The Effects of Energy Prices on Groundwater Extraction in Agriculture in the High Plains Aquifer[1]

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Abstract

In this paper we examine the effects of energy prices on groundwater extraction using an econometric model of a farmer's irrigation water pumping decision that accounts for both the intensive and extensive margins. Our results show that energy prices have an important effect on both the intensive and extensive margin. Increasing energy prices would affect crop selection decisions, crop acreage allocation decisions, and the demand for water by farmers. Our estimated total marginal effect, which sums the effects at the intensive and extensive margins, is that an increase in the natural gas futures contract price of 1 cent/1000 btu would decrease water extraction by an individual framer by 102.88 acre-feet per year, which is approximately 63% of the average amount pumped in a year by a farmer.

Keywords: groundwater extraction, energy
JEL codes: Q15, Q40

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1. Introduction

Many of the world's most productive agricultural basins depend almost exclusively on groundwater. The food we eat, the farmers who produce that food, and the local economies supporting that production are all affected by the availability of groundwater. Worldwide, about 70 percent of water extracted or diverted for consumptive use goes to agriculture, but in many groundwater basins, this proportion can be as high as 95 to 99 percent. In many agricultural regions throughout the world, energy is an important input used to extract groundwater for irrigation (Schoengold and Zilberman, 2007; Dumler et al., 2009). Rising energy prices are therefore a potential concern for agriculture, as they may affect the groundwater extraction and crop choice decisions of farmers that require energy to pump groundwater. In this paper we examine the effects of energy prices on groundwater extraction using an econometric model of a farmer’s irrigation water pumping decision that accounts for both the intensive and extensive margins.

Our research focuses on the groundwater used for agriculture in the High Plains (Ogallala) Aquifer system of the midwestern United States. There, 99 percent of the water extracted is used for crop production; the remaining one percent is used for livestock, domestic, and industrial purposes. The economy of the region is based almost entirely on irrigated agriculture. The corn, soybeans, alfalfa, wheat, and sorghum grown there is used for local livestock production or exported from the region. The small local communities support the agricultural industry with farm implement dealers, schools, restaurants, and other services. The state governments are also greatly concerned with supporting their agricultural industry.

Energy is an important input needed to extract groundwater for irrigation in the High Plains Aquifer. Dumler et al. (2009) estimate that the energy cost of extracting irrigation water represents approximately 10% of the costs for growing corn in western Kansas, which is a slightly greater share of costs than land rent. Over 50% of the acres irrigated from groundwater wells in Kansas are powered by natural gas (FRIS, 2004). Huge natural gas deposits underlie much of western Kansas, especially the southwest where irrigation is the most intensive. Thousands of wells dot the landscape, and landowners lease their mineral rights to natural gas companies. Although specific data on these contracts is not available, often negotiated into these leases are agreements that the landowner can tap directly into the gas line and obtain natural gas for domestic and irrigation purposes at a greatly reduced rate, or even for free. Thus, while energy is an important input into extraction costs, it is an empirical question whether farmers respond to rising national energy prices. In this paper we examine if energy prices impact groundwater extraction in western Kansas. Our use of national natural gas prices as our measure of the energy prices faced by farmers enables us to obtain a lower bound on the magnitude of the effect of energy prices on water extraction.

For the empirical analysis, we use a unique data set that combines well-level groundwater extraction data with physical, hydrological, and economic data. Our econometric model of a farmer's irrigation water pumping decision has two components: the intensive margin and the extensive margin. For the extensive margin, we estimate the farmer's choice of how many acres to allocate to each crop using a simultaneous equations selection model. For the intensive margin, we estimate the farmer's water demand conditional on his crop acreage allocation decisions. In addition to energy prices, we also control for other factors that may affect groundwater extraction, including depth to groundwater, precipitation, irrigation technology, saturated thickness, recharge, and crop prices.

Our results show that energy prices have an important effect on both the intensive and extensive margin. Increasing energy prices would affect crop selection decisions, crop acreage allocation decisions, and the demand for water by farmers. Our estimated total marginal effect, which sums the effects at the intensive and extensive margins, is that an increase in the energy price of 1 cent/1000btu would decrease water extraction by an individual framer by 102.88 acre-feet per year, which is approximately 63% of the average amount pumped in a year by a farmer.

Our paper builds upon the work of Zilberman et al. (2008), who develop theoretical models to analyze the effects of rising energy prices on the economics of water in agriculture, and who find that the higher cost of energy will substantially increase the cost of groundwater. Our empirical analysis also builds upon the work of Zhu et al. (2013), who simulate the effects of energy prices on groundwater extraction in India, China, the U.S., and Vietnam. We build upon these previous theory and simulation papers by empirically analyzing the effects of energy prices on groundwater extraction.

