Property Rights and Groundwater Management in the High Plains Aquifer

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Abstract

In western Kansas, the prior appropriation doctrine gives producers rights to extract groundwater for crop production. This property rights system may distort the incentive for rights-holders to optimize dynamically, leading to a deviation from the economically efficient extraction path. We develop an empirical model to test whether groundwater users faced with the prior appropriation doctrine are behaving in a manner consistent with a dynamic model of nonrenewable resource extraction, and apply it to data from western Kansas. We 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. We also find evidence that the original appropriations were allocated in a manner consistent with notions of allocative efficiency.

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1. Introduction

Groundwater users extract water under an institutional setting that governs their property rights to the groundwater and affects the constraints they face and the choices they make. Ideally, property rights should take into consideration the hydrological characteristics of the aquifer from which the groundwater is extracted.

If an aquifer receives little recharge, then the groundwater is essentially a nonrenewable resource. In this case, the economically efficient extraction path would consider the nonrenewable nature of the resource and manage the resource is a manner consistent with a Hotelling-like model of dynamic optimization (Hotelling, 1931). Institutions governing property rights to the groundwater of low-recharge aquifers should therefore take into consideration the need to manage the resource dynamically.

The purpose of this paper is to investigate how farmers manage groundwater over time and under an existing property rights regime. Specifically, our empirical analysis focuses on the portion of western Kansas that overlies the High Plains (Ogallala) Aquifer. This portion of the High Plains Aquifer receives very little recharge. Its social welfare maximizing extraction path can therefore be described by a Hotelling-like model (Hotelling, 1931). Kansas has used the doctrine of prior appropriation to govern the management of groundwater since 1945.

Hotelling (1931) argues that the socially optimal rate of extraction of a nonrenewable resource over time is achieved in a competitive market equilibrium, provided that the social discount rate equals the market interest rate and that there are no market failures such as externalities or incomplete property rights. The prior appropriation doctrine is an example of an incomplete property rights system, and thus may distort the incentive of a groundwater user to manage a resource dynamically, causing extraction to occur at a rate faster than is socially optimal.

We develop an empirical model to test whether groundwater users faced with the prior appropriation doctrine are behaving in a manner consistent with a dynamic model of nonrenewable resource extraction. In particular, do groundwater managers (individual farmers, in this case) consider the scarcity rent or shadow value of their resource when making extraction decisions? Or are they more myopic in their water extraction behavior, perhaps due to the incentives they face from the prior appropriation doctrine? This is one of the first studies to empirically test the hypotheses of the theoretical groundwater management literature.

We 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. Although producers are allotted a time-invariant maximum amount that they can extract each year, they still consider their remaining stock of water, pumping by nearby neighbors, and projections of future commodities prices when making crop choice and pumping decisions. Our results therefore provide evidence that farmers recognize the nonrenewable nature of the resource that they manage, even though their property rights do not.

We also examine the optimality of the Kansas water authorities' appropriated allocations of groundwater and find evidence that the original appropriations were allocated in a manner consistent with notions of allocative efficiency.

The balance of this paper proceeds as follows. We discuss institutions governing groundwater in Kansas in Section 2 and describe the High Plains Aquifer in Section 3. We present our theory model in Section 4, our empirical model in Section 5, and our data in Section 6. Section 7 presents our results. Section 8 concludes.

2. Institutions Governing Groundwater in Kansas

A variety of property rights doctrines and institutions governing groundwater have evolved in the western United States. Many more institutions, both formal and informal, are in place in other locations around the world. Table 1 lists the states that overlie the High Plains Aquifer and the property rights system in place to govern its extraction.

The absolute ownership doctrine, which is the groundwater rights doctrine in Texas, gives owners of land the absolute right to extract water from their parcels. The correlative rights doctrine, which is the groundwater rights doctrine in Nebraska and Oklahoma, relates a property right to a portion of the aquifer to the size of the land parcel owned.

The prior appropriation doctrine, which is the groundwater rights doctrine in Colorado, Kansas, New Mexico, South Dakota, and Wyoming, allots water rights based on historical use, with priority going to those who claimed their right first. Often, rights holders under the prior appropriation doctrine are allowed a maximum level of extraction per year (Sax and Abrams, 1986). Leonard and Libecap (2016) analyze the economic determinants and effects of prior appropriation water rights that were voluntarily implemented across a vast area of the US West, replacing common-law riparian water rights.

Our focus is on Kansas, a state that overlies a portion of the High Plains Aquifer. Kansas is the only state where a rich set of data on the recent history of groundwater extraction is available. Current water rights in Kansas follow the prior appropriation doctrine. Before 1945, Kansas applied the common law of absolute ownership doctrine to groundwater. Water rights were not quantified in any way (Peck, 2007). In 1945, following multiple conflicts between water users and several major water cases that reached the Kansas Supreme Court, the "Arid Region Doctrine of

Appropriation" was adopted, which permitted water extraction based on the principle of "first in time, first in right" (Peck, 1995).

The earliest appropriators of water maintain the first rights to continue to use water in times of shortage or conflict. The water right comes with an abandonment clause; if the water is not used for beneficial purposes for longer than the prescribed time period, then it is subject to revocation (Peck, 2003). To obtain a new water right, an application stating the location of the proposed point of diversion, the maximum flow rate, the quantity desired, the intended use, and the intended place of use must be submitted to and approved by the Department of Water Resources (*Kansas Handbook of Water Rights*, n.d.). Since 1945, Kansas has issued more than 40,000 groundwater appropriation permits (Peck, 1995).[2] The permits specify an amount of water that can be extracted each year and are constant over time.

Through the 1970s, the period of intensive agricultural development in Kansas, groundwater pumping permits were granted to nearly anyone who requested them. Some permits are as old as 1945, but the majority (about 75 percent) were allocated between 1963 and 1981.

In the early 1970s, it was recognized that Kansas's groundwater resources were being depleted at a rapid rate in some locations. By 2008, in parts of southwestern Kansas, the water table has declined by over 150 feet since predevelopment.[3] This area was the first to be intensively developed, and continues to have the highest average extraction per square mile (Wilson, Young and Buddemeier, 2002).

