Land Market Valuation of Groundwater

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Title

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Abstract: This paper takes the hedonic price model approach to determine the implicit values of irrigation and groundwater in-storage for irrigated parcels over the Kansas portion of the High Plains Aquifer. Exploiting a unique set of land sale transaction data coupled with spatially explicit hydrological characteristics, we estimate that the water value component of irrigated land sales transactions account for about 55% of the total sale price. We estimate the capitalized value of saturated thickness of the underlying aquifer to be \$1.3/ft. Our results imply that estimated land value premiums capitalized the Kansas High Plains Aquifer groundwater at approximately \$5 billion.

Introduction

Water resources are fundamental to agricultural production in arid parts of the world such as the California Central Valley, Great Plains region of the United States, and many parts of Asia. Increasingly, irrigation water for agriculture is sourced from aquifers (Wada, et al., 2010). In the United States, over 56 million acres of agricultural land is irrigated and approximately 60% of this total is irrigated from groundwater (Siebert, et al., 2010). Growing dependence of agricultural production on groundwater is causing rapid depletion of large aquifers, however. In the United States, depletion of the Kansas portion of the High Plains Aquifer is particularly problematic.

It is difficult to directly observe the marginal value of groundwater used in agriculture due to a general lack of competitive water markets. One approach to assess the value of groundwater irrigation is to use calibrated programming models (Howitt, 1995) that identify optimal inputs given limitations to irrigation water (Koundouri, 2004 reviews the literature). The value of irrigation is obtained as a shadow value of the optimization program. An alternative approach to estimating the value of groundwater irrigation is to use revealed preference methods. A commonly used revealed preference method is the hedonic price model, which obtains an implicit valuation of the focal characteristic (e.g. irrigation) as a differentiated attribute of farmland (Rosen, 1974).

This paper takes the hedonic price model approach to determine the implicit values of irrigation and groundwater in-storage for irrigated parcels. In particular, we combine a unique set of land sale transaction data with spatially explicit hydrological characteristics for the Kansas portion of the High Plains Aquifer to analyze the effects of groundwater availability on land values. Spatial and temporal variation in depth to water across the aquifer are exploited to analyze impacts of changes in saturated thickness (i.e. groundwater stocks) on land values. Kansas is a top 10 national producer of wheat, grain sorghum, and grain corn and the High Plains Aquifer is the main source of irrigation used in agricultural production. Secure availability of irrigation water, therefore, has direct policy relevance and information on the value of irrigation water is consequential to public policy makers in Kansas and elsewhere.

The hedonic price model approach has been used to evaluate a wide range of environmental policies, from the Clean Air Act (Chay, et al., 2005) to Superfund (Greenstone and Gallagher, 2008). Hedonic modeling has also been undertaken to evaluate the effects of water quality on residential real estate (Leggett and Bockstael, 2000, Walsh, et al., 2017), the effects of climate on agriculture (Mendelsohn, et al., 1994, Schlenker, et al., 2005, Ashenfelter and Storchmann, 2010), and the economic impact of changes in groundwater supplies on agricultural land values (Faux and Perry, 1999, Mendelsohn and Dinar, 2003, Schlenker, et al., 2007, Hornbeck and Keskin, 2014). With respect to hedonic analyses of agricultural groundwater, the literature has produced mixed conclusions. For instance, Torell et al. (1990) and Hornbeck and Keskin (2014) find a statistically significant relationship between groundwater and farmland values while neither Schlenker et al. (2007) nor Mendelsohn and Dinar (2003) find statistical significance. Recently, there has been a surge of methodological studies on how spatial measurement of localized amenities affects hedonic estimates (Abbott and Klaiber, 2011, Gamper-Rabindran and Timmins, 2013). A related literature has demonstrated the use of quasi-experimental techniques to control for time-variant and time-invariant omitted variables (Kuminoff, et al., 2010, Klaiber and Smith, 2013).

This paper provides several innovations to the existing literature. First, rather than relying on land values from county-level census data (e.g. Hornbeck and Keskin, 2014), we are able to exploit a unique set of parcel-level transaction data from the Property Valuation Division (PVD) of the Kansas Department of Revenue (Fig. 1). Second, the period of our analysis is 1988 to 2015, which is both a longer and a more recent period of analysis than previous studies of the High Plains Aquifer (e.g. Torell, et al., 1990). Third, we are able to exploit a rich set of highly spatially resolved data on soil, weather, and hydrologic characteristics that plausibly affect agricultural land values and evolution of the aquifer (see Figure 1 for saturated thickness heterogeneity).

We find that agricultural land values are 55% higher for irrigated parcels than non-irrigated parcels on average. In contrast to recent literature on the High Plains Aquifer (e.g. Hornbeck and Keskin, 2014), we find evidence that farmland irrigation premiums have increased in recent years (i.e. 2006-2015). We also estimate the capitalized value of saturated thickness (a measure of the stock of groundwater available for future irrigation) in farmland sales. A parcel having saturated thickness 100 feet below the mean is estimated to have a 17% lower land value. The average value that water in-storage contributes to the price per acre of farmland is about $1.3/ft. Our results imply that estimated land value premiums capitalized the Kansas High Plains Aquifer groundwater at approximately $5 billion.

In the next section, we provide background on the Kansas High Plains Aquifer and further literature review. Following that, we develop a conceptual model of groundwater valuation to motivate our empirical approach. In the following section, we present our empirical strategy. We then describe the data. Following the data section, we present baseline results along with exploring temporal and spatial patterns in groundwater valuations. We then test robustness of the results to alternative functional form specifications. The paper concludes with a brief discussion.

Study area and background

Our study area is the state of Kansas, where production agriculture relies heavily on groundwater irrigation from the High Plains Aquifer. Kansas ranks in the top 10 nationally in wheat, grain sorghum, and grain corn production. Current irrigation water withdrawals from the Kansas High Plains Aquifer are about 3.5 million acre-feet annually, which are used to irrigate about 3 million acres. Recharge of the aquifer is low relative to the annual withdrawals and water tables have dropped substantially since predevelopment (see Figure A1). Secure water availability for agriculture is a significant concern going forward.

Rights to groundwater in Kansas are both appurtenant to and severable from the land (K.S.A. 82a-701(g)). This means that a water right holder may sell the land with the appurtenant water right. Land transactions with an appurtenant water right are the most straight forward and do not require approval of the state chief engineer. A holder may also sell the land but retain the water right. However, land transactions with a severable water right can present onerous transactions costs if the water right is to be exercised in a different location. Water rights in Kansas are limited in several important ways. First, a water right is limited in maximum annual quantity (i.e. acre-feet) and rates of withdrawal (i.e. gallons per minute) (K.S.A. 82a-701(f)). Second, the water can only be put to beneficial use within authorized locations (K.S.A. 82a-712). Third, the water can only be withdrawn from authorized points of diversion (K.S.A. 82a-701(f)). Any proposed change must demonstrate that it will not materially injure a more senior right. Additionally, a holder seeking to make a change to the water right must demonstrate that the change will pertain to the "same local source of supply" authorized in the original right (K.S.A. 1987 Supp. 82a-708b (a)(3)). The state chief engineer has a stringent policy pertaining to "local" as one-quarter mile or less within the same aquifer.

