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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 effect on both types of margins. Increasing energy prices would affect crop selection decisions, crop acreage allocation decisions, and farmers' demand for water. Our estimated total marginal effect, which sums the effects on the intensive and extensive margins, suggests that a \$1 per million btu increase in the energy price would decrease water extraction by an individual farmer by 5.89 acre-feet per year, a decrease of 3.6 percent of the average annual extraction rate. Our estimated elasticity of water extraction with respect to energy price is −0.26.

Key words: Energy, groundwater extraction.

JEL codes: Q15, Q40.

Many of the world's most productive agricultural basins depend on groundwater. The food that consumers 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% of water extracted or diverted for consumptive use goes to agriculture, but in many groundwater basins, this proportion can be as high as 95–99%. 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 article we examine the effects that energy prices have 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 central United States. There, 99% of the water extracted is used for crop production, while the remaining 1% is used for livestock, domestic, and industrial purposes. The economy of the region is based almost entirely on irrigated agriculture. The alfafa, corn, sorghum, soybeans, and wheat grown there are 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 required 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. In this article we examine whether energy prices impact groundwater 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

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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 effect on both the intensive and extensive margins. Increasing energy prices would affect crop selection decisions, crop acreage allocation decisions, and the demand for water by farmers. The total marginal effect, which sums the effects on the intensive and extensive margins, estimates that a $1 per million btu increase in the energy price would decrease water extraction by an individual farmer by 5.89 acre-feet per year. Our estimated elasticity of water extraction with respect to energy price is −0.26.

Our article 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, Ringler, and Cai (2013), who simulate the effects of energy prices on groundwater extraction in India, China, the United States, and Vietnam. We build upon these previous theory and simulation papers by empirically analyzing the effects that energy prices have on groundwater extraction.

Some of the existing empirical work on the effects of energy prices on groundwater extraction has taken place 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, Gulati, and Sukhadeo 2008; Kumar 2005; Scott and Shah 2004).

In the U.S. context, Caswell and Zilberman (1986), as well as Ogg and Gollehon (1989), both use pumping costs as proxies for water prices in California and the western United States, respectively. While these papers do not specifically focus on energy, they implicitly acknowledge the role of energy costs in on-farm pumping as a driver of water use decisions in the United States. Similarly, in their estimates of crop choice, supply, land allocation, and water demand, Moore, Gollehon, and Carey (1994) use as their water price an engineering formula that translates groundwater pumping lift into marginal cost in dollars per acre-foot.

In a related paper, estimate irrigation water demand in Kansas using an estimate of extraction cost as their proxy for water price. We build on these authors' 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 to calculate the cost of reducing irrigation water use through water pricing, irrigation cessation, and intensity-reduction programs, our article 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 allocation decisions in the estimation of water demand on the intensive margin, but it 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.

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 increased from 1 million acres in 1960 to 3.1 million acres in 2005, and accounts for 99% of all groundwater withdrawals (Kenny and Hansen

2004). Irrigation converted the region from the "Great American Desert" into the "Breadbasket of the World" (Muilenburg et al. 1975).

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 (Miller and Appel 1997).

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.

Water recharge to the Kansas portion of the High Plains aquifer is very small, and is primarily completed 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).

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 and is the same fixed amount each year (Pfeiffer and Lin 2012). Appropriation contracts are stated in terms of a maximum acre-feet of extraction per year with a "use it or lose it" clause. Until recently (2012), farmers must use their allocation each year and are unable to bank any unused portions of the water allocation in a particular year for use in future years. However, since the groundwater