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[2] In the 2007 Census, there were 65,531 farms in all of Kansas, of which approximately 29,039 were located in regions that roughly overlie the aquifer (USDA, 2011).

[3] "Predevelopment" is defined as the water level in about 1960, when the first measurements were made.

In 1972, owing to concerns that the aquifer was over-appropriated, Kansas created five groundwater management districts (GMDs). The GMDs regulate well spacing and prohibit new water extraction within a designated radius of existing wells, which varies by GMD.

The adoption of the prior appropriation doctrine, together with the development of GMDs to regulate new appropriations of water rights, arguably eliminated uncontrolled entry and the resulting over-exploitation commonly associated with common property resources. Restricting water rights can reduce groundwater extraction in Kansas even when ex post the water rights are not binding (Li and Zhao, 2016). However, appropriation contracts distort the incentive to optimize dynamically over the life of the resource, because the farmer is essentially guaranteed his appropriated amount of water until the resource becomes so scarce that it is no longer economical to pump.

3. 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."

Increased access to the High Plains Aquifer increased agricultural land values and initially reduced the impact of droughts. Over time, however, land use adjusted toward high-value water-intensive crops and drought sensitivity increased (Hornbeck and Keskin, 2014). Similarly, measures taken by the state of Kansas to subsidize a shift toward more efficient irrigation systems led to perverse effect of increasing extraction through a shift in cropping patterns (Pfeiffer and Lin, 2014a).

The High Plains Aquifer (also known as known as the Ogallala Aquifer) underlies approximately 174,000 square miles. It is the principle source of groundwater in the Great Plains region of the United States. Although the High Plains Aquifer system is now known to include several other aquifer formations, the portion of the aquifer that underlies western Kansas pertains mainly to the High Plains Aquifer (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. 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).

Recharge to the Kansas portion of the High Plains aquifer is relatively 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 are alfalfa, corn, sorghum, soybean, and wheat (High Plains Regional Climate Center, 2014). 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.

4. Theory Model

To characterize the differences between myopic and dynamic decision-making, we present a theoretical model that contrasts the decisions of a myopic farmer with those of a dynamically optimizing farmer.

4.1. The hydrological system

Our model of the hydrological system follows that of Pfeiffer and Lin (2012). To capture the important characteristics of groundwater movement, while avoiding the complications of a sophisticated hydrological model, each farmer's land can be thought of as a "patch" that is connected to neighboring patches via a simplified hydrological model.

Although our model is a simplification of the true physical nature of groundwater flows, it has several advantages over the standard groundwater extraction model that assumes that an aquifer is like a bathtub. In the simple bathtub model, a decrease in the level of the aquifer caused by extraction by any individual is transmitted immediately and completely to all other users of the aquifer, and all users are homogeneous (Burt, 1964; Negri, 1989). In fact, aquifer systems do not adjust instantaneously to withdrawals, and the response can be complex and heterogeneous, even within a small geographic area (Heath, 1983; Brozovic, Sunding and Zilberman, 2002).

We assume that each farmer owns one patch $i \in \{1, ..., I\}$ that has one point of extraction, or well, on it. The change in groundwater stock s_i from one period to the next depends on the total amount of water w_i agent *i* is pumping, recharge, and net flow. The equation of motion, which is derived from simplified hydrological mass-balance equations (Freeze and Cherry, 1979), is given by:

$$s_{i,t+1} = s_{it} - w_{it} + g_{it}(w_{it}) + \sum_{j=1}^{I} \theta_{ji}(s_{1t},\dots,s_{It}) s_{jt} \ . \tag{1}$$

Recharge $g_{it}(w_{it})$ is a function of return flow (the proportion of the amount pumped that returns to the groundwater table) and precipitation, thus $0 \le \frac{\partial g_{it}}{\partial w_{it}} \le 1$.

The stock $s_{i,t+1}$ next period also depends on the net flow into *i*'s land that is caused by physical height gradients or other hydrological factors that determine how water flows within an aquifer. $\theta_{ij}(\cdot)$ is defined as the proportion of the water that starts in patch *i* and disperses to patch *j* by the next period, so $\sum_{j=1}^{I} \theta_{ji}(\cdot) s_{jt}$ is the net amount of water that flows into patch *i* from all other patches in the system. Groundwater flow is generally stock dependent; net flow is a function of the stocks of water in all the other patches $s_1,\dots,s_I$ and the more stock is in patch *i*, the less the net flow from other patches: $\frac{\partial \theta_{ji}}{\partial s_i} \le 0$. The net flow into patch *i* from patch *j* may also depend on the transmissivity of the material holding the water, the physical gradients between patches, and the distance between plots *i* and *j* (Brutsaert, 2005; Pfeiffer and Lin, 2012).

4.2. Myopic farmer

The optimization problem faced by a myopic farmer is:

$$\max_{w_{it}} \pi_{it} = R_{it}(w_{it}) - C^{w}(s_{it}) w_{it} \, , \tag{2}$$

where $R_{it}(w_{it})$ is the per-period revenue that can be generated by producing crops with extracted irrigation water w_{it}, assuming crops are chosen optimally to maximize revenue given extracted irrigation water w_{it}; and $C^{w}(s_{it})w_{it}$ is the cost of extracting water, which depends on the distance that the water must be pumped from the aquifer to the surface of the ground. The distance the water must be pumped depends on the stock of water s_{it}; as the stock decreases, pumping cost increases, or $\frac{\partial C^{w}(s_{it})}{\partial s_{it}} < 0$. The resource user would equate the marginal value product of water with the marginal cost of extraction to choose his level of extraction in each period:

$$\frac{\partial R_{it}}{\partial w_{it}} - C^{w}(s_{it}) = 0 \Rightarrow w_{it}^{*}. \qquad (3)$$

Notice that this individual's water demand is a function of marginal profits and marginal pumping costs.