There is a rich literature in agricultural and environmental economics investigating farmland amenity values through stated and revealed preference (Bergstrom and Ready, 2009 reviews the literature). Previous work has demonstrated that the availability of groundwater for agricultural production has affected land values in the High Plains Aquifer region (Lee and Bagley, 1972, Torell, et al., 1990, Hornbeck and Keskin, 2014, Jenkins, et al., 2017). Related research has demonstrated the significance of irrigation to agricultural land values in broader contexts (Xu, et al., 1993, Darwin, 1999, Faux and Perry, 1999, Mendelsohn and Dinar, 2003, Buck, et al., 2014). One of the earliest studies to document the implicit value of irrigation water in Kansas is Lee and Bagley (1972), who estimate a value of approximately \$600/acre (after converting to present dollars) using farmland sales price data for southwestern Kansas. Torrell et al. (1990) use data for the five states overlying the Ogallala Aquifer and find irrigation premiums ranging from \$500 to \$1,300 per acre and that the premiums declined over the study period (1979-1986). More recently, Jenkins et al (2017) find that distinctions in water marketing rights across the states overlying the High Plains Aquifer generate differences to the implicit value of groundwater for agriculture.

Conceptual model of aquifer water value

While the objective of the paper is empirical, we develop a simple theoretical model of groundwater valuation to complement our later empirical approach. Land rents for a plot in period t are a function of irrigated water, $R\big(I(t)\big)$, and the cost of irrigation, which is a function of saturated thickness, $c\big(W(t)\big) \times I(t)$. As saturated thickness declines, the distance the water must be lifted out of the aquifer increases, requiring greater energy expenditures in the process. A potential parcel owner recognizes that irrigable land comes with a stock of groundwater. The objective of a potential parcel buyer is to evaluate the contribution of irrigation water to the present value of rents from agriculture:

$$\max_{I(t)} \int_0^T e^{-\rho t} \Big(R\big(I(t)\big) - c\big(W(t)\big) \times I(t) \Big)\, dt \tag{1}$$

Objective function (1) is subject to the evolution of the aquifer's saturated thickness over time. In particular, the saturated thickness grows at the natural rate of recharge σ, declines from pumping withdrawals on the plot at the constant rate γ, and declines due to outflow to neighboring plots at a constant proportional rate δ. The equation of motion for the saturated thickness is:

$$\dot{W}(t) = \sigma - \delta W(t) - \gamma I(t) \tag{2}$$

Combining (1) and (2) into a Hamiltonian gives:

$$H = e^{-\rho t}\Big(R\big(I(t)\big) - c\big(W(t)\big) \times I(t)\Big) + \lambda(t)\big(\sigma - \delta W(t) - \gamma I(t)\big) \tag{3}$$

Optimal functions of I, W, and λ will satisfy (2) and the following necessary conditions:

$$H_{I(t)} = e^{-\rho t}\left(\frac{\partial R\big(I(t)\big)}{\partial I(t)} - c\big(W(t)\big)\right) - \gamma\lambda(t) = 0 \tag{4}$$

$$-H_{W(t)} = e^{-\rho t}\frac{\partial c\big(W(t)\big)}{\partial W(t)} I(t) + \delta\lambda(t) = \dot{\lambda}(t) \tag{5}$$

From (4), we derive a condition that the net marginal benefit from irrigation equals the user cost of reduced saturated thickness contemporaneously at time t along the optimal path:

$$\frac{\partial R\big(I(t)\big)}{\partial I(t)} - c\big(W(t)\big) = e^{\rho t}\gamma\lambda(t) \tag{6}$$

Condition (5) relates to the rate of change of the user cost of saturated thickness. From (5), subtract $\delta\lambda(t)$ from both sides, multiply by the integrating factor $e^{-\delta t}$, and integrate using the transversality condition $\lambda(T) = 0$ to give:

$$e^{-\delta t}\lambda(t) = \int_t^T e^{-(\rho+\delta)s}\frac{\partial c\big(W(s)\big)}{\partial W(s)} I(s)ds$$

Because saturated thickness is declining over time at the proportional rate δ, at each time $s > t$ a unit of saturated thickness contributes $e^{-\delta s}$ of what was contributed at time t. Rearranging, we obtain the solution to the costate equation, which is the marginal valuation of saturated thickness at time t:

$$\lambda(t) = e^{\delta t}\int_t^T e^{-(\rho+\delta)s}\frac{\partial c\big(W(s)\big)}{\partial W(s)} I(s)ds \tag{7}$$

From (7), we see that the marginal value that saturated thickness contributes to land rents is realized through irrigation pumping cost savings (i.e. from having marginally greater saturated thickness). Using the above, the value to land rents at time t from a marginal unit of saturated thickness is the discounted stream of marginal cost savings it generates from the present until terminal time T:

$$e^{\rho t}\lambda(t) = \int_t^T e^{-(\rho+\delta)(s-t)} \frac{\partial c(W(s))}{\partial W(s)} I(s)ds \tag{8}$$

Using (6) together with (8) gives the condition that the marginal benefits from irrigation equal the marginal cost of pumping in addition to the discounted stream of user costs associated with decreased saturated thickness:

$$\frac{\partial R(I(t))}{\partial I(t)} = c(W(t)) + \gamma \int_t^T e^{-(\rho+\delta)(s-t)} \frac{\partial c(W(s))}{\partial W(s)} I(s)ds \tag{9}$$

Empirical strategy

We model land values in a hedonic pricing framework. The premise of the hedonic model is that the i^{th} parcel is a good composed of a bundle of observable attributes $\mathcal{Z}_i$ (Rosen, 1974). Of particular significance is that in hedonic analysis the price of agricultural land equals the net present value of economic rents from agriculture. Additionally, the price of the stock of groundwater below a parcel as a differentiated attribute is the shadow value in terms of net present value (i.e. condition (8)). Let the real price per acre for $\mathcal{Z}_i$ as a function of its attributes, be $P(\mathcal{Z}_i)$. The $\mathcal{Z}_i$ vector in this analysis is composed of various subvectors over the following characteristics: irrigation z_{IRR}, saturated thickness z_W, other aquifer characteristics z_{AQ}, soils characteristics z_S, long-run location-specific weather z_C, characteristics of water rights appurtenant to the parcel z_{WR}, and urban influence characteristics z_D. In total, the observed price in the market for $\mathcal{Z}_i$ is represented by:

$$P(\mathcal{Z}_i) = P(z_{IRR}, z_W, z_{AQ}, z_S, z_C, z_{WR}, z_D) \tag{10}$$

The market value of irrigated parcels and marginal impact of saturated thickness on parcel price can be obtained from function (10). Hedonic theory does not indicate a strict functional form that ought to be used in the hedonic pricing model. The semi-log is a commonly used functional form because of the ease of interpreting coefficients as proportional change and also to handle binary variables, though there are others which we describe in more detail below. We specify that the value of irrigated land is equal to the discounted present value of the future stream of earnings from the land and groundwater. Adding to this the value of the other associated hedonic characteristics in (10), we obtain the following form for parcel i evaluated in the base year:

$$P_{i,0}^{IRR} = \int_{t=1}^{T} e^{-\rho t} \left(R_i^W(t) + R_i^{IL}(t) \right) dt + \nu_i \tag{11}$$

where $P_{i,0}^{IRR}$ is the observed land price per acre for irrigated parcel i in year 0. We express $P_{i,0}^{IRR}$ as three parts: (i) the present value of rents from the water resource (R_i^W), (ii) the present value of rents from irrigated production (R_i^{IL}), and (iii) the value of all other income and price influences from ν_i.

The price for non-irrigated parcels is expressed as:

$$P_{i,0}^{NIRR} = \int_{t=1}^{T} e^{-\rho t} R_i^{DL}(t) dt + \nu_i \tag{12}$$

where $P_{i,0}^{NIRR}$ is the observed land price per acre for non-irrigated parcel i in year 0 and R_i^{DL} is the present value of rents from dryland production.

