Property Rights and Groundwater Management in the High Plains Aquifer[1]

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Abstract

Groundwater is an important natural resource that needs to be managed dynamically. Ideally, institutions governing property rights to the groundwater of low-recharge aquifers should not discourage or disincentivize groundwater users from dynamic management. We develop an empirical model to examine whether agricultural groundwater users faced with prior appropriation property rights to groundwater in western Kansas exhibit dynamic, forward-looking behavior consistent with dynamic management. We find that although farmers are allotted a time-invariant maximum amount of groundwater that they can extract each year, they still behave in a manner consistent with dynamic management. Their groundwater extraction decisions are not significantly affected by the quantity they are authorized to extract, but are instead affected by expected future crop prices, expected future energy prices, and groundwater extraction by neighbors. Our results provide evidence that farmers manage their groundwater resource dynamically, even if their property rights do not necessarily encourage or incentivize them to do so.

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1. Introduction

In both teaching and research, Greg spoke passionately on the importance of understanding economic behavior and economic incentives when trying to formulate public policy to correct for the over-harvest of renewable resources and the pollution of air, water, and land.

- Faculty memorial statement about Gregory L. Poe
(Conrad, Boisvert and Lee, 2017)

Groundwater is an important natural resource that needs to be managed dynamically. The idea behind dynamic management is that groundwater users need to account for the future when making current decisions. In particular, if they wish to benefit from the opportunity to use groundwater in the future, groundwater users may wish to extract less groundwater today in order to save more for tomorrow (Gisser and Sanchez, 1980; Feinerman and Knapp, 1983; Sears and Lin Lawell, 2019).

There are two main reasons why groundwater needs to be managed dynamically, particularly if the aquifer receives very little recharge. First, groundwater extraction today decreases the amount of groundwater available tomorrow. Aquifers are recharged through the percolation of rain and snow (Hartwick and Olewiler, 1998). If an aquifer receives very little recharge, then it is at least partially a nonrenewable resource and therefore should be managed dynamically and carefully for long-term sustainable use in a manner consistent with a Hotelling-like model of dynamic optimization (Hotelling, 1931). A second reason that groundwater needs to be managed dynamically is that groundwater extraction today increases the cost of extraction tomorrow because the removal of water today increases the "lift-height" needed to lift the remaining stock to the surface tomorrow, thereby increasing the pumping cost tomorrow (Timmins, 2002). Thus, because the extraction of groundwater both decreases the future amount of groundwater available and increases the future cost of extracting groundwater, groundwater users should manage groundwater dynamically and consider the future when making their current groundwater extraction decisions (Sears, Lim and Lin Lawell, 2018; Sears and Lin Lawell, 2019; Sears, Bertone Oehninger, Lim, and Lin Lawell, 2020).

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, institutions governing property rights to the groundwater of low-recharge aquifers should not discourage or disincentivize groundwater users from managing the resource dynamically.

The purpose of this paper is to investigate how agricultural groundwater users[2] manage groundwater over time 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. Water rights holders under the prior appropriation doctrine are allowed a maximum level of extraction per year (Sax and Abrams, 1986).

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. By granting permits that specify a time-invariant maximum amount of groundwater that can be extracted each year, however, the prior appropriation doctrine is an example of an incomplete property rights system that may discourage or disincentivize dynamic management, causing extraction to occur at a rate faster than is dynamically optimal. In contrast, a well-defined property rights system would define exclusive rights to the stock rather than to a flow from the asset (Lueck, 1995). Under a more complete property rights system, therefore, an individual groundwater user would be granted a total amount of water (rather than a maximum amount each year) to manage dynamically over time as the user sees fit (Anderson, Burt and Fractor, 1983).[3]

We develop an empirical model to examine whether agricultural groundwater users faced with the prior appropriation doctrine exhibit dynamic, forward-looking behavior consistent with dynamic management. In particular, do individual farmers consider the marginal user cost (or

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[2] Throughout this paper, we use the terms "agricultural groundwater user", "farmer", "grower", and "agricultural producer" interchangeably.

[3] The dynamically optimal decisions of an individual groundwater user may not necessarily be socially optimal, however, if there is significant spatial movement of water between patches owned by different groundwater users (Provencher and Burt, 1993; Brozović, Sunding and Zilberman, 2002; Koundouri, 2004; Saak and Peterson, 2007; Brozović, Sunding and Zilberman, 2010; Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears and Lin Lawell, 2019; Sears, Lim and Lin Lawell, 2019; Sears, Lin Lawell and Lim, 2020). A complete property rights system would enable groundwater users to internalize any spatial externalities as well, for example by defining exclusive rights to the groundwater stock in the entire aquifer.

shadow price) of their resource when making extraction decisions? Or are they more myopic in their water extraction behavior, perhaps because the prior appropriation doctrine does not encourage or incentivize dynamic management? This is one of the first studies to our knowledge to empirically examine the hypotheses of the theoretical groundwater management literature.

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 marginal user cost of that resource, or the value of the resource left in the ground (Withagen, 1998; Chermak and Patrick, 2001; Lin and Wagner, 2007; Livernois, 2008; Slade and Thille, 2009; Zhang and Lin Lawell, 2017; Lin Lawell, 2020). 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. These studies are plagued by a lack of data and inappropriate levels of data aggregation, however, 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 develop an empirical model of the factors affecting groundwater extraction in order to examine whether groundwater users faced with the prior appropriation doctrine exhibit dynamic, forward-looking behavior consistent with dynamic management.

According to our theory model, we expect that certain variables – including expected future crop prices, expected future energy prices, and groundwater extraction by neighbors – would affect a farmer's water pumping decision if the farmer were behaving dynamically, but would not affect a farmer's water pumping decision if the farmer were behaving myopically, whether or not the farmer was constrained by a maximum allowable amount in each year owing to a prior appropriation property rights system. Thus, to empirically examine whether groundwater users faced with the prior appropriation doctrine exhibit dynamic, forward-looking behavior consistent with dynamic management, we examine whether expected future crop prices, expected future energy prices, and/or groundwater extraction by neighbors affect their groundwater extraction decisions. Our empirical analysis builds on recent work by Anderson, Kellogg and Salant (2018) that uses futures prices to measure future expected prices in a modified Hotelling model for oil production.

We find that although the prior appropriation doctrine may not necessarily encourage dynamic management, farmers make groundwater extraction decisions that are dynamic and forward-looking. Although agricultural producers are allotted a time-invariant maximum amount that they can extract each year, they still consider expected future crop prices, expected future energy prices, and groundwater extraction by neighbors when making groundwater extraction decisions. Our results therefore provide evidence that growers manage their groundwater resource dynamically, even if their property rights do not necessarily encourage or incentivize them to do so.

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

2. Institutional and Hydrological Setting

2.1. Groundwater Property Rights 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.[4] Table A1 in the Appendix lists the states that overlie the High Plains Aquifer and the property rights system in place to govern its extraction.[5]

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. In theory, the prior appropriation doctrine uses first possession to establish permanent rights to a stock. In practice, however, when the costs to enforcing a claim to the asset are prohibitive, first possession results in the rule of capture whereby rights are defined over flows rather than the stock (Lueck, 1995). Thus, in many cases, rights holders under the prior appropriation doctrine are allowed a maximum level of extraction

[4] The previous empirical literature on groundwater property rights includes empirical analyses of groundwater rights in California (Ayres, Meng and Plantinga, 2019; Sears, Lin Lawell and Walter, 2020) and in Idaho (Browne, 2018).

[5] 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.

per year (Sax and Abrams, 1986).[6] Leonard and Libecap (2019) analyze the economic determinants and effects of prior appropriation water rights that were voluntarily implemented across a vast area of the western United States, 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. Kansas adopted the prior appropriation doctrine in 1945, following multiple conflicts between water users and several major water cases that reached the Kansas Supreme Court (Peck, 1995; Peck 2007). Rights holders under the prior appropriation doctrine are allowed a maximum level of extraction per year (Sax and Abrams, 1986).

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 Division of Water Resources in the Kansas Department of Agriculture (Kansas Handbook of Water Rights, n.d.). Since 1945, Kansas has issued more than 40,000 groundwater appropriation permits (Peck, 1995).[7] Some permits are as old as 1945, but the majority (about 75 percent) were allocated between 1963 and 1981.

Each permit specifies a maximum amount of water that can be extracted each year and is constant over time. 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 the water right is subject to revocation (Peck, 2003). In particular, a water right is considered abandoned after five successive years of non-use without due and sufficient cause (Kansas Water Appropriation Act, n.d.).

The adoption of the prior appropriation doctrine in Kansas, together with the development of groundwater management districts (GMDs) to regulate new appropriations of water rights, arguably eliminated uncontrolled entry in the Kansas portion of the High Plains Aquifer and the resulting over-exploitation commonly associated with common property resources. Li and Zhao (2018) find that restricting water rights in Kansas will reduce groundwater extraction in the long

[6] Gisser (1983) notes that supplementing an annual groundwater allocation with a guaranteed time period of depletion effectively transforms the prior appropriation rights to 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.

[7] 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).

run. Similarly, Tsvetanov and Earnhardt (2020) find that the retirement of water rights in High Priority Areas in Kansas substantially reduces groundwater extraction.

As documented in more detail in Section 5.2 below, however, during the time period of our analysis (1996 to 2012), farmers frequently extracted more than the maximum amount of water they were authorized to extract. These frequent violations suggest that the prior appropriation doctrine was not always enforced. For instance, when water users who violated their water right were issued a "warning" or notice of their first offense from the state, many regarded this "warning" as a free year to overpump (Bickel, 2015).

Nevertheless, there are several features of the prior appropriation rights system in Kansas that may discourage groundwater users from dynamic management. First, the appropriation contracts specify a time-invariant maximum amount of groundwater that can be extracted each year (Kansas Water Appropriation Act, n.d.). Thus, a farmer with a water right will still have the right to extract the same time-invariant maximum amount of groundwater each year in the future, whether he extracts the maximum amount this year or less, thereby diminishing his incentive to manage the resource dynamically and extract less today in order to save more for tomorrow. Second, a water right is considered abandoned after five successive years of non-use without due and sufficient cause (Kansas Water Appropriation Act, n.d.); there is thus an incentive to continue to extract water, perhaps more than what would otherwise be dynamically optimal to extract, in order to maintain the water right. Third, authorized quantities cannot be increased, but can be decreased as a condition for granting a change (Kansas Water Appropriation Act, n.d.; Griggs, 2017), which again provides an incentive to continue to extract water, perhaps more than what would otherwise be dynamically optimal to extract, in order to maintain the water right.

2.2. The High Plains Aquifer in Kansas

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

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 primary 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.

Energy is an important input needed to extract groundwater for irrigation in the High Plains Aquifer (Pfeiffer and Lin, 2014c). 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. 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).

3. 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. We do not impose a constraint that a farmer's groundwater extraction cannot exceed the maximum allowable amount in each year owing to a prior appropriation property rights system because, as documented in more detail in Section 5.2 below, during the time period of our analysis (1996 to 2012), farmers frequently extracted more than the maximum amount of water they were authorized to extract, which suggests that the prior appropriation doctrine was not always enforced.

3.1. Hydrological Model

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 reality, however, aquifer systems do not adjust instantaneously to withdrawals, and the response can be complex and heterogeneous, even within a small geographic area (Heath, 1983; Brozović, 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 farmer *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:

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

where 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, and thus $0 \le \frac{dg_{it}(w_{it})}{dw_{it}} \le 1$.

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 $s_1,...,s_I$ 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).

3.2. Myopic Farmer

The static optimization problem faced by a myopic farmer *i* is given by:

$$\max_{w_{it}} \pi_{it} = R(w_{it}, p_{it}) - C(w_{it}, s_{it}, e_{it}) \ , \tag{2}$$

where p_{it} is a vector of crop prices faced by farmer *i* at time *t*; $R(w_{it}, p_{it})$ is the per-period revenue that can be generated by producing crops with extracted irrigation water w_{it} at crop prices p_{it}, assuming crops are chosen optimally to maximize revenue given extracted irrigation water w_{it}; and $C(w_{it}, s_{it}, e_{it})$ is the cost of extracting water. The cost of extracting water depends on the distance that the water must be pumped from the aquifer to the surface of the ground, and on the price of the energy e_{it} needed to power the pump. The distance the water must be pumped depends on the stock of water s_{it}. As the stock s_{it} decreases, both pumping cost and marginal pumping cost increase: $\frac{\partial C(w_{it}, s_{it}, e_{it})}{\partial s_{it}} < 0$ and $\frac{\partial^2 C(w_{it}, s_{it}, e_{it})}{\partial w_{it} \partial s_{it}} < 0$. Similarly, as the energy price e_{it} increases, both pumping cost and marginal pumping cost increase: $\frac{\partial C(w_{it}, s_{it}, e_{it})}{\partial e_{it}} < 0$ and $\frac{\partial^2 C(w_{it}, s_{it}, e_{it})}{\partial w_{it} \partial e_{it}} < 0$.

The solution to the myopic farmer's static optimization problem in (2) would be to choose the level of groundwater extraction in each period to equate the marginal value product of water that period with the marginal cost of extraction that period:

$$\frac{\partial R(w_{it}, p_{it})}{\partial w_{it}} - \frac{\partial C(w_{it}, s_{it}, e_{it})}{\partial w_{it}} = 0 \Rightarrow w_{it}^* . \tag{3}$$

3.3. Dynamically Optimizing Farmer

Optimal groundwater management, even at the individual level, requires dynamic optimization. There are two main reasons why groundwater needs to be managed dynamically, particularly if the aquifer receives very little recharge. First, groundwater extraction today decreases the amount of groundwater available tomorrow. Second, groundwater extraction today increases the cost of extraction tomorrow because the removal of water today increases the "lift-height" needed to lift the remaining stock to the surface tomorrow, thereby increasing the pumping cost tomorrow (Timmins, 2002). Thus, because the extraction of groundwater both decreases the future amount of groundwater available and increases the future cost of extracting groundwater, groundwater users should manage groundwater dynamically and consider the future when making their current groundwater extraction decisions (Sears, Lim and Lin Lawell, 2018; Sears and Lin Lawell, 2019; Sears, Bertone Oehninger, Lim, and Lin Lawell, 2020).[8]

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[8] 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, the dynamically optimal decisions of an individual groundwater user may not necessarily be socially optimal if there is significant spatial movement of water between patches owned by different groundwater users (Provencher and Burt, 1993; Brozović, Sunding and Zilberman, 2002; Koundouri, 2004; Saak and Peterson, 2007; Brozović, Sunding and Zilberman, 2010; Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears and Lin Lawell, 2019; Sears, Lim and Lin Lawell, 2019; Sears, Lin Lawell and Lim, 2020).