Most of the empirical work on the effects of energy prices on groundwater extraction to date to our knowledge has been in a developing country context. For example, Badiani and Jessoe (2013) empirically analyze the impact of electricity subsidies on groundwater extraction and agricultural production in India. Other studies have used interviews or survey data to analyze the relationship between energy and groundwater extraction in India and/or Mexico (Birner et al., 2007; Fan et al., 2008; Kumar, 2005; Scott and Shah, 2004).

In a related paper in the U.S. context, Hendricks and Peterson (2012) estimate irrigation water demand in Kansas using an estimate of extraction cost as their proxy for water price. We build on their work in two ways. First, while the focus of Hendricks and Peterson (2012) is on the effects of water price, which they compute using a pre-specified function of the natural gas price and the depth to groundwater, our focus is on the effects of energy price. Thus, while Hendricks and Peterson (2012) focus on estimating the own-price elasticity of irrigation water demand in order to calculate the cost of reducing irrigation water use through water pricing, irrigation cessation, and intensity-reduction programs, our paper focuses on the effects of energy prices on water demand and crop choices in order to examine the effects of rising energy prices.

The second way in which we build upon Hendricks and Peterson (2012) is that our econometric model not only controls for crop acreage allocations decisions in the estimation of water demand on the intensive margin, but also explicitly models the crop choice and crop acreage allocation decisions in our estimation of the extensive margin. Unlike Hendricks and Peterson (2012), our model enables us to examine how changes in energy prices affect not only water demand conditional on crop choice, but also crop choice and crop acreage allocation decisions as well.

2. The High Plains Aquifer in Kansas

Exploitation of the High Plains Aquifer system began in the late 1800s but was greatly intensified after the “Dust Bowl” decade of the 1930s (Miller and Appel, 1997). Aided by the development of high capacity pumps and center pivot systems, irrigated acreage went from 1 million acres in 1960 to 3.1 million acres in 2005, and accounts for 99 percent of all groundwater withdrawals (Kenny and Hansen, 2004). Irrigation converted the region from the “Great American Desert” into the “Breadbasket of the World.”

The High Plains Aquifer underlies approximately 174,000 square miles, and eight states overlie its boundary. It is the principle source of groundwater in the Great Plains region of the United States. Also known as the Ogallala Aquifer, the High Plains Aquifer system is now known to include several other aquifer formations. The portion of the aquifer that underlies western Kansas, however, pertains mainly to the Ogallala, and this is why the name persists.

The High Plains aquifer is underlain by rock of very low permeability that creates the base of the aquifer. The distance from this bedrock to the water table is a measure of the total water available and is known as the saturated thickness. Figure 1 shows that the saturated thickness of the High Plains aquifer in Kansas ranges from nearly zero to over 300 feet (Buddemeier, 2000).

The depth to water is the difference between the altitude of the land surface and the altitude of the water table. In areas where surface and groundwater are hydrologically connected, the water table can be very near to the surface. In other areas, the water table is much deeper; the depth to water is over 400 feet below the surface in a portion of southwestern Kansas (Miller and Appel, 1997). The depth to groundwater is shown in Figure 2.

Recharge to the Kansas portion of the High Plains aquifer is very small. It is primarily by percolation of precipitation and return flow from water applied as irrigation. The rates of recharge vary between 0.05 and 6 inches per year, with the greatest rates of recharge occurring where the land surface is covered by sand or other permeable material (Buddemeier, 2000).

The main crops grown in western Kansas, in order of decreasing water intensiveness, are alfalfa, corn, soybean, grain sorghum, and wheat (Automated Weather Data Network, 2013). Corn production accounts for more than 50 percent of all irrigated land (Buddemeier, 2000). Soil types and access to high volumes of irrigation water determine the suitability of a particular piece of land to various crops.

3. Data

We use a particularly rich data set for our empirical analysis. Kansas has required the reporting of groundwater pumping by water rights holders since the 1940s, although only data from 1996 to the present are considered to be complete and reliable. The data are available from the Water Information Management and Analysis System (WIMAS). Included are spatially referenced pumping data at the source (well or pump) level, and each data point has the farmer, field, irrigation technology, amount pumped, and crops grown identified.

The crop price data we use are a combination of spring futures contracts for September delivery for commodities with futures contracts and average price received for crops without futures contracts. Futures prices are from the Commodity Research Board (CRB), and price received is from the USDA Economic Research Service.

Natural gas prices come from the U.S. Energy Information Administration. Over 50% of the acres irrigated from groundwater wells in Kansas are powered by natural gas (FRIS, 2004). Our use of natural gas prices as our measure of the energy prices faced by farmers enables us to obtain a lower bound on the magnitude of the effect of energy prices on water extraction.

Soil characteristics come from the Web Soil Survey of the USDA Natural Resources Conservation Service. The irrigated capability class is a dummy variable equal to 1 if the soil is classified as the best soil for irrigated agriculture with few characteristics that would limit its use, and zero otherwise. Precipitation data come from the PRISM group.