4.3. Dynamically optimizing farmer

Groundwater management, even at the individual level, is generally modeled as a dynamic optimization problem. This is because marginal pumping costs are a function of the stock of groundwater, and that stock is affected by decisions the manager has made in the past. This would more precisely model a farmer's decision if an individual were granted a *total* amount of water (not an allocation per year) to manage as he sees fit; this would pertain to a more complete property rights system like the one described in Anderson, Burt and Fractor (1983).[4]

[4] Gisser (1983) notes that the addition of a guaranteed time period of depletion to a per year, groundwater allocation effectively defines a stock quota. Correlative rights define a stock that is proportional to the amount of land owned as long as there is no spatial movement of water. Absolute ownership similarly defines a stock if there is no spatial movement, but does not disallow free entry.

However, owing to the dependence of the stock $s_{i,t+1}$ next period on the stock of farmer *i*'s neighbors *j* via the proportion $\theta_{ji}(\cdot)$ of the water that starts in patch *j* and disperses to patch *i* by the next period, it is possible that a farmer considers the effect that his pumping has on future groundwater levels, both his own and that of his neighbors, and his extraction path would correspond to dynamic optimization. The individual dynamic optimizer may still not be making *socially* optimal decisions, however, if there is significant spatial movement of water between patches owned by different people (Provencher and Burt, 1993; Koundouri, 2004; Pfeiffer and Lin, 2012).

The optimization problem faced by an individual dynamically optimizing farmer is:

$$\max_{\{w_{it}\}_t} \sum_{t=0}^{\infty} \left(\frac{1}{1+r} \right)^t \left(R_{it}(w_{it}) - C^w(s_{it}) w_{it} \right), \tag{4}$$

subject to the equation of motion (1) and to the following transversality condition:

$$\lim_{t \to \infty} \left(\frac{1}{1+r} \right)^t \lambda_{it} s_{it} = 0 . \tag{5}$$

The decision of how much water to pump in the current period versus how much water to pump in future periods can be expressed using the following Bellman equation (Bellman, 1957):

$$V_{it}(s_{it}) = \max_{\{w_{it}\}_t} R_{it}(w_{it}) - C^w(s_{it}) w_{it} + \frac{1}{1+r} EV_{i,t+1}(s_{i,t+1}) , \tag{6}$$

subject to the equation of motion (1).

The first order conditions of the Bellman equation produce the Euler equation, which holds for a dynamic problem at all points in time. Taking the derivative of the value function $V_{it}(s_{it})$ with respect to the choice variable w_{it} and setting it equal to zero yields:

$$\frac{\partial R_{it}(w_{it})}{\partial w_{it}} - C^w(s_{it}) = \frac{1}{1+r} \left(1 - \frac{\partial g_{it}}{\partial w_{it}} \right) EV'_{i,t+1}(s_{i,t+1}) , \tag{7}$$

which can also be written as:

$$\frac{\partial R_{i,t-1}(w_{i,t-1})}{\partial w_{i,t-1}} - C^w(s_{i,t-1}) = \frac{1}{1+r}\left(1 - \frac{\partial g_{i,t-1}}{\partial w_{i,t-1}}\right) EV_{it}^{'}(s_{it})\,. \tag{8}$$

The derivative of the value function with respect to the state variable produces what is known as the Benveniste-Scheinkman condition (Benveniste and Scheinkman, 1979), giving the relationship of groundwater levels between time periods along the optimal extraction path:

$$V_{it}^{'}(s_{it}) = -\frac{\partial C^w(s_{it})}{\partial s_{it}} w_{it} + \frac{1}{1+r} EV_{i,t+1}^{'}(s_{i,t+1})\left(1 + \sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1t},\dots,s_{It})}{\partial s_{it}} s_{jt}\right). \tag{9}$$

By substituting equations (7) and (8) into equation (9), the following Euler equation is obtained:

$$\begin{aligned}
\frac{\partial R_{it}}{\partial w_{it}} - C^w(s_{it}) = &-\frac{1}{1+r}\left(1-g'\left(w_{it}\right)\right) E\left[\frac{\partial C^w(s_{i,t+1})}{\partial s_{i,t+1}}\right] w_{i,t+1} \\
&+ \frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right) E\left[\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right] \\
&+ \frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right) E\left[\left(\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}} - C^w(s_{i,t+1})\right) \sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1,t+1},\dots,s_{I,t+1})}{\partial s_{i,t+1}} s_{j,t+1}\right].
\end{aligned} \tag{10}$$

The Euler equation is the standard marginal condition for a resource problem; the decision maker will extract until the marginal revenue from pumping water is equal to the marginal cost plus the user cost of the resource. The user cost is the value to the user of leaving the marginal unit in the ground for future extraction. Dasgupta and Heal (1979) note that when the stock of a resource is very large, the user cost is small relative to the cost of extraction, and the resource is treated similarly to a conventional input. However, when the resource becomes more scarce, the user cost makes up a larger and larger component of the total "cost" of extraction.

The left-hand side of the Euler equation (10) can be interpreted as the marginal net benefits from consuming one additional unit of the resource in period *t*, while the right-hand side is what the user gives up in period $t+1$ by consuming that unit in *t*.

Costs are stock dependent, so costs decrease as groundwater stock increases and the first term on the right-hand side of the Euler equation (10) is positive:

$$-\frac{1}{1+r}\left(1-g'\left(w_{it}\right)\right)E\left[\frac{\partial C^{w}(s_{i,t+1})}{\partial s_{i,t+1}}\right]w_{i,t+1}>0. \tag{11}$$

By consuming an extra unit of groundwater in period *t*, the individual would have to bear the resulting increase in extraction cost in $t+1$. Because some of the extracted water returns to the aquifer as recharge, however, the increase in extraction cost is not as large as it would be if recharge did not occur.