To determine the dynamically optimal water extraction policy, we characterize and solve the optimization problem faced by an individual dynamically optimizing farmer who does not face any incentives or constraints from any prior appropriation doctrine. The optimization problem faced by an individual dynamically optimizing farmer is given by:

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

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):

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

subject to the equation of motion (1). From the equation of motion (1) for groundwater stock, the groundwater stock $s_{i,t+1}$ for farmer *i* at time $t+1$ depends on the groundwater stock s_{jt} of each of *i*'s neighbors *j* at time *t*, which in turn depends on the groundwater extraction $w_{j,t-1}$ of each of *i*'s neighbors *j* at time $t-1$.[9]

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:

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

which can also be written as:

$$\frac{\partial R(w_{i,t-1}, p_{i,t-1})}{\partial w_{i,t-1}} - \frac{\partial C(w_{i,t-1}, s_{i,t-1}, e_{i,t-1})}{\partial w_{i,t-1}} = \frac{1}{1+r} \left(1 - \frac{\partial g_{i,t-1}(w_{i,t-1})}{\partial w_{i,t-1}} \right) EV'_{it}(s_{it}) . \tag{8}$$

[9] As the primary focus of our paper is on dynamic management rather than spatial considerations, we assume that each farmer *i* takes the groundwater extraction $w_{j,t-1}$ of each of *i*'s neighbors *j* at time $t-1$ as given. This enables us to characterize the dynamic management problem as the dynamic optimization problem faced by each individual farmer, rather than as a dynamic game among multiple farmers. Sears, Lim and Lin Lawell (2019) present a dynamic game framework for analyzing spatial groundwater management, characterizing the Markov perfect equilibrium resulting from non-cooperative behavior, and comparing it with the socially optimal coordinated solution.

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:

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

where $s_{-it} \equiv (s_{1t}, ...s_{i-1,t}, s_{i+1,t}, ..., s_{It})$ is the vector of stocks s_{jt} of all of *i*'s neighbors *j*.

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

$$\frac{\partial R(w_{it}, p_{it})}{\partial w_{it}} - \frac{\partial C(w_{it}, s_{it}, e_{it})}{\partial w_{it}} = \mu_{it}, \qquad (10)$$

where the marginal user cost μ_{it} is given by:

$$\begin{aligned}
\mu_{it} = & \\
& -\frac{1}{1+r}\left(1 - g_{it}{'}(w_{it})\right) E\left[\frac{\partial C(w_{i,t+1}, s_{i,t+1}, e_{i,t+1})}{\partial s_{i,t+1}}\right] \\
& + \frac{1}{1+r} E\left[\left(\frac{1 - g_{it}{'}(w_{it})}{1 - g_{i,t+1}{'}(w_{i,t+1})}\right)\left(\frac{\partial R(w_{i,t+1}, p_{i,t+1})}{\partial w_{i,t+1}} - \frac{\partial C(w_{i,t+1}, s_{i,t+1}, e_{i,t+1})}{\partial w_{i,t+1}}\right)\right] \qquad (11) \\
& + \frac{1}{1+r} E\left[\left(\frac{1 - g_{it}{'}(w_{it})}{1 - g_{i,t+1}{'}(w_{i,t+1})}\right)\left(\frac{\partial R(w_{i,t+1}, p_{i,t+1})}{\partial w_{i,t+1}} - \frac{\partial C(w_{i,t+1}, s_{i,t+1}, e_{i,t+1})}{\partial w_{i,t+1}}\right)\sum_{j=1}^{I} \frac{\partial \theta_{ji}(s_{1,t+1}, ..., s_{I,t+1})}{\partial s_{i,t+1}} s_{j,t+1}\right],
\end{aligned}$$

The Euler equation (10) is the standard dynamic optimality condition for a resource problem: the decision maker will extract until the marginal revenue from pumping water is equal to the marginal extraction cost plus the marginal user cost of the resource. 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 marginal user cost on the right-hand side is what the user gives up in period $t+1$ by consuming that unit in *t*.

Also known as the shadow price, the marginal user cost in equation (11) 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 marginal user cost is small relative to the marginal cost of extraction, and the resource is treated similarly to a conventional input. However, when the resource becomes more scarce, the marginal user cost makes up a larger and larger component of the total marginal "cost" of extraction.

Costs are stock dependent, so costs decrease as groundwater stock increases and the first term in the marginal user cost in equation (11) is positive:

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

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 in the marginal user cost in equation (11), which is also positive:

$$\frac{1}{1+r}E\left[\left(\frac{1-g_{it}\,'(w_{it})}{1-g_{i,t+1}\,'(w_{i,t+1})}\right)\left(\frac{\partial R(w_{i,t+1},p_{i,t+1})}{\partial w_{i,t+1}}-\frac{\partial C(w_{i,t+1},s_{i,t+1},e_{i,t+1})}{\partial w_{i,t+1}}\right)\right]>0\,. \tag{13}$$

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

$$\frac{\partial\theta_{ji}(s_{1,t+1},\ldots,s_{I,t+1})}{\partial s_{i,t+1}}<0\,, \tag{14}$$

meaning that the opportunity cost of extracting one additional unit in period *t* is smaller owing to the increase in in-flow resulting from the decrease in stock. A dynamically optimizing farmer would balance 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 in the marginal user cost in equation (11) is negative and offsets the second term on in the marginal user cost in equation (11):

$$\frac{1}{1+r}E\left[\left(\frac{1-g_{it}\,'(w_{it})}{1-g_{i,t+1}\,'(w_{i,t+1})}\right)\left(\frac{\partial R(w_{i,t+1},p_{i,t+1})}{\partial w_{i,t+1}}-\frac{\partial C(w_{i,t+1},s_{i,t+1},e_{i,t+1})}{\partial w_{i,t+1}}\right)\sum_{j=1}^{I}\frac{\partial\theta_{ji}(s_{1,t+1},\ldots,s_{I,t+1})}{\partial s_{i,t+1}}s_{j,t+1}\right]<0\,. \tag{15}$$

3.4. Myopic vs. Dynamic Behavior

According to our theory model, we expect that certain variables would affect a farmer's water pumping decision if the farmer were behaving dynamically, but would not affect a farmer's water pumping decision if the farmer were behaving myopically, whether or not the farmer was constrained by a maximum allowable amount in each year owing to a prior appropriation property rights system. 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 management. In particular, comparing the optimality condition for a myopic farmer in equation (3) with the Euler equation (10) for a dynamically optimizing farmer, the "dynamic" variables are variables that affect the marginal user cost μ_{it} in equation (11) but not the current marginal revenue from pumping water or the current marginal cost of extraction.

One "dynamic" variable that affects the marginal user cost μ_{it} but not the current marginal revenue from pumping water or the current marginal cost of extraction is the farmer's expected future crop prices $p_{i,t+1}$. Long-run expectations of future crop prices would affect a farmer's water pumping decision if the farmer were behaving dynamically, but would not affect a farmer's water pumping decision if the farmer were behaving myopically. Higher expected future crop prices would lead a dynamic optimizer to pump less in the current period, instead saving more of his stock for the future when future expected crop prices are higher. Thus, if the farmer is behaving dynamically, we would expect that expected future crop prices for crops farmers expects to plant in the future would have a negative effect on current groundwater extraction w_{it}.

A second "dynamic" variable that affects the marginal user cost μ_{it} but not the current marginal revenue from pumping water or the current marginal cost of extraction is the farmer's expected future energy prices $e_{i,t+1}$. Long-run expectations of future energy prices would affect a farmer's water pumping decision if the farmer were behaving dynamically, but would not affect a farmer's water pumping decision if the farmer were behaving myopically. Lower expected future energy prices would lead a dynamic optimizer to pump less in the current period, instead saving more of his stock for the future when future expected energy prices are lower. Thus, if the farmer is behaving dynamically, we would expect that expected future energy prices for sources of energy the farmer expects to use in the future would have a positive effect on current groundwater extraction w_{it}.

A third "dynamic" variable that affects the marginal user cost μ_{it} but not the current marginal revenue from pumping water or the current marginal cost of extraction is the groundwater extraction by neighbors. From the equation of motion (1) for groundwater stock, the groundwater stock $s_{i,t+1}$ for farmer *i* at time $t+1$ depends on the groundwater stock s_{jt} of each of *i*'s neighbors *j* at time *t*, which in turn depends on the groundwater extraction $w_{j,t-1}$ of each of *i*'s neighbors *j* at time $t-1$. Water extraction by neighbors would affect a farmer's water pumping decision if the farmer were behaving dynamically, but would not affect a farmer's water pumping decision if the farmer were behaving myopically. Higher water extraction by neighbors would lead a dynamic optimizer to pump more in the current period (Pfeiffer and Lin, 2012). Thus, if the farmer is behaving dynamically, we would expect that groundwater extraction by neighbors would have a positive effect on current groundwater extraction w_{it}.

Although a significant positive effect of extraction by neighbors is consistent with dynamic, forward-looking behavior on the part of farmers, an increase in groundwater extraction in response to neighbor extraction may not be socially optimal (Pfeiffer and Lin, 2012). In particular, 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, the dynamically optimal decisions of an individual groundwater user may not necessarily be socially optimal if there is significant spatial movement of water between patches owned by different groundwater users (Provencher and Burt, 1993; Brozović, Sunding and Zilberman, 2002; Koundouri, 2004; Saak and Peterson, 2007; Brozović, Sunding and Zilberman, 2010; Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears and Lin Lawell, 2019; Sears, Lim and Lin Lawell, 2019; Sears, Lin Lawell and Lim, 2020).

Thus, while a negative effect of expected future crop prices and a positive effect of expected future energy prices on groundwater extraction may be consistent with both dynamic groundwater management on the part of an individual farmer and socially optimal groundwater management, a positive effect of extraction by neighbors may be consistent with dynamic groundwater management on the part of an individual farmer, but not with socially optimal groundwater management.

We do not impose a constraint that a farmer's groundwater extraction cannot exceed the maximum allowable amount in each year owing to a prior appropriation property rights system because, as documented in more detail in Section 5.2 below, during the time period of our analysis (1996 to 2012), farmers frequently extracted more than the maximum amount of water they were authorized to extract. These frequent violations suggest that the prior appropriation doctrine was not always enforced. Nevertheless, we expect that our dynamic variables would affect a farmer's water pumping decision if the farmer were behaving dynamically, but would not affect a farmer's water pumping decision if the farmer were behaving myopically, whether or not the farmer was constrained by a maximum allowable amount in each year owing to a prior appropriation property rights system.

4. Empirical Model

4.1. Dynamic Variables

According to our theory model, we expect that certain variables – including expected future crop prices, expected future energy prices, and groundwater extraction by neighbors – would affect a farmer's water pumping decision if the farmer were behaving dynamically, but would not affect a farmer's water pumping decision if the farmer were behaving myopically, whether or not the farmer was constrained by a maximum allowable amount in each year owing to a prior appropriation property rights system. Thus, to empirically examine whether groundwater users faced with the prior appropriation doctrine are behaving in a dynamic, forward-looking manner consistent with dynamic management, we examine whether these "dynamic" variables – expected future crop prices, expected future energy prices, and groundwater extraction by neighbors – affect their groundwater extraction decisions.

As explained in more detail in our theory model, if the farmer is behaving dynamically, we would expect that expected future crop prices for crops farmers expects to plant in the future would have a negative effect on current groundwater extraction, that expected future energy prices for sources of energy the farmer expects to use in the future would have a positive effect on current groundwater extraction, and that groundwater extraction by neighbors would have a positive effect on current groundwater extraction. In addition, as explained in more detail in our theory model, while a negative effect of expected future crop prices and a positive effect of expected future energy prices on groundwater extraction may be consistent with both dynamic groundwater management on the part of an individual farmer and socially optimal groundwater management, a positive effect of extraction by neighbors may be consistent with dynamic groundwater management on the part of an individual farmer, but not with socially optimal groundwater management.

We conduct a falsification test by also including the expected future crop prices of two crops that are not grown in Kansas as regressors in our empirical model: cocoa and coffee. We do not expect that the expected future crop prices of crops that are not grown in Kansas would affect groundwater use decisions of farmers in Kansas, even if they were behaving in a dynamic, forward-looking manner consistent with dynamic management.

4.2. Groundwater Extraction

Building on previous empirical models of water demand (Schoengold, Sunding and Moreno, 2006; Hendricks and Peterson, 2012), our fixed effects regression model for groundwater extraction is given by:

$$w_{it} = h(D_{it}, n_{it}, x_{it}, \alpha_i, t), \tag{16}$$

where w_{it} is the amount of water extracted by farmer *i* in year *t*; D_{it} are the dynamic variables, including expected future crop prices, expected future energy prices, and groundwater extraction by neighbors; $n_{it} = \{n_{ict}, n_{ict}{}^2 \mid c \in \{alfalfa,\ corn,\ sorghum,\ soybeans,\ wheat\}\}$ are the crop acreage variables, including the number of acres n_{ict} planted to each crop *c* and the number of acres planted to each crop squared; x_{it} are the controls, including the quantity authorized for extraction, hydrological and field characteristics (evapotranspiration, recharge, slope, soil quality, soil moisture, field size, depth to groundwater,[10] saturated thickness), irrigation technology, crop prices (alfalfa price, corn price, sorghum price, soybean price, and wheat price) from the previous year,[11] energy prices (diesel price, electricity price, and natural gas price), and weather (annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity); α_i are grower fixed effects; and *t* is a time trend.

[10] As seen in our groundwater stock equation of motion in equation (1), groundwater extraction affects future, but not current, groundwater stock. Thus, depth to groundwater (our measure of groundwater stock) is not endogenous to groundwater extraction.

[11] We use previous-year crop prices instead of current-year crop prices for three reasons. First, crop prices at the end of the current season are endogenous to groundwater extraction decisions made during the season. Second, since this year's crop prices are not known for certainty until the end of the season, we assume farmers' best guess for this year's crop prices is last year's crop prices. Third, when we use current-year crop prices instead of previous-year crop prices, we get the wrong sign on crop prices: the significant coefficients on crop prices are negative instead of positive. We also try using the current year's crop prices instead of the previous year's crop prices as controls, and then instrumenting for the current year's crop prices using the previous year's crop prices as instrumental variables to address the endogeneity of current-year crop prices. Our results for the dynamic variables are robust to whether we use current-year crop prices (instrumented for by previous-year crop prices) or previous-year crop prices as our controls for crop prices.

The grower fixed effects α_i control for unobservable grower characteristics such the number years of experience in farming. The time trend t controls for unobservable trends that affect all fields over time. We are unable to include year fixed effects because some of our dynamic variables, including expected future crop prices and expected future energy prices, and some of our controls, including crop prices, are common to all fields in a given year. We use robust standard errors.

We use water extraction intensity (in acre-feet of water per acre) as our dependent variable w_{it}. In an alternative specification, we use water extraction (in acre-feet) instead of water extraction intensity (in acre-feet of water per acre) as our dependent variable. We also run a regression using the difference between water extracted and the quantity authorized for extraction as the dependent variable, and a regression using a dummy for water extraction being equal to the quantity authorized for extraction as the dependent variable.

For robustness, we try using 9-year, 8-year, and 7-year projections instead of 10-year projections for our expected future crop and energy prices.

We try an instrumental variable (IV) fixed effects specification in we use the lagged quantity authorized for extraction by neighbors as an instrument for neighbors' lagged extraction instead of as a dynamic variable, to address the potential endogeneity of neighbors' lagged extraction. We also try using the current year's crop prices instead of the previous year's crop prices as controls, and then instrumenting for the current year's crop prices using the previous year's crop prices to address the endogeneity of current-year crop prices.

Our empirical model of groundwater extraction explains groundwater extraction as a function of those variables that should be included in a farmer'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), including crop prices, extraction costs, the number of acres he is irrigating, current stock (as measured by saturated thickness), and precipitation, as well as some control variables such as irrigation technology and soil quality. If the farmer is behaving myopically, but is constrained by the prior appropriation doctrine, his decision will additionally depend on the quantity of water authorized for extraction. If the farmer is behaving dynamically, then his marginal pumping will also depend on the dynamic variables explaining the marginal user cost of water in equation (11), including expected future crop prices, expected future energy prices, and groundwater extraction by neighbors.