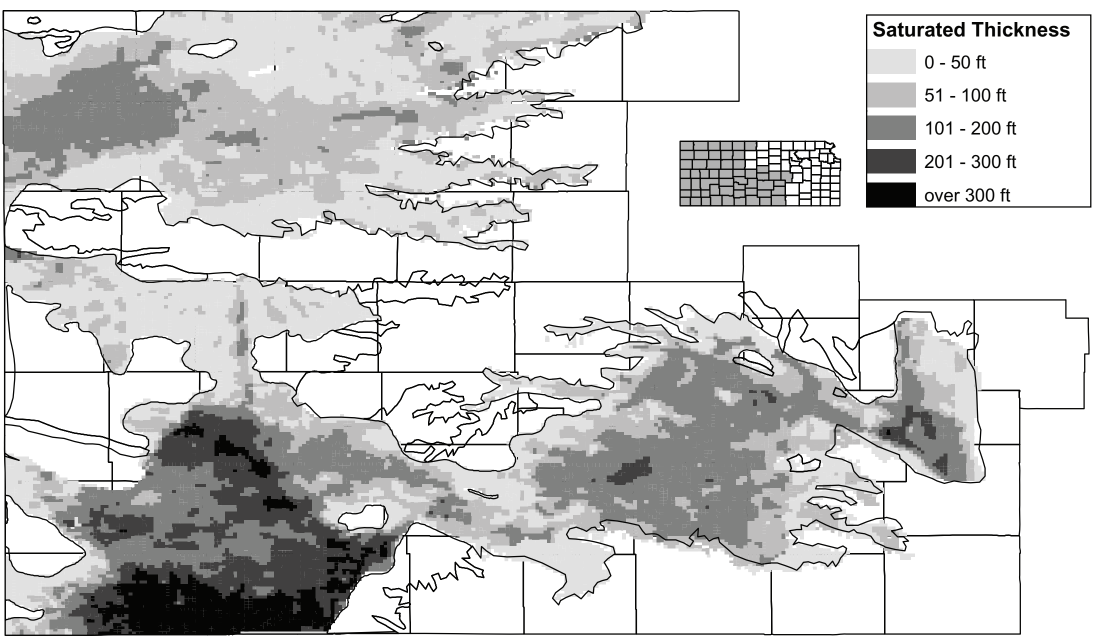

Figure 1. Predevelopment saturated thickness of the Kansas portion of the High Plains Aquifer

Source: Kansas Geological Survey.

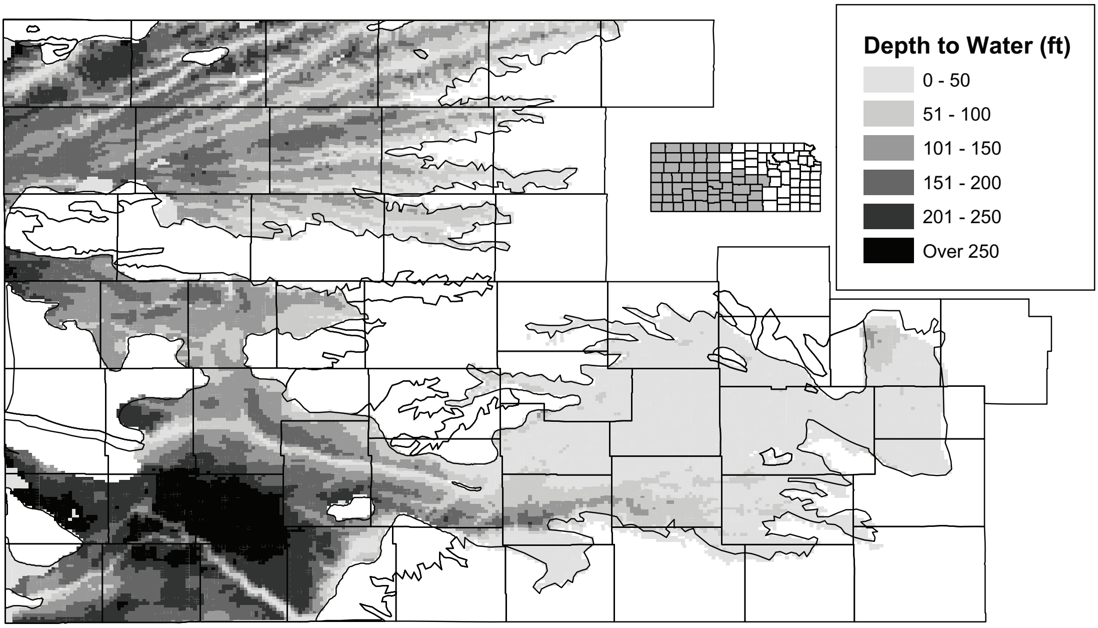

Figure 2. Average 2004-2006 depth to groundwater in the Kansas portion of the High Plains Aquifer

Source: Kansas Geological Survey.

is in part a nonrenewable resource, and since the availability of water is stochastic owing to variable weather and rainfall and since demand for water is greater when it is less available, farmers could operate in a more dynamically efficient manner if the appropriator could use less water in some years and more in others (Lin and Pfeiffer, forthcoming). Nevertheless, Pfeiffer and Lin (2013) find that despite the incentives given to groundwater users to pump their maximum allowable amount in each year by the prior appropriation doctrine, farmers extract water consistent with a dynamic model of resource extraction.

The main crops grown in western Kansas are alfalfa, corn, sorghum, soybean, and wheat (High Plains Regional Climate Center 2014). Corn production accounts for more than 50% of all irrigated land (Buddemeier 2000), with soil types and access to high volumes of irrigation water determining the suitability of a particular piece of land to various crops.

Evapotranspiration is the loss of water to the atmosphere by the combined processes of evaporation (from soil and plant surfaces) and transpiration (from plant tissues). This process is thus an indicator of how much water crops require for healthy growth and productivity. Many factors affect evapotranspiration: weather parameters such as solar radiation, air temperature, relative humidity, and wind speed; soil factors such as soil texture, structure, density, and chemistry; and plant factors such as plant type, root depth and foliar density, height, and stage of growth. Since there are so many factors that affect evapotranspiration, it is extremely difficult to formulate an equation that can produce estimates of evapotranspiration under different sets of conditions. Therefore, the idea of reference crop evapotranspiration was developed by researchers; this refers to the evapotranspiration rate of a reference crop expressed in inches or millimeters (CIMIS 2009).

Reference crops are alfalfa surfaces, whose biophysical characteristics have been studied extensively. The logic behind the reference evapotranspiration idea is to establish weather stations on standardized reference surfaces for which most of the biophysical properties used in evapotranspiration equations are known. Using these known parameters and measured weather parameters, evapotranspiration from such surfaces is estimated. Then a crop factor, commonly known as crop coefficient, is used to calculate the actual evapotranspiration for a specific crop in the same microclimate as the weather station site (CIMIS 2009). The

Table 1. Evapotranspiration Crop Coefficients

Crop	Crop Coefficient
Alfafa	0.10 – 1.00
Corn	0.10 – 1.10
Sorghum	0.10 – 1.10
Soybeans	0.10 – 1.10
Wheat	0.10 – 1.10

Source: High Plains Regional Climate Center, 2014.

crop coefficient for a particular crop varies depending on the stage of growth for the crop.

Table 1 presents the range of the crop coefficients for the High Plains for each of the main crops grown in western Kansas as calculated by the High Plains Regional Climate Center (2014). As table 1 illustrates, the range of the crop coefficients overlap with each other so that the relative ranking of the crops by water intensiveness may vary depending on the stage of growth for each crop. There is therefore no clear ranking of these crops by water intensiveness, and the upper bound crop coefficient for alfafa is lower than that for the other crops.

The quality of water in the High Plains aquifer is affected by many factors. These factors include the chemical composition and solubility of aquifer materials, the increase in dissolved solids concentrations in groundwater in areas where the water discharges by evapotranspiration, and the chemical composition of water that recharges the aquifer. The dissolved solids concentration in groundwater is a general indicator of the chemical quality of the water. In most of Kansas, dissolved solids concentrations in water from the High Plains aquifer are less than 500 milligrams per liter, the limit of dissolved solids recommended by the U.S. Environmental Protection Agency for drinking water, but locally can exceed 1,000 milligrams per liter (Miller and Appel 1997).

Excessive concentrations of sodium in water adversely affect plant growth and soil properties, and constitute salinity and sodium hazards that may limit irrigation development. Sodium that has been concentrated in the soil by evapotranspiration and ion exchange decreases soil tillability and permeability; areas of high or very high sodium hazard occur in parts of Kansas, while sodium concentrations in water from the High Plains aquifer are less than 25 milligrams per liter in most of northern Kansas. Concentrations are greatest in southwestern Kansas where evapotranspiration rates are high and in south-central Kansas, where the High Plains aquifer overlies Permian bedrock that contains saline water derived from the partial dissolution of salt beds (Miller and Appel 1997).

Overall, it does not seem that significant irrigation-related increases in salinity exist in western Kansas, except in the Valley-Fill Alluvium soils along river beds and in the Permian rock bed area. The Valley-Fill Alluvium unit is susceptible to increasing salinity because irrigation water is recycled along alluvial valleys in a downstream direction as water is pumped from the aquifer or diverted from the river, applied to fields, and then returned to the aquifer as irrigation drainage. During each irrigation/return flow cycle, salinity is increased as water is transpired by crops and as return-flow water dissolves additional minerals from the soil (Litke 2001). Nitrate and pesticide contamination appears to be a problem in some areas and is related to land use (Steichen et al. 1998; Helgesen, Stullken, and Rutledge 1994).

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). Spatially referenced pumping data at the source (well or pump) level is included, and each data point identifies the farmer, field, irrigation technology, amount pumped, and crops grown.

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 taken from the Commodity Research Board, and price received is from the United States Department of Agriculture (USDA) Economic Research Service.

Of the acres irrigated from groundwater wells in Kansas, about 50% are supplied by pumps powered with natural gas, 25% are supplied by pumps powered with diesel fuel, and 22% are supplied by pumps powered with electricity (FRIS 2004); our water data does not indicate the type of energy used for irrigation.

Table 2. Summary Statistics

	Obs	Mean	Std. Dev.	Min	Max
Individual-year level variables					
Irrigation water pumped (af)	154,619	164.37	124.12	0.00	1,491.48
Acres planted to alfafa	154,619	11.92	39.22	0.00	640.00
Acres planted to corn	154,619	59.90	74.32	0.00	640.00
Acres planted to sorghum	154,619	5.12	24.23	0.00	620.00
Acres planted to soybeans	154,619	11.09	33.82	0.00	542.00
Acres planted to wheat	154,619	16.49	43.18	0.00	584.00
Irrigation water used by neighbors (1 mile radius, af)	154,619	437.72	428.38	0.00	4,586.97
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	283.81	206.90	0.00	2,400.00
Field size (ac)	17,960	183.97	102.76	60.59	640.00
Year-level variables					
Corn price futures ($/bu)	10	2.56	0.32	2.24	3.20
Sorghum price futures ($/bu)	10	6.84	1.84	5.17	11.12
Soy price futures ($/bu)	10	5.95	1.17	4.52	7.73
Wheat price futures ($/bu)	10	3.57	0.32	3.18	4.19
Alfalfa price ($/ton)	10	81.23	9.51	70.58	95.92
10 year forecast of the real acreage-weighted price of commodities ($/bu)	10	2.70	0.31	2.29	3.14
Energy price, base case ($/million btu)	10	7.33	2.54	5.15	13.39
Energy price, alternative A ($/million btu)	10	11.21	1.35	10.12	14.50
Energy price, alternative B ($/million btu)	10	4.99	2.35	3.00	10.56

Notes: In the base case specification, we use the natural gas price as the energy price for farmers in counties with natural gas production, and the diesel price as the energy price for all other farmers. In specification A, we use the natural gas price as the energy price for farmers in counties with natural gas production, and the electricity price as the energy price for all other farmers. In specification B, we use the natural gas price as the energy price for all farmers.

In our base case specification, we use the natural gas price as the energy price for farmers in counties with natural gas production, which represents 55.2% of the farmers, and the diesel price as the energy price for all other farmers. For robustness, we also run our model using two alternative specifications for the energy price. In specification A, we use the natural gas price as the energy price for farmers in counties with natural gas production and the electricity price as the energy price for all other farmers. In specification B, we use the natural gas price as the energy price for all farmers. County-level natural gas production data used to determine which counties had natural gas production are taken from the Kansas Geological Survey. Natural gas prices, diesel prices and electricity prices come from the U.S. Energy Information Administration and are all converted to units of dollars per million btu.

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 2. 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%. About 45% of the plots are in irrigated capability class 1. Field size is an average of 183.97 acres. Energy prices for our base case specification are, on average, \$7.33 per million btu.

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, and 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 $n_{ict}*$ to each crop c by each farmer i in each time period t can be estimated as:

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

$$n_{ict}^{*} = g(e_t, p_{ct}, \boldsymbol{x_{it}}, d_{it}, IMR_c), \quad c = \textit{soybeans, wheat, sorghum, soybeans, wheat} \tag{2}$$

where q_{ict} 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; 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) also 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 to measure 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). The ratios are estimated as a simultaneous system of equations to exploit the information contained in the cross-equation correlations.[1]

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 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.

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), we exclude the lagged crop choice variables z_{it-1} from the crop acreage equations (2), but not from 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 during the previous year may affect which crops he plants this year due to crop rotation patterns, but conditional on making a particular crop choice in the

[1] Correlation across the errors in different equations can provide links that can be exploited in a system estimation to improve estimator efficiency (Ruud 2000; Wooldridge 2002). Even if the system estimators are asymptotically equivalent to the equation-by-equation estimators, system estimation enables one to estimate the covariances between the estimators from different equations (Wooldridge 2002).

Table 3. Probit Results for Crop Selection

	Dependent variable is probability of planting:				
	Alfalfa	Corn	Sorghum	Soybeans	Wheat
Energy price ($/million btu)	−0.023***	0.001	0.023***	−0.028***	0.023***
	(0.004)	(0.002)	(0.004)	(0.003)	(0.003)
Energy price ($/million btu)* Depth to groundwater (ft)	−0.0001***	0.0001**	−0.0001***	0.0002***	−0.0001***
	(0.00003)	(0.00002)	(0.00003)	(0.00002)	(0.00002)
Depth to groundwater (ft)	−0.0007**	0.0003**	0.0005*	−0.0017***	0.0004*
	(0.0002)	(0.0001)	(0.0002)	(0.0002)	(0.0002)
Alfalfa price ($/ton yearly average)	0.003**	−0.001*	0.002**	−0.001	−0.002*
	(0.001)	(0.0005)	(0.0008)	(0.001)	(0.0006)
Corn price ($/bu futures)	0.269*	0.160*	−0.807***	0.515***	−0.462***
	(0.119)	(0.070)	(0.117)	(0.093)	(0.086)
Sorghum price ($/bu spring average)	−0.062***	−0.090***	0.190***	−0.054***	0.111***
	(0.016)	(0.009)	(0.014)	(0.012)	(0.011)
Soybeans price ($/bu futures)	−0.052*	0.043**	0.016	−0.003	0.029
	(0.023)	(0.013)	(0.022)	(0.018)	(0.016)
Kansas wheat price ($/bu futures)	0.329***	0.063**	−0.105**	−0.173***	−0.071*
	(0.040)	(0.023)	(0.038)	(0.029)	(0.028)
Recharge (in)	0.046***	−0.109***	−0.009	0.012	−0.032**
	(0.014)	(0.007)	(0.011)	(0.007)	(0.010)
Average yearly precipitation, 1971–2001 (in)	−0.043***	0.042***	0.009*	0.134***	−0.054***
	(0.005)	(0.003)	(0.004)	(0.003)	(0.004)
Average evapotranspiration (in)	0.044***	0.059***	−0.013	0.182***	−0.058***
	(0.011)	(0.006)	(0.011)	(0.008)	(0.008)
Slope (% of distance)	0.082***	0.004	0.030***	−0.058***	−0.006
	(0.007)	(0.005)	(0.007)	(0.007)	(0.006)
Irrigated Capability Class = 1	−0.269***	0.023*	0.107***	0.026*	0.056***
	(0.016)	(0.009)	(0.014)	(0.011)	(0.011)
Saturated thickness of the aquifer (ft)	−0.269***	0.023*	0.107***	0.026*	0.056***
	(0.012)	(0.009)	(0.014)	(0.011)	(0.011)
Quantity authorized for extraction (af)	−0.00008	0.00005*	0.00005	−0.00004	0.00002
	(0.00004)	(0.00002)	(0.00003)	(0.00003)	(0.00002)
Field size (ac)	−0.0003***	−0.0002***	0.0007***	−0.0002*	0.0011***
	(0.0001)	(0.0000)	(0.0001)	(0.0001)	(0.0000)
Center pivot irrigation system (compared to flood)	0.079***	0.166***	−0.258***	−0.023	0.030*
	(0.021)	(0.012)	(0.018)	(0.016)	(0.015)
Center pivot irrigation system with dropped nozzles (compared to flood)	0.076***	0.201***	−0.324***	0.048***	0.008
	(0.018)	(0.010)	(0.014)	(0.013)	(0.012)
10-year forecast of the real acreage-weighted price of commodities ($/bu)	−0.383***	0.401***	0.091	−0.396***	0.136***
	(0.052)	(0.030)	(0.050)	(0.040)	(0.037)
Quantity of water used by neighbors in 1 mile radius in *t*-1 (af)	0.0001***	0.0001***	−0.0001***	0.0001***	−0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Planted alfafa in *t*-1 (dummy)	2.521***	−0.494***	−0.066**	−0.267***	−0.153***
	(0.015)	(0.014)	(0.022)	(0.022)	(0.017)
Planted corn in *t*-1 (dummy)	−0.336***	1.400***	−0.091***	0.630***	0.114***
	(0.014)	(0.008)	(0.013)	(0.011)	(0.010)
Planted sorghum in *t*-1 (dummy)	−0.170***	0.022	1.552***	0.447***	0.301***
	(0.028)	(0.015)	(0.015)	(0.018)	(0.016)
Planted soybeans in *t*-1 (dummy)	−0.251***	0.787***	0.280***	0.905***	0.291***
	(0.025)	(0.012)	(0.018)	(0.013)	(0.015)
Planted wheat in *t*-1 (dummy)	0.050**	0.089***	0.414***	0.122***	1.636***
	(0.018)	(0.010)	(0.014)	(0.014)	(0.010)
Left land fallow or planted with a non-irrigated plot in *t*-1 (dummy)	−0.070**	−0.261***	0.057**	−0.080***	0.039*
	(0.024)	(0.015)	(0.022)	(0.024)	(0.018)

continued.

Table 3. continued

	Dependent variable is probability of planting:				
	Alfalfa	Corn	Sorghum	Soybeans	Wheat
Constant	−3.279***	−6.465***	−0.804	−13.72***	2.827***
	(0.657)	(0.365)	(0.606)	(0.465)	(0.463)
Observations	154,619	154,619	154,619	154,619	154,619

Notes: Marginal effects are reported. Standard errors appear in parentheses. For the energy price, we use the natural gas price as the energy price for farmers in counties with natural gas production and the diesel price as the energy price for all other farmers. Significance is denoted as follows: * = 5% level, ** = 1% level, and *** = 0.1% level.

present year, the previous year's crop choice is unlikely to affect the acreage allocated to each crop for the present year.[2]

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

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

where w_{it} is the amount of water extracted by farmer i in year t. In the water demand equation (3), we include both energy price and energy price squared, as well as energy price interacted with depth to groundwater. We also include number of acres planted to each crop and the number of acres planted to each crop squared.

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 (Moore, Gollehon, and Carey 1994) in equation (2):[3]

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

[2] Even though excluding last year's crop choice from the acreage allocation regressions improves the efficiency of our estimators, this exclusion restriction is not necessary for identification (Wooldridge 2002). Our results on the effects of energy price were robust regarding whether the lagged crop choice variables are excluded from the crop acreage allocation regressions and also robust regarding whether lagged crop acreage is added to both the crop choice and the crop acreage allocation regressions.

[3] Another possible decision is to not 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.

Results

Tables 3 and 4 show the estimation results for equations (1) and (2), respectively, using our base case specification for energy price. When considering only the significant coefficients on energy price and on the interaction between energy price and depth to groundwater in table 4, and when evaluated at the mean depth to groundwater, our results show that energy prices cause a significant decrease in the acreage allocated to corn, sorghum, soybeans, and wheat, and a significant increase in the acreage allocated to alfafa. An increase in the energy price of $1 per million btu decreases the number of acres allocated to corn, sorghum, soybeans, and wheat by 1.30, 0.83, 2.21, and 0.80 acres per farmer, respectively. These acreage values are between 0.43% and 1.20% of the average field size. An increase in the energy price of $1 per million btu increases the number of acres allocated to alfafa by 0.03 acres per farmer, which is 0.02% of the average field size.

The results of estimating equation (3), water use along the intensive margin, conditional on crop choice, for the base case specification of energy price, are presented in table 5. 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 as the depth to groundwater increases.

Table 6 summarizes the calculations used to derive the total intensive margin, which are based on the coefficients on the energy price, on energy price squared, and on the interaction between energy price and depth to groundwater in the water use regression in table 5, all of which are significant. Evaluated at mean energy price and mean depth to groundwater, an increase in energy prices by $1 per

Table 4. Selectivity-corrected Results for Crop Acreage Allocation (Extensive Margin)

	Dependent variable is number of acres allocated to:				
	Alfalfa	Corn	Sorghum	Soybeans	Wheat
Energy price ($/million btu)	−0.969***	−2.430***	−0.831**	−2.213***	−0.797***
	(0.251)	(0.126)	(0.305)	(0.174)	(0.216)
Energy price ($/million btu) * Depth to groundwater (ft)	0.008***	0.009***	−0.002	0.002	0.002
	(0.002)	(0.001)	(0.002)	(0.001)	(0.001)
Depth to groundwater (ft)	−0.069***	−0.033***	−0.001	−0.019	0.024*
	(0.014)	(0.007)	(0.016)	(0.012)	(0.009)
Alfalfa price ($/ton yearly average)	0.109*	0.015	−0.016	−0.043	0.063
	(0.051)	(0.027)	(0.068)	(0.043)	(0.041)
Corn price ($/bu futures)	−4.808	8.840**	−17.96	18.82***	−2.484
	(6.681)	(3.338)	(9.286)	(5.702)	(5.287)
Sorghum price ($/bu spring average)	1.527	−3.845***	3.627**	−4.949***	−0.347
	(0.864)	(0.473)	(1.163)	(0.727)	(0.704)
Soybeans price ($/bu futures)	−1.719	0.370	−0.723	0.631	0.693
	(1.269)	(0.653)	(1.727)	(1.096)	(1.004)
Kansas wheat price ($/bu futures)	−0.860	3.290**	5.072	−2.189	0.105
	(2.193)	(1.134)	(3.036)	(1.777)	(1.745)
Recharge (in)	−1.662	−4.023***	−4.197***	−0.660	−1.955**
	(1.003)	(0.367)	(0.823)	(0.389)	(0.749)
Average yearly precipitation, 1971–2000 (in)	−0.537	3.207***	2.051***	3.245***	0.923***
	(0.344)	(0.141)	(0.343)	(0.225)	(0.226)
Average evapotranspiration (in)	−6.177***	2.577***	3.337***	0.127	2.838***
	(0.704)	(0.323)	(0.902)	(0.517)	(0.561)
Slope (% of distance)	0.679	0.477	−0.829	−1.939***	1.215**
	(0.388)	(0.247)	(0.583)	(0.412)	(0.374)
Irrigated Capability Class = 1	−11.51***	−6.963***	−5.352***	−4.800***	−5.511***
	(0.989)	(0.434)	(1.127)	(0.678)	(0.662)
Saturated thickness of the aquifer (ft)	0.061***	0.094***	0.033***	0.018***	0.058***
	(0.004)	(0.002)	(0.006)	(0.004)	(0.003)
Quantity authorized for extraction (af)	0.013***	0.022***	0.0130***	0.013***	0.013***
	(0.003)	(0.001)	(0.002)	(0.002)	(0.001)
Field size (ac)	0.266***	0.272***	0.195***	0.195***	0.229***
	(0.005)	(0.002)	(0.005)	(0.005)	(0.003)
Center pivot irrigation system (compared to flood)	48.08***	33.17***	23.54***	28.60***	19.16***
	(1.262)	(0.603)	(1.490)	(0.962)	(0.886)
Center pivot irrigation system with dropped nozzles (compared to flood)	45.55***	34.47***	21.91***	29.96***	19.18***
	(1.114)	(0.505)	(1.191)	(0.787)	(0.703)
10 year forecast of the real acreage-weighted price of commodities ($/bu)	0.781	−8.826***	−1.948	−23.23***	1.797
	(2.952)	(1.508)	(4.016)	(2.485)	(2.342)
Quantity of water used by neighbors in 1 mile radius in t-1 (af)	0.006***	0.011***	0.003*	0.009***	0.004***
	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)
Inverse Mills Ratio	−8.028***	−1.374**	3.787***	22.91***	1.897***
	(0.466)	(0.513)	(0.769)	(0.814)	(0.501)
Constant	391.3***	−159.5***	−180.5***	−9.437	−163.9***
	(41.92)	(18.55)	(51.90)	(31.01)	(31.69)
Observations	154,619	154,619	154,619	154,619	154,619

Notes: Standard errors appeaer in parentheses. For the energy price, we use the natural gas price as the energy price for farmers in counties with natural gas production and the diesel price as the energy price for all other farmers. Significance is denoted as follows: * = 5% level, ** = 1% level, and *** = 0.1% level.

million btu decreases water demand conditional on crop choice by 5.145 acre-feet along the intensive margin.

Table 7 summarizes the calculations used to derive the total extensive margin. We consider only the significant coefficients on the energy price and on the interaction between energy price and depth to groundwater in table 4, and only the significant coefficients on acres allocated to each crop and acres allocated to each crop squared in table 5. We evaluate the effects of crop acreage on water use at the mean acres

Table 5. Results for Water Demand Conditional on Crop Choice (Intensive Margin)

	Dependent variable is quantity of irrigation water pumped (acre-feet)
Energy price ($/million btu)	−5.029***
	(0.292)
Energy price ($/million btu) squared	0.163***
	(0.014)
Energy price ($/million btu) * Depth to groundwater (ft)	−0.020***
	(0.001)
Depth to groundwater (ft)	0.290***
	(0.008)
Acres planted to alfalfa	0.483***
	(0.012)
Acres planted to alfalfa squared	−0.00026***
	(0.00006)
Acres planted to corn	0.307***
	(0.006)
Acres planted to corn squared	0.00038***
	(0.00002)
Acres planted to sorghum	−0.168***
	(0.017)
Acres planted to sorghum squared	0.00069***
	(0.00009)
Acres planted to soybeans	0.226***
	(0.015)
Acres planted to soybeans squared	0.00026**
	(0.00010)
Acres planted to wheat	−0.104***
	(0.0114)
Acres planted to wheat squared	0.00035***
	(0.00006)
Recharge (in)	−3.914***
	(0.425)
Average yearly precipitation, 1971–2000 (in)	1.271***
	(0.167)
Average evapotranspiration (in)	0.990**
	(0.373)
Slope (% of distance)	2.423***
	(0.282)
Irrigated Capability Class = 1 (Dummy)	−12.04***
	(0.525)
Saturated thickness of the aquifer (ft)	0.159***
	(0.003)
Quantity authorized for extraction (af)	0.062***
	(0.001)
Field size (ac)	0.336***
	(0.003)
Center pivot irrigation system (compared to flood)	−6.251***
	(0.713)
Center pivot irrigation system with dropped nozzles (compared to flood)	−4.298***
	(0.584)
10 year forecast of the real acreage-weighted price of commodities ($/bu)	−40.69***
	(1.038)
Left land fallow or planted with a non-irrigated plot (dummy)	−134.8***
	(0.865)
Quantity of water used by neighbors in 1 mile radius in *t*-1 (af)	0.0194***
	(0.001)
Constant	85.01***
	(21.35)
Observations	154,619
R-squared	0.53

Notes: Standard errors appear in parentheses. For the energy price, we use the natural gas price as the energy price for farmers in counties with natural gas production and the diesel price as the energy price for all other farmers. Significance is denotes as follows: * = 5% level, ** = 1% level, and *** = 0.1% level.

Table 6. Total Intensive Margin

Coefficient on energy price	5.029
Coeffficient on energy price squared	0.163
Coefficient on energy price * depth to groundwater	−0.020
Mean energy price ($/million btu)	7.33
Mean depth to groundwater (ft)	125.27
TOTAL INTENSIVE MARGIN $\left(\frac{\partial w}{\partial e}\right)$	**−5.145**

Notes: Only significant coefficients are used in the calculation. The effect of energy price on water use is evaluated at the mean energy price and the mean depth to groundwater. Energy prices e are in $/million btu. Water use w is in acre-feet. For the energy price, we use the natural gas price as the energy price for farmers in counties with natural gas production, and the diesel price as the energy price for all other farmers.

Table 7. Total Extensive Margin

	$\frac{\partial w}{\partial n_c{}^*}$	$\frac{\partial n_c{}^*}{\partial e}$	$\frac{\partial w}{\partial n_c{}^*}\frac{\partial n_c{}^*}{\partial e}$
Alfafa	0.477	0.033	0.016
Corn	0.352	−1.303	−0.459
Sorghum	−0.161	−0.831	0.134
Soybeans	0.232	−2.213	−0.513
Wheat	−0.092	−0.797	0.074
TOTAL EXTENSIVE MARGIN $\left(\sum_c \frac{\partial w}{\partial n_c{}^*}\frac{\partial n_c{}^*}{\partial e}\right)$			**−0.749**

Notes: Only significant coefficients are used in the calculation. The effects of crop acreage on water use are evaluated at mean crop acreage. The effects of energy price on crop acreage are evaluated at the mean depth to groundwater. Energy prices e are in $/million btu. Water use w is in acre-feet. The number of acres n_c* planted to each crop c is in acres. For the energy price, we use the natural gas price as the energy price for farmers in counties with natural gas production and the diesel price as the energy price for all other farmers.

allocated to each crop, and evaluate the effects of energy price on crop acreage at the mean depth to groundwater. An increase in energy prices by $1 per million btu decreases water use by 0.749 acre-feet along the extensive margin.

We are mainly interested in the total marginal effects of an increase in the energy price, calculated using equation (4) and reported in table 8. 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 on the intensive and extensive margins, is that an increase in the energy price of $1 per million btu, which is approximately 13.6% of its mean value over the time period of our data set, would decrease water extraction by an individual farmer by 5.89 acre-feet per year, which is approximately 3.6% of the average amount pumped in a year by a farmer. Our estimated elasticity of water extraction with respect to energy price is −0.26.

In table 8, we also report the total marginal effects resulting from two alternative specifications for the energy price. In specification A, we use the natural gas price as the energy price for farmers in counties with natural gas production and the electricity price (instead of the diesel price) as the energy price for all other farmers, and find that an increase in the energy price of $1 per million btu, which is approximately 8.9% of its mean value over the time period of our data set, would decrease water extraction by an individual farmer by 2.17 acre-feet per year, which is approximately 1.3% of the average amount pumped in a year by a farmer. Our estimated elasticity of water extraction with respect to energy price under specification A is −0.15.

In specification B, we use the natural gas price as the energy price for all farmers, and find that an increase in the energy price of $1 per million btu, which is approximately 20.0% of its mean value over the time period of our data set, would decrease water extraction by an individual farmer by 8.57 acre-feet per year, which

Table 8. Total Marginal Effects

	Base case	Alternative A	Alternative B
Total intensive margin $\left(\frac{\partial w}{\partial e}\right)$	−5.145	−2.002	−8.126
Total extensive margin $\left(\sum_c \frac{\partial w}{\partial n_c{}^*}\frac{\partial n_c{}^*}{\partial e}\right)$	−0.749	−0.170	−0.439
TOTAL MARGINAL EFFECT $\left(\frac{dw}{de} = \frac{\partial w}{\partial e} + \sum_c \frac{\partial w}{\partial n_c{}^*}\frac{\partial n_c{}^*}{\partial e}\right)$	−5.89	−2.17	−8.57

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 energy price and the mean depth to groundwater. The effects of crop acreage on water use are evaluated at mean crop acreage. Energy prices e are in $/million btu. Water use w is in acre-feet. The number of acres n_c* planted to each crop c is in acres. Results are presented for three specifications of the energy price. In the base case specification, we use the natural gas price as the energy price for farmers in counties with natural gas production and the diesel price as the energy price for all other farmers. In specification A, we use the natural gas price as the energy price for farmers in counties with natural gas production and the electricity price as the energy price for all other farmers. In specification B, we use the natural gas price as the energy price for all farmers.

is approximately 5.2% of the average amount pumped in a year by a farmer. Our estimated elasticity of water extraction with respect to energy price under specification B is −0.26.

The total marginal effect for the base case specification of energy price is in between the total marginal effect for specification A and the total marginal effect for specification B. The estimated elasticities for all three specifications are similar, and are equal to −0.26 for both the base case and for specification B. Our results on the effects of energy price therefore appear robust to the energy price specification used.

Conclusion

In this article 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 effect on both margins. Higher energy prices affect crop selection decisions, crop acreage allocation decision, and farmers' demand for water. Higher energy prices decrease water use along both the intensive and extensive margins.

Our estimated total marginal effect, which sums the effects at the intensive and extensive margins, shows that a $1 increase in the energy price, which is approximately 13.6% of its mean value over the time period of our data set, would decrease water extraction by an individual farmer by 5.89 acre-feet per year, which is approximately 3.6% of the average amount pumped in a year by a farmer. The estimated elasticity of water extraction with respect to energy price is −0.26.

Our results suggest that energy prices do have an effect on groundwater extraction, causing water use to decrease along both the intensive and extensive margins. This finding is particularly important in the face of possible increases in energy prices in the future, which may cause farmers to respond by decreasing their water use. Our results also suggest that policies that reduce energy prices would cause groundwater extraction to increase, therefore posing a potential concern to conservationists who are worried about declining water table levels in many of the world's most productive agricultural basins that depend on groundwater.

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