By extracting the marginal unit in *t*, the individual would also give up the discounted marginal benefit from that unit in the next period, which is given by the second term on the right-hand side of the Euler equation (10), which is also positive:

$$\frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right)E\left[\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}}-C^{w}(s_{i,t+1})\right]>0. \tag{12}$$

Finally, we assume that flow between patches is stock dependent:

$$\frac{\partial \theta_{ji}(s_{1,t+1},\ldots,s_{I,t+1})}{\partial s_{i,t+1}}<0, \tag{13}$$

meaning that the opportunity cost of extracting one additional unit in period *t* is smaller resulting from the increase in in-flow resulting from the decrease in stock. The plot owner is balancing current profits with discounted future profits, the negative impact of stock reduction (through increased cost of pumping) and the fact that a smaller stock may induce transmission of water into his plot. Thus the third term on the right-hand side of the Euler equation (10) is negative and offsets the second term on the right-hand side:

$$\frac{1}{1+r}\left(\frac{1-g'(w_{it})}{1-g'(w_{i,t+1})}\right)E\left[\left(\frac{\partial R_{i,t+1}}{\partial w_{i,t+1}}-C^{w}(s_{i,t+1})\right)\sum_{j=1}^{I}\frac{\partial\theta_{ji}(s_{1,t+1},\ldots,s_{I,t+1})}{\partial s_{i,t+1}}s_{j,t+1}\right]<0\ . \qquad (14)$$

4.4. Comparing myopic and dynamic optimizing behavior

According to our theory model, we expect that certain variables should not affect a farmer's water pumping decision if the farmer is behaving myopically. We call these variables "dynamic" variables, because if they have an effect on the farmer's pumping decision, it would indicate that the farmer is behaving in a manner consistent with dynamic optimization. The "dynamic"' variables include the individual's total stock of water (the saturated thickness beneath his land), the amount of water pumped by neighbors, and future commodity price expectations. These are variables that affect the user cost of the resource.

If the saturated thickness beneath one's land is large, the resource constraint is less binding and the optimal extraction rate looks more like the solution to the myopic problem (Dasgupta and Heal, 1979). Thus, a larger saturated thickness should be associated with a higher extraction rate.

Anything that increases the gradient between patches will also increase present period pumping, including higher pumping by neighboring farmers (Pfeiffer and Lin, 2012).

Long-run expectations of future commodity prices will also affect the dynamic optimizer's decisions. If real prices are expected to increase in the future, a dynamic optimizer would pump less in the current period, saving his stock for times when commodity prices are high.

5. Empirical Model

A rather large literature exists that consists of empirical tests of the Hotelling Rule, which posits that resource managers, when making extraction decisions over time, consider the user cost of that resource, or the value of the resource left in the ground (see reviews in Livernois, 2008; Chermak and Patrick, 2001; Withagen, 1998). In general, the tests involve looking for price trends or trends in the estimated marginal user cost (marginal revenue minus marginal cost) that increase approximately at the rate of interest, the central tenant of the Hotelling Rule. However, these studies are plagued by a lack of data and inappropriate levels of data aggregation, as data are often proprietary, firms are few, or the data are simply nonexistent (Withagen, 1998).

As we do not have data on individual-level marginal revenue and costs, and as there is no price data for the groundwater in our data set, we instead use a reduced-form estimation procedure to empirically model the solution to the first order conditions of the model presented in Section 4. We can test the hypothesis that farmers make their extraction decisions myopically, without consideration of the resource's user cost, a hypothesis that corresponds with the definition of property rights in Kansas. Rejection of this hypothesis would lend support to a dynamic model of groundwater management.

The assumption that groundwater users optimize over time is standard in much of the groundwater management literature, despite the very different property rights systems governing groundwater extraction. Here we develop an econometric model of a farmer's irrigation water pumping decision and test this assumption, specifically, that they consider the effect of pumping on future availability and extraction costs.

We examine the factors affecting 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 $n_{ict}*$ to each crop *c* by each farmer *i* in each time period *t* can be estimated as:

$$q_{ict} = f(D_{it}, p_{ct}, x_{it}, e_t, z_{it-1}),\ c = \textit{alfalfa, corn, sorghum, soybeans, wheat} \tag{15}$$

$$n_{ict}* = g(D_{it}, p_{ct}, x_{it}, e_t, IMR_c),\ c = \textit{alfalfa, corn, sorghum, soybeans, wheat}, \tag{16}$$

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 $q_{ict} > 0$; D_{it} are variables that would impact a farmer's decision if he optimized dynamically, including saturated thickness, the amount pumped in the previous period by neighbors, and a 10-year forecast of future commodities prices; p_{ct} are crop price futures (for delivery at harvest); x_{it} is a vector of plot-level variables including irrigation technology, average precipitation, average evapotranspiration, recharge, slope, soil quality, quantity of water authorized for extraction, field size,[5] and depth to groundwater; e_t are energy prices; 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.

The system of equations corresponding to (15) and (16) can be estimated using Lee's generalization of Amemiya's two-step estimator to a simultaneous equation model (Lee, 1990).

[5] All else equal, we expect the acres allocated to the chosen crop to be greater when the field size is greater.

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 (15) 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 (16). They are estimated as a simultaneous system of equations to exploit the information contained in the cross-equation correlations.[6]

The coefficients of interest are the coefficients on the dynamic variables D_{it} in the selectivity-corrected cropland allocation models in equation (16). If the dynamic variables D_{it} have a significant effect on the farmer's pumping decision then this would be an indication that the farmer is behaving in a manner consistent with dynamic optimization.

Parameters in selection models are estimated with more precision if some regressors in the selection equation can be excluded from the outcome equation, although the exclusion restriction is not necessary for identification (Wooldridge, 2002). To estimate the coefficients on the dynamic variables D_{it} in the crop acreage equations (16) with more precision, we exclude the lagged crop choice variables z_{it-1} from the crop acreage equations (16) but not the crop choice equations (15). 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. As we show below, our results are robust to whether the lagged crop choice variables are excluded from the

[6] 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).

crop acreage allocation regressions and also robust to whether lagged crop acreage is added to both the crop choice and the crop acreage allocation regressions.

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

$$w_{it} = h(D_{it}, n_{ict}*, x_{it}, e_t), \tag{17}$$

where w_{it} is the amount of water extracted by farmer i in year t. In the water demand equation (17), we include number of acres planted to each crop and the number of acres planted to each crop squared.[7]

This model explains groundwater pumping as a function of those variables that should be included in a producer's marginal pumping decision. These regressions can be used to empirically determine whether a farmer is making choices in a myopic or a dynamic framework. If the farmer is behaving myopically, then his decision will depend on the variables in the myopic farmer's first order condition in equation (3): crop prices, extraction costs, the number of acres he is irrigating, and precipitation, as well as some control variables like irrigation technology and soil quality. If he is behaving dynamically, then his marginal pumping will also depend on the dynamic variables explaining the shadow value of water in the Euler equation: saturated thickness, the amount pumped in the previous period by neighbors, and a 10-year forecast of future commodities prices.