Conditional on the many covariates we control for, including the plot-level variables x_{it}, the dynamic variables D_{it} we use – expected future crop prices, expected future energy prices, and lagged groundwater extraction by neighbors – are exogenous to the farmer's water demand decisions. Expected future crop prices and expected future energy prices are exogenous to an individual farmer's current water pumping decision because one single farmer's water pumping decision is unlikely to affect expected future crop prices or expected future energy prices, particularly those 10 years later. We mitigate concerns about endogeneity of groundwater extraction by neighbors by using their lagged values. The quantity authorized for extraction by neighbors within a 1-mile radius at time $t-1$ is exogenous to a farmer's water demand decisions because it is pre-determined. As mentioned above, we also try an instrumental variable (IV) fixed effects specification in we use the lagged quantity authorized for extraction by neighbors as an instrument for neighbors' lagged extraction instead of as a dynamic variable, to address the potential endogeneity of neighbors' lagged extraction.

4.3. Total Marginal Effect

We also estimate an econometric model of a farmer's irrigation water pumping decision that accounts for both the extensive margin and the intensive margin. The intensive margin of the groundwater extraction decision is the farmer's groundwater extraction holding crop acreage constant, as given by our empirical model for groundwater extraction in equation (16) above. The extensive margin of the groundwater extraction decision is the crop acreage allocation decision.

For the extensive margin, since the dependent variables (the number of acres planted to each crop) are left-censored at zero, we estimate the acreage n_{ict} allocated to each crop *c* by each farmer *i* in each time period *t* using the following set of random effects tobit regressions:

$$n_{ict} = g(D_{it}, x_{it}, z_{it-1}, \alpha_i, t),\ c = \textit{alfalfa, corn, sorghum, soybeans, wheat}, \qquad (17)$$

where n_{ict} is the number of acres planted to crop *c*; D_{it} are the dynamic variables, including expected future crop prices, expected future energy prices, and groundwater extraction by neighbors; x_{it} are the controls, including the quantity authorized for extraction, hydrological and field characteristics (evapotranspiration, recharge, slope, soil quality, soil moisture, field size,[12] depth to groundwater, saturated thickness), irrigation technology, crop prices (alfalfa price, corn price, sorghum price, soybean price, and wheat price) from the previous year,[13] energy prices (diesel price, electricity price, and natural gas price), and weather (annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity); z_{it-1} is a vector of lagged dummy variables for each crop (alfalfa, corn, sorghum, soybeans, and wheat), indicating if that crop was planted in the previous season to account for crop rotation patterns (Hendricks, Smith and Sumner, 2014); α_i are grower random effects; and t is a time trend.

Conditional on the many covariates we control for, including the plot-level variables x_{it}, the dynamic variables D_{it} we use – expected future crop prices, expected future energy prices, and groundwater extraction by neighbors – are exogenous to the farmer's crop acreage decisions. Expected future crop prices and expected future energy prices are exogenous to an individual farmer's current water pumping decision because one single farmer's water pumping decision is unlikely to affect expected future crop prices or expected future energy prices, particularly those 10 years later. We mitigate concerns about endogeneity of groundwater extraction by neighbors by using their lagged values. The quantity authorized for extraction by neighbors within a 1-mile radius at time $t-1$ is exogenous to a farmer's water demand decisions because it is pre-determined.

Following the empirical models of total marginal effects in Moore, Gollehon and Carey, (1994) and Pfeiffer and Lin (2014c), we calculate the total marginal effect of each of the dynamic variables D_{it} as the sum of the effect along the intensive margin from the groundwater extraction model in equation (16) and the effects along the extensive margin from the crop acreage allocation models in equation (17):

[12] All else equal, we expect the acres allocated to the chosen crop to be greater when the field size is greater. We use crop acreage rather than fraction of field planted to the crop as our dependent variable since our groundwater extraction regressions model groundwater extraction conditional on crop acreage, and since doing so best enables us to calculate and interpret the intensive and extensive margins and total marginal effect.

[13] We use previous-year crop prices instead of current-year crop prices for two reasons. First, crop prices at the end of the current season are endogenous to crop acreage decisions made at the beginning of the season. Second, since crop prices are not known for certainty until the end of the season, we assume farmers' best guess for this year's crop prices is last year's crop prices.

$$\frac{dw}{dD} = \frac{\partial w}{\partial D} + \sum_c \frac{\partial w}{\partial n_c} \frac{\partial n_c}{\partial D}. \tag{18}$$

We calculate the standard errors for the total intensive margin, the total extensive margin, and the total marginal effect using the Delta Method (DeGroot, 1986).

5. Data

5.1. Panel Data Set

For our empirical analysis, we have constructed a detailed panel data set of annual data for over 29,000 groundwater-irrigated fields in western Kansas from 1996 to 2012. We build on the data used in previous empirical analyses of groundwater in western Kansas (Pfeiffer and Lin, 2009; Pfeiffer and Lin, 2010; Pfeiffer and Lin, 2012; Pfeiffer and Lin, 2014a; Pfeiffer and Lin, 2014b; Pfeiffer and Lin, 2014c; Lin and Pfeiffer, 2015; Lin Lawell, 2016), which spanned 10 years between 1996 and 2005, and have extended the data set to cover the years 1996 to 2012.

Groundwater extraction data at the “point of diversion” level (usually a single well that irrigates a single field) was collected from the Water Information Management and Analysis System (WIMAS), which is maintained by the Kansas Department of Agriculture, Division of Water Resources. The data set includes spatially referenced pumping data at the source (well or pump) level on water rights, water extraction, crop choice, field characteristics, and irrigation technology for all irrigation wells in Kansas. Although there may be more than one point of diversion on what a producer considers a “field”, we assume for the analysis, following Pfeiffer and Lin (2014a) and Pfeiffer and Lin (2014c), that one point of diversion irrigates one field. We use only those grower-year observations for which the grower was authorized to extract a positive amount of water that year. Specific data related to wells’ characteristics (for example depth) was obtained from the Water Well Completion Records (WWC5) Database, also created by the Kansas Geological Survey.

For soil quality, we use the irrigated capability class, which 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. Following the work of Ortiz-Bobea et al. (2019), we control for soil moisture. Soil moisture data on the soil moisture content in the 0-10 cm layer was obtained from NASA’s NLDAS-2 (North American Land Data Assimilation System), the same source used by Ortiz-Bobea et al. (2019).

Crop prices for alfalfa and sorghum are from the USDA – ERS Feed Grains Database. For alfalfa price, we use the yearly average price for "alfalfa hay" received by farmers, averaged from May one year to April the following year. For sorghum price, we use the cash prices for "No. 2 yellow, Kansas City, MO" at principal markets, averaged over January to March.

Crop prices for corn, soybeans, and wheat are from quandl.com. For corn price, we use the average of daily corn future prices, averaged over January to March, for a contract that expires in September. For soybean price, we use the average of daily soybean future prices, averaged over January to March, for a contract that expires in September. For wheat price, we use the average of daily wheat future prices, averaged over January to March, for a contract that expires in September.

Energy prices are from the Energy Information Administration (EIA) for Kansas. For diesel price, we use the annual price of diesel for the Midwest. For electricity price, we use the annual price of commercial electricity for Kansas. For natural gas price, we use the annual price of commercial natural gas for Kansas.

Weather data on temperature, precipitation, and humidity was obtained from the High Plains Regional Climate Center (HPRCC), which contains information from the Automated Weather Data Network; and the National Weather Service and Cooperative Observer Network. The furthest the closest weather station is to any field is 93.65 miles. For each field, for each weather variable (temperature, precipitation, and humidity), we calculate a weighted average using all the stations within 93.65 miles (the furthest the closest weather station is to any field) of that field so that the data from each station within 93.65 miles of that field is weighted inversely proportional to its distance to the field.[14]

We obtain projections for future crop prices for corn, sorghum, soybeans, and wheat from the USDA Economics, Statistics and Market Information System (ESMIS). For our base case, we use 10-year projections; for robustness, we use 9-year projections, 8-year projections, and 7-year projections as well. We were unfortunately unable to find projections for future crop prices for alfalfa.

[14] An alternative to inverse distance weighting is to average each weather variable over all the stations within 93.65 miles (the furthest the closest weather station is to any field) of that field. We find that the weather variables calculated by these two methods are highly correlated: the correlation between the weather variables obtained from our technique of inverse distance weighting and the weather variables calculated by averaging over the close stations is over 0.971 for all weather variables. Thus, using averages instead of inverse distance weighting for the weather variables is unlikely to change our results by much.

We obtain projections for future energy prices for natural gas, electricity, and diesel from the Energy Information Administration (EIA) Annual Energy Outlook. For our base case, we use 10-year projections; for robustness, we use 9-year projections, 8-year projections, and 7-year projections as well.

We construct two variables related to a farmer's neighbors. One variable is the quantity of water extracted by neighbors within a 1-mile radius at time $t-1$, summed over all neighbors within a 1-mile radius at time $t-1$. The second variable is the quantity authorized for extraction by neighbors within a 1-mile radius at time $t-1$, summed over all neighbors within a 1-mile radius at time $t-1$.[15]

We obtain projections for future prices for coffee and cocoa from Quandl.com. Futures prices for Coffee and Cocoa are available for 2 years in the future. For cocoa, we use the 2-year projection of cocoa price from the Continuous Contract CC6. For coffee, we use the 2-year projection of the Coffee Arabica price from the Continuous Contract KC6. We use continuous contract #6, the furthest month available in the future. We use continuous contracts because individual futures contracts trade for very short periods of time, and are hence unsuitable for long-horizon analysis. Continuous futures contracts solve this problem by chaining together a series of individual futures contracts, to provide a long-term price history that is suitable for trading, behavioral, and strategy analysis (Quandl, 2019).

Summary statistics for the variables used in our base-case empirical analysis are presented in Table 1. The average quantity of water extracted per grower per year is 172.38 acre-feet. The average annual quantity authorized for extraction is 290.12 acre-feet.

Figure A1 in the Appendix plots total groundwater extraction over time. For each year, total groundwater extraction is calculated by summing groundwater extraction over all growers that were authorized to extract a positive amount of water that year.

Figure A2a in the Appendix presents time series plots of the expected future crop prices. Figure A2b in the Appendix presents time series plots of the expected future energy prices. Figure

[15] We include extraction by neighbors and the quantity authorized for extraction by neighbors instead of the groundwater stock of neighbors (for example, as proxied by the depth to groundwater of neighbors) in our empirical model since previous extraction by neighbors and the quantity authorized for extraction by neighbors are more likely to be observable to a farmer than is the neighbors' groundwater stock. In previous empirical work on spatial externalities, Pfeiffer and Lin (2012) similarly examine the effects of extraction by neighbors rather than the effects of neighbors' groundwater stock.

A2c in the Appendix presents time series plots of the expected future crop prices of two crops that are not grown in Kansas, cocoa and coffee, that we use for our falsification test.

Summary statistics for the 9-year projections, 8-year projections, and 7-year projections for future crop prices and future energy prices that we use for robustness are in Table A2 in the Appendix.

5.2. Actual vs. Authorized Water Extraction

We first compare farmers' actual groundwater extraction with the quantity authorized for extraction by their water rights. We define the variable "overuse" as the difference between water extraction and quantity authorized for extraction, in acre-feet. As seen in the summary statistics in Table 1, although the mean difference between water extraction and quantity authorized for extraction is negative, the maximum difference between water extraction and quantity authorized for extraction is positive. Thus, although less water is extracted than is authorized for extraction on average, for some grower-years, more water is extracted than is authorized for extraction.

Figure 1 and Figure A3 in the Appendix present histograms for the difference between water extraction and quantity authorized for extraction, pooled over all years from 1996-2012 (Figure 1) and by year (Figure A3 in the Appendix). As seen these histograms, while the water extraction is less than or equal to the quantity authorized for most observations, for many observations, water extraction is exactly equal or slightly less than the quantity authorized; and for some observations, water extraction exceeds the quantity authorized.

For the majority of grower-years, the grower extracts less than the quantity authorized that year. In particular, there are 233,136 grower-years in which the grower extracts less than the quantity authorized that year. There are 20,113 growers who extract less than the quantity authorized for at least one year during the 1996-2012 time period of our data set. For each year over the 1996-2012 time period of our data set, there are growers who extract less than the quantity authorized that year.

There are 1,646 grower-years in which the grower extracts exactly the quantity authorized that year. There are 1,241 growers who extract exactly the quantity authorized for at least one year during the 1996-2012 time period of our data set. For each year over the 1996-2012 time period of our data set, there are growers who extract exactly the quantity authorized that year.

There are 38,640 grower-years in which the grower extracts more than the quantity authorized that year. There are 10,091 growers who extract more than the quantity authorized for at least one year during the 1996-2012 time period of our data set. Growers extract more than the quantity authorized for an average of 1.702 years, or an average of 14.3% of the years. Figure A4 in the Appendix presents a histogram for the number of years a grower extracts more than the authorized quantity over the 1996-2012 time period of our data set. Each observation in the histogram is a grower. A substantial proportion of growers extract more than the authorized quantity for five or more years, and some extract more than the authorized quantity for 15 or more years, out of the 17 years of our data set.

Figure 2 presents a histogram for the fraction of years a grower extracts more than the authorized quantity over the 1996-2012 time period of our data set. Each observation in the histogram is a grower. A substantial proportion of growers extract more than the authorized quantity for more than 20 percent (i.e., more than one-fifth) of the years.

For each year over the 1996-2012 time period of our data set, there are growers who extract more than the quantity authorized that year. The number of growers who extract more than the authorized quantity in a given year is on average 2,272.94 growers, or on average 14.1% of the growers authorized to extract water in that year. Figures A5a and A5b in the Appendix present the number and fraction, respectively, of growers who extract more than the authorized quantity in each year.

Thus, during the time period of our analysis (1996 to 2012), farmers frequently extracted more than the maximum amount of water they were authorized to extract. These frequent violations suggest that the prior appropriation doctrine was not always enforced. For instance, when water users who violated their water right were issued a "warning" or notice of their first offense from the state, many regarded this "warning" as a free year to overpump (Bickel, 2015).

Nevertheless, there are several features of the prior appropriation rights system in Kansas that may discourage groundwater users from dynamic management. First, the appropriation contracts specify a time-invariant maximum amount of groundwater that can be extracted each year (Kansas Water Appropriation Act, n.d.). Thus, a farmer with a water right will still have the right to extract the same time-invariant maximum amount of groundwater each year in the future, whether he extracts the maximum amount this year or less, thereby diminishing his incentive to manage the resource dynamically and extract less today in order to save more for tomorrow.

Second, a water right is considered abandoned after five successive years of non-use without due and sufficient cause (Kansas Water Appropriation Act, n.d.); there is thus an incentive to continue to extract water, perhaps more than what would otherwise be dynamically optimal to extract, in order to maintain the water right. Third, authorized quantities cannot be increased, but can be decreased as a condition for granting a change (Kansas Water Appropriation Act, n.d.; Griggs, 2017), which again provides an incentive to continue to extract water, perhaps more than what would otherwise be dynamically optimal to extract, in order to maintain the water right.