Summary statistics for the variables used in the analysis are presented in Table 1. The average quantity of irrigation water pumped per individual farmer per year is 164.37 acre-feet. In a one-mile radius, an average of 437.72 acre-feet of water are pumped by neighboring farmers. The average depth from the surface of the ground to groundwater is 125.27 feet.

Potential recharge to the Kansas portion of the High Plains Aquifer is low; the average potential recharge is 1.25 inches annually. Each farmer received an average of 21.64 inches of precipitation per year. The average slope of the ground surface, as a percentage of distance, is 1.07 percent. About 45 percent of plots are in irrigated capability class 1. Field sizes are on average 183.97 acres. Natural gas futures contract prices are on average $0.38 per 1000 btu.

4. Empirical Model

We examine the effects of energy prices on groundwater extraction using an econometric model of a farmer's irrigation water pumping decision that accounts for both the intensive and extensive margins. The extensive margin of the groundwater extraction decision is the crop choice and crop acreage allocation decision, and involves a simultaneous equation model in which the dependent variables (the number of acres planted to each crop) are censored by sample selection. A positive number of acres planted to crop *c* is observed only when the farmer chooses to plant crop *c*. Thus, the sample of crop *c*-planters is non-random, drawn from a wider population of farmers. Both choices (the decision to plant and the number of acres planted to crop *c*) must be modeled to avoid sample selection bias. Optimal land allocation in each time period $n_{ict}*$ can be estimated as:

$$q_{ict} = f(e_t, p_{ct}, x_{it}, z_{it-1}, d_{it}),\ c = alfalfa,\ corn,\ soybeans,\ sorghum,\ wheat; \quad (1)$$

$$n_{ict}* = g(e_t, p_{ct}, x_{it}, d_{it}, IMR_c), c = alfalfa,\ corn,\ soybeans,\ sorghum,\ wheat; \quad (2)$$

where q represents the decision to plant crop c; $n_{ict}*$ is the number of acres planted to each crop c and is observed only when $q_{ict} > 0$; e_t are energy prices; p_{ct} are crop price futures (for delivery at harvest); x_{it} is a vector of plot-level variables including field size, irrigation technology, average precipitation, average evapotranspiration, slope, soil quality, and quantity of water authorized for extraction;[2] and z_{it-1} is a vector of lagged dummy variables indicating if various crops were planted in the previous season to account for crop rotation patterns. Following Pfeiffer and Lin (2013), d_{it} are variables that would impact a farmer's decision if he optimized dynamically, including recharge, saturated thickness, the amount pumped in the previous period by neighbors, and a 10 year forecast of future commodities prices.

The system of equations corresponding to (1) and (2) can be estimated using Lee's generalization of Amemiya's two-step estimator to a simultaneous equation model (Lee, 1990). Lee (1990) shows that this procedure leads to estimates that are asymptotically more efficient than the Heckman selection model (Heckman, 1978). In the first step, probit regressions corresponding to the crop selection equations (1) are estimated, measuring the effect of the explanatory variables on the decision to grow each crop *c*. Inverse-Mills ratios (IMR_c) are calculated for each crop. In the second step, the inverse-Mills ratios are included as explanatory variables in the crop acreage allocation equations corresponding to equation (2). They are estimated as a simultaneous system of equations to exploit the information contained in the cross-equation correlations.

The coefficients of interest are the coefficients on energy prices e_t in the selectivity-corrected cropland allocation models in equation (2). We include energy prices both by themselves and also interacted with depth to groundwater, since we expect that the energy costs of pumping may increase with the distance the water needs to be pumped.

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[2] Groundwater users in Kansas extract water under the doctrine of prior appropriation, meaning that they are allotted a maximum amount to extract each year. This annual amount was determined when the user originally applied for the permit (Pfeiffer and Lin, 2012).

Parameters in selection models are estimated with more precision if some regressors in the selection equation can be excluded from the outcome equation (Wooldridge, 2002). To estimate the coefficients on energy price and on energy price interacted with depth to groundwater in the crop acreage equations (2) with more precision, we exclude the lagged crop choice variables z_{it-1} from the crop acreage equations (2) but not the crop choice equations (1). Lagged crop choices are likely to affect a farmer's crop choice decisions but arguably do not affect the crop acreage decision. Whether or not a farmer planted a particular crop last year may affect which crops he plants this year due to crop rotation patterns, but conditional on making a particular crop choice this year, last year's crop choice is unlikely to affect the acreage allocated to each crop this year.

The intensive margin of the groundwater extraction decision is the water demand conditional on crop choice, which is estimated using ordinary least squares:

$$w_{it} = h(e_t, n_{ict}*, x_{it}, d_{it}) . \qquad (3)$$

The total marginal effect of energy prices is the sum of the effect along the intensive margin from the water demand equation (3) and the effects along the extensive margin from the selectivity-corrected cropland allocation models in equation (2) (Moore, Gollehon and Carey, 1994): [3]

$$\frac{dw}{de} = \frac{\partial w}{\partial e} + \sum_c \frac{\partial w}{\partial n_c *} \frac{\partial n_c *}{\partial e} . \qquad (4)$$

[3] Another possible decision is the decision not to irrigate some acres. Unfortunately, the data does not permit us to analyze this decision. We only observe if the entire field was not irrigated, but we do not observe whether part of the field was not irrigated, nor do we observe the number of acres that were not irrigated. In the regressions of water demand conditional on crop choice we control for whether the entire field was not irrigated. In the probit regressions of crop choice, we control for whether the entire field was not irrigated in the previous year.

