irrigation in the current period are sufficiently large to offset increased downside price risk. Given the importance of the well's geophysical characteristics on variable irrigation costs, we expect farmers with inherently cheaper groundwater-irrigated production costs to adopt earlier in the adoption process, as energy prices have a smaller effect on production costs.

Data and Estimation

Description of the Study Area

Primarily situated in the northern High Plains, much of Nebraska could generally be characterized by expansive, unbroken swaths of range land, pasture, and marginal cropland prior to the 1960s (Center for Rural Affairs). The terrain, especially in the central and western parts of the state, is dominated by sandy soils and low precipitation. The water-holding capacity of the soil makes surface irrigation techniques like gravity systems impractical and costly, so cropland was typically devoted to producing less water sensitive crops such as hay and wheat (Lichtenberg 1989). However, 83% of Nebraska is underlain by the Ogallala Formation (Torell, Libbin, and Miller 1990), whose geologic properties make large-scale pumping at shallow levels possible, given the appropriate technology. By the mid-1960s, the development of center pivot irrigation technology and the availability of inexpensive electric power made production of water sensitive crops such as corn and soybeans possible on marginal lands that were previously considered unirrigable (Center for Rural Affairs).

In a report on the impact of center pivot irrigation on Nebraska farmers by the Center for Rural Affairs (1976), the production risk-reducing effect of switching from dryland agriculture to groundwater groundwater-irrigated production was recognized as significant in value for the producer. This reduction in production risk is offset by price risk caused by much higher operating costs associated with center pivot irrigation. It notes that "the high costs and risks inherent in center pivot irrigation have discouraged many farmers from investing in them. However, many non-farm investors view pivots as a high return investment for which it is worth risking excess income" (Center for Rural Affairs). This observation lends support to evidence from economic research that risk and uncertainty regarding future market conditions caused farmers to delay investment until more was known about the distribution of future prices and climate conditions.

Figure gives the general trend of the adoption decision from 1960 – 2005 and Figure 1 illustrates the upward trend through time of mean pumping water level of installed wells. Examination of the figures reveals important information about the decision to irrigate: a period of rapid adoption occured from the mid-1960s through the 1970s, and most of the wells installed were shallow relative to more recently installed irrigation wells. Note that several regions of Nebraska have imposed well drilling moratoria within the last few year. However, as Figure shows, well installing is still occurring in other parts of Nebraska.

Data for every irrigation well installed in the state of Nebraska from 1900–2006 were made available by the Nebraska Department of Natural Resources.[4] Beginning in 1960, reporting was mandatory once drilling began, so the database is complete and the registration requirement makes time dependent analysis possible for the study period 1960–2005. The database provides spatially referenced information on intended irrigated acreage, well depth, well yield, and the current owner. Since center pivot technology is operated only on quarter-sections, analysis is constrained to wells that irrigated between 120 and 170 acres. Otherwise, observed installation of other irrigation technologies with different profit functions may introduce unobserved heterogeneity into the model, confounding the results.

Given these constraints, data on 35,502 wells make up the population under consideration: dryland farm operators in Nebraska that chose to invest in irrigated production, likely center-pivot irrigation, during the time period 1960–2005.

Data for Estimation

Dependent Variable

The decision to adopt is assumed to be observed in the next time period, so explanatory variables are lagged one year. The decision to invest in capital-intensive production requires planning and wells are not registered until drilling actually begins, so a one year lag should be sufficient for analyzing the correct data trends. Registration was not mandatory until 1960 and the previous literature suggest that this is a reasonable starting point.[5] A summary of well characteristics is found in Table 1. To build the time-series associated with each registered well, explanatory data for each well are considered up to the year that the well was registered. This gives an unbalanced panel where adopt equals zero up to the registration year, at which point it equals one. The plot is then dropped from the estimation sample for later years, which implies irreversibility of the investment decision. Given the high cost of largely unrecoverable capital investment, this assumption is a reasonable approximation of the population. From a cross-section of approximately 35,000 plots with registered irrigation wells, a panel of over 700,000 observed adoption decisions is created. In 1960, there are 35,502 observations; by 2005 there are 926.