6. Results

6.1. Groundwater Extraction

Table 2 presents the results of our fixed effects (FE) regressions for groundwater extraction. As seen in Specification (1), our base-case specification, most of the dynamic variables, including expected future crop prices for corn, sorghum, and wheat; expected future energy prices for diesel, electricity, and natural gas; extraction by neighbors and the quantity authorized for extraction by neighbors, have a statistically significant effect on groundwater extraction. Thus, groundwater users faced with the prior appropriation doctrine are behaving in a dynamic-forward-looking manner consistent with dynamic management.

We conduct a falsification test by also including the expected future crop prices of two crops that are not grown in Kansas as regressors in our empirical model: cocoa and coffee. We do not expect that the expected future crop prices of crops that are not grown in Kansas would affect groundwater use decisions of farmers in Kansas, even if they were behaving in a manner consistent with dynamic management. Indeed, we find in our base-case Specification (1) in Table 2 that neither the expected future crop price for cocoa nor the expected future crop price for coffee has a statistically significant effect on groundwater extraction.

We also find in our base-case Specification (1) in Table 2 that the quantity authorized for extraction does not have a statistically significant effect on groundwater extraction. As expected, crop prices for alfalfa and soybean have significant positive effects on groundwater extraction.

For robustness, Table 3 presents results from using alternative measures of groundwater extraction. In Specification (2), we use water extraction (in acre-feet) instead of water extraction intensity (in acre-feet of water per acre) as our dependent variable, and we similarly find that most dynamic variables have a significant effect on groundwater extraction, while expected future crop prices for crops that are not grown in Kansas and the quantity authorized for extraction do not. In Specification (3), we use the difference between water extracted and the quantity authorized for extraction as the dependent variable, and we again find that most dynamic variables have a significant effect on the difference between water extracted and the quantity authorized for extraction, while expected future crop prices for crops that are not grown in Kansas do not.

For further robustness, in Table 4 we present results from using 9-year, 8-year, and 7-year projections instead of 10-year projections for our expected future crop and energy prices. As seen in Table 4, our results are robust to whether we use 10-year, 9-year, 8-year, or 7-year projections for our expected future crop and energy prices.

In Table 5, we present results of instrumental variable (IV) fixed effects (IV-FE) regressions of groundwater extraction. We try an instrumental variable fixed effects (IV-FE) specification in we use the lagged quantity authorized for extraction by neighbors as an instrument for neighbors' lagged extraction instead of as a dynamic variable, to address the potential endogeneity of neighbors' lagged extraction. We also try using the current year's crop prices instead of the previous year's crop prices as controls, and then instrumenting for the current year's crop prices using the previous year's crop prices to address the endogeneity of current-year crop prices. As seen in Table 5, our results that most dynamic variables have a significant effect on groundwater extraction, while expected future crop prices for crops that are not grown in Kansas and the quantity authorized for extraction do not, are robust to whether we instrument for crop prices or neighbor extraction.

In terms of expected future crop prices, if the farmer is behaving dynamically, we would expect that expected future crop prices for crops the farmer expects to plant in the future would have a negative effect on current groundwater extraction w_{it}. Across the different specifications in Tables 2-5, we find the robust result that the expected future crop price for wheat has a significant and negative effect on groundwater extraction, which is consistent with dynamic, forward-looking behavior on the part of farmers. We also find that the expected future crop prices for sorghum and soybeans have significant and negative effects on groundwater extraction in some specifications, which is consistent with dynamic, forward-looking behavior on the part of farmers as well. We find that the expected future crop price for corn has an effect on groundwater extraction that is significant at a 5% level in some specifications, which is consistent with dynamic, forward-looking behavior on the part of farmers, although the sign of this effect is mixed across specifications, likely because the expected future crops prices for the four different crops are somewhat correlated and we are including the expected future crop prices for each of four crops as dynamic variables.

While the expected future crop price for wheat has a significant and negative effect on groundwater extraction, we find, as expected, that crop prices have a significant positive effect on groundwater extraction. As seen in Table 2, alfalfa price and soybean price both have significant positive effects on groundwater extraction.

In terms of expected future energy prices, if the farmer is behaving dynamically, we would expect that expected future energy prices for sources of energy the farmer expects to use in the future would have a positive effect on current groundwater extraction w_{it}. 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). Across the different specifications in Tables 2-5, we find that the expected future energy prices for diesel and natural gas, which are the energy sources for the majority of the pumps in Kansas, have significant and positive effects on groundwater extraction, which is consistent with dynamic, forward-looking behavior on the part of farmers. We also find that the expected future energy price for electricity, which is the third major source of energy for pumps in Kansas, behind diesel and natural gas, has an effect on groundwater extraction that is significant at a 5% level as well, which is also consistent with dynamic, forward-looking behavior, though its sign is negative, likely because the expected future energy prices for all three sources of energy are somewhat correlated, we are including all three expected future energy prices as dynamic variables, and electricity is less important a source of energy for pumps in Kansas than are the other two sources of energy whose expected future energy price we include as dynamic variables.

In terms of extraction by neighbors, if the farmer is behaving dynamically, we would expect that groundwater extraction by neighbors would have a positive effect on current groundwater extraction w_{it}. Across the different specifications in Tables 2-5, we find that extraction by neighbors has a significant and positive effect on a farmer's own groundwater extraction, which is consistent with dynamic, forward-looking behavior on the part of farmers.

Although a significant positive effect of extraction by neighbors is consistent with dynamic, forward-looking behavior on the part of farmers, an increase in groundwater extraction in response to neighbor extraction may not be socially optimal (Pfeiffer and Lin, 2012). We find across the different specifications in Tables 2-5 that the quantity authorized for extraction by neighbors has a significant and negative effect on a farmer's own groundwater extraction, however, which offsets in part the significant positive effect of extraction by neighbors. Thus, the property rights system in Kansas partially offsets socially inefficient strategic interactions resulting from the dynamic, forward-looking behavior of individual farmers faced with spatial externalities.

We conduct a falsification test by also including the expected future crop prices of two crops that are not grown in Kansas as regressors in our empirical model: cocoa and coffee. We do not expect that the expected future crop prices of crops that are not grown in Kansas would affect groundwater use decisions of farmers in Kansas, even if they were behaving in a manner consistent with dynamic management. Indeed, we find across the different specifications in Tables 2-5 that neither the expected future crop price for cocoa nor the expected future crop price for coffee has a statistically significant effect on groundwater extraction.

Table 6 presents the results of fixed effects (FE) and instrumental variables fixed effects (IV-FE) regressions of the probability that groundwater extraction is equal to the quantity authorized for extraction as the dependent variable. Across the different specifications, we find the robust result that none of the dynamic variables has a statistically significant effect on whether a grower extracts exactly the quantity authorized for extraction.

6.2. Total Marginal Effect

Table A3 in the Appendix presents the results of our tobit regressions of crop acreage allocated to alfalfa, corn, sorghum, soybeans, and wheat, respectively. Results show that each of the dynamic variables has a statistically significant effect on crop acreage decisions for at least one crop. We also find that the expected future crop prices for crops that are not grown in Kansas affect the crop acreage decisions of growers in Kansas. In addition, we find that the quantity authorized for extraction has a statistically significant effect on the crop acreage decisions for some crops as well.

Table 7 presents the total intensive margin $\left(\frac{\partial w}{\partial D_j}\right)$, total extensive margin $\left(\sum_c \frac{\partial w}{\partial n_c}\frac{\partial n_c}{\partial D_j}\right)$, and the total marginal effect $\left(\frac{dw}{dD_j} = \frac{\partial w}{\partial D_j} + \sum_c \frac{\partial w}{\partial n_c}\frac{\partial n_c}{\partial D_j}\right)$, as calculated using the groundwater extraction regression results from the base-case Specification (1) in Table 2, and the crop acreage regressions results in Table A3 in the Appendix. Groundwater extraction w is extraction intensity in acre-feet per acre. For each crop c, the number of acres n_c planted to crop c is in acres and is evaluated at its mean value in the data. We find that the total intensive margin, the total extensive margin, and the total marginal effect of many of the dynamic variables, including expected future crop prices, expected future energy prices, and groundwater extraction by neighbors, are statistically significant. In contrast, the total intensive margin, the total extensive margin, and the total marginal effect of the expected future crop prices for crops that are not grown in Kansas are not statistically significant. Thus, while the expected future crop prices for crops that are not grown in Kansas affect crop acreage decisions, neither the total extensive margin nor the total marginal effect of the expected future crop prices for crops that are not grown in Kansas is statistically significant.

In terms of expected future crop prices, if the farmer is behaving dynamically, we would expect that expected future crop prices for crops the farmer expects to plant in the future would have a negative effect on current groundwater extraction w_{it}. As seen in Table 7, we find that the total marginal effect of the expected future wheat price is significant and negative, which is consistent with dynamic, forward-looking behavior on the part of farmers.

In terms of expected future energy prices, if the farmer is behaving dynamically, we would expect that expected future energy prices for sources of energy the farmer expects to use in the future would have a positive effect on current groundwater extraction w_{it}. As seen in Table 7, we find that the total marginal effect of expected future energy prices for diesel and natural gas, which are the energy sources for the majority of the pumps in Kansas, are significant and positive, which is consistent with dynamic, forward-looking behavior on the part of farmers. We also find that the total marginal effect of expected future energy price for electricity, which is the third major source of energy for pumps in Kansas, behind diesel and natural gas, is significant at a 0.1% level as well, which is also consistent with dynamic, forward-looking behavior, though its sign is negative, likely because the expected future energy prices for all three sources of energy are somewhat correlated, we are including all three expected future energy prices as dynamic variables, and electricity is less important a source of energy for pumps in Kansas than are the other two sources of energy whose expected future energy price we include as dynamic variables.

In terms of extraction by neighbors, if the farmer is behaving dynamically, we would expect that groundwater extraction by neighbors would have a positive effect on current groundwater extraction w_{it}. As seen in Table 7, the total marginal effect of extraction by neighbors is significant and positive, which is consistent with dynamic, forward-looking behavior on the part of farmers.

Although a significant positive total marginal effect of extraction by neighbors is consistent with dynamic, forward-looking behavior on the part of farmers, an increase in groundwater extraction in response to neighbor extraction may not be socially optimal (Pfeiffer and Lin, 2012). We find in Table 7 that the total marginal effect of the quantity authorized for extraction by neighbors is significant and negative, however, which offsets in part the significant positive total marginal effect of extraction by neighbors. Thus, the property rights system in Kansas partially offsets socially inefficient strategic interactions resulting from the dynamic, forward-looking behavior of individual farmers faced with spatial externalities.

For robustness, Table A4 in the Appendix presents the total marginal effect when using water extraction (in acre-feet) instead of water extraction intensity (in acre-feet of water per acre) as our measure of groundwater extraction *w*. In particular, Specification (B) is calculated using the groundwater extraction regression results from Specification (2) in Table 3, and the crop acreage regressions results in Table A3 in the Appendix. As seen in Table A4 in the Appendix, whether we use water extraction intensity (in acre-feet of water per acre) or water extraction (in acre-feet) as our measure of groundwater extraction *w,* we find the robust result that many of the dynamic variables, including expected future crop prices, expected future energy prices, and groundwater extraction by neighbors, have a statistically significant total marginal effect, while the expected future crop prices for crops that are not grown in Kansas do not.

7. Discussion and Conclusion

Groundwater is an important natural resource that needs to be managed dynamically. Ideally, institutions governing property rights to the groundwater of low-recharge aquifers should not discourage or disincentivize groundwater users from dynamic management. We develop an empirical model to examine whether agricultural groundwater users faced with the prior appropriation doctrine exhibit dynamic, forward-looking behavior consistent with dynamic management. We find that although prior appropriation groundwater property rights in western

Kansas do not encourage or incentivize dynamic management, individual agricultural producers make groundwater extraction decisions that are consistent with dynamic management.

Although agricultural producers are allotted a time-invariant maximum amount of groundwater that they can extract each year, we find that, during the time period of our analysis (1996 to 2012), farmers frequently extracted more than the maximum amount of water they were authorized to extract. These frequent violations suggest that the prior appropriation doctrine was not always enforced. For instance, when water users who violated their water right were issued a "warning" or notice of their first offense from the state, many regarded this "warning" as a free year to overpump (Bickel, 2015).

Moreover, although agricultural producers are allotted a time-invariant maximum amount of groundwater that they can extract each year, we find that the quantity authorized for extraction does not have a statistically significant effect on groundwater extraction. Instead, although their groundwater property rights do not encourage or incentivize dynamic management, farmers consider expected future crop prices, expected future energy prices, and groundwater extraction by neighbors when making groundwater extraction decisions.

In terms of expected future crop prices, if the farmer is behaving dynamically, we would expect that expected future crop prices for crops the farmer expects to plant in the future would have a negative effect on current groundwater extraction. Across different specifications, we find the robust result that the expected future crop price for wheat has a significant and negative effect and total marginal effect on groundwater extraction, which is consistent with dynamic, forward-looking behavior on the part of farmers. Using the results from our base-case Specification (1), and evaluated at their mean values in the data, the elasticity of groundwater extraction with respect to expected future crop price for wheat is -0.485.

In terms of expected future energy prices, if the farmer is behaving dynamically, we would expect that expected future energy prices for sources of energy the farmer expects to use in the future would have a positive effect on current groundwater extraction. 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). Across the different specifications, we find that the expected future energy prices for diesel and natural gas, which are the energy sources for the majority of the pumps in Kansas, have significant and positive effects and total marginal effects on groundwater extraction, which is consistent with dynamic, forward-looking behavior on the part of farmers. Using the results from our base-case Specification (1), and evaluated at their mean values in the data, the elasticity of groundwater extraction with respect to expected future energy price for natural gas is 0.350; and the elasticity of groundwater extraction with respect to expected future energy price for diesel is 0.458.

We also find that the expected future energy price for electricity, which is the third major source of energy for pumps in Kansas, behind diesel and natural gas, has an effect and total marginal effect on groundwater extraction that is significant at a 5% level as well, which is also consistent with dynamic, forward-looking behavior, though its sign is negative, likely because the expected future energy prices for all three sources of energy are somewhat correlated, we are including all three expected future energy prices as dynamic variables, and electricity is less important a source of energy for pumps in Kansas than are the other two sources of energy whose expected future energy price we include as dynamic variables. Using the results from our base-case Specification (1), and evaluated at their mean values in the data, the elasticity of groundwater extraction with respect to expected future energy price for electricity is -1.909.

In terms of extraction by neighbors, if the farmer is behaving dynamically, we would expect that groundwater extraction by neighbors would have a positive effect on current groundwater extraction. Across the different specifications, extraction by neighbors has a significant and positive effect and total marginal effect on a farmer's own groundwater extraction, which is consistent with dynamic, forward-looking behavior on the part of farmers. Using the results from our base-case Specification (1), and evaluated at their mean values in the data, the elasticity of groundwater extraction with respect to extraction by neighbors is 0.049.

Although a significant positive effect of extraction by neighbors is consistent with dynamic, forward-looking behavior on the part of farmers, an increase in groundwater extraction in response to neighbor extraction may not be socially optimal (Pfeiffer and Lin, 2012). We find across the different specifications that the quantity authorized for extraction by neighbors has a significant and negative effect and total marginal effect on a farmer's own groundwater extraction, however, which offsets in part the significant positive effect and total marginal effect of extraction by neighbors. Using the results from our base-case Specification (1), and evaluated at their mean values in the data, the elasticity of groundwater extraction with respect to quantity authorized for extraction by neighbors is -0.018. Thus, the property rights system in Kansas partially offsets socially inefficient strategic interactions resulting from the dynamic, forward-looking behavior of individual farmers faced with spatial externalities.