The data used in R_i^W is saturated thickness of the aquifer (W). We allow for declining marginal value of the stock of groundwater by specifying a quadratic form for saturated thickness. The data composing R_i^{IL} include various soils, hydrology, climate, and water right characteristics, the details of which are provided below (denoted IL for irrigated lands). The data composing R_i^{DL} include soils and climate characteristics (denoted DL for dryland). The vector ν_i includes measurements for distance to major population centers and the proportion of the parcel that is grassland. Taken together, the estimating equation for the real price per acre for parcel i in year t is:

$$\ln \frac{Price}{Acre}_{i,t} = \beta_1 W_{it} + \beta_2 W_{it}^2 + \Phi' IL_{it} + \xi' DL_{it} + \Omega' \nu_i + \eta_l + \tau_{d,t,q} + \epsilon_{it} \qquad (13)$$

Agricultural district by year by quarter fixed effects $\tau_{d,t,q}$ are included in all specifications to control for spatial-temporal factors influencing land sales prices (e.g. commodity price fluctuations). Spatial fixed effects, η_l, are used to control for time-invariant unobserved heterogeneity in land prices. Our scale of spatial fixed effects ranges from no controls to controlling at range-township-level (i.e. 575 spatial units). In order to make predictions of the model in levels more attractive and to avoid potential bias from OLS estimates of the log-linearized model (e.g. Silva and Tenreyro, 2006), we estimate (13) using a generalized linear model (GLM) with a log link function and sandwich variance estimator. That is, define $\mu = E\left(\frac{price}{acre}\right)$ and $\zeta = g(\mu) = \ln \mu$. Then, $g(\mu)$ maps $E\left(\frac{price}{acre}\right)$ to $\zeta = \beta_1 W_{it} + \beta_2 W_{it}^2 + \Phi' IL_{it} + \xi' DL_{it} + \Omega' \nu_i$.

Consideration of functional form

Hedonic price theory does not provide guidelines for functional form in empirical applications. The Box-Cox transformation is a commonly used method to test several different popular specifications. Cropper et al. (1988) use simulation to show that with no omitted variables, linear and quadratic Box-Cox transformed variables provide the best goodness-of-fit in estimating hedonic price functions. However, when mis-specification is a possibility, then simple linear, semi-log, and Box-Cox linear outperform quadratic and Box-

Cox quadratic functions (Cropper, et al., 1988). Based on the evidence in Cropper et al. (1988) and concerns for omitted variables, many studies have relied on simple functional forms (Kuminoff, et al., 2010 reviews the literature). This includes the study by Torell et al. (1990), who estimate the value of water in-storage most directly comparable to our own estimates. In order to build off of existing studies, we consider the semi-log specification as the relevant baseline functional form. To test the sensitivity of our results to functional form, we also estimate Poisson and Box-Cox models in later sections.

Data

The data used for our estimation are drawn from multiple sources. Information about groundwater use rights and irrigation are obtained from the Water Information Management and Analysis System maintained by the Kansas Division of Water Resources and are spatially matched to the coordinates of the parcel. Our regression specifications include information on maximum permissible amounts of irrigated acres and acre feet of extraction. As mentioned earlier, it is possible for a water right to be severable from the land. However, water rights transactions that are separate from land title transactions are accompanied by substantial permitting burdens. For this reason, we make the assumption that any water rights are appurtenant to the land transaction.

Soils

Spatially explicit soils characteristics likely to affect rents to dryland and irrigated parcels are obtained from the SSURGO soil survey on the website of the USDA Natural Resource Conservation Service (NRCS). These characteristics include detailed information on soil composition and water storability. Our regression specifications include the following soil characteristics as controls: proportion of cropland with pH less than 6 (acidic soils), proportion of cropland with pH greater than 7.5 (basic soils), plant available water storage, and soil organic carbon. These soil characteristics were chosen to represent agricultural productivity and water storability.

Soils with a pH less than 6 or greater than 7.5 are known to affect crop yields (USDA Natural Resource Conservation Service, 1998). We expect negative coefficients on these variables. Greater plant available water storage allows the grower to schedule irrigation activities over longer intervals. We expect positive coefficients on this variable. We likewise expect a positive coefficient on soil organic carbon.

Hydrology

Spatially explicit hydrology characteristics for the High Plains Aquifer are obtained from The Kansas Geological Survey. These variables include the following: hydraulic conductivity and saturated thickness at five-year intervals. We do not obtain well capacity data. However, well capacity is likely to be a mixed function of saturated thickness and hydraulic conductivity. Greater hydraulic conductivity should lower pumping costs, as water moves more freely across porous spaces of the aquifer. Saturated thickness is our measure of the stock of availability groundwater beneath the parcel. We expect positive coefficients on hydraulic conductivity and saturated thickness.

Climate

Climate data at the county level are obtained from PRISM using the method described in Schlenker and Roberts (2009). We construct four climate variables for each county: average precipitation during the growing season, the average number of annual degree days over 10 degrees Celsius, the average number of annual degree days greater than 32 Celsius (heat levels that are detrimental to crop growth (Schlenker, et al., 2006)), and average reference evapotranspiration during the growing season.

Urban Influence

We compute the commute time to the nearest towns having populations of at least 10,000 and 40,000. We truncate the commute time ceilings at 30 minutes with the rationale that close proximity to towns is likely to impart a premium, while longer commute times are unlikely to have an impact.

Land Transactions

A unique aspect of our research is parcel-level sales data for every land transaction in Kansas from 1988 to 2015 (Fig. 1). We restrict our analysis to arms-length transactions to ensure accurate reflections of fair market values. In total we have data on 12,965 unique parcels and 15,779 transactions. Our PVD sales data include information on total amount of sale, estimates of dollar amount improvements to land, and acres of the parcel that are dryland, irrigated, or grass. All prices are converted to 2015 dollars using the consumer price index.

We spatially merge PVD sales data to the soils, hydrology, and water right data. We also merge long-run weather information from PRISM Climate Group to the PVD data. The sample period used in the analysis is 1988-2015. Table 1 presents summary statistics of the variables used in model estimation.

Sample Selection

Our farmland sales data are limited to parcels overlying the spatial extent of the High Plains Aquifer (Fig. 1). The dataset is limited to arm's length sales in order to more accurately represent market values. We drop parcels having multiple sales within the same month. We also omit parcels with reported sales prices per acre in the upper or lower one percentiles.

The dependent variable is the real price per acre excluding improvements (measured in 2015 dollars).

Results

We center all continuous independent variables so that the coefficient on the irrigated parcel dummy can be interpreted as the effect of irrigation on land values having average irrigation characteristics. The main results of the analysis are summarized in Table 2, which presents primary results using GLM with a log link. The dependent variable in all specifications is the log of the real price of land and the focal independent variables are a dummy variable for whether the parcel is irrigated (irrigated parcel) and saturated thickness of the aquifer. We allow for declining marginal value of water in-storage by specifying saturated thickness as a quadratic. All specifications control for unobserved spatial-temporal variation such as commodity price shocks by including agricultural district by year by quarter dummies (see Fig. A2 for agricultural district locations). In column 1, we present point estimates when no spatial controls for time-invariant heterogeneity are included. In column 2, we control spatial heterogeneity by including dummies for the 33 counties in our study area. In column 3, we present point estimates when county subdivision-level dummies are included. County subdivisions are defined by the US Census Bureau and are delineated for the purpose of reporting census data. There are 244 county subdivisions in our study area. Column 4 uses range-township dummies to control for time invariant heterogeneity at a finer scale (575 townships in the study area).