Land Quality Data

Spatially referenced weather station data on monthly heating degree days and total monthly precipitation in tenths of an inch for the study period are available from the National Climatic Data Center.[6] Precipitation data were annualized and monthly heating degree days were summed over the growing period from April to September. In order to match this data to well location, weather station data were used to create the surface (lon,lat,climate variable) using a cubic spline. Well location was then interpolated to this surface using a cubic interpolation.

In order to estimate the potential gain in crop yields associated with switching from dryland to irrigated production, field-level agronomic data were used in WaterOptimizer–developed by University of Nebraska-Lincoln Extension[7]–to calculate the maximal farm yields per acre of dryland wheat production and irrigated corn production. This optimization technique is based on current input costs and output prices, so estimated yields are not exact measures for farm yields during the study period, but they are an accurate approximation of the magnitude of the gain associated with switching to irrigation, since time-invariant, field-level agronomic data are used in estimation. Because switching to irrigated production is tied to the shift in cropping patterns from wheat to corn (Lichtenberg 1989), irrigated corn yields are compared to dryland wheat yields when calculating the gain in revenue associated with the decision to irrigate. The annual means of real farm prices per bushel from the USDA are used to calculate potential revenue gains.

Profit Variables

In order to calculate the potential revenue gain associated with irrigation investment on plot *i*, the difference in plot revenue per acre of irrigated corn and dryland wheat are multiplied by irrigated acreage reported at the time of registration. Alternatively, price and yield data for the respective crops could be included separately along with irrigated acreage, but this method presents multicollinearity problems in estimation and the coefficients would not be as easily interpreted. A summary of the variables used in the estimation sample is found in Table 2 and an explanation of the variables used is provided in Table 3.

The magnitude of pumping cost risk is determined by the field's relative pumping requirements, which are primarily affected by well depth and well yield. If energy prices increase, variable operating costs for plots with relatively high pumping requirements increase by several magnitudes greater that the increase in operating costs for plots with relatively low pumping requirements. Pumping costs are estimated using two variables by multiplying real crude oil prices by pumping water level and by multiplying prices by well yield.

Land value is estimated using real average state farmland value from the previous year, which is used to proxy farm credit constraints, past farm profits, and temporal agricultural policy effects. Average assessed state farmland values per acre were obtained from the USDA. In future work, tax assessor data on individual farmers will be used, but this data is not ready to be used in estimation yet.

Econometric Specification

The condition of adoption implies that the expected value of adoption, given by (2), is positive. The decision to adopt is determined by the farm operator's expectations of future revenue and future costs, which are a function of heterogeneous farm characteristics, climate variability, and market prices. The probability of adoption on plot i at time t is conditional on the value of adoption from the previous season $\boldsymbol{V}_{it}$, related to the farmer's expected revenue gain, pumping costs, land value, total annual precipitation, and heating degree days during the growing season from April to September. This can be represented as a linear probability model,

$$(3) \qquad P(y_{it} = 1|\boldsymbol{V}_{it}) = G(\boldsymbol{V}_{it}\boldsymbol{\beta})$$

where $G(\cdot)$ is a known function. In the case of a binary limited dependent variable, either the logit or probit functions are suitable (Feder, Just, and Zilberman 1985). Estimates for the logit specification are reported in Table 4.

Unobservable Heterogeneity

In the absence of unobserved heterogeneity, a pooled analysis yields a $\sqrt{N}$-consistent estimator of $\boldsymbol{\beta}$ by maximizing the partial log-likelihood function,

$$(4) \quad \sum_i \sum_t \{y_{it} \log G(\boldsymbol{V}_{it}\boldsymbol{\beta}) + (1 - y_{it}) \log[1 - G(\boldsymbol{V}_{it}\boldsymbol{\beta})]\}$$

In the presence of unobserved heterogeneity though, estimation requires additional assumptions. Consider the case where some farmers have an inherent ability to be more profitable with center pivot technology than others. The farmer may have more technical expertise and expertise, greater access to credit, or a different attitude towards risk than other farmers in the data. Since land values per acre are at the state level, they are an inexact proxy of farm value and access to credit. This is problematic because unobserved heterogeneity biases the coefficient on any variable with which it is correlated (Cameron 1999).