We conduct a falsification test by also including the expected future crop prices of two crops that are not grown in Kansas as regressors in our empirical model: cocoa and coffee. We do not expect that the expected future crop prices of crops that are not grown in Kansas would affect groundwater use decisions of farmers in Kansas, even if they were behaving in a dynamic, forward-looking manner consistent with a dynamic management. Indeed, we find the robust result across specifications that neither the expected future crop price for cocoa nor the expected future crop price for coffee has a statistically significant effect or total marginal effect on groundwater extraction.

When examining the behavior of those farmers who choose to extract exactly the quantity authorized for extraction, we find the robust result that none of the dynamic variables has a statistically significant effect on whether a grower extracts exactly the quantity authorized for extraction. This suggests that farmers who opt to abide by their property right and extract exactly the quantity authorized for extraction in a given year do not consider the future when making the decision to do so. In contrast, for farmers in years in which they do not extract exactly the quantity authorized for extraction, their groundwater extraction decisions are influenced by dynamic variables and not by the quantity authorized for extraction; and are consistent with dynamic, forward-looking behavior.

Our results therefore show that even though groundwater property rights in Kansas do not encourage or incentivize dynamic management, farmers still behave in a dynamic, forward-looking manner consistent with dynamic management. This suggests that agricultural producers understand the physical properties of the aquifer from which they are drawing, are concerned with future profits, recognize that using less water this year means more is available next year, and make groundwater extraction decisions accordingly.

There are several potential avenues for future research. First, the prior appropriation property rights system in Kansas stipulates that in times of shortage or conflict, the earliest appropriators of water maintain the first rights to continue to use water (Peck, 2003). In future work we hope to obtain data on the priority or seniority of the water rights to each farmer, and examine whether high-priority and low-priority claimants behave differently. For example, it is possible that low-priority claimants might discount the future more heavily and therefore be less responsive to dynamic variables if they think there is a possibility that they might not be authorized to extract water in the future owing to potential future shortage or conflict.

Second, in our paper we estimate an econometric model of groundwater extraction conditional on crop acreage decisions, and we also estimate an econometric model of a farmer's irrigation water pumping decision that accounts for both the extensive margin and the intensive margin, where the extensive margin is the crop acreage allocation decision and the intensive margin is the groundwater extraction decision holding crop acreage allocation constant. Groundwater extraction and crop acreage allocation may be at least partially jointly determined and jointly chosen, however, and crop acreage allocation may therefore be endogenous to groundwater extraction. These endogeneity concerns are mitigated in part because crop acreage decisions are made by the beginning of the season while groundwater extraction decisions are made throughout the season; thus, crop acreage decisions tend to be pre-determined before much of the groundwater extraction decisions are made. We further address concerns about the endogeneity of crop acreage allocation by controlling for crop prices, grower fixed effects, and other determinants of both crop acreage allocation and groundwater extraction in our empirical model of groundwater extraction. In future work, we hope to develop a structural econometric model of grower's groundwater extraction and crop acreage allocation decisions that more explicitly models their joint and simultaneous nature.

A third avenue for potential future research to analyze well ownership. In our paper, we have modeled neighbors as all neighbors within one mile of a given farmer. In previous empirical work, Pfeiffer and Lin (2012) contrast the behavioral response to extraction by nearby neighbors with extraction from nearby wells that the grower himself controls, and finds that the average effect of extraction at neighboring wells owned by the same grower is smaller than the effects of neighboring wells owned by others. In future work, we hope to identify ownership and distinguish among wells owned by the same groundwater user and wells owned by other groundwater users.

A fourth avenue for potential future research regards more fully modeling both the dynamic and strategic dimensions of groundwater extraction. As the primary focus of our paper is on dynamic management rather than spatial considerations, we assume that each farmer takes the previous groundwater extraction by neighbors as given. This enables us to characterize the dynamic management problem as the dynamic optimization problem faced by each individual farmer, rather than as a dynamic game among multiple farmers. Sears, Lim and Lin Lawell (2019) present a dynamic game framework for analyzing spatial groundwater management, characterizing the Markov perfect equilibrium resulting from non-cooperative behavior, and comparing it with the socially optimal coordinated solution. In future work, we hope to more explicitly model both the dynamic and strategic dimensions of groundwater extraction by developing and estimating a structural econometric model of the dynamic game among groundwater users, building on structural econometric models of dynamic games that have been developed to model petroleum production and extraction (Lin, 2013; Kheiravar, Lin Lawell and Jaffe, 2020).

A fifth avenue for potential future research is to more fully model the effects of weather. As the focus of this paper is on dynamic management over years rather than within a season, we control for the following weather variables in our empirical model: annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity. Hendricks and Peterson (2012) control for precipitation by growing season to capture how water demand depends on the dates of arrival of rain within a year. The growing seasons in western Kansas differ for each of the major crops grown in western Kansas (Bertone Oehninger, Lin Lawell and Springborn, 2020), however, which makes defining the dates of the growing season and separating precipitation by growing season tricky. Results of our preliminary analysis show that it is important to evaluate the effects of climate-related variables by month rather than only at an annual level (Bertone Oehninger, Lin Lawell and Springborn, 2020). We hope in future work to more fully model the effects of weather and climate change, and to evaluate how expectations about climate change affect and interact with dynamic management.

Our research has important implications for the design of groundwater property rights and institutions, and for the sustainable management of groundwater.

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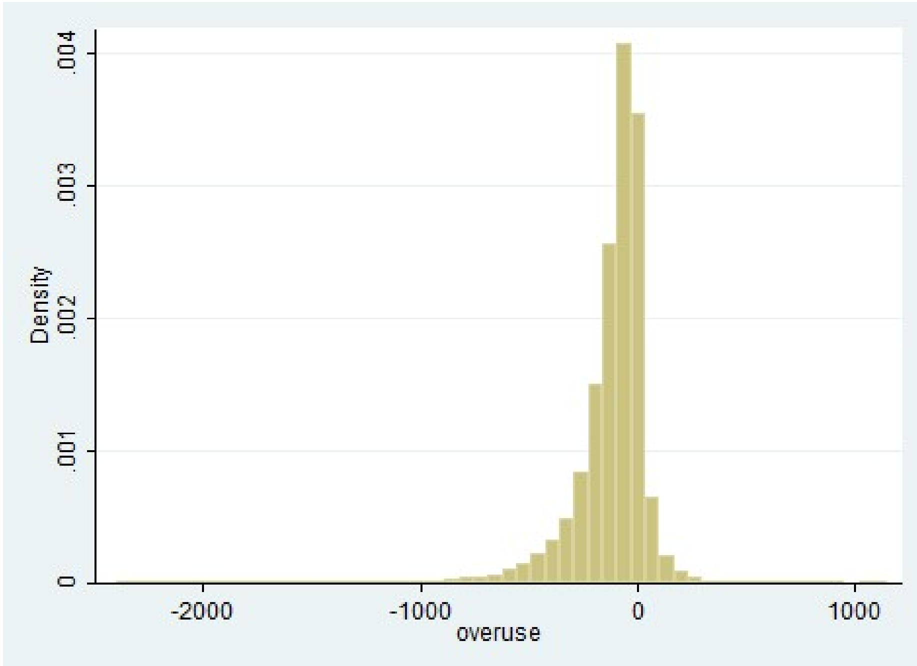
Table 1. Summary statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Groundwater extraction					
Extraction (acre-feet)	293,342	172.38	122.60	0	1988.64
Extraction intensity (acre-feet/acre)	291,694	1.167	0.557	0	17.415
Authorized quantity					
Quantity authorized for extraction (acre-feet)	273,422	290.12	199.79	0.37	2400
Difference between extraction and quantity authorized for extraction (acre-feet)	273,422	-117.76	180.55	-2400	1153.88
Dummy variable for extraction equals quantity authorized for extraction	293,342	0.01	0.07	0	1
Crop acreage					
Acres planted with alfalfa (acres)	293,342	11.43	38.34	0	640
Acres planted with corn (acres)	293,337	64.08	74.51	0	640
Acres planted with sorghum (acres)	293,342	5.07	23.87	0	620
Acres planted with soybeans (acres)	293,342	12.27	35.23	0	550
Acres planted with wheat (acres)	293,337	16.92	43.47	0	625
Hydrological and field characteristics					
Evapotranspiration, average (in)	293,342	55.12	1.07	43.54	62.39
Recharge (in)	293,267	1.34	1.22	0.3	6
Slope (% of distance)	290,456	1.08	0.87	0.01	8.68
Irrigated Capability Class=1 (dummy)	293,342	0.17	0.37	0	1
Soil moisture content in the layer 0-10 cm (kg/m^2)	274,305	22.42	4.08	11.67	35.46
Field size (acres)	293,342	181.94	102.13	60	640
Depth to groundwater (ft)	293,342	123.42	78.17	4.72	396.48
Saturated thickness (ft)	293,342	120.17	113.73	-257.35	643.91
Irrigation technology					
Center pivot sprinkler use (dummy)	293,342	0.36	0.48	0	1
Center pivot with drop nozzles use (dummy)	293,342	0.32	0.46	0	1
Crop prices					
Alfalfa price ($/ton)	293,342	119.41	36.52	80.42	211.92
Corn price (cents/bushel)	293,342	340.77	129.90	224.28	629.03
Sorghum price ($/cwt)	293,342	5.58	2.52	3.27	11.26
Soybean price (cents/bushel)	293,342	774.93	285.90	451.95	1353.64

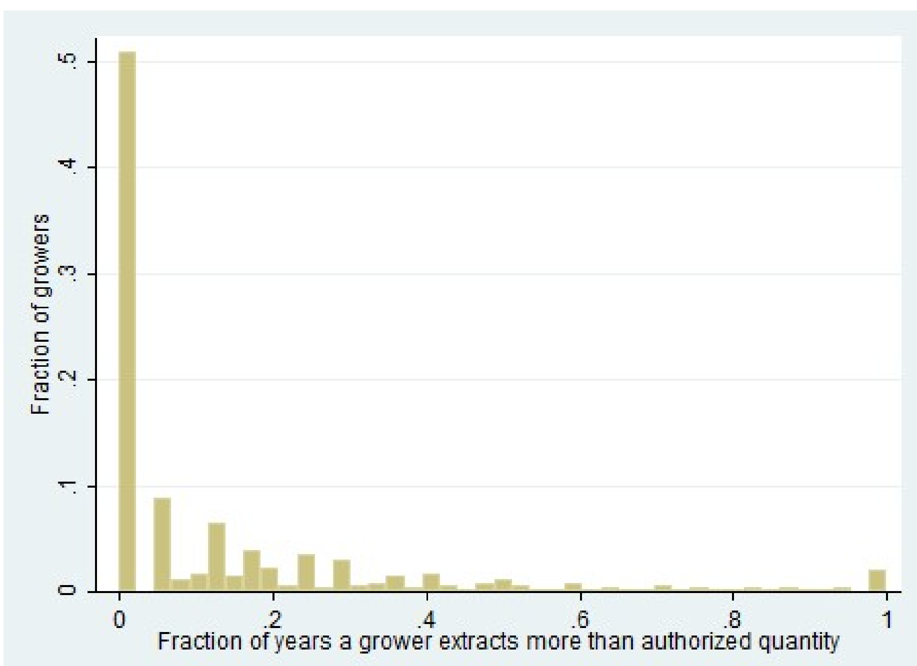
Wheat price (cents/bushel)	293,342	465.97	199.62	287.94	968.91
Energy prices					
Diesel price ($/gal)	293,342	2.17	0.99	1.023	3.899
Electricity price (cents/kwh)	293,342	7.03	0.93	6.2	9.24
Natural gas price ($/mcf)	293,342	8.60	2.58	4.61	12.44
Weather					
Annual average temperature (°F)	293,342	54.21	1.53	50.42	58.25
Annual precipitation (in)	293,342	18.60	6.30	6.31	51.81
Annual average humidity (%)	293,342	64.11	4.65	51.80	77.29
Future crop prices					
Corn price, 10-year projection ($/bushel)	293,342	3.13	0.65	2.35	4.65
Sorghum price, 10-year projection ($/bushel)	293,342	2.89	0.61	2.1	4.35
Soybean price, 10-year projection ($/bushel)	293,342	7.39	1.69	5.6	11.35
Wheat price, 10-year projection ($/bushel)	293,342	4.35	0.80	3	5.9
Future energy prices					
Diesel price, 10-year projection ($/million Btu)	293,342	13.75	7.19	7.87	28.63
Electricity price, 10-year projection ($/million Btu)	293,342	21.42	3.61	17.2	28.17
Natural gas price, 10-year projection ($/million Btu)	293,342	5.76	1.73	3.44	9.05
Groundwater extraction by neighbors					
Extraction by neighbors in *t*-1 (acre-feet)	293,342	728.32	625.14	0	5404.05
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	293,342	1084.79	919.79	0	15162
Future crop prices for crops that are not grown in Kansas					
Cocoa price, 2-year projection ($/ton)	293,342	1873.38	635.02	935.52	3035.97
Coffee price, 2-year projection ($/lb)	293,342	126.28	46.29	63.23	258.12

Figure 1. Water extraction minus quantity authorized for extraction



Notes: "Overuse" is defined as the difference between water extraction and quantity authorized for extraction, in acre-feet. We use only those grower-year observations over the period 1996-2012 for which the grower was authorized to extract a positive amount of water that year.

Figure 2. Fraction of years a grower extracts more than quantity authorized



Note: Each observation in the histogram is a grower. The fraction of years a grower extracts more than the authorized quantity is calculated over the period 1996-2012.