Looking across specifications, our results provide clear evidence of an irrigation premium in land sales transactions. Regardless of whether we include county or range-township controls, the point estimate on irrigated parcels is positive and economically and statistically significant at 0.01. The coefficient on irrigation is presented as a semi-elasticity. Thus, parcels that are irrigated fetch about a 55% premium over dryland parcels.

The other focal independent variable is saturated thickness, which is a measure of water in-storage for parcels having irrigation rights. The coefficients on saturated thickness and its square indicate there are slight diminishing marginal valuations of water in-storage. This pattern is repeated across specifications. For ease of interpretation, we convert the semi-elasticities in Table 2 to model predictions for valuations at different levels of saturated thickness. These are presented in Table 3 and saturated thickness are given in levels relative to the cross-sectional mean saturated thickness. Thus, a saturated thickness of 0 ft represents average saturated thickness for irrigated parcels. Columns 1-4 of Table 3 correspond to the saturated thickness point estimates in columns 1-4 of Table 2. Using the specification in column 4, a parcel that has a saturated thickness 100 ft below average procures a price that is about 17% lower ($471/acre) than an otherwise equivalent parcel having average saturated thickness and this difference is statistically significant at 0.01. For a parcel having saturated thickness 100 ft above average, the implicit price is about 12% higher than the average and this difference is significant at 0.01.

Our estimates provide evidence of diminishing marginal value of water in-storage (Fig. 2). Average saturated thickness for irrigated parcels is about 164 ft and the average annual drawdown during our period of analysis is about 1 ft/year. Using the Kansas Geological Survey method of estimating aquifer usable lifetime (Schloss, et al., 2000), this suggests a time to depletion of about 130 years for the average saturated thickness. By comparison, saturated thickness of 100 ft below average would only provide about 30 years of usable lifetime. Our estimates also indicate that the average per-acre capitalized value of water in-storage for perpetuity is about $1.30/foot.

Our results highlight the role of other land and climate characteristics in determining land prices. As expected, greater soil organic carbon increases parcel prices. The effect of soil organic carbon does not appear to be different for irrigated and non-irrigated land. Precipitation generally does not affect farmland prices in meaningful ways net of the agricultural district by year by quarter dummies. For our preferred specification in column 4, increased degree days between 10 and 32 Celsius (i.e. favorable growing conditions) lead to increased parcel prices while increased degree days over 32 Celsius (i.e. unfavorable conditions) lead to decreased parcel prices.

Land Values and Irrigation Premiums Over Time

Prior research has questioned whether implicit prices can be treated as time invariant when evaluating over long time periods (Kuminoff, et al., 2010). We explore whether the implicit irrigation premiums should be regarded as time invariant due to the relatively long 28-year period of analysis (1988-2015). For instance, our land transaction data covers the food commodity price boom of the late 2000s. Between 2002 and 2008, price indexes for basic crops (wheat, rice, corn, soybeans) rose over 220%, compared with a 130% increase for overall food commodities (Trostle, 2011). The left panel of Figure 3 presents a plot of the predicted real price per acre for non-irrigated and irrigated parcels for each year of the study period using the specification in column 4 of Table 2. Price trends are summarized by slight increases from 1988-2005 and more dramatic increases from 2006-2015. Estimated irrigation premiums are fairly constant between $800/acre and $1,100/acre from 1988 to 2005 (Fig. 3, right panel). From 2006 to 2015, irrigation premiums increase from about

$1,300/acre to $2,400/acre. We also break out plots of predicted price per acre by irrigation status for the five agricultural districts in our study area in Figure A3.

We conduct a series of tests to explore time variability in greater detail. First, to explore statewide differential rates of growth in the real prices of non-irrigated and irrigated parcels, we interact a time trend with the irrigation dummy. Note that there is little temporal variation left after controlling for agricultural district by year by quarter effects, so we drop these controls in favor of the trend interaction. Results of interacting a statewide trend with the irrigation dummy are presented in column 1 of Table 4 (full results reported in Table A3). We find that on average the real price per acre for non-irrigated parcels have grown at a rate of 3.4% per year while irrigated parcels have grown at a rate of 4.0% per year. A Wald test indicates the difference in price trends is statistically significant at 0.05.

In column 2 of Table 4, we estimate a model where the irrigation dummy is interacted with time trends that are specific to the five agricultural districts in our study area (Fig. A2) (full results reported in Table A3). We find that in districts 30 (southwest Kansas) and 60 (southcentral Kansas), the annual real price growth for irrigated parcels outpaced non-irrigated parcels and the difference is statistically significant at 0.01. Conversely, for districts 10 (northwest Kansas), 20 (western Kansas), and 50 (central Kansas) there was no statistical difference in the growth of real prices.

Third, we estimate a model in which we interact the irrigation dummy with year-specific dummy variables and present results in Figure A4. We find that the implicit irrigation premium for the years 1988-2000 was generally constant. For 2004-2015, we find that the implicit price premium for these years are statistically larger than the baseline year of 1988. The results suggest that the value of irrigated parcels relative to non-irrigated parcels have been growing over time for the last 15 years of the sample period.

Spatial Heterogeneity in Irrigation Premiums

There is increasing interest in agriculture-agriculture and agriculture-urban water transfers (Colby, 2000, Wheeler, et al., 2016). In Kansas, municipalities are targeting agricultural water rights to satisfy increasing water demand. For instance, the City of Hays in northwest Kansas purchased 30 water rights with entitlements exceeding 2,000 acre-feet from the 7,000 acre R9 Ranch with the intention of using the water to supplement the City's water supply (Ogle, 2018). Elsewhere, groundwater trading activities within agriculture are already occurring in Nebraska and regulations in the Texas Edwards Aquifer allow groundwater trading (Wheeler, et al., 2016).

If a single price for groundwater were to emerge from well-functioning water markets, it seems clear that irrigators facing the lowest irrigation premiums would be the first to explore transfers. We investigate spatial heterogeneity in county-level irrigation premiums by separately estimating equation (13) for the 33 counties in our study area. We provide a map of estimated irrigation premiums at the county-level in Figure 4. We find a pattern of the highest premiums in the southwest and southcentral portion of the state, consistent with these counties having large corn and soybean yields and also having greater saturated thickness. Counties in the west and northwest portion of the Kansas High Plains Aquifer have consistently lower estimated premiums.

Water Values Comparison

The study by Torell et al. (1990) provides estimates of the value of water in-storage most directly comparable to our own estimates. For Kansas, Torell et al. (1990) estimate an irrigation premium of 43% and an average value of water in-storage of approximately $4.90. They also found that irrigation premiums and water value fell throughout their study period (1979-1986). By comparison, we obtain a similar estimate for the irrigation premiums (55%) but a smaller value of water in-storage ($1.27).

Using county data, Hornbeck and Keskin (2014) show that the irrigation premium for the High Plains Aquifer was approximately constant from 1980 to 2002. By comparison, by exploiting more recent and more detailed data from Kansas, we show that the irrigation premium has been increasing in recent years. Hornbeck and Keskin also find that the effect of access to the High Plains Aquifer on land values is higher in counties with lower average annual rainfall. Rainfall gradients in Kansas are typified as being dry in the west and wet in the east, with little latitudinal variation (Fig. A5). Differences in average county precipitation therefore do not appear to explain the county-level heterogeneity in irrigation premiums that we find (Fig. 4). Additionally, while we do find that the interaction term between irrigation and average growing season precipitation is negative in most specifications (Table 2), the effect is not statistically significant. We attribute these differences to having more precise controls over unobserved spatial, temporal, and spatial-temporal heterogeneity than Hornbeck and Keskin.