Unexplained heterogeneity, c_i, can be modeled as a random effect or as a fixed effect. The fixed effect logit makes no assumptions regarding the expectation of c_i, in contrast to the random effects probit, which assumes a normal conditional distribution for c_i. The fixed effects logit requires conditional independence for consistency in estimation, which requires that $y_{i1}, \ldots, y_{iT}$ are independent conditional on $\boldsymbol{V}_i, c_i$. Random effects estimation is not appropriate for large T–large N data, so the fixed effects logit estimator is compared to pooled estimation of an ordinary logit, which assumes no unobserved heterogeneity. Estimates are reported in Table 4.

Estimation Results

Table 4 reports the estimation results for the pooled logit model, the fixed effect and random effect logit models[8]. The dependent variable is the probability of adoption conditional on farm characteristics and market prices. All time-varying covariates are lagged one year. Clustered robust standard errors are reported for obtained to account for correlation in the pooled model.

The estimated coefficients for the fixed effects model and the pooled model are similar in magnitude and significance. The oil price-well depth interaction term is the only variable that the models estimate coefficients with different magnitudes. The oil price-well depth interaction term is negative and significant at the 0.05% level and the coefficient for the fixed effects model is positive, but statistically insignificant. The oil price-well yield interaction term is positive and significant at the 0.001% level in both models. The lagged price of oil is negative and significant. The estimated coefficient for revenue is positive and significant. This suggests that farmers respond to revenue signals when making the adoption decision. The estimated coefficient for pumping cost is negative and significant, but the magnitude of its average marginal effect is small compared to the other variables. The implications for positive revenue responses and negative pumping cost responses suggest that farmers exhibit profit maximizing behavior when making production decision, though the nature of their relative effects warrant further investigation.

The estimated coefficient for land value is positive and significant. As a state-level average farmland value per acre, the relationship should capture general trends in the value agricultural production statewide. This phenomenon is likely correlated with changes in agricultural policy, expectations of farm profitability and other system-level changes that affect farmers' access to credit.

The estimated coefficients reported in Table 4 for the climate variables are negative, implying that lower rainfall and fewer heating degree days in the previous year are correlated positively with the probability of adoption. This result is supported by the observation made in Carey and Zilberman (2002) that adoption tends to place after shocks. Since every plot in the population decides to adopt at some point, relatively poor climate variables in the previous growing season should be correlated with a higher probability of adoption.

Conclusion

This paper set out to empirically investigate the factors that affect farm decisions regarding irrigation technology adoption in the presence of production risk and price risk, which are influenced by heterogeneous farm characteristics related to land quality and well depth. To assess the impact of changes in potential profitability on the adoption decision, a pooled logit model and of adoption was estimated as a function of the revenue differential between irrigated corn and dryland wheat, pumping cost risk, land value, precipitation, and heating degree days. For farmers that eventually decide to irrigate, the probability of adoption is negatively impacted higher pumping costs, high rainfall, and a high number of heating degree days in the previous year. The probability of adoption is positively impacted by farmland value and a high revenue differential in the previous year. These impacts are qualitatively similar to those reported by Lichtenberg (1989), though that analysis assumed a fixed pumping water level for the study region.

It is unclear from the estimates that unobserved heterogeneity is a significant source of bias in the pooled model. The magnitude of the estimated coefficients between the fixed effects logit and the pooled logit only differ with respect to the oil price-well depth interaction term and the term is insignificant in the fixed effects model.

Though this study treats expected revenue and expected cost in a simplistic manner, it does suggest areas for further work. The first is to improve the data used to estimate the model. By merging the well database with county tax records, it will become possible to get a more complete picture of farm ownership and land quality and include farmers that still use dryland production. Detailed soil data also need to be processed into a usable form. Work also needs to be done to improve the econometric model. With spatially referenced observations, accounting for the diffusion of technology through time and space is a potentially useful exercise that could improve the predictive power of the model. Alternative specifications that offer more precise estimates of the determinants of the adoption decision need to be explored. Discrete time duration models will be investigated in future work.

Another direction for study in this area is to investigate whether groundwater depth is factored into the value of groundwater. Since depth is not factored into assessed land values, a hedonic analysis of land sales prices might reveal a situation where assessed land values do not accurately reflect the actual value in farming. The existence of a negative relationship between depth to groundwater and the land's value to the farmer is unknown.