Table 2. Groundwater Extraction Regression Results

	Dependent variable is: Extraction intensity (acre-feet per acre)
	(1, Base)
Dynamic variables	
Corn price, 10-year projection ($/bushel)	0.506**
	(0.180)
Sorghum price, 10-year projection ($/bushel)	-0.401*
	(0.181)
Soybean price, 10-year projection ($/bushel)	-0.0311
	(0.0298)
Wheat price, 10-year projection ($/bushel)	-0.130***
	(0.0319)
Diesel price, 10-year projection ($/million Btu)	0.0389***
	(0.00906)
Electricity price, 10-year projection ($/million Btu)	-0.104***
	(0.00882)
Natural gas price, 10-year projection ($/million Btu)	0.0710***
	(0.0118)
Extraction by neighbors in *t*-1 (acre-feet)	7.93e-05***
	(5.49e-06)
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	-1.98e-05***
	(5.53e-06)
Future crop prices for crops that are not grown in Kansas	
Cocoa price, 2-year projection ($/ton)	3.54e-05
	(3.39e-05)
Coffee price, 2-year projection ($/lb)	-0.000661
	(0.000643)
Authorized quantity	
Quantity authorized for extraction (acre-feet)	-0.000121
	(0.000169)
Crop acreage variables	
Acres planted with alfalfa (acres)	0.00201***
	(0.000126)
Acres planted with alfalfa (acres), squared	-7.09e-06***
	(6.89e-07)
Acres planted with corn (acres)	0.00197***
	(4.89e-05)
Acres planted with corn (acres), squared	-6.61e-06***
	(2.12e-07)
Acres planted with sorghum (acres)	-0.000528***

	(9.09e-05)
Acres planted with sorghum (acres), squared	-1.10e-06*
	(4.71e-07)
Acres planted with soybeans (acres)	0.00159***
	(8.96e-05)
Acres planted with soybeans (acres), squared	-6.90e-06***
	(6.15e-07)
Acres planted with wheat (acres)	-0.00170***
	(6.62e-05)
Acres planted with wheat (acres), squared	6.46e-07*
	(3.26e-07)
Crop price variables	
Alfalfa price ($/ton)	0.00201***
	(0.00030)
Corn price (cents/bushel)	-0.00048
	(0.00035)
Sorghum price ($/cwt)	0.00591
	(0.0153)
Soybean price (cents/bushel)	0.000172*
	(7.10e-05)
Wheat price (cents/bushel)	-0.00014
	(0.00016)
Controls	Y
Time Trend	Y
Grower Fixed Effects	Y
# Observations	241,091
# Growers	29,323

Notes: Robust standard errors are in parentheses. The crop price variables include crop prices (alfalfa price, corn price, sorghum price, soybean price, and wheat price) from the previous year. The controls include hydrological and field characteristics (evapotranspiration, recharge, slope, soil quality, soil moisture, field size, depth to groundwater, saturated thickness), irrigation technology, energy prices (diesel price, electricity price, and natural gas price), and weather (annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity). Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table 3. Robustness: Groundwater Extraction Regression Results Varying Measure of Extraction

	Dependent variable is:		
	Extraction intensity (acre-feet per acre)	*Extraction (acre-feet)*	*Difference between extraction and quantity authorized for extraction (acre-feet)*
	(1, Base)	(2)	(3)
Dynamic variables			
Corn price, 10-year projection ($/bushel)	0.506**	-14.59	-12.37
	(0.180)	(23.85)	(23.96)
Sorghum price, 10-year projection ($/bushel)	-0.401*	44.70	42.73
	(0.181)	(23.80)	(23.91)
Soybean price, 10-year projection ($/bushel)	-0.0311	6.836	6.509
	(0.0298)	(3.991)	(4.007)
Wheat price, 10-year projection ($/bushel)	-0.130***	-33.86***	-34.02***
	(0.0319)	(4.075)	(4.094)
Diesel price, 10-year projection ($/million Btu)	0.0389***	10.23***	10.43***
	(0.00906)	(1.302)	(1.308)
Electricity price, 10-year projection ($/million Btu)	-0.104***	-19.45***	-19.26***
	(0.00882)	(1.234)	(1.240)
Natural gas price, 10-year projection ($/million Btu)	0.0710***	14.70***	14.45***
	(0.0118)	(1.627)	(1.642)
Extraction by neighbors in *t*-1 (acre-feet)	7.93e-05***	0.0169***	0.0173***
	(5.49e-06)	(0.00106)	(0.00108)
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	-1.98e-05***	-0.00498***	-0.00454***
	(5.53e-06)	(0.00101)	(0.00104)
Future crop prices for crops that are not grown in Kansas			
Cocoa price, 2-year projection ($/ton)	3.54e-05	-0.00776	-0.00726
	(3.39e-05)	(0.00452)	(0.00455)
Coffee price, 2-year projection ($/lb)	-0.000661	0.137	0.148
	(0.000643)	(0.0860)	(0.0863)

Authorized quantity			
Quantity authorized for extraction (acre-feet)	-0.000121	0.0267	
	(0.000169)	(0.0429)	
Crop Acreage and Crop Price Variables	Y	Y	Y
Controls	Y	Y	Y
Time Trend	Y	Y	Y
Grower Fixed Effects	Y	Y	Y
# Observations	241,091	242,537	242,537
# Growers	29,323	29,376	29,376

Notes: Robust standard errors are in parentheses. Specification (1) is the same base-case Specification (1) that is in Table 2. The crop acreage variables include the number of acres planted to each crop (alfalfa, corn, sorghum, soybeans, and wheat) and the number of acres planted to each crop squared. The crop price variables include crop prices (alfalfa price, corn price, sorghum price, soybean price, and wheat price) from the previous year. The controls include hydrological and field characteristics (evapotranspiration, recharge, slope, soil quality, soil moisture, field size, depth to groundwater, saturated thickness), irrigation technology, energy prices (diesel price, electricity price, and natural gas price), and weather (annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity). Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$.

Table 4. Robustness: Groundwater Extraction Regression Results Varying Crop and Energy Price Futures

	Dependent variable is: Extraction intensity (acre-feet per acre)			
Expected future crop and energy prices, X-year projection:	10-year projection (1, Base)	9-year projection (4)	8-year projection (5)	7-year projection (6)
Dynamic variables				
Corn price, X-year projection ($/bushel)	0.506**	0.712***	0.605***	0.681**
	(0.180)	(0.208)	(0.172)	(0.211)
Sorghum price, X-year projection ($/bushel)	-0.401*	-0.403	-0.195	-0.325
	(0.181)	(0.208)	(0.139)	(0.177)
Soybean price, X-year projection ($/bushel)	-0.0311	-0.0790*	-0.112**	-0.0764*
	(0.0298)	(0.0372)	(0.0361)	(0.0307)
Wheat price, X-year projection ($/bushel)	-0.130***	-0.228***	-0.225***	-0.177***
	(0.0319)	(0.0413)	(0.0269)	(0.0414)
Diesel price, X-year projection ($/million Btu)	0.0389***	0.0421***	0.0429***	0.0203
	(0.00906)	(0.0109)	(0.0109)	(0.0207)
Electricity price, X-year projection ($/million Btu)	-0.104***	-0.102***	-0.127***	-0.123***
	(0.00882)	(0.00563)	(0.00985)	(0.0207)
Natural gas price, X-year projection ($/million Btu)	0.0710***	0.0846***	0.105***	0.103*
	(0.0118)	(0.0104)	(0.0167)	(0.0432)
Extraction by neighbors in *t*-1 (acre-feet)	7.93e-05***	7.93e-05***	7.93e-05***	8.13e-05***
	(5.49e-06)	(5.48e-06)	(5.51e-06)	(5.47e-06)
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	-1.98e-05***	-1.98e-05***	-1.98e-05***	-2.06e-05***
	(5.53e-06)	(5.53e-06)	(5.53e-06)	(5.52e-06)
Future crop prices for crops that are not grown in Kansas				
Cocoa price, 2-year projection ($/ton)	3.54e-05	8.28e-06	2.52e-05	-2.30e-06
	(3.39e-05)	(3.98e-05)	(3.12e-05)	(2.35e-05)
Coffee price, 2-year projection ($/lb)	-0.000661	-0.000317	-0.000427	-0.000135
	(0.000643)	(0.000801)	(0.000630)	(0.000635)

Authorized quantity				
Quantity authorized for extraction (acre-feet)	-0.000121	-0.000121	-0.000121	-0.000120
	(0.000169)	(0.000169)	(0.000170)	(0.000169)
Crop Acreage and Crop Price Variables	Y	Y	Y	Y
Controls	Y	Y	Y	Y
Time Trend	Y	Y	Y	Y
Grower Fixed Effects	Y	Y	Y	Y
# Observations	241,091	241,091	241,091	241,091
# Growers	29,323	29,323	29,323	29,323

Notes: Robust standard errors are in parentheses. Specification (1) is the same base-case Specification (1) that is in Table 2. The crop acreage variables include the number of acres planted to each crop (alfalfa, corn, sorghum, soybeans, and wheat) and the number of acres planted to each crop squared. The crop price variables include crop prices (alfalfa price, corn price, sorghum price, soybean price, and wheat price) from the previous year. The controls include hydrological and field characteristics (evapotranspiration, recharge, slope, soil quality, soil moisture, field size, depth to groundwater, saturated thickness), irrigation technology, energy prices (diesel price, electricity price, and natural gas price), and weather (annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity). Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table 5. Robustness: Groundwater Extraction IV-FE Regression Results

	Dependent variable is: Extraction intensity (acre-feet per acre)		
	FE (1, Base)	IV-FE (7)	IV-FE (8)
Dynamic variables			
Corn price, 10-year projection ($/bushel)	0.506**	0.441***	-0.482*
	(0.180)	(0.124)	(0.195)
Sorghum price, 10-year projection ($/bushel)	-0.401*	-0.349**	0.000
	(0.181)	(0.125)	(0.000)
Soybean price, 10-year projection ($/bushel)	-0.0311	-0.0215	-0.482
	(0.0298)	(0.0209)	(0.436)
Wheat price, 10-year projection ($/bushel)	-0.130***	-0.109***	0.832
	(0.0319)	(0.0230)	(0.511)
Diesel price, 10-year projection ($/million Btu)	0.0389***	0.0338***	0.166***
	(0.00906)	(0.00667)	(0.0162)
Electricity price, 10-year projection ($/million Btu)	-0.104***	-0.101***	-0.374*
	(0.00882)	(0.00645)	(0.152)
Natural gas price, 10-year projection ($/million Btu)	0.0710***	0.0663***	0.000
	(0.0118)	(0.00924)	(0.000)
Extraction by neighbors in *t*-1 (acre-feet)	7.93e-05***	8.53e-06	8.00e-05***
	(5.49e-06)	(1.36e-05)	(4.32e-06)
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	-1.98e-05***		-2.09e-05***
	(5.53e-06)		(4.01e-06)
Future crop prices for crops that are not grown in Kansas			
Cocoa price, 2-year projection ($/ton)	3.54e-05	2.48e-05	0.000639
	(3.39e-05)	(2.46e-05)	(0.000377)
Coffee price, 2-year projection ($/lb)	-0.000661	-0.000656	-0.0122
	(0.000643)	(0.000448)	(0.00925)

Authorized quantity			
Quantity authorized for extraction (acre-feet)	-0.000121	-0.000141	-0.000122
	(0.000169)	(0.000103)	(0.000103)
Crop Acreage and Crop Price Variables	Y	Y	Y
Controls	Y	Y	Y
Time Trend	Y	Y	Y
Grower Fixed Effects	Y	Y	Y
IV for Neighbor Extraction	N	Y	N
IV for Crop Prices	N	N	Y
# Observations	241,091	238,936	238,934
# Growers	29,323	27,168	27,167

Notes: Standard errors are in parentheses. Specification (1) is the same base-case fixed effects (FE) Specification (1) that is in Table 2, and uses robust standard errors. In instrumental variable (IV) fixed effects (IV-FE) Specification (7), we use the lagged quantity authorized for extraction by neighbors as an instrument for neighbors' lagged extraction instead of as a dynamic variable, to address the potential endogeneity of neighbors' lagged extraction. In instrumental variable fixed effects (IV-FE) Specification (8), we use the current year's crop prices instead of the previous year's crop prices as controls, and then instrument for the current year's crop prices using the previous year's crop prices to address the endogeneity of current-year crop prices. The crop acreage variables include the number of acres planted to each crop (alfalfa, corn, sorghum, soybeans, and wheat) and the number of acres planted to each crop squared. The crop price variables include alfalfa price, corn price, sorghum price, soybean price, and wheat price. The controls include hydrological and field characteristics (evapotranspiration, recharge, slope, soil quality, soil moisture, field size, depth to groundwater, saturated thickness), irrigation technology, energy prices (diesel price, electricity price, and natural gas price), and weather (annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity). Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$.

Table 6. Groundwater Extraction Equals Quantity Authorized Regression Results

	Dependent variable is: Probability of extracting the quantity authorized for extraction		
	FE	IV-FE	IV-FE
	(i)	(ii)	(iii)
Dynamic variables			
Corn price, 10-year projection ($/bushel)	0.00992	0.00410	0.0805
	(0.0245)	(0.0229)	(0.0417)
Sorghum price, 10-year projection ($/bushel)	-0.00896	-0.00356	0.000
	(0.0251)	(0.0229)	(0.000)
Soybean price, 10-year projection ($/bushel)	-0.000411	0.000509	0.171
	(0.00387)	(0.00388)	(0.0935)
Wheat price, 10-year projection ($/bushel)	0.00481	0.00432	-0.203
	(0.00427)	(0.00411)	(0.110)
Diesel price, 10-year projection ($/million Btu)	-0.00179	-0.00132	0.00256
	(0.00145)	(0.00121)	(0.00339)
Electricity price, 10-year projection ($/million Btu)	0.000919	0.000397	0.0601
	(0.00127)	(0.00120)	(0.0325)
Natural gas price, 10-year projection ($/million Btu)	-0.00230	-0.00190	0.000
	(0.00168)	(0.00174)	(0.000)
Extraction by neighbors in *t*-1 (acre-feet)	-5.52e-07	1.05e-07	7.68e-07
	(8.76e-07)	(2.61e-06)	(2.63e-06)
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	1.85e-07		
	(7.71e-07)		
Future crop prices for crops that are not grown in Kansas			
Cocoa price, 2-year projection ($/ton)	7.11e-07	3.17e-07	-0.000150
	(4.48e-06)	(4.55e-06)	(8.08e-05)
Coffee price, 2-year projection ($/lb)	-0.000110	-9.51e-05	0.00359
	(9.44e-05)	(8.09e-05)	(0.00199)

Crop Acreage and Crop Price Variables	Y	Y	Y
Controls	Y	Y	Y
Time Trend	Y	Y	Y
Grower Fixed Effects	Y	Y	Y
IV for Neighbor Extraction	N	Y	Y
IV for Crop Prices	N	N	Y
# Observations	253,741	251,245	251,245
# Growers	31,281	28,786	28,786

Notes: Standard errors are in parentheses. Specification (i) is a fixed effects (FE) specification using robust standard errors. In instrumental variable (IV) fixed effects (IV-FE) Specification (ii), we use the lagged quantity authorized for extraction by neighbors as an instrument for neighbors' lagged extraction instead of as a dynamic variable, to address the potential endogeneity of neighbors' lagged extraction. In instrumental variable fixed effects (IV-FE) Specification (iii), we also use the current year's crop prices instead of the previous year's crop prices as controls, and then instrument for the current year's crop prices using the previous year's crop prices to address the endogeneity of current-year crop prices. The crop acreage variables include the number of acres planted to each crop (alfalfa, corn, sorghum, soybeans, and wheat) and the number of acres planted to each crop squared. The crop price variables include alfalfa price, corn price, sorghum price, soybean price, and wheat price. The controls include hydrological and field characteristics (evapotranspiration, recharge, slope, soil quality, soil moisture, field size, depth to groundwater, saturated thickness), irrigation technology, energy prices (diesel price, electricity price, and natural gas price), and weather (annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity). Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$.