Conditional on the many covariates we control for, including the plot-level variables x_{it}, the dynamic variables D_{it} we use – saturated thickness, the amount pumped in the previous period by neighbors, and a 10-year forecast of future commodities prices – are exogenous to the farmer's crop choice, crop acreage allocation, and water demand decisions.

[7] Schoengold, Sunding and Moreno (2006) develop and apply a reduced-form econometric model of a conditional water demand function, explaining water use at a particular location as a function of land allocation, relative prices, and other factors such as environmental characteristics.

As seen in the equation of motion (1), the stock of water $s_{i,t+1}$ in period $t+1$ is affected by the water pumping w_{it} in the previous period, t, but not the water pumping in the current period. Thus, saturated thickness, which is a measure of the individual's total stock of water, is exogenous to current crop choice, crop acreage, and water pumping decisions.

The amount pumped in the previous period by neighbors is exogenous to current crop choice, crop acreage, and water pumping decisions because we use the neighbors' pumping in the previous period, so the neighbors' pumping has already occurred.

The 10-year forecast of future commodities prices is exogenous to the current crop choice and crop acreage decisions because crops are unlikely to be stored for 10 years, so the crops chosen this year are unlikely to affect crop prices 10 years later. The 10-year forecast of future commodities prices is exogenous to an individual farmer's current water pumping decision because one single farmer's water pumping decision is unlikely to affect crop prices, particularly those 10 years later.

The total marginal effect of each of the *j* dynamic variables D_{jit} in D_{it} is the sum of the effect along the intensive margin from the water demand equation (17) and the effects along the extensive margin from the selectivity-corrected cropland allocation models in equation (16) (Moore, Gollehon and Carey, 1994):[8]

$$\frac{dw}{dD_j} = \frac{\partial w}{\partial D_j} + \sum_c \frac{\partial w}{\partial n_c^*} \frac{\partial n_c^*}{\partial D_j} . \tag{18}$$

[8] 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.

In addition to analyzing whether dynamic variables affect farmer's irrigation water pumping decision on the intensive and extensive margins, we also examine the optimality of the Kansas water authorities' appropriated allocations of groundwater.

The state of Kansas made a series of decisions concerning the appropriation of groundwater from 1945 to the present. Some blame the state for decreasing water table levels, claiming that the state over-allocated groundwater in some areas, perhaps even before good information on the stock of water existed. Groundwater allocations, once made, are legally difficult to adjust, so individuals would have to act against their self-interest to bring total extraction toward the social optimum if the state had allocated too much. If the original appropriations allocated by Kansas water authorities are actually optimal, however, at least in the sense of allocative efficiency where marginal values are equated over space, then it would be optimal for producers not to deviate from their allocated amount of water except to adjust to changing stock (saturated thickness) amounts.

To test whether the appropriated allocations were optimal, we regress the individual specific appropriation allocations on a set of physical variables including precipitation, recharge, saturated thickness, and soil quality to determine whether hydrology and physical properties were considered when the appropriation amounts were allocated. We expect the effect of farm size to be positive, precipitation to be negative, and recharge and pre-development saturated thickness to be positive. We also expect the coefficient on the soil quality variables of irrigated capability class and slope to be negative, because higher numbers indicate poorer quality soil and where more runoff would occur, respectively. Available water capacity should also be negative because a higher value indicates that the soil holds more water naturally.

Finally, we include as a regressor the year that the prior appropriation contract was allocated. There are two competing hypotheses that we wish to examine with this variable. One is that the coefficient on the year when the appropriation was given is insignificant. Optimally, the allocations should have been determined by locational characteristics, not the year in which the allocation was made. A significantly negative estimate may indicate that higher allocations were given when Kansas was first beginning the appropriation system. Regulators may have appropriated too much groundwater early in the game and when they were trying to develop western Kansas into a leading agricultural region, perhaps before it was known that the aquifer was depletable (Wilson, Young and Buddemeier, 2002). Under Kansas law, a reduction in appropriated quantity would amount to an unconstitutional taking of property and so cannot be done without compensation (Peck, 2003). Over-appropriation in the early years of the doctrine would be difficult to correct.

The competing prediction is that the coefficient on year of the appropriation contract *should* be negative. If groundwater extraction contracts were allocated consistently with the Ricardian model of land allocation (Ricardo, 1891), the first and largest groundwater permits would have been allocated to the highest quality land that was most suitable to irrigated agriculture. As more and more marginal lands were put into irrigated production, the groundwater allocations to those parcels would have grown optimally smaller.

6. Data

We use panel data from over 20,000 groundwater-irrigated fields in western Kansas over the period 1996 to 2005. 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.

County-level natural gas production data used to determine which counties had natural gas production are 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 Climate Group (2014).

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. Farmers 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. Energy prices for our base case specification are on average $7.33 per million btu.

7. Results

The base case results of the selectivity-corrected crop acreage models in equation (16) are presented in Table 3. The base case results for the water demand conditional on crop choice equation (17) are presented in Table 4.

We are mainly interested in the total marginal effects, calculated using equation (18) of the dynamic variables D_{it}: saturated thickness, the amount pumped in the previous period by neighbors, and a 10-year forecast of future commodity prices. Table 5 presents the total intensive margin, the total extensive margin, and the total marginal effect of each of the dynamic variables, for the base case specification as well as four alternative specifications, calculated using only the coefficients from the selectivity-corrected crop acreage models in Table 3 and the water demand conditional on crop choice model in Table 4 that are significant at a 5% level.

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. Following Pfeiffer and Lin (2014b), in our base case specification, we use the natural gas price as the energy price for farmers in counties with natural gas production, which represent 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 energy price alternative 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 energy price alternative specification B, we use the natural gas price as the energy price for all farmers.