Hornbeck and Keskin also provide estimates of the implied value of the High Plains Aquifer over time using county-level land values weighted by the share of county land overlying the High Plains Aquifer. They estimate that total valuation of the groundwater peaked at about $33 billion in 1964 and declined to about $13 billion in 2002 (expressed in 2015 dollars using the Consumer Price Index). Consistent with the calculation by Hornbeck and Keskin, we estimate the total valuation of the Kansas High Plains Aquifer over time by multiplying the land value premium from groundwater irrigation by the total number of acres irrigated over the High Plains Aquifer (obtained from WIMAS). Irrigated acres over the Kansas High Plains Aquifer increased from about 2.2 million acres in 1988 to about 3 million acres in 2015. We estimate that the value of High Plains Aquifer groundwater in Kansas fluctuated around $2.0-2.5 billion from 1988 to 2005 and then increased from about $2.5 billion to $5 billion from 2006 to 2015.

Alternative Functional Forms

We perform several sensitivity checks to the log-linear specification used in our main analysis. In Table A1 we report coefficient estimates from a Poisson regression with robust standard errors (which relaxes the assumption that variance and expected value of the dependent variable are equal). All coefficients are given in incident rate ratios, thus providing how a change in the independent variable affects the rate ratio of land sales. The log linear regression can lead to inconsistent estimates (Silva and Tenreyro, 2006) and estimating the Poisson via maximum likelihood is a convenient alternative because multiplicative adjustments are not needed for converting partial effects and predictions from logs to levels. Table A2 reports predicted valuations at varying levels of saturated thickness and the average marginal effect of saturated thickness on land value. In sum, the results are entirely consistent with the main analysis.

Kuminoff et al. (2010) review 123 hedonic studies published between 1988 and 2008. In their review, Kuminoff et al. (2010) emphasize that flexible specifications such as the Box-Cox may outperform more common specifications like the linear or semi-log when spatial fixed effects are included. Additionally, Crouter (1987) recommends flexible methods like

Box-Cox to identify functional form when water is not appurtenant to the land (i.e. separable from the land).

Because water rights can be considered appurtenant to the land in our setting and unobserved spatial heterogeneity is a possibility, we use the Box-Cox procedure to test sensitivity of our baseline specification assumption. In particular, we test sensitivity of the semi-log specification of the hedonic price function.[1] Using the Box-Cox model and adapting equations (10) and (11), letting θ be the transformation parameter on the dependent variable, the regression equations for observing the real sale price per acre of parcel i in a given year are:

$$P_i^{\theta} = \beta_1 z_{1i} + \cdots + \beta_k z_{ki} + \eta_l + \psi_q + \epsilon_i \tag{14}$$

where $P_i^{\theta} = \frac{price}{acre}$ if $\theta = 1$, $P_i^{\theta} = \ln\left(\frac{price}{acre}\right)$ if $\theta = 0$, and $P_i^{\theta} = \frac{1}{\frac{price}{acre}}$ if $\theta = -1$.

A Box-Cox regression model suggests a best fitting value of $\theta = 0.104$. We estimate the implicit premium of irrigated land relative to non-irrigated land using the optimal Box-Cox transformation and compare to the baseline semi-log (Fig. A6). In short, both models generate similar estimates, which is not surprising given how close the optimal θ is to zero. Estimating the hedonic model with the price and saturated thickness variables transformed via the optimal θ presents an important issue of interpretation. Here, we opt to use the Box-

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[1] Performing Box-Cox transformations on the focal independent variable (saturated thickness) is problematic for two reasons. First, as mentioned previously, we center the continuous independent variables for ease of interpretation of the implicit value of irrigation relative to dryland (predicted implicit irrigation premium for otherwise equivalent parcels having zero saturated thickness is neither interesting nor realistic). Second, optimal transformation of single-variable predictors then raises the question of simultaneous estimation of optimal transformations of the interactions terms that depend on those variables.

Cox method as guidance to one of the more economically sensible specifications. The value of θ maximizing likelihood score is close to zero, suggesting the log specification provides a better fit than either a linear or inverse specification. Additionally, power parameters in popular statistical packages such as R and Stata are rounded to the closest "interpretable fraction" (Sheather, 2009, Lindsey and Sheather, 2010). For these reasons and the fact that the optimal transformation and semi-log produce similar outcomes, we argue for keeping the semi-log as the preferred specification.

Conclusion

Agricultural productivity increased substantially during the 20th century and the spread of irrigation has been noted as an important factor underlying the increased productivity (Edwards and Smith, Forthcoming). Decades of intensive water use has raised concerns over the sustainability of water sources in the semi-arid western United States and elsewhere (Scanlon, et al., 2012). Information on the value of irrigation water therefore has direct relevance to policy making. Using unique parcel-level land sales transaction data for the Kansas portion of the High Plains Aquifer, we estimate irrigation premiums and the value of water in-storage. Results indicate that water value component of irrigated land sales transactions account for about 55% of the total sale price. Irrigation premiums are highest in regions of the aquifer having the greatest saturated thickness.

The value of water in the High Plains Aquifer in Kansas has grown over the last decade. Market value of irrigation water has increased by about 75% following the upswing in food commodity prices. As a result, the estimated value of High Plains Aquifer groundwater in Kansas has increased from about \$2 billion in the late 1980s to about \$5 billion presently.

Tables

Table 1. Summary statistics

Variable (units)	Definition	Mean	Std.D	Min	Max
Price per acre	Real price per acre excluding improvements	2,001.6	1,895.8	35.6	9,982.1
Proportion grassland	Proportion of parcel that is grass	0.03	0.06	0.0	0.25
Hydraulic Conductivity (ft/day)	Ease with which water moves through aquifer	76.6	27.0	14.0	120.0
Saturated thickness (ft)	Depth of the aquifer	163.8	106.8	0.0	562.4
Authorized quantity (in/acre)	Inches of water per acre authorized from water right	13.1	6.2	0.0	24.0
Commute time to 10,000 population (hrs)	Drive time to nearest city of 10,000 or more	0.48	0.07	0.06	0.50
Commute time to 40,000 population (hrs)	Drive time to nearest city of 40,000 or more	0.50	0.003	0.39	0.50
Root Zone Available Water Storage (mm)	Volume of plant available storage in root zone	265.3	53.2	34.0	335.0
Soil Organic Carbon (g/m^2)	Total organic carbon in soil	8,632.5	2,737.7	903.2	24,249.0
Acidic soils	Proportion of land with soil pH level less than 6.0	0.0	0.0	0.0	0.8
Basic soils	Proportion of land with soil pH level greater than 7.5	0.7	0.4	0.0	1.0
Growing season precipitation (inches)	Average growing season precipitation	15.5	2.2	12.5	21.0
Evapotranspiration (inches)	Average reference evapotranspiration	36.1	1.0	33.9	38.1
Degree days between 10 and 32 Celsius (degrees*days)	Number of days with temperature between 10 and 32 Celsius	1,954.4	126.3	1,643.2	2,155.6
Degree days over 32 Celsius (degrees*days)	Number of days with temperature at least 32 Celsius	45.4	7.9	23.0	68.3

Table 2. Regression results for hedonic model.