Table 7. Total Marginal Effect

	Total intensive margin $\left(\frac{\partial w}{\partial D_j}\right)$	Total extensive margin $\left(\sum_c \frac{\partial w}{\partial n_c}\frac{\partial n_c}{\partial D_j}\right)$	**TOTAL MARGINAL EFFECT** $\left(\frac{dw}{dD_j}=\frac{\partial w}{\partial D_j}+\sum_c \frac{\partial w}{\partial n_c}\frac{\partial n_c}{\partial D_j}\right)$
			(A, Base)
Dynamic variables D_j			
Corn price, 10-year projection ($/bushel)	0.506**	-0.126	0.3798
	(0.18)	(0.149)	(0.2337)
Sorghum price, 10-year projection ($/bushel)	-0.401*	0.166	-0.2347
	(0.181)	(0.160)	(0.2418)
Soybean price, 10-year projection ($/bushel)	-0.031	0.036	0.0054
	(0.030)	(0.029)	(0.0412)
Wheat price, 10-year projection ($/bushel)	-0.13***	-0.092**	-0.2222***
	(0.0319)	(0.034)	(0.0466)
Diesel price, 10-year projection ($/million Btu)	0.0389***	0.0259***	0.0648***
	(0.0091)	(0.0075)	(0.0118)
Electricity price, 10-year projection ($/million Btu)	-0.104***	-0.008	-0.1120***
	(0.0088)	(0.007)	(0.0114)
Natural gas price, 10-year projection ($/million Btu)	0.071***	0.019	0.0904***
	(0.012)	(0.018)	(0.0216)
Extraction by neighbors in *t*-1 (acre-feet)	7.93E-05***	5.09E-05***	0.00013***
	(5.49E-06)	(1.07E-05)	(1.20E-05)
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	-1.98E-05***	-9.21E-08	-1.99E-05**
	(5.53E-06)	(2.88E-06)	(6.24E-06)
Future crop prices for crops that are not grown in Kansas			
Cocoa price, 2-year projection ($/ton)	3.54E-05	-3.24E-06	3.22E-05
	(3.39E-05)	(2.80E-05)	(4.39E-05)
Coffee price, 2-year projection ($/lb)	-0.00066	0.001	0.0006
	(0.00064)	(0.001)	(0.0009)

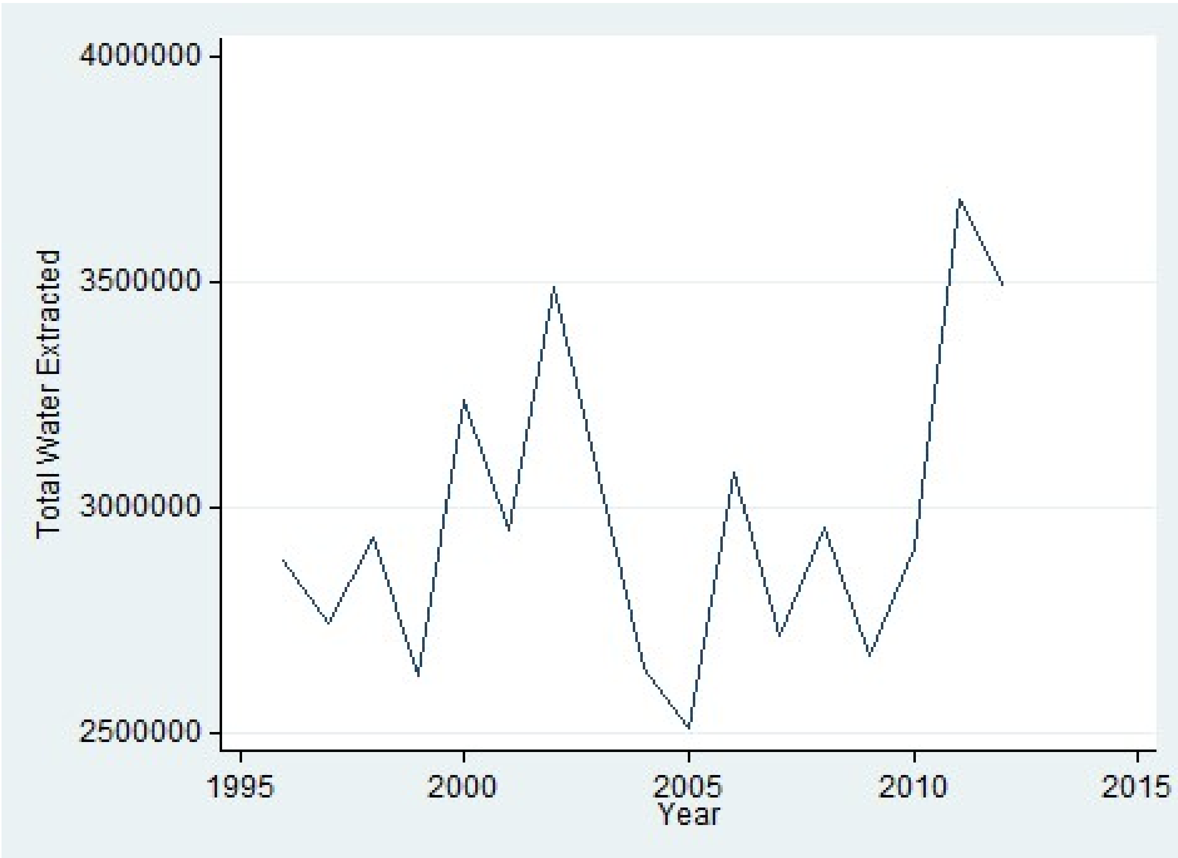
Notes: Standard errors are in parentheses. Groundwater extraction w is extraction intensity in acre-feet per acre. For each crop c, the number of acres n_c planted to crop c is in acres and is evaluated at its mean value in the data. Results are calculated using the groundwater extraction regression results from the base-case Specification (1) in Table 2, and the crop acreage regressions results in Table A3 in the Appendix. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Appendix

Table A1: 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

Figure A1. Total groundwater extracted each year

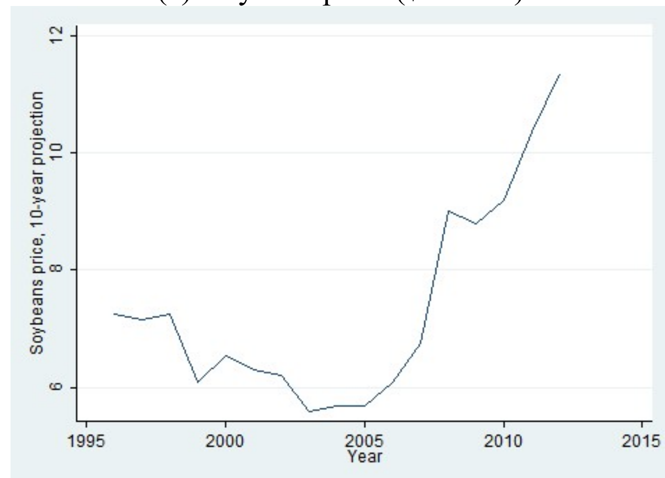


Note: Total water extracted is in units of acre-feet. For each year, total water extracted is calculated by summing groundwater extraction over all growers that were authorized to extract a positive amount of water that year.

Figure A2a. Expected future crop prices, 10-year projections

(a) Corn price ($/bushel)

(c) Soybean price ($/bushel)

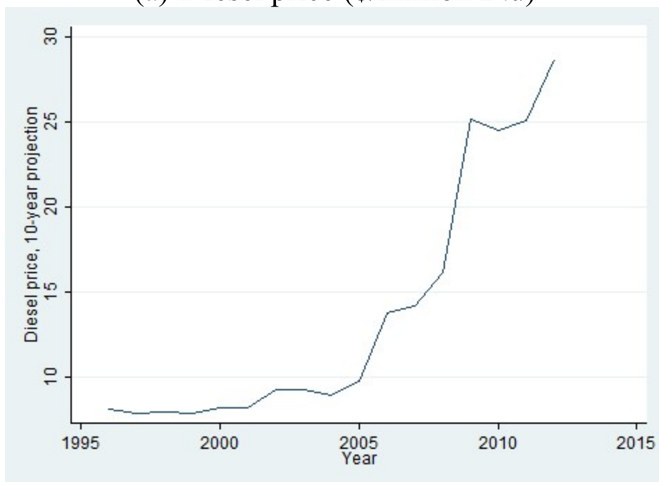


(b) Sorghum price ($/bushel)

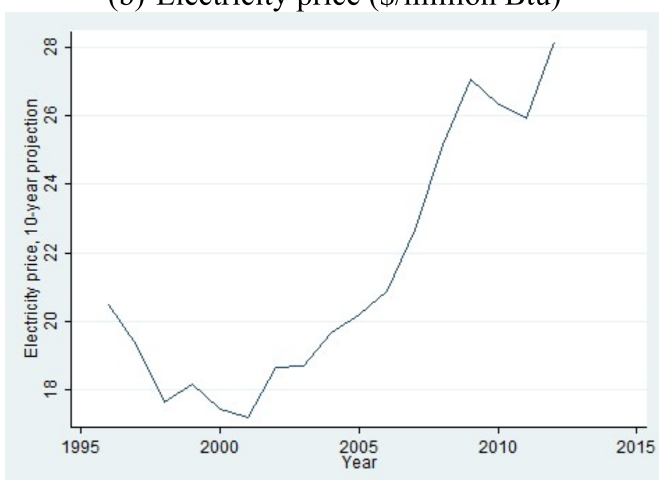
(d) Wheat price ($/bushel)

Figure A2b. Expected future energy prices, 10-year projections

(a) Diesel price ($/million Btu)



(b) Electricity price ($/million Btu)



(c) Natural gas price ($/million Btu)

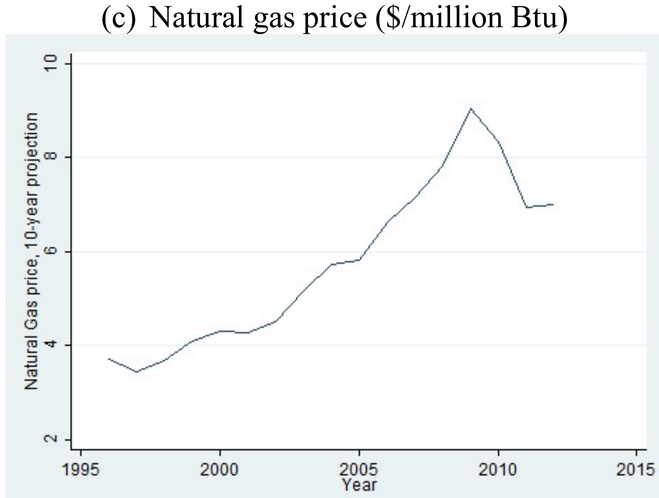
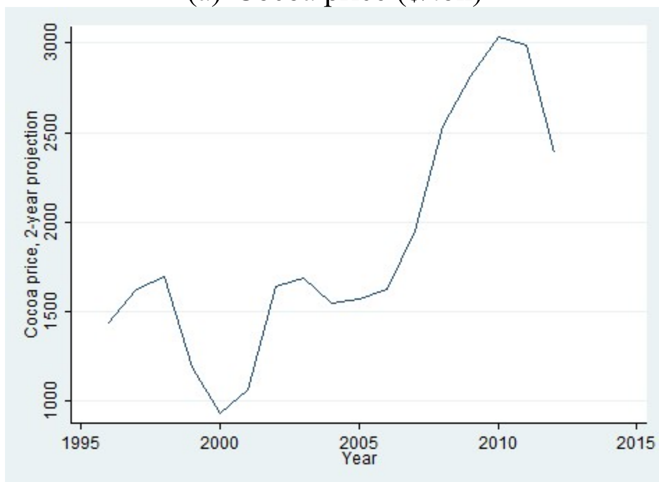


Figure A2c. Expected future crop prices for crops that are not grown in Kansas

(a) Cocoa price ($/ton)



(b) Coffee price ($/lb)

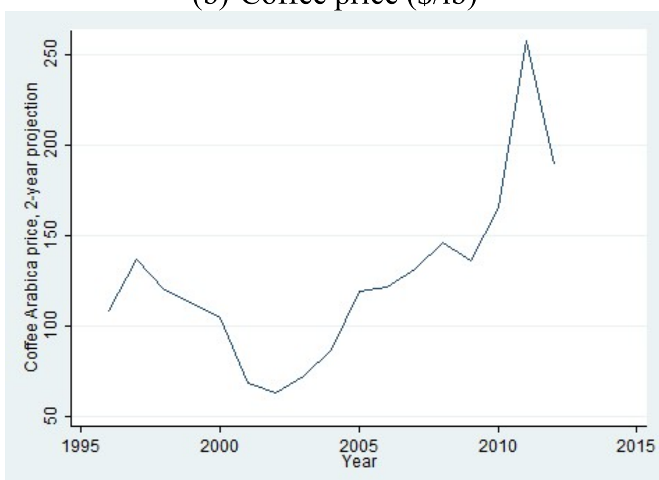
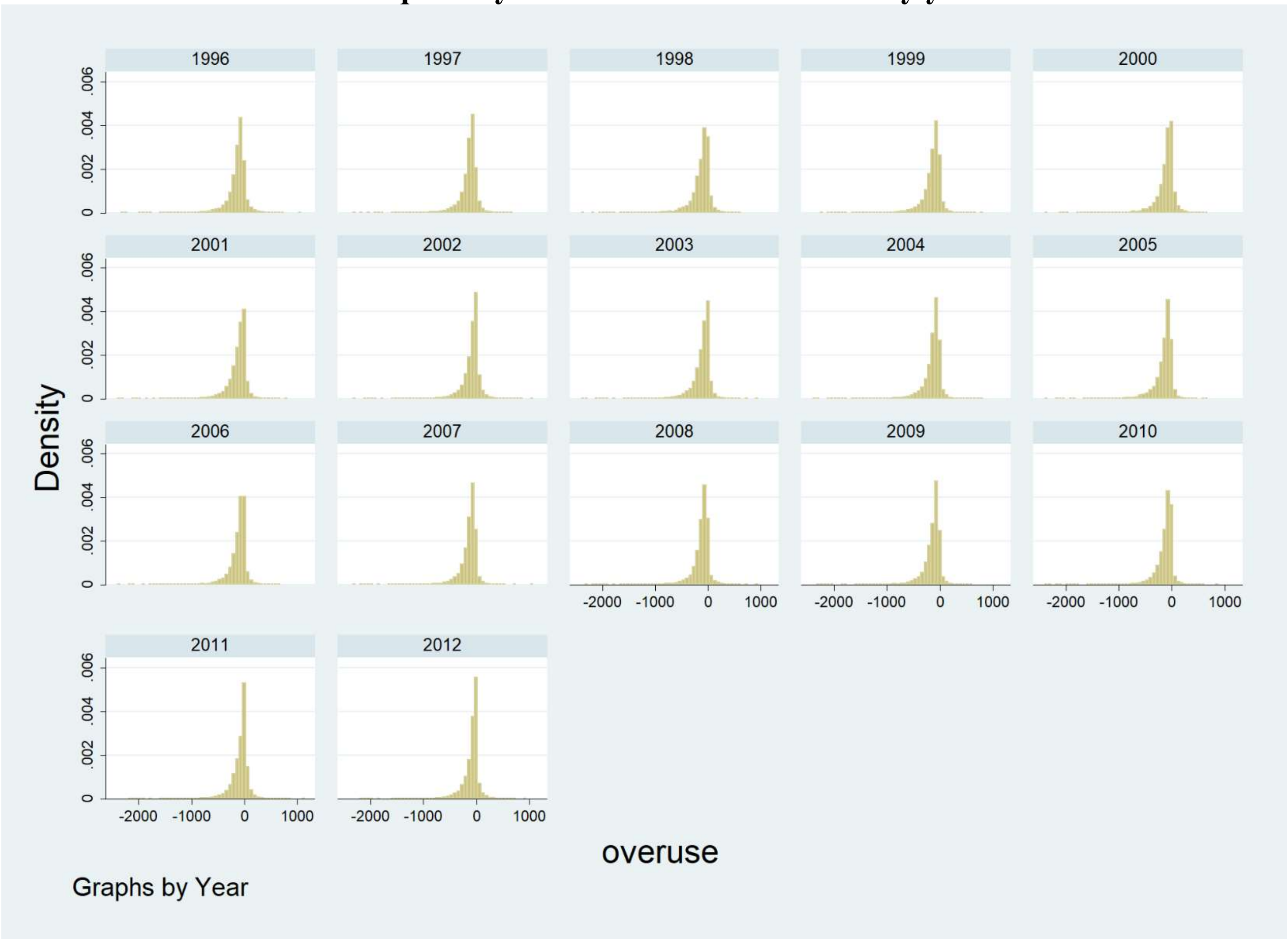