We also run a specification in which the lagged crop choice variables are not excluded from the crop acreage allocation regressions and also another specification in which lagged crop acreage is added to both the crop choice and the crop acreage allocation regressions.

We find that our results in Table 5 on the total intensive margin, the total extensive margin, and the total marginal effect of each of the dynamic variables are robust across the different specifications.

The marginal effects of the dynamic variables give insight into whether farmers consider the value of the resource left in the ground. It is expected that the estimated coefficients on saturated thickness and water pumped by neighbors will be positive if farmers are optimizing dynamically. We find that the saturated thickness and the number of acre-feet pumped by neighbors within a one-mile radius both have the expected positive signs. This is evidence that farmers do consider the effects that they and their neighbors have on their own future availability.

The total intensive margin, the total extensive margin, and the total marginal effect of saturated thickness are all positive for all specifications. An increase in saturated thickness by 1 foot increases the irrigation water pumped by an individual farmer by 0.215 acre-feet in the base case, with a range of 0.196 to 0.240 acre-feet across all specifications, yielding an elasticity in the range 0.151 to 0.185. The fact that farmers respond positively to the saturated thickness of the aquifer beneath their land, controlling for the amount that was allocated by the government, is an indication that the farmers are behaving in a manner consistent with dynamic optimization.

The total intensive margin, the total extensive margin, and the total marginal effect of the amount pumped by neighbors in the previous period are all positive for all specifications. An increase in the quantity of water used by neighbors in a 1-mile radius in the previous period by 1 acre-feet increases the irrigation water pumped by an individual farmer by 0.027 acre-feet in the base case, with a range of 0.021 to 0.027 acre-feet across all specifications, yielding an elasticity in the range 0.056 to 0.073. The positive total marginal effect of water pumped by neighbors means that, while farmers behave in accordance with a dynamic model, their extraction rate is *greater* than it would be under a myopic model because of inefficiencies due to spatial externalities (Pfeiffer and Lin, 2012). Essentially, farmers may worry about not capturing the full benefits from their water allocation due to movement of the water beneath the land and thus extract more at the margin than they otherwise would (Provencher and Burt, 1993).[9]

Figure 1 shows that commodity prices, while being subject to shocks, have steadily declined over the last 60 years. If farmers have rational expectations about the future real price of commodities, it is dynamically optimal for producers to extract more in the current periods when real prices are relatively high.

The total intensive margin, the total extensive margin, and the total marginal effect of the 10-year forecast of the real acreage-weighted price of commodities are all negative for all specifications. An increase in the 10-year forecast of the real acreage-weighted price of commodities by 1 dollar per bushel decreases the irrigation water pumped by an individual farmer by 48.87 acre-feet in the base case, with a range of 38.58 to 64.51 acre-feet across all specifications, yielding an elasticity in the range -1.060 to -0.552. The negative total marginal effect of the price forecast indicates that producers are behaving in a manner that is consistent with dynamic optimization and rational expectations. If future real prices were expected to increase, water would be conserved for future use.

[9] Pfeiffer and Lin (2012) analyze the effects of neighbors' pumping on a farmer's extraction decision in detail, and use the neighbors' permitted water allocation as an instrument for their pumping to address the endogeneity of neighbors' decisions.

The total marginal effects of the dynamic variables provide evidence that groundwater extractors consider the future value of their groundwater resource when making their irrigation water pumping decisions. 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.

In addition to analyzing whether dynamic variables affect farmer's irrigation water pumping decision on the intensive and extensive margins, we also examine the optimality of the Kansas water authorities' appropriated allocations of groundwater. To test whether the appropriated allocations were optimal, we regress the individual specific appropriation allocations on a set of physical variables including precipitation, recharge, saturated thickness, and soil quality, as well as on the year that the prior appropriation contract was allocated.

The results in Table 6 show that groundwater allocations in Kansas were made in a manner consistent with predictions resulting from dynamic optimality. While we cannot determine if the relative magnitudes of the coefficients are optimal, the signs of all of the coefficients are as expected, so we fail to reject the hypothesis of optimal permit allocation. Allocations are larger to larger farms and where there is more stock and recharge; allocations are smaller where there is more precipitation and where soil quality is lower.

We also find that the coefficient on year of appropriation is negative. This could indicate misallocation if larger contracts were given out early, without regard to soil characteristics; it could also indicate optimality if the highest quality plots were given the largest groundwater allocations (Ricardo, 1891). To determine which of these two hypotheses explain the negative coefficient on year of appropriation, we plot average measures of soil quality against the year of appropriation. If higher quality plots were brought into production first and thus allocated larger quantities of groundwater, the relationship between year and average slope and irrigated capability class will be upward sloping (higher numbers indicate poorer quality soil), and the relationship between year and average available water capacity should be downward sloping (higher quality soils hold more water).

As seen in Figure 2, average slope and irrigated capability class increase with year of appropriation and average available water capacity decreases with year of appropriation.[10] Thus, it appears that higher quality plots were brought into production first and thus allocated larger quantities of groundwater. Our results therefore suggest that groundwater extraction contracts were allocated consistently with the Ricardian model of land allocation (Ricardo, 1891).

8. Conclusion

This paper is one of the first studies to empirically test hypotheses from the groundwater management literature. We come to the somewhat surprising conclusion that despite the "static" definition of groundwater property rights in western Kansas, an area governed by the prior appropriation doctrine of groundwater law, individual agricultural producers extract water consistent with a dynamic model of resource extraction.

Although producers are allotted a time-invariant maximum amount that they can extract each year, they still consider the effects of their remaining stock, pumping by nearby neighbors that may affect their stock in the future, and projections of future commodities prices when making crop choice and pumping decisions. The effect of each variable is small, but this is consistent with findings that the user cost of a natural resource has only a small effect on its management; bounded rationality, short- and medium-term price fluctuations, and technical change tend to dominate the

[10] Regressions of soil quality on year of appropriation were statistically significant.

decision-making process (Livernois, 2008). Our findings support the use of a dynamic model for modeling agricultural groundwater extractors.