	(1)	(2)	(3)	(4)
Irrigated parcel	0.610***	0.577***	0.569***	0.553***
	(0.019)	(0.020)	(0.023)	(0.027)
Time to 10K population center	0.391**	-0.213	-0.00217	-0.195
	(0.170)	(0.211)	(0.347)	(0.158)
Time to 40K population center	-1.568	3.937	11.95	0.0685
	(3.457)	(5.159)	(10.200)	(0.096)
Average growing season precipitation	0.019	0.010	0.033	-0.117
	(0.019)	(0.027)	(0.051)	(0.127)
Reference evapotranspiration	0.104*	-0.037	0.034	0.185
	(0.053)	(0.091)	(0.159)	(0.234)
Degree days between 10 and 32 Celsius	-0.00128**	-0.00409***	-0.001	0.00792***
	(5.20E-04)	(0.001)	(0.002)	(0.003)
Degree days over 32 Celsius	-0.0048	0.0316**	0.0221	-0.0808**
	(0.008)	(0.014)	(0.023)	(0.035)
Root zone available water storage	2.96E-04	4.47E-04	4.61E-04	6.40E-04
	(3.94E-04)	(4.79E-04)	(5.55E-04)	(7.17E-04)
Soil organic carbon	1.58e-05***	1.82e-05***	1.91e-05***	1.88e-05***
	(4.71E-06)	(5.52E-06)	(6.37E-06)	(7.09E-06)
Acidic soils	0.207	0.451	0.377	0.468
	(0.330)	(0.321)	(0.316)	(0.358)
Basic soils	0.0785**	0.064	0.142***	0.085
	(0.038)	(0.044)	(0.049)	(0.052)
Proportion of parcel grassland	-0.190	-0.114	-0.152	(0.318)
	(0.162)	(0.175)	(0.191)	(0.198)
Variables interacted with irrigated parcels				
Saturated thickness	0.000490***	0.000476**	0.000786***	0.00164***
	(1.74E-04)	(1.99E-04)	(2.25E-04)	(2.50E-04)
Square of saturated thickness	-5.56e-06***	-4.83e-06***	-2.54e-06**	-2.65e-06**
	(8.47E-07)	(8.48E-07)	(1.04E-06)	(1.18E-06)
Hydraulic conductivity	0.00051	1.37E-04	1.40E-05	-2.65e-06**
	(4.54E-04)	(4.99E-04)	(5.55E-04)	(1.18E-06)
Authorized inches per acre	2.44E-04	-6.73E-04	-3.67E-04	1.38E-03
	(0.002)	(0.002)	(0.002)	(0.002)
Average growing season precipitation	-0.001	-0.013	0.008	-0.007
	(0.027)	(0.030)	(0.033)	(0.089)
Reference evapotranspiration	0.083	0.031	0.094	0.150
	(0.078)	(0.086)	(0.099)	(0.098)

Degree days between 10 and 32 Celsius	0.00148***	5.53E-04	8.20E-04	7.12E-05
	(4.64E-04)	(5.13E-04)	(6.21E-04)	(7.98E-04)
Degree days over 32 Celsius	-0.0191*	-0.003	-0.014	-0.010
	(0.011)	(0.012)	(0.015)	(0.016)
Root zone available water storage	-0.00109**	-0.00184***	-0.00208***	-1.25E-03
	(5.00E-04)	(5.49E-04)	(5.99E-04)	(8.39E-04)
Soil organic carbon	-8.97E-06	-6.71E-06	-2.62E-06	-6.10E-06
	(7.55E-06)	(8.09E-06)	(8.52E-06)	(9.86E-06)
Spatial Controls	None	County (33)	County Subdivisions (244)	Township (575)
Observations	15,420	15,420	15,420	15,420

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Controls for agricultural district by year by quarter dummies

Table 3. Value of water in-storage for parcels having different saturated thickness, relative to the mean saturated thickness ($/acre).

Saturated thickness	(1)	(2)	(3)	(4)
-150 ft	2344.1***	2366.3***	2340.6***	2094.4***
	(75.4)	(81.4)	(91.1)	(91.7)
-100 ft	2583.0***	2574.0***	2512.8***	2352.5***
	(48.3)	(52.0)	(54.6)	(57.0)
-50 ft	2773.7***	2733.2***	2663.7***	2598.8***
	(35.0)	(36.1)	(37.6)	(40.8)
0 ft	2902.3***	2833.0***	2788.0***	2823.5***
	(42.8)	(42.3)	(48.8)	(56.1)
+50 ft	2959.3***	2866.4***	2881.4***	3016.9***
	(57.6)	(57.9)	(68.5)	(82.3)
+100 ft	2940.4***	2830.9***	2940.5***	3170.4***
	(72.1)	(74.3)	(88.8)	(111.2)
+150 ft	2846.9***	2729.1***	2962.9***	3276.6***
	(87.4)	(91.9)	(112.5)	(146.8)
Average marginal effect	0.52***	0.37**	0.67***	1.27***
	(0.15)	(0.17)	(0.19)	(0.22)

Controls for agricultural district by year by quarter and township effects

Table 4. Regression results for time-variant models.

	(1)	(2)
Irrigated parcel	0.469***	0.399***
	(0.050)	(0.050)
Ag district 10 trend (non-irrigated)		0.0518***
		(0.004)
Ag district 20 trend (non-irrigated)		0.0318***
		(0.006)
Ag district 30 trend (non-irrigated)		0.0195***
		(0.003)
Ag district 50 trend (non-irrigated)		0.0517***
		(0.010)
Ag district 60 trend (non-irrigated)		0.0502***
		(0.004)
Statewide trend (non-irrigated)	0.0342***	
	(0.002)	
Variables interacted with irrigated parcels		
Ag district 10 trend (irrigated)		0.0514***
		(0.005)
Ag district 20 trend (irrigated)		0.0307***
		(0.007)
Ag district 30 trend (irrigated)		0.0344***
		(0.002)
Ag district 50 trend (irrigated)		0.0572***
		(0.010)
Ag district 60 trend (irrigated)		0.0645***
		(0.003)
Statewide trend (irrigated)	0.0403***	
	(0.002)	
Saturated thickness	0.00152***	0.00140***
	(2.66E-04)	(2.71E-04)
Square of saturated thickness	-2.50e-06**	-2.66e-06**
	(1.22E-06)	(1.25E-06)
Spatial Controls	Township	Township
Observations	15,420	15,420

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Additional Tables

Table A1. Regression results for Poisson models.

	(1)	(2)	(3)	(4)
Irrigated parcel	1.792***	1.747***	1.727***	1.730***
	(0.030)	(0.030)	(0.033)	(0.034)
Time to 10K population center	1.248	0.836	1.164	0.938
	(0.178)	(0.148)	(0.318)	(0.353)
Time to 40K population center	6.399	7.35	129.9	133.7
	(18.170)	(21.660)	(778.300)	(792.500)
Average growing season precipitation	0.994	0.998	1.001	0.907*
	(0.016)	(0.022)	(0.037)	(0.048)
Reference evapotranspiration	1.073	0.877*	0.858	0.938
	(0.050)	(0.062)	(0.099)	(0.163)
Degree days between 10 and 32 Celsius	0.999**	0.996***	0.998	1.006**
	(4.64E-04)	(8.01E-04)	(0.001)	(0.002)
Degree days over 32 Celsius	0.997	1.036***	1.037**	0.958
	(0.007)	(0.011)	(0.018)	(0.026)
Root zone available water storage	1.000	1.000	1.000	1.000
	(3.30E-04)	(3.54E-04)	(3.84E-04)	(3.99E-04)
Soil organic carbon	1.00002***	1.00002***	1.00002***	1.00001***
	(4.12E-06)	(4.33E-06)	(4.70E-06)	(4.99E-06)
Acidic soils	1.416	1.542	1.294	1.624
	(0.378)	(0.423)	(0.362)	(0.483)
Basic soils	1.070**	1.064*	1.137***	1.078*
	(0.035)	(0.038)	(0.043)	(0.042)
Proportion of parcel grassland	0.861	0.898	0.873	(8.01E-01)
	(0.119)	(0.125)	(0.124)	(0.115)
Variables interacted with irrigated parcels				
Saturated thickness	1.001***	1.0001***	1.001***	1.001***
	(1.61E-04)	(1.77E-04)	(1.93E-04)	(2.08E-04)
Square of saturated thickness	0.999***	0.999***	0.999**	0.999***
	(7.08E-07)	(7.47E-07)	(8.90E-07)	(9.63E-07)
Hydraulic conductivity	1.001**	1.001	1.001	1.001**
	(4.28E-04)	(4.51E-04)	(4.80E-04)	(5.66E-04)
Authorized inches per acre	1.000	1.000	1.000	1.002
	(0.002)	(0.002)	(0.002)	(0.002)
Average growing season precipitation	1.018	1.009	1.030	1.055**