Table 1. Characteristics of the Study Region

Variable	Mean	Std. Dev.	Min	Max
Investment Year	1987.20	12.44	1960.	2005.
Irrigated Acres	141.35	14.09	120.00	170.00
Pumping Water Level, ft	126.71	70.35	1.00	1967.00
Well Yield, ft^3/sec	968.50	409.86	0.00	9020.00
Optimal Corn Yield, bu/acre	204.35	7.53	161.31	215.24
Optimal Wheat Yield, bu/acre	47.41	2.97	35.43	54.42

Table 2. Summary Statistics for Estimation Sample

Variable	Observations	Mean	Std. Dev.	Min	Max
Revenue ($100,000)	768,892	0.33	0.15	0.12	0.88
Oil*Depth ($100,000)	768,892	0.12	0.43	0.000	8.91
Oil*Yield ($100,000)	768,892	0.15	0.91	0.000	4.85
Land Value ($100)	768,892	1.17	0.04	0.69	2.66
Heating Degree Days (100 degrees Fahrenheit)	733,392	8.85	2.92	0.86	20.55
Precipitation (100 inches)	733,392	23.27	6.54	4.86	59.70

Table 3. Description of Variables

Variables	Description	Expected Sign
Dependent variable		
adopt	Binary variable equal to one if irrigation technology is installed in the current period *t*, zero if no well is registered.	
Explanatory variables	All variables are lagged one year prior to the year the well was registered.	
Revenue	Difference between irrigated corn revenue and dryland wheat revenue using farm prices, assuming maximal crop yield for plot (per $100,000)	+
	Source: USDA, NE DNR, UNL	
Oil*Depth	Interaction between pumping water level and real crude oil costs (per $1000,000)	-
	Source: USDA, NE DNR	
Oil*Depth	Interaction between well yield and real crude oil costs (per $1000,000)	+
	Source: USDA, NE DNR	
Land value	State farmland value ($100 per acre)	+
	Source: USDA	
Heating degrees	Sum of monthly heating degree days for April – September (per 100 degree days).	-
	Source: NOAA	
Precipitation	Total annual precipitation (per 100 inches)	-
	Source: NOAA	