5. Results

Tables 2 and 3 show the results of estimation of equations (1) and (2), respectively. When considering only the significant coefficients on the natural gas futures contract price and on the interaction between natural gas futures contract price and depth to groundwater in Table 3, and when evaluated at the mean depth to groundwater, our results show that energy prices cause a significant decrease in the acreage allocated to soybeans and a significant increase in the acreage allocated to wheat. An increase in the natural gas futures contract price of 1 cent/1000 btu decreases the number of acres allocated to soybeans by 9.974 acres per farmer and increases the number of acres allocated to wheat, the least water intensive crop, by 6.264 acres per farmer, These acreage values are approximately 5.4% and 3.4%, respectively, of the average field size.

The results of the estimation of equation (3), water use along the intensive margin, conditional on crop choice, are presented in Table 4. The crops in order of decreasing water intensiveness should be alfalfa, corn, soybean, grain sorghum, and wheat (Automated Weather Data Network, 2013). Our empirical results support this ordering, as the point estimates of the coefficients in the water use regression on the acreage allocated to each crop decrease in this same order. Also as expected, the coefficient on the interaction between energy price and depth to groundwater is negative. As the distance the water needs to be pumped increases, the energy costs of pumping increases. Thus, increases in energy prices cause a greater decrease in water use conditional on crop choice the greater the depth to groundwater.

Table 5 summarizes the calculations used to derive the total intensive margin, which are based on the coefficients on the natural gas futures contract price and on the interaction between natural gas futures contract price and depth to groundwater in the water use regression in Table 4, both of which are significant. Evaluated at mean depth to groundwater, an increase in energy prices by 1 cent/1000 btu decreases water demand conditional on crop choice by 99.72 acre-feet along the intensive margin.

Table 6 summarizes the calculations used to derive the total extensive margin. We consider only the significant coefficients on the natural gas futures contract price and on the interaction between natural gas futures contract price and depth to groundwater in Table 3, and only the significant coefficients on acres allocated to each crop in Table 4, and we evaluate the effects of energy price on crop acreage at the mean depth to groundwater. An increase in energy prices decreases the acres allocated to soybeans, but because the effects of soybean acreage on water use is positive, the effect of an increase on energy prices on water use on soybeans is negative. An increase in the natural gas futures contract price of 1 cent/1000 btu decreases the water use by each farmer on soybeans by 2.78 acre-feet per year.

On the other hand, an increase in energy prices increases the acres allocated to wheat, the least water intensive crop, but because the effect of wheat acreage on water use is negative, the effect of an increase on energy prices on water use on wheat is negative. An increase in the natural gas futures contract price of 1 cent/1000 btu decreases the water use by each farmer on wheat by 0.376 acre-feet per year.

We are mainly interested in the total marginal effects of an increase in the energy price, calculated using equation (4) and reported in Table 7. An increase in energy prices would decrease water use along both the intensive and extensive margins. Our estimated total marginal effect of energy prices, which sums the effects at the intensive and extensive margins, is that an increase in the natural gas futures contract price of 1 cent/1000btu, which is approximately 2.6% of its mean value over the time period of our data set, would decrease water extraction by an individual framer by 102.88 acre-feet per year, which is approximately 63% of the average amount pumped in a year by a farmer.

6. Conclusion

In this paper we examine the effects of energy prices on groundwater extraction using an econometric model of a farmer's irrigation water pumping decision that accounts for both the intensive and extensive margins. Our results show that energy prices have an important effect on both the intensive and extensive margin. Increasing energy prices would affect crop selection decisions, crop acreage allocation decision, and the demand for water by farmers. In particular, along the extensive margin, an increase in energy prices would lead farmers to substitute away from soybeans towards wheat, the least water intensive crop. Along the intensive margin, an increase in energy prices would further decrease water use conditional on crop choice.

Our estimated total marginal effect, which sums the effects at the intensive and extensive margins, is that an increase in the natural gas futures contract price of 1 cent/1000btu, which is approximately 2.6% of its mean value during the time period of our data set, would decrease water extraction by an individual framer by 102.88 acre-feet per year, which is approximately 63% of the average amount pumped in a year by a farmer. Our results therefore suggest that the effects of energy prices on groundwater extraction can be quite substantial. This finding is particularly important in the face of possible increases in energy prices in the future.