	(0.024)	(0.024)	(0.026)	(0.028)
Reference evapotranspiration	1.132*	1.084	1.162**	1.174**
	(0.078)	(0.077)	(0.088)	(0.093)
Degree days between 10 and 32 Celsius	1.001***	1.001	1.001*	1.000
	(4.16E-04)	(4.34E-04)	(4.88E-04)	(5.17E-04)
Degree days over 32 Celsius	0.980**	0.991	0.980*	0.986
	(0.010)	(0.010)	(0.011)	(0.012)
Root zone available water storage	0.999**	0.999***	0.999***	0.999**
	(4.35E-04)	(4.38E-04)	(4.51E-04)	(4.57E-04)
Soil organic carbon	1.000	1.000	1.000	1.000
	(6.72E-06)	(6.63E-06)	(6.69E-06)	(6.81E-06)
Spatial Controls	None	County	County Subdivisions	Township
Observations	15,420	15,420	15,420	15,420

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Controls for agricultural district by year by quarter dummies

Table A2. Value of water in-storage for parcels having different saturated thickness using Poisson model ($/acre).

Saturated thickness	(1)	(2)	(3)	(4)
-150 ft	2382.1***	2395.3***	2369.7***	2206.7***
	(69.5)	(74.0)	(78.8)	(78.2)
-100 ft	2599.3***	2586.2***	2528.6***	2429.9***
	(44.4)	(46.5)	(47.0)	(47.9)
-50 ft	2769.7***	2732.7***	2670.1***	2634.4***
	(32.0)	(32.4)	(32.8)	(33.9)
0 ft	2882.2***	2826.0***	2789.9***	2812.1***
	(38.5)	(39.0)	(42.8)	(45.1)
+50 ft	2928.9***	2860.0***	2884.7***	2955.7***
	(51.4)	(53.0)	(59.9)	(64.7)
+100 ft	2906.7***	2832.7***	2951.6***	3058.7***
	(63.5)	(66.7)	(77.4)	(85.6)
+150 ft	2817.0***	2745.9***	2988.5***	3116.7***
	(75.3)	(80.5)	(98.1)	(110.6)
Average marginal effect	0.45***	0.36**	0.66***	0.98***
	(0.13)	(0.15)	(0.16)	(0.18)

Controls for agricultural district by year by quarter and township effects

Table A3. Regression results for time variant models.

	(1)	(2)
Irrigated parcel	0.469***	0.399***
	(0.050)	(0.050)
Time to 10K population center	-0.139	-0.138
	(0.499)	(0.512)
Time to 40K population center	0.106	-0.635
	(11.220)	(9.698)
Average growing season precipitation	-0.091	-0.105
	(0.070)	(0.070)
Reference evapotranspiration	0.131	0.121
	(0.229)	(0.230)
Degree days between 10 and 32 Celsius	0.00832***	0.00857***
	(0.003)	(0.003)
Degree days over 32 Celsius	-0.0701**	-0.0698**
	(0.034)	(0.034)
Root zone available water storage	3.44E-06	5.93E-05
	(5.56E-04)	(5.49E-04)
Soil organic carbon	1.96e-05***	1.80e-05***
	(6.52E-06)	(6.57E-06)
Acidic soils	0.465	0.702**
	(0.349)	(0.337)
Basic soils	0.0900*	0.079
	(0.050)	(0.050)
Proportion of parcel grassland	-0.269	-0.314
	(0.199)	(0.200)
Ag district 10 trend (non-irrigated)		0.0518***
		(0.004)
Ag district 20 trend (non-irrigated)		0.0318***
		(0.006)
Ag district 30 trend (non-irrigated)		0.0195***
		(0.003)
Ag district 50 trend (non-irrigated)		0.0517***
		(0.010)
Ag district 60 trend (non-irrigated)		0.0502***
		(0.004)
Statewide trend (non-irrigated)	0.0342***	
	(0.002)	
Variables interacted with irrigated parcels		
Ag district 10 trend (irrigated)		0.0514***

		(0.005)
Ag district 20 trend (irrigated)		0.0307***
		(0.007)
Ag district 30 trend (irrigated)		0.0344***
		(0.002)
Ag district 50 trend (irrigated)		0.0572***
		(0.010)
Ag district 60 trend (irrigated)		0.0645***
		(0.003)
Statewide trend (irrigated)	0.0403***	
	(0.002)	
Saturated thickness	0.00152***	0.00140***
	(2.66E-04)	(2.71E-04)
Square of saturated thickness	-2.50e-06**	-2.66e-06**
	(1.22E-06)	(1.25E-06)
Hydraulic conductivity	0.00147**	0.00115*
	(6.61E-04)	(6.67E-04)
Authorized inches per acre	2.84E-03	3.22E-03
	(0.002)	(0.002)
Average growing season precipitation	0.041	0.051
	(0.032)	(0.039)
Reference evapotranspiration	0.095	0.042
	(0.096)	(0.106)
Degree days between 10 and 32 Celsius	0.001	-7.34E-04
	(6.48E-04)	(8.52E-04)
Degree days over 32 Celsius	-0.011	-0.003
	(0.015)	(0.016)
Root zone available water storage	-5.13E-04	-5.10E-04
	(6.06E-04)	(6.03E-04)
Soil organic carbon	-1.08E-05	-9.29E-06
	(8.63E-06)	(8.85E-06)
Spatial Controls	Township	Township
Observations	15,420	15,420

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Figures

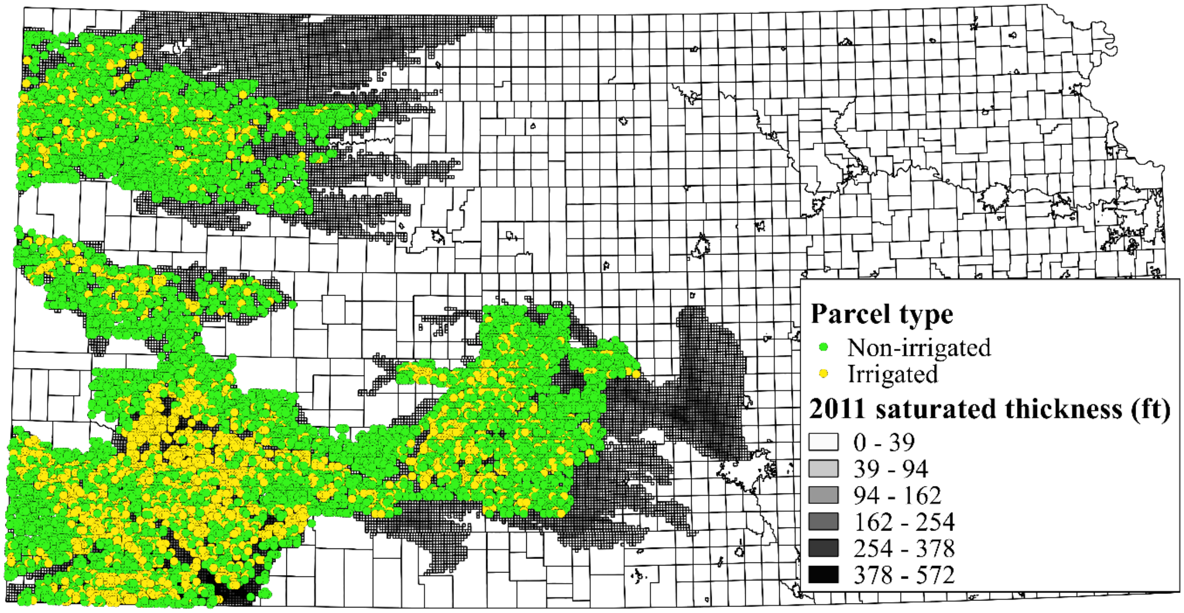

Figure 1. Parcel locations and 2011 saturated thickness for the High Plains Aquifer.