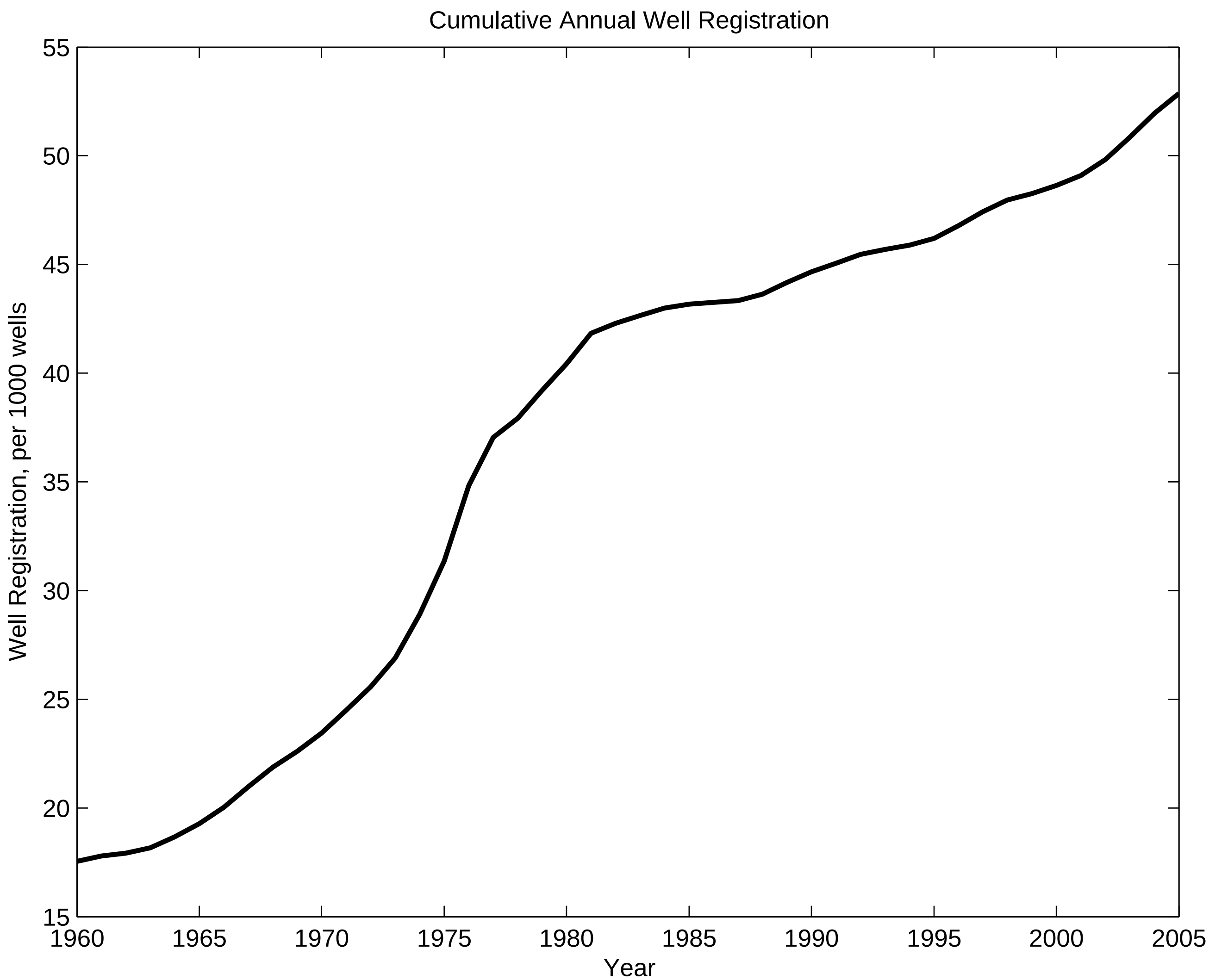
Table 4. Estimates for Logit Models

	(1) Pooled Logit	(2) Fixed Effects
Precipitation	-0.332^{***}	-0.247^{***}
	(0.00804)	(0.00965)
Heating Deg.	-0.0109^{***}	-0.0349^{***}
	(0.00172)	(0.00368)
Oil*Depth	-0.769^{*}	1.272
	(0.302)	(0.990)
Oil*Yield	2.696^{***}	4.574^{***}
	(0.293)	(0.245)
Oil Price	-0.0403^{***}	-0.0353^{***}
	(0.00272)	(0.00274)
Revenue	3.427^{***}	5.873^{***}
	(0.0354)	(0.0484)
Land Value	0.0858^{***}	0.140^{***}
	(0.00347)	(0.00452)
Constant	-3.886^{***}	
	(0.0344)	
Log-likelihood	−133721.3	−82984.4

Standard errors in parentheses

All variables are lagged one year

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$


Cumulative Annual Well Registration
Well Registration, per 1000 wells
Year
55
50
45
40
35
30
25
20
15
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005