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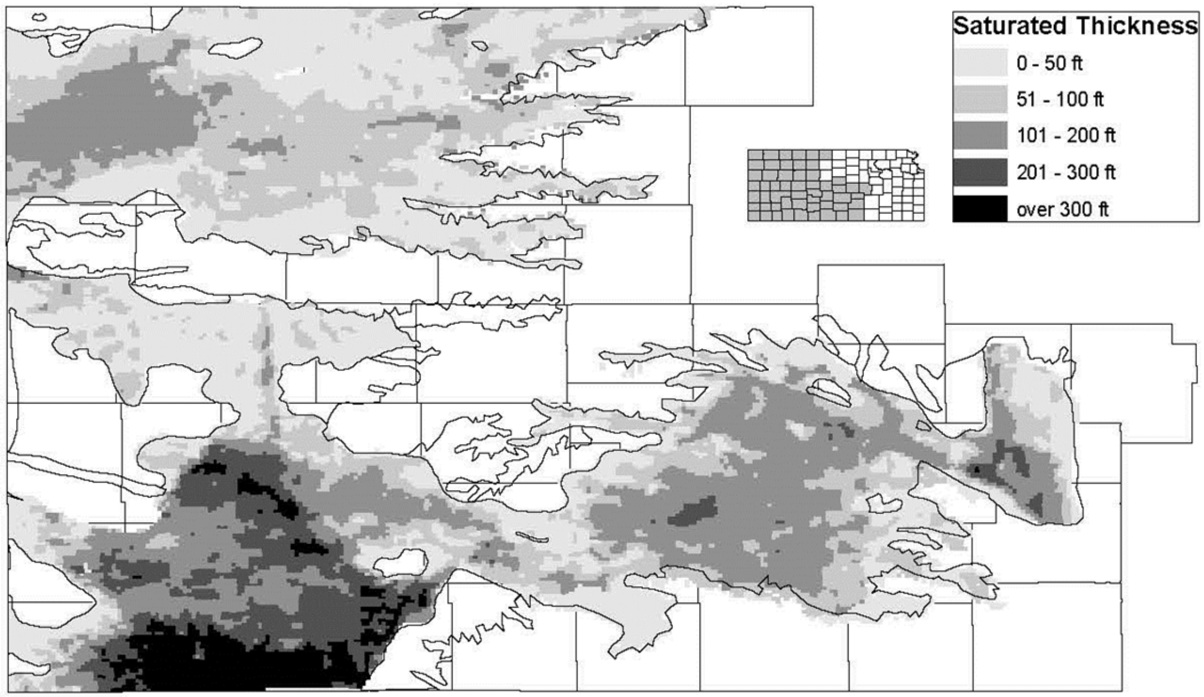
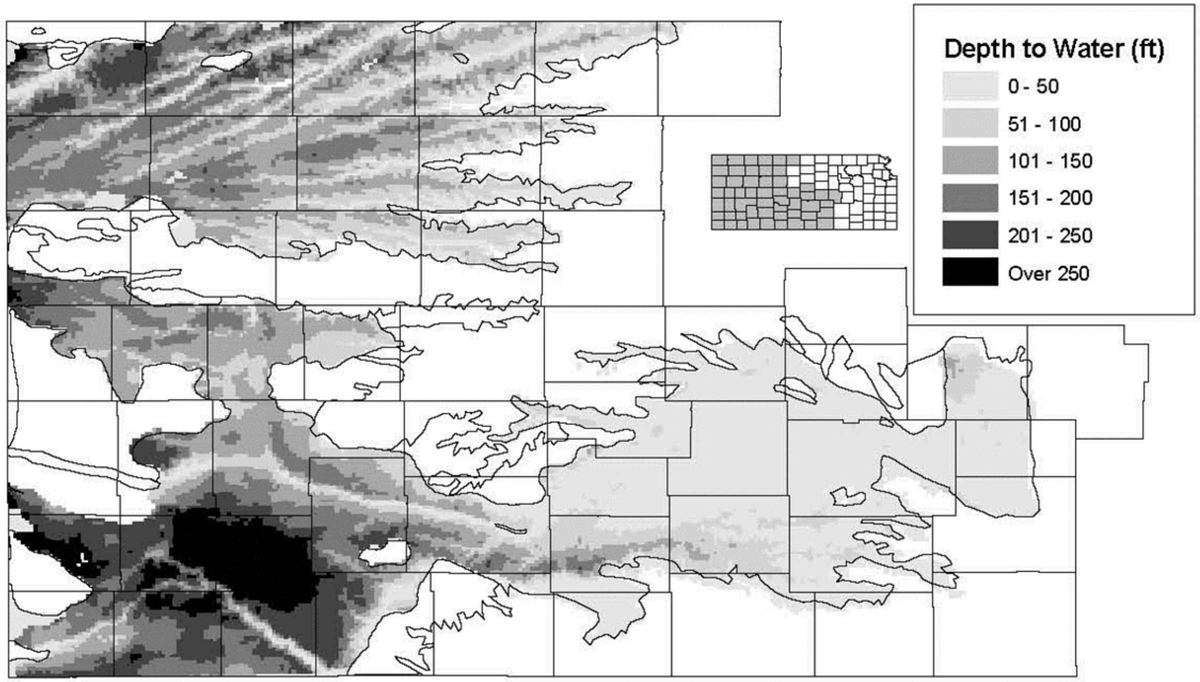
Figure 1: Predevelopment saturated thickness of the Kansas portion of the High Plains Aquifer