Our results show that even though the law allows, and perhaps even encourages, groundwater owners to and extract the maximum appropriated amount each year, they do not. The reason for this lies in the amount of understanding that agricultural producers have about the physical properties of the aquifer from which they are drawing. In a system where the groundwater is finite, producers are not actually assured of their appropriative right in perpetuity. The right would be lost if there is insufficient groundwater. If producers are concerned with future profits, they will treat the groundwater as a nonrenewable resource. Thus, our empirical results suggest that agricultural producers recognize that using less water this year means more is available next year.

These findings are significant because they show that the physical realities of a resource can swamp the incentives given by institutions and property rights. The property rights system that governs the High Plains Aquifer does not recognize that the depletable resource cannot be mined indefinitely. However, agricultural producers in western Kansas do recognize the physical attributes of their asset. They make groundwater extraction decisions accordingly. Efforts to change the long term extraction path should therefore be cognizant of a dynamic model of resource extraction.

In addition, groundwater allocations should be made in accordance with the characteristics of the land to which it will be applied and aquifer from which it is extracted. Our findings suggest that Kansas water authorities have appropriated groundwater extraction permits in an allocatively efficient manner since the prior appropriation doctrine was adopted in 1945.

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Table 1: Property Rights Doctrines Governing the High Plains Aquifer

State	Groundwater rights doctrine
Colorado	Prior appropriation
Kansas	Prior appropriation
Nebraska	Correlative rights
New Mexico	Prior appropriation
Oklahoma	Correlative rights
South Dakota	Prior appropriation
Texas	Absolute ownership
Wyoming	Prior appropriation

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	1491.48
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	4586.97
Depth to groundwater (ft)	154,619	125.27	74.48	4.77	355.87
Individual level variables					
Saturated thickness of the aquifer (ft)	17,960	126.27	104.86	0.00	553.64
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
Recharge (in)	17,960	1.25	1.13	0.30	6.00
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
Quantity authorized for extraction (af)	17,960	283.81	206.90	0.00	2400
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 energy price alternative 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 energy price alternative specification B, we use the natural gas price as the energy price for all farmers.

Table 3: Selectivity-Corrected Results for Crop Acreage Allocation

	Dependent variable is number of acres allocated to:				
	Alfalfa	Corn	Sorghum	Soybeans	Wheat
Dynamic Variables					
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 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)
10-year forecast of the real acreage-weighted price of commodities ($/bu)	0.781	-8.826***	-1.948	-23.23***	1.797
	(2.952)	(1.508)	(4.016)	(2.485)	(2.342)
Controls					
Alfalfa price ($/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)
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)
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)
Recharge (in)	-1.662	-4.023***	-4.197***	-0.660	-1.955**
	(1.003)	(0.367)	(0.823)	(0.389)	(0.749)
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)
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)
Depth to groundwater (ft)	-0.069***	-0.033***	-0.001	-0.019	0.024*
	(0.014)	(0.007)	(0.016)	(0.012)	(0.009)
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)
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	154619	154619	154619	154619	154619

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

Table 4: Results for Water Demand Conditional on Crop Choice

Dependent variable is quantity of irrigation water pumped (acre-feet)	
Dynamic Variables	
Saturated thickness of the aquifer (ft)	0.159***
	(0.003)
Quantity of water used by neighbors in 1 mile radius in *t*-1 (af)	0.0194***
	(0.001)
10-year forecast of the real acreage-weighted price of commodities ($/bu)	-40.69***
	(1.038)
Controls	
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)
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)
Average yearly precipitation, 1971-2000 (in)	1.271***
	(0.167)
Average evapotranspiration (in)	0.990**
	(0.373)
Recharge (in)	-3.914***
	(0.425)

Slope (% of distance)	2.423***
	(0.282)
Irrigated Capability Class = 1 (Dummy)	-12.04***
	(0.525)
Quantity authorized for extraction (af)	0.062***
	(0.001)
Field size (ac)	0.336***
	(0.003)
Depth to groundwater (ft)	0.290***
	(0.008)
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)
Left land fallow or planted with a non-irrigated plot (dummy)	-134.8***
	(0.865)
Constant	85.01***
	(21.35)
Observations	154619
R-squared	0.53

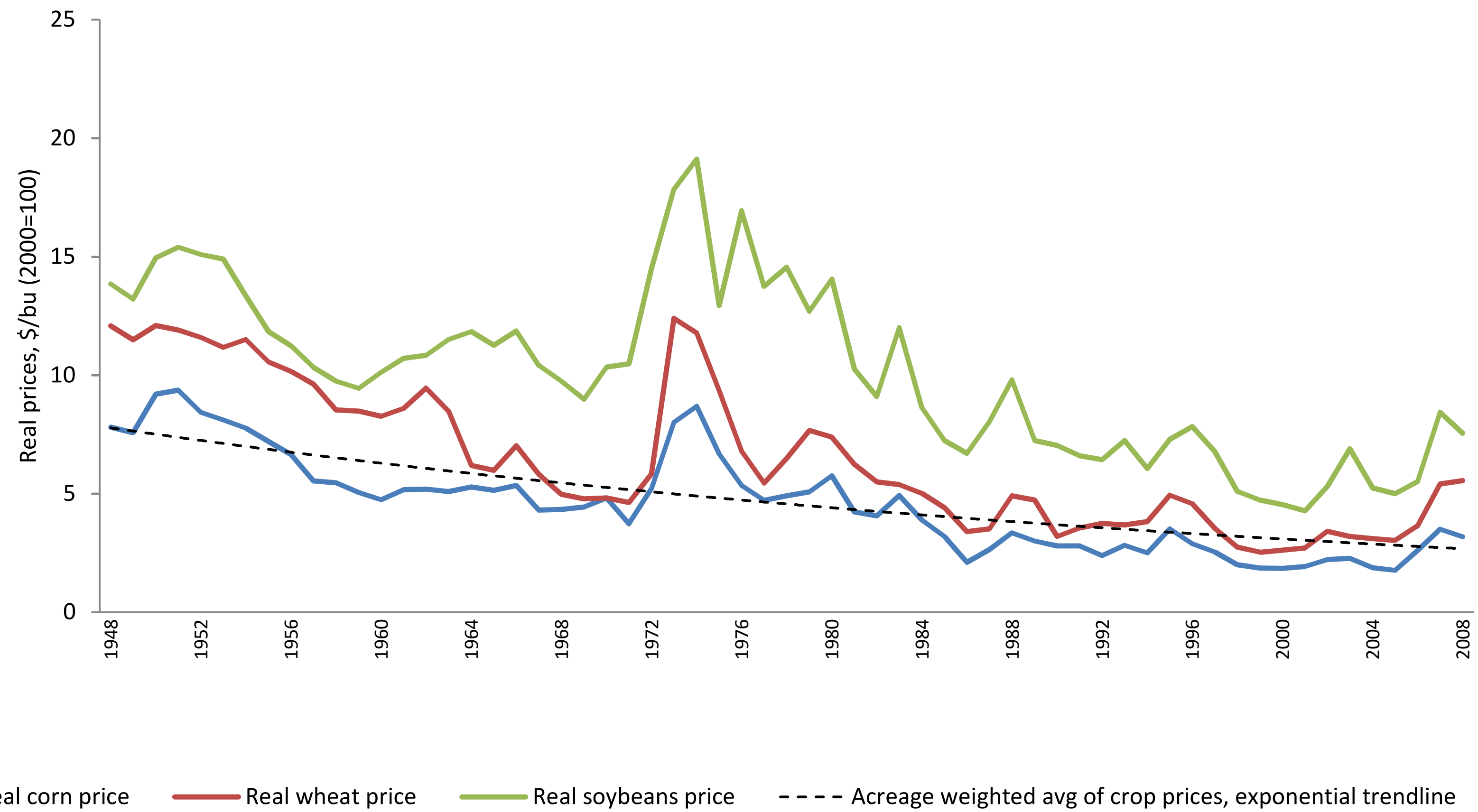
Notes: Standard errors in parentheses. For the energy price, we use the natural gas price as the energy price for farmers in counties with natural gas production and the diesel price as the energy price for all other farmers. Significance codes: * 5% level, ** 1% level, and *** 0.1% level.