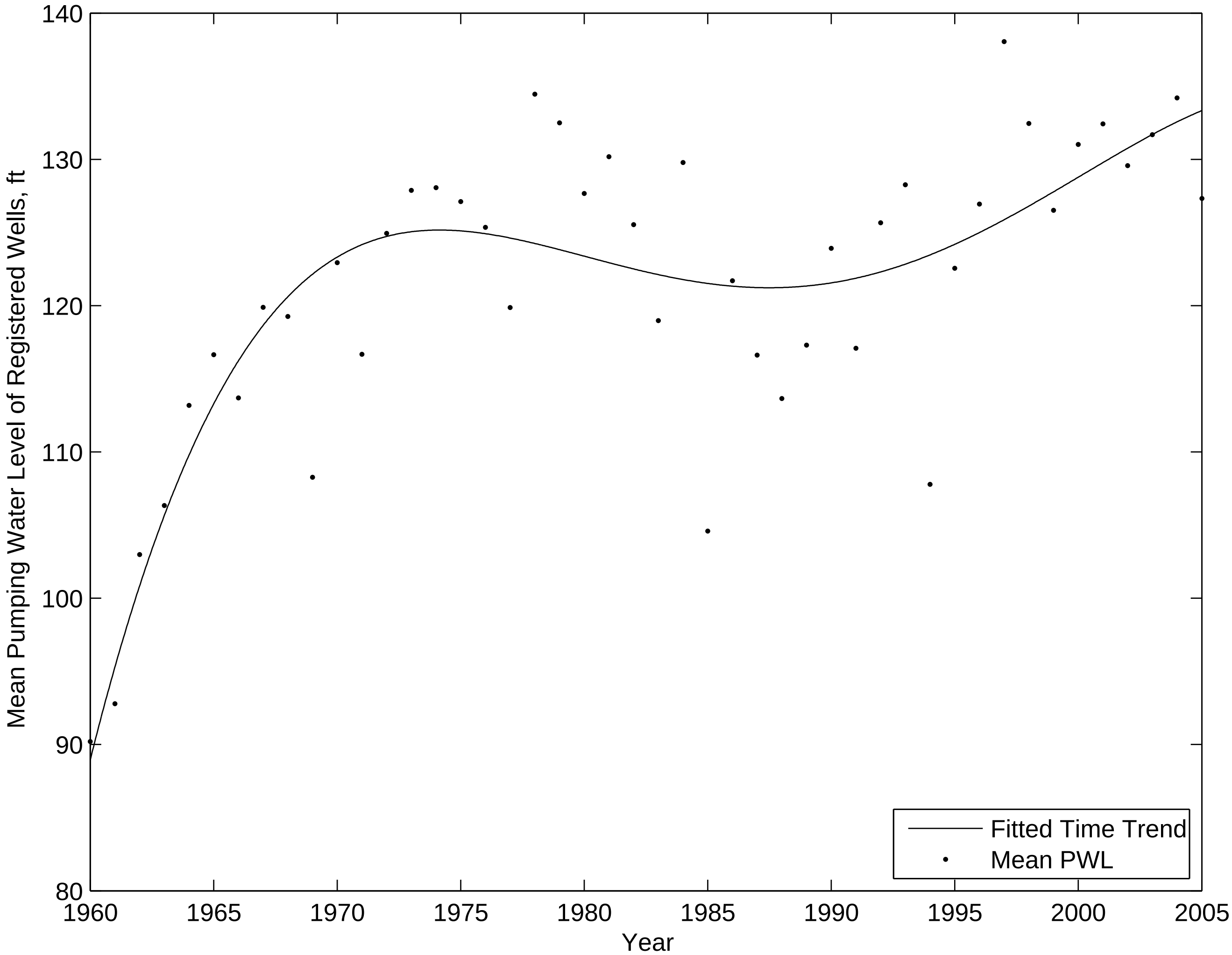


Figure 1. Mean Pumping Water Level of Registered Wells

Notes

[1]Feder, Just, and Zilberman (1985) provides a detailed survey on technology adoption literature. Besley and Case (1993) review the existing empirical technological adoption models in the context of their consistency to an underlying theoretical model of optimizing behavior.

[2]Future analysis will include data currently in dryland production, which should improve the scope and richness of the model. Since data processing and matching up databases can be quite arduous, the dataset containing both dryland and irrigated production is not complete.

[3]The nonjoint marginal products assumption is necessary to estimate the effect of changes in water input cost requirements in the absence of data on technology-specific cost requirements for the time period of analysis.

[4]A description of the data, along with a complete library of spatially referenced data can be accessed at http://www.dnr.state.ne.us/

[5] (Lichtenberg 1989) analyzed the period of most rapid adoption of center pivot irrigation technology and observations made in (The Kerr Center for Sustainable Agriculture) and (Center for Rural Affairs) suggest that growth in groundwater irrigation investment began in 1960s.

[6]Global monthly surface data are accessible at http://cdo.ncdc.noaa.gov

[7]WaterOptimizer was developed by researchers at University of Nebraska to investigate optimal planting strategies when water supply is constrained. For additional information, see http://extension-water.unl.edu/

[8]The results from the pooled logit specification were similar to a pooled model using time dummies, following the recommendation of by Wooldridge Wooldridge (2002). The estimated coefficients were similar to the reported pooled model that included time-varying covariates that are fixed across units, including land value and crude oil price.