Source: Kansas Geological Survey

Figure 2: Average 2004-2006 depth to groundwater in the Kansas portion of the High Plains Aquifer



Source: Kansas Geological Survey

Table 1: Summary Statistics

	Obs	Mean	Std. Dev.	Min	Max
Individual-year level variables					
Irrigation water pumped (af)	154,619	164.37	124.12	0.00	1491.48
Irrigation water used by neighbors (1 mile radius, af)	154,619	437.72	428.38	0.00	4586.97
Depth to groundwater (ft)	154,619	125.27	74.48	4.77	355.87
Individual level variables					
Recharge (in)	17,960	1.25	1.13	0.30	6.00
Average precipitation (in)	17,960	21.64	3.77	16.00	32.90
Average evapotranspiration(in)	17,960	55.19	1.02	48.89	58.75
Slope (% of distance)	17,960	1.07	0.88	0.01	8.68
Irrigated Capability Class=1 (dummy)	17,960	0.45	0.50	0.00	1.00
Saturated Thickness of the aquifer (ft)	17,960	126.27	104.86	0.00	553.64
Quantity authorized for extraction (af)	17,960	2.84	2.07	0.00	24.00
Field size (ac)	17,960	183.97	102.76	60.59	640.00
Year level variables					
Corn price futures ($/bu)	9	2.49	0.25	2.24	2.87
Sorghum price futures ($/bu)	9	6.37	1.13	5.17	8.21
Soy price futures ($/bu)	9	5.81	1.14	4.52	7.73
Wheat price futures ($/bu)	9	3.54	0.33	3.18	4.19
Alfalfa price ($/ton)	9	81.17	10.08	70.58	95.92
10 year forecast of the real acreage-weighted price of commodities ($/bu)	9	2.66	0.29	2.29	3.09
Natural gas futures contract price ($/1000 btu)	9	0.38	0.18	0.19	0.65

Table 2: Probit Results for Crop Selection

	Dependent variable is probability of planting:				
	Alfalfa	Corn	Soybeans	Sorghum	Wheat
Natural gas futures contract price ($/1000 btu)	0.964	14.73**	-37.80***	-4.602	61.30***
	(8.79)	(5.14)	(6.13)	(8.23)	(6.66)
Depth to groundwater (ft)	-0.0019***	0.0016***	-0.0020***	-0.0002	0.0010***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Natural gas futures contract price * Depth to groundwater	-0.024	-0.194***	0.357***	0.0332	-0.300***
	(0.05)	(0.03)	(0.04)	(0.04)	(0.03)
Alfalfa price ($/ton yearly average)	0.00429***	-0.00117*	-4.6E-05	0.00216**	-0.00136*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Corn price ($/bu futures)	0.201	0.131	0.478***	-0.872***	-0.543***
	(0.12)	(0.07)	(0.09)	(0.11)	(0.08)
Soybeans price ($/bu futures)	-0.0816***	0.0590***	-0.0167	0.0477*	0.0565***
	(0.02)	(0.01)	(0.02)	(0.02)	(0.02)
Sorghum price ($/bu spring average)	-0.0054	-0.098***	-0.036**	0.171***	0.098***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Kansas wheat price ($/bu futures)	0.195***	0.0895***	-0.196***	-0.0606	-0.0832**
	(0.04)	(0.02)	(0.03)	(0.04)	(0.03)
Recharge (in)	0.0855***	-0.107***	-0.0012	-0.00329	-0.0304**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Average yearly precipitation, 1971-2001 (in)	-0.0567***	0.0457***	0.144***	0.0180***	-0.0481***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Average evapotranspiration (in)	0.0145	0.0877***	0.186***	-5.5E-05	-0.0461***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Slope (% of distance)	0.0770***	-0.0006	-0.0646***	0.0424***	-0.0112
	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)
Irrigated Capability Class = 1	-0.255***	0.0476***	0.0417***	0.144***	0.0938***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Saturated thickness of the aquifer (ft)	0.0001	0.0006***	-6E-05	-0.0003***	-0.0001**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)