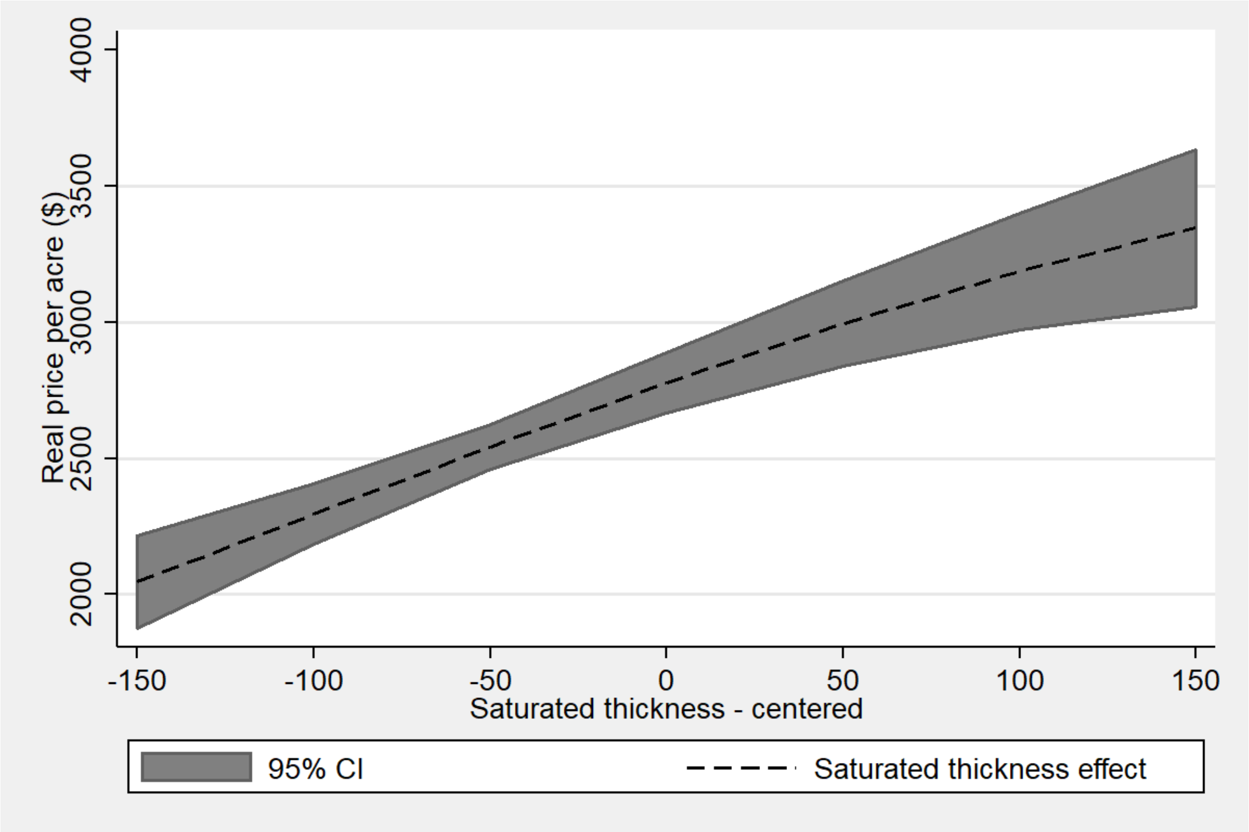

Figure 2. Predicted price per acre for different levels of saturated thickness.

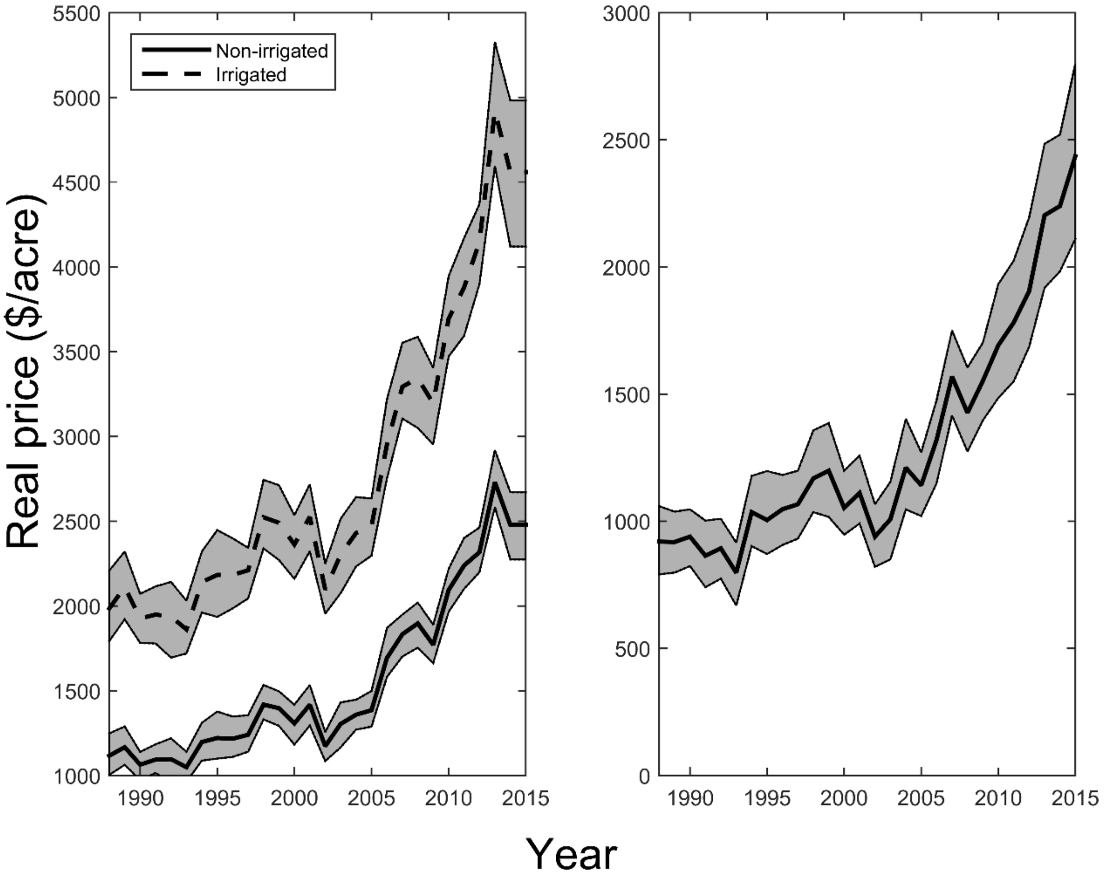

Figure 3. Real price per acre for dryland (non-irrigated) and irrigated parcels over time (left) and irrigation premiums over time (right).

Note: bootstrapped 95% confidence intervals shown as shaded regions.