Table A2. Summary statistics for alternative futures prices

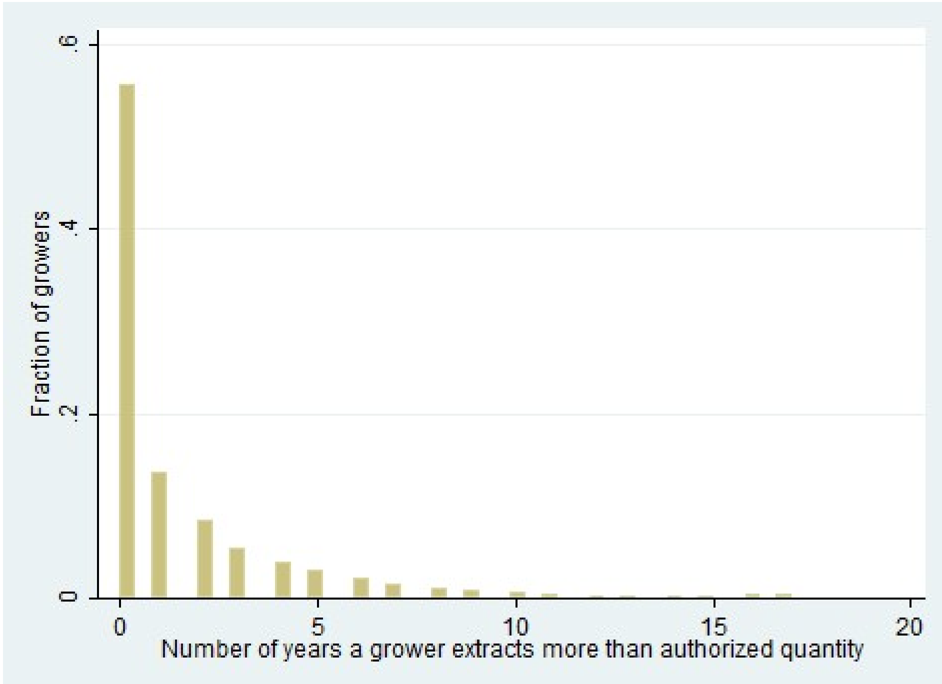
Variable	Obs	Mean	Std. Dev.	Min	Max
Corn price, 10-year projection ($/bushel)	293,342	3.13	0.65	2.35	4.65
Corn price, 9-year projection ($/bushel)	293,342	3.10	0.67	2.3	4.65
Corn price, 8-year projection ($/bushel)	293,342	3.07	0.67	2.3	4.6
Corn price, 7-year projection ($/bushel)	293,342	3.03	0.68	2.25	4.55
Sorghum price, 10-year projection ($/bushel)	293,342	2.89	0.61	2.1	4.35
Sorghum price, 9-year projection ($/bushel)	293,342	2.86	0.63	2.05	4.35
Sorghum price, 8-year projection ($/bushel)	293,342	2.83	0.64	2.1	4.3
Sorghum price, 7-year projection ($/bushel)	293,342	2.79	0.66	2.1	4.3
Soybean price, 10-year projection ($/bushel)	293,342	7.39	1.69	5.6	11.35
Soybean price, 9-year projection ($/bushel)	293,342	7.34	1.69	5.6	11.25
Soybean price, 8-year projection ($/bushel)	293,342	7.30	1.69	5.5	11.15
Soybean price, 7-year projection ($/bushel)	293,342	7.20	1.71	5.4	11
Wheat price, 10-year projection ($/bushel)	293,342	4.35	0.80	3	5.9
Wheat price, 9-year projection ($/bushel)	293,342	4.33	0.83	2.95	5.9
Wheat price, 8-year projection ($/bushel)	293,342	4.28	0.86	2.9	5.95
Wheat price, 7-year projection ($/bushel)	293,342	4.21	0.88	2.85	5.95
Diesel price, 10-year projection ($/million Btu)	293,342	13.75	7.19	7.87	28.63
Diesel price, 9-year projection ($/million Btu)	293,342	13.64	7.09	7.75	28.36
Diesel price, 8-year projection ($/million Btu)	293,342	13.55	6.97	7.79	28.12
Diesel price, 7-year projection ($/million Btu)	293,342	13.46	6.88	7.71	27.98
Electricity price, 10-year projection ($/million Btu)	293,342	21.42	3.61	17.2	28.17
Electricity price, 9-year projection ($/million Btu)	293,342	21.41	3.54	17.21	28.09
Electricity price, 8-year projection ($/million Btu)	293,342	21.41	3.50	17.32	28
Electricity price, 7-year projection ($/million Btu)	293,342	21.44	3.47	17.54	28.18
Natural gas price, 10-year projection ($/million Btu)	293,342	5.76	1.73	3.44	9.05
Natural gas price, 9-year projection ($/million Btu)	293,342	5.70	1.68	3.45	8.87
Natural gas price, 8-year projection ($/million Btu)	293,342	5.67	1.66	3.46	8.73
Natural gas price, 7-year projection ($/million Btu)	293,342	5.63	1.66	3.47	8.64

Figure A3. Water extraction minus quantity authorized for extraction by year



Notes: "Overuse" is defined as the difference between water extraction and quantity authorized for extraction, in acre-feet. We use only those grower-year observations for which the grower was authorized to extract a positive amount of water that year.

Figure A4. Number of years a grower extracts more than quantity authorized



Note: Each observation in the histogram is a grower. The number of years a grower extracts more than the authorized quantity is calculated over the period 1996-2012.

Figure A5a. Number of growers who extract more than the authorized quantity

Figure A5b. Fraction of growers who extract more than the authorized quantity

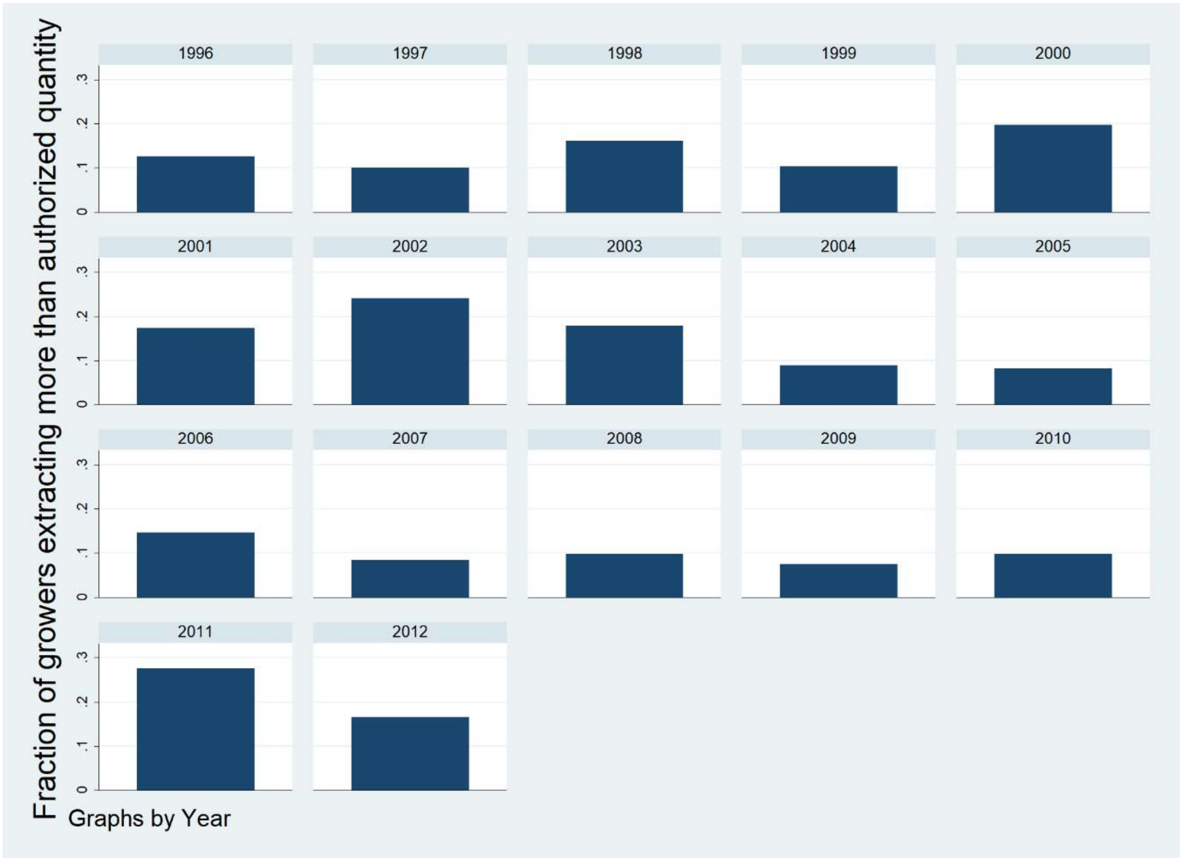


Table A3. Crop Acreage Tobit Regression Results

	Dependent variable is number of acres allocated to:				
	Alfalfa	*Corn*	*Sorghum*	*Soybeans*	*Wheat*
Dynamic variables					
Corn price, 10-year projection ($/bushel)	115.8	-38.73	319.6***	236.9***	-80.75
	(60.45)	(28.97)	(83.97)	(64.60)	(46.99)
Sorghum price, 10-year projection ($/bushel)	-131.5*	76.62*	-374.7***	-219.0**	50.81
	(63.85)	(30.50)	(88.71)	(68.04)	(49.30)
Soybean price, 10-year projection ($/bushel)	-23.25*	4.825	-69.42***	-10.39	12.47
	(11.67)	(5.608)	(16.02)	(12.49)	(9.072)
Wheat price, 10-year projection ($/bushel)	-10.16	-23.33***	101.5***	0.988	11.85
	(12.75)	(5.960)	(17.28)	(13.41)	(9.450)
Diesel price, 10-year projection ($/million Btu)	8.920***	5.374***	-21.58***	-12.14***	-4.480*
	(2.428)	(1.141)	(3.424)	(2.603)	(1.885)
Electricity price, 10-year projection ($/million Btu)	5.599	-2.065	10.92*	-1.482	1.438
	(3.350)	(1.633)	(4.682)	(3.731)	(2.553)
Natural gas price, 10-year projection ($/million Btu)	-25.32***	1.729	-40.61***	-5.421	6.474
	(7.314)	(3.538)	(10.25)	(8.031)	(5.647)
Extraction by neighbors in *t*-1 (acre-feet)	0.0316***	0.0104***	-0.0337***	-0.00502**	-0.0121***
	(0.00157)	(0.000849)	(0.00239)	(0.00190)	(0.00132)
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	-0.00644***	-0.00578***	0.00399**	-0.00264*	0.00125
	(0.00124)	(0.000625)	(0.00149)	(0.00131)	(0.000884)
Future crop prices for crops that are not grown in Kansas					
Cocoa price, 2-year projection ($/ton)	0.0394***	0.000832	0.0574***	0.0365**	-0.0292***
	(0.0112)	(0.00533)	(0.0155)	(0.0118)	(0.00870)
Coffee price, 2-year projection ($/lb)	-0.126	0.272*	-1.891***	-0.673**	0.193
	(0.245)	(0.116)	(0.333)	(0.258)	(0.187)
Authorized quantity					
Quantity authorized for extraction (acre-feet)	-0.00129	0.0162***	-0.00650	-0.0221***	0.0121**
	(0.00563)	(0.00310)	(0.00572)	(0.00568)	(0.00381)

Dummies for Previous Year's Crop Choice	Y	Y	Y	Y	Y
Crop Price Variables	Y	Y	Y	Y	Y
Controls	Y	Y	Y	Y	Y
Time Trend	Y	Y	Y	Y	Y
Grower Random Effects	Y	Y	Y	Y	Y
# Observations	242,542	242,537	242,542	242,542	242,537
# Growers	29,376	29,376	29,376	29,376	29,376

Notes: Standard errors are in parentheses. The dummies for previous year's crop choice are lagged dummy variables for each crop (alfalfa, corn, sorghum, soybeans, and wheat), indicating if that crop was planted in the previous year. The crop price variables include crop prices (alfalfa price, corn price, sorghum price, soybean price, and wheat price) from the previous year. The controls include hydrological and field characteristics (evapotranspiration, recharge, slope, soil quality, soil moisture, field size, depth to groundwater, saturated thickness), irrigation technology, energy prices (diesel price, electricity price, and natural gas price), and weather (annual average temperature, annual average temperature squared, annual precipitation, annual precipitation squared, and annual average humidity). Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$.

Table A4. Robustness: Total Marginal Effect Varying Measure of Groundwater Extraction

	TOTAL MARGINAL EFFECT $\left(\frac{dw}{dD_j}=\frac{\partial w}{\partial D_j}+\sum_c \frac{\partial w}{\partial n_c}\frac{\partial n_c}{\partial D_j}\right)$	
	(A, Base)	(B)
Groundwater extraction w:	*Extraction intensity (acre-feet per acre)*	*Extraction (acre-feet)*
Dynamic variables D_j		
Corn price, 10-year projection ($/bushel)	0.3798	54.999
	(0.2337)	(42.388)
Sorghum price, 10-year projection ($/bushel)	-0.2347	-21.386
	(0.2418)	(46.048)
Soybean price, 10-year projection ($/bushel)	0.0054	-1.406
	(0.0412)	(8.175)
Wheat price, 10-year projection ($/bushel)	-0.2222***	-37.634***
	(0.0466)	(10.531)
Diesel price, 10-year projection ($/million Btu)	0.0648***	10.812***
	(0.0118)	(2.481)
Electricity price, 10-year projection ($/million Btu)	-0.1120***	-18.412***
	(0.0114)	(1.898)
Natural gas price, 10-year projection ($/million Btu)	0.0904***	6.966
	(0.0216)	(4.645)
Extraction by neighbors in *t*-1 (acre-feet)	0.00013***	0.0248***
	(1.20E-05)	(0.00345)
Quantity authorized for extraction by neighbors in *t*-1 (acre-feet)	-1.99E-05**	-0.0077***
	(6.24E-06)	(0.0012)
Future crop prices for crops that are not grown in Kansas		
Cocoa price, 2-year projection ($/ton)	3.22E-05	0.0096
	(4.39E-05)	(0.0079)
Coffee price, 2-year projection ($/lb)	0.0006	-0.0063
	(0.0009)	(0.2023)

Notes: Standard errors are in parentheses. Specification (A) is the same base-case Specification (A) that is in Table 7, and is calculated using the groundwater extraction regression results from the base-case Specification (1) in Table 2, and the crop acreage regressions results in Table A3 in the Appendix. Specification (B) is calculated using the groundwater extraction regression results from Specification (2) in Table 3, and the crop acreage regressions results in Table A3 in the Appendix. The number of acres n_c planted to each crop c is in acres. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.