Quantity authorized for extraction (af)	-0.0008	0.0082***	-0.0006	0.0087**	0.0069**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Field size (ac)	0.0002**	0.0004***	0.0003***	0.0012***	0.0018***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Center pivot irrigation system (compared to flood)	-0.0581**	0.0447***	-0.123***	-0.359***	-0.0675***
	(0.02)	(0.01)	(0.02)	(0.02)	(0.01)
Center pivot irrigation system with dropped nozzles (compared to flood)	-0.0522**	0.0808***	-0.0424***	-0.413***	-0.0868***
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
10 year forecast of the real acreage-weighted price of commodities ($/bu)	0.00473	0.318***	-0.251***	0.0701	0.281***
	(0.06)	(0.04)	(0.05)	(0.06)	(0.04)
Quantity of water used by neighbors in 1 mile radius in *t*-1 (af)	0.0001***	0.0001***	0.0001***	-0.0001***	-0.00005***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Planted alfafa in *t*-1 (dummy)	2.858***	-0.405***	-0.408***	-0.102**	-0.173***
	(0.02)	(0.02)	(0.03)	(0.03)	(0.02)
Planted corn in *t*-1 (dummy)	-0.304***	1.663***	0.566***	-0.0647***	0.145***
	(0.02)	(0.01)	(0.01)	(0.02)	(0.01)
Planted soybeans in *t*-1 (dummy)	-0.285***	1.365***	0.871***	0.456***	0.532***
	(0.03)	(0.02)	(0.02)	(0.03)	(0.02)
Planted wheat in *t*-1 (dummy)	0.248***	0.705***	0.455***	0.811***	2.365***
	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)
Planted sorghum in *t*-1 (dummy)	-0.0839*	0.354***	0.668***	2.102***	0.722***
	(0.04)	(0.02)	(0.03)	(0.02)	(0.02)
Left land fallow or planted with a non-irrigated plot in *t*-1 (dummy)	-0.102***	-0.231***	-0.222***	-0.0078	-0.0874***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Constant	-2.282***	-8.143***	-14.38***	-1.605**	1.688***
	(0.60)	(0.34)	(0.43)	(0.57)	(0.43)
Observations	154619	154619	154619	154619	154619

Notes: Marginal effects are reported. Standard errors in parentheses. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

Table 3: Selectivity-Corrected Results for Crop Acreage Allocation (Extensive Margin)

	Dependent variable is number of acres allocated to:				
	Alfalfa	Corn	Soybeans	Sorghum	Wheat
Natural gas futures contract price ($/1000 btu)	334.7	-72.34	648.6	810.7	1432.0**
	(510.10)	(273.50)	(362.80)	(686.40)	(461.80)
Depth to groundwater (ft)	0.011	0.00305	0.0247	0.0121	0.0601***
	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)
Natural gas futures contract price * Depth to groundwater	-4.89	-1.312	-7.962**	-5.661	-6.431**
	(2.89)	(1.45)	(2.46)	(3.46)	(2.22)
Alfalfa price ($/ton yearly average)	0.137**	0.0609*	0.0238	0.0162	0.0988*
	(0.05)	(0.03)	(0.04)	(0.07)	(0.04)
Corn price ($/bu futures)	-3.092	7.048*	7.582	-12.69	-2.156
	(6.61)	(3.43)	(5.73)	(9.35)	(5.32)
Soybeans price ($/bu futures)	-1.66	-1.554*	-1.717	-2.486	-0.191
	(1.24)	(0.66)	(1.08)	(1.71)	(0.99)
Sorghum price ($/bu spring average)	1.036	-0.628	-0.476	4.195***	0.363
	(0.81)	(0.46)	(0.69)	(1.12)	(0.67)
Kansas wheat price ($/bu futures)	-0.00431	-0.918	-3.413	0.891	-1.962
	(2.16)	(1.16)	(1.79)	(3.08)	(1.76)
Recharge (in)	-1.496	-2.678***	-0.451	-3.781***	-1.268
	(0.93)	(0.37)	(0.38)	(0.81)	(0.74)
Average yearly precipitation, 1971-2000 (in)	-0.241	1.478***	-1.804***	1.520***	1.087***
	(0.31)	(0.14)	(0.26)	(0.32)	(0.22)
Average evapotranspiration (in)	-5.707***	-1.679***	-8.962***	2.240**	2.767***
	(0.65)	(0.28)	(0.47)	(0.84)	(0.52)
Slope (% of distance)	0.145	0.445	-0.266	-1.107	1.270***
	(0.38)	(0.25)	(0.42)	(0.58)	(0.37)
Irrigated Capability Class = 1	-8.449***	-7.648***	-6.519***	-6.961***	-6.544***
	(0.97)	(0.44)	(0.68)	(1.13)	(0.66)
Saturated thickness of the aquifer (ft)	0.0586***	0.0893***	0.0224***	0.0422***	0.0595***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)