References

Antle, J.M. 1983a. “Incorporating Risk in Production Analysis.” *American Journal of Agricultural Economics* 65:1099–1106.

—. 1983b. “Testing the Stochastic Structure of Production: A Flexible Moment-Based Approach.” *Journal of Business & Economic Statistics* 1:192–201.

Besley, T., and A. Case. 1993. “Modeling Technology Adoption in Developing Countries:.” *American Economic Review* 83:396–402.

Cameron, L.A. 1999. “The Importance of Learning in the Adoption of High-Yielding Variety Seeds.” *American Journal of Agricultural Economics* 81:83–94.

Carey, J.M., and D. Zilberman. 2002. “A Model of Investment Under Uncertainty: Modern Irrigation Technology and Emerging Markets in Water.” *American Journal of Agricultural Economics* 84:171–183.

Caswell, M., and D. Zilberman. 1986. “The Effects of Well Depth and Land Quality on the Choice of Irrigation Technology.” *American Journal of Agricultural Economics* 68:798–811.

Center for Rural Affairs. 1976. “Wheels of Fortune.” Working paper, Center for Rural Affairs, Walthill, NE, January.

Feder, G., R.E. Just, and D. Zilberman. 1985. “Adoption of Agricultural Innovations in Developing Countries: A Survey.” *Economic Development and Cultural Change* 33:255–298.

Foltz, J.D. 2003. “The Economics of Water-Conserving Technology Adoption in Tunisia: An Empirical Estimation of Farmer Technology Choice.” *Economic Development and*

Cultural Change 51:359–373.

Foster, A.D., and M.R. Rosenzweig. 2004. “Technological Change and the Distribution of Schooling: Evidence From Green-Revolution India.” *Journal of Development Economics* 74:87–111.

Gonzalez-Alvarez, Y., A.G. Keeler, and J.D. Mullen. 2006. “Farm-level irrigation and the marginal cost of water use: Evidence from Georgia.” *Journal of Environmental Management* 80:311–317.

Isik, M. 2004. “Incentives for Technology Adoption Under Environmental Policy Uncertainty: Implications for Green Payment Programs.” *Environmental and Resource Economics* 27:247–263.

Just, R.E., and R.D. Pope. 1979. “Production Function Estimation and Related Risk Considerations.” *American Journal of Agricultural Economics* 61:276–284.

Kim, K., and J.P. Chavas. 2003. “Technological Change and Risk Management: An Application to the Economics of Corn Production.” *Agricultural Economics* 29:125–142.

Koundouri, P., C. Nauges, and V. Tzouvelekas. 2006. “Technology Adoption Under Production Uncertainty: Theory and Application to Irrigation Technology.” *American Journal of Agricultural Economics* 88:657–670.

Lichtenberg, E. 1989. “Land Quality, Irrigation Development, and Cropping Patterns in the Northern High Plains.” *American Journal of Agricultural Economics* 71:188–194.

Norwood, C. 2000. “Water use and yield of limited-irrigated and dryland corn.” *Soil Science Society of America* 64:365–370.

O’Brien, D., F. Lamm, L. Stone, and D. Rogers. 2001. “Corn yields and profitability for low-capacity irrigation systems.” *Applied Engineering in Agriculture* 17:315–321.

Peterson, J., and Y. Ding. 2005. “Economic adjustments to groundwater depletion in the high plains: Do water-saving irrigation systems save water?” *American Journal of Agricultural Economics* 87:147–159.

Purvis, A., W.G. Boggess, C.B. Moss, and J. Holt. 1995. "Technology Adoption Decisions Under Irreversibility and Uncertainty: An *Ex Ante* Approach." *American Journal of Agricultural Economics* 77:541–551.

Sandmo, A. 1971. "On the Theory of the Competitive Firm Under Price Uncertainty." *The American Economic Review* 61:65–73.

The Kerr Center for Sustainable Agriculture. 2000. *The Ogalla Aquifer*. Poteau, OK, July.

Torell, L.A., J.D. Libbin, and M.D. Miller. 1990. "The Market Value of Water in the Ogalla Aquifer." *Land Economics* 66:163–175.

Wooldridge, J.M. 2002. *Econometric Analysis of Cross Section and Panel Data*. The MIT Press.