Table 5. Total Marginal Effects

	Base case	Energy price alternative A	Energy price alternative B	Do not exclude lagged crop choice	Lagged acres
Saturated thickness of the aquifer (ft)					
Total intensive margin $\left(\frac{\partial w}{\partial D_j}\right)$	0.159	0.167	0.186	0.159	0.159
Total extensive margin $\left(\sum_c \frac{\partial w}{\partial n_c{*}} \frac{\partial n_c{*}}{\partial D_j}\right)$	0.056	0.054	0.054	0.037	0.038
TOTAL MARGINAL EFFECT $\left(\frac{dw}{dD_j} = \frac{\partial w}{\partial D_j} + \sum_c \frac{\partial w}{\partial n_c{*}} \frac{\partial n_c{*}}{\partial D_j}\right)$	**0.215**	0.221	0.240	0.196	0.197
Quantity of water used by neighbors in 1 mile radius in t-1 (af)					
Total intensive margin $\left(\frac{\partial w}{\partial D_j}\right)$	0.0194	0.0197	0.0186	0.0194	0.0194
Total extensive margin $\left(\sum_c \frac{\partial w}{\partial n_c{*}} \frac{\partial n_c{*}}{\partial D_j}\right)$	0.008	0.006	0.007	0.002	0.007
TOTAL MARGINAL EFFECT $\left(\frac{dw}{dD_j} = \frac{\partial w}{\partial D_j} + \sum_c \frac{\partial w}{\partial n_c{*}} \frac{\partial n_c{*}}{\partial D_j}\right)$	**0.027**	0.026	0.025	0.021	0.027
10-year forecast of the real acreage-weighted price of commodities ($/bu)					
Total intensive margin $\left(\frac{\partial w}{\partial D_j}\right)$	-40.69	-31.63	-63.28	-40.69	-40.69
Total extensive margin $\left(\sum_c \frac{\partial w}{\partial n_c{*}} \frac{\partial n_c{*}}{\partial D_j}\right)$	-8.182	-1.948	-1.229	-6.068	-1.633
TOTAL MARGINAL EFFECT $\left(\frac{dw}{dD_j} = \frac{\partial w}{\partial D_j} + \sum_c \frac{\partial w}{\partial n_c{*}} \frac{\partial n_c{*}}{\partial D_j}\right)$	**-48.872**	-38.578	-64.509	-46.758	-42.323

Notes: Only coefficients that are significant at a 5% level are used in the calculation. The effects of crop acreage on water use are evaluated at mean crop acreage. 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 the specification with energy price alternative 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 the specification with energy price alternative B, we use the natural gas price as the energy price for all farmers. We also run a specification in which the lagged crop choice variables are not excluded from the crop acreage allocation regressions and also another specification in which lagged crop acreage is added to both the crop choice and the crop acreage allocation regressions.

Figure 1. Real prices of agricultural commodities, 1948-2008



Note: Prices are marketing-year average prices from the USDA, deflated using the Bureau of Economic Analysis GDP implicit price deflator (2000 = 100).

Table 6. Optimality of Appropriated Quantity

Dependent variable is quantity of water authorized for extraction	
Predevelopment saturated thickness of the aquifer (ft)	0.3511 ***
	(0.020)
Farm size (acres)	0.0198 ***
	(0.004)
Average yearly precipitation, 1971-2000 (in)	-19.9102 ***
	(1.863)
Annual recharge (in)	49.1253 ***
	(7.671)
Hydraulic conductivity (ft/day)	0.2881
	(0.300)
Year of prior appropriation contract	-3.8049 ***
	(0.246)
Slope (% of distance)	-16.996 ***
	(2.645)
Irrigated Capability Class = 1 (Dummy)	Omitted group
Irrigated Capability Class = 2 (Dummy)	-18.005 ***
	(5.447)
Irrigated Capability Class = 3-6 (Dummy)	-32.327 ***
	(9.594)
Available water capacity	-187.397
	(114.385)
Constant	8153.12 ***
	(483.782)
Observations	6427
R-squared	0.2433

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

Figure 2. Relationship between the year of the appropriation contract and measures of soil quality