Quantity authorized for extraction (af)	1.356***	2.093***	1.140***	1.186***	1.297***
	(0.26)	(0.12)	(0.23)	(0.23)	(0.14)
Field size (ac)	0.281***	0.277***	0.186***	0.186***	0.216***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Center pivot irrigation system (compared to flood)	44.59***	32.38***	33.86***	28.10***	19.67***
	(1.24)	(0.61)	(0.94)	(1.50)	(0.88)
Center pivot irrigation system with dropped nozzles (compared to flood)	42.14***	32.69***	32.82***	27.50***	19.99***
	(1.09)	(0.51)	(0.77)	(1.20)	(0.70)
10 year forecast of the real acreage-weighted price of commodities ($/bu)	-1.047	-4.275*	2.018	7.604	8.519**
	(3.43)	(1.85)	(2.89)	(4.81)	(2.84)
Quantity of water used by neighbors in 1 mile radius in *t*-1 (af)	0.00585***	0.00844***	0.00787***	0.00523***	0.00442***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Inverse Mills Ratio	-15.07***	-23.67***	-9.582***	-7.872***	-8.359***
	(0.46)	(0.53)	(1.45)	(0.91)	(0.59)
Constant	355.3***	107.7***	579.4***	-122.1*	-174.5***
	(39.97)	(17.66)	(31.81)	(50.46)	(30.50)
Observations	154619	154619	154619	154619	154619

Notes: Standard errors in parentheses. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

Table 4: Results for Water Demand Conditional on Crop Choice (Intensive Margin)

Dependent variable is quantity of irrigation water pumped (acre-feet)	
Natural gas futures contract price ($/1000 btu)	-2672.7***
	(302.2)
Depth to groundwater (ft)	0.389***
	(0.00849)
Natural gas futures contract price * Depth to groundwater	-58.27***
	(1.673)
Acres planted to alfalfa	0.466***
	(0.00600)
Acres planted to corn	0.391***
	(0.00338)
Acres planted to soybeans	0.279***
	(0.00695)
Acres planted to sorghum	-0.0459***
	(0.00920)
Acres planted to wheat	-0.0600***
	(0.00539)
Recharge (in)	-1.172**
	(0.420)
Average yearly precipitation, 1971-2000 (in)	-0.806***
	(0.161)
Average evapotranspiration (in)	-6.832***
	(0.340)
Slope (% of distance)	2.606***
	(0.283)
Irrigated Capability Class = 1 (Dummy)	-13.34***
	(0.525)
Saturated thickness of the aquifer (ft)	0.186***
	(0.00260)
Quantity authorized for extraction (af)	6.116***
	(0.128)
Field size (ac)	0.358***
	(0.00273)
Center pivot irrigation system (compared to flood)	-4.224***
	(0.710)
Center pivot irrigation system with dropped nozzles (compared to flood)	-4.227***
	(0.581)
10 year forecast of the real acreage-weighted price of commodities ($/bu)	-60.05***
	(1.410)
Left land fallow or planted with a non-irrigated plot (dummy)	-131.3***
	(0.854)
Quantity of water used by neighbors in 1 mile radius in *t*-1 (af)	0.0210***

	(0.000537)
Constant	580.0***
	(20.61)
Observations	154619
R-squared	0.529

Notes: Standard errors in parentheses. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

Table 5: Total Intensive Margin

Coefficient on energy price	-2672.7
Coefficient on energy price * depth to groundwater	-58.27
Mean depth to groundwater (ft)	125.27
TOTAL INTENSIVE MARGIN $\left(\frac{\partial w}{\partial e}\right)$	**-9972.18**

Notes: Only significant coefficients are used in the calculation. The effect of energy price on water use is evaluated at the mean depth to groundwater. Energy prices *e* are in $/1000 btu. Water use *w* is in acre-feet.

Table 6: Total Extensive Margin

	$\frac{\partial w}{\partial n_c*}$	$\frac{\partial n_c*}{\partial e}$	$\frac{\partial w}{\partial n_c*}\frac{\partial n_c*}{\partial e}$
Soybeans	0.279	-997.4	-278.275
Wheat	-0.060	626.4	-37.583
TOTAL EXTENSIVE MARGIN $\left(\sum_c \frac{\partial w}{\partial n_c*}\frac{\partial n_c*}{\partial e}\right)$			**-315.858**

Notes: Only significant coefficients are used in the calculation. The effects of energy price on crop acreage are evaluated at the mean depth to groundwater. Energy prices e are in \$/1000 btu. Water use w is in acre-feet. The number of acres n_c* planted to each crop c is in acres.

Table 7: Total Marginal Effects

Total intensive margin $\left(\frac{\partial w}{\partial e}\right)$	-9972.18
Total extensive margin $\left(\sum_c \frac{\partial w}{\partial n_c^*}\frac{\partial n_c^*}{\partial e}\right)$	-315.86
TOTAL MARGINAL EFFECT $\left(\frac{dw}{de} = \frac{\partial w}{\partial e} + \sum_c \frac{\partial w}{\partial n_c^*}\frac{\partial n_c^*}{\partial e}\right)$	**-10,288.04**

Notes: Only significant coefficients are used in the calculation. The effects of energy price on crop acreage and on water use are evaluated at the mean depth to groundwater. Energy prices e are in \$/1000 btu. Water use w is in acre-feet. The number of acres n_c^* planted to each crop c is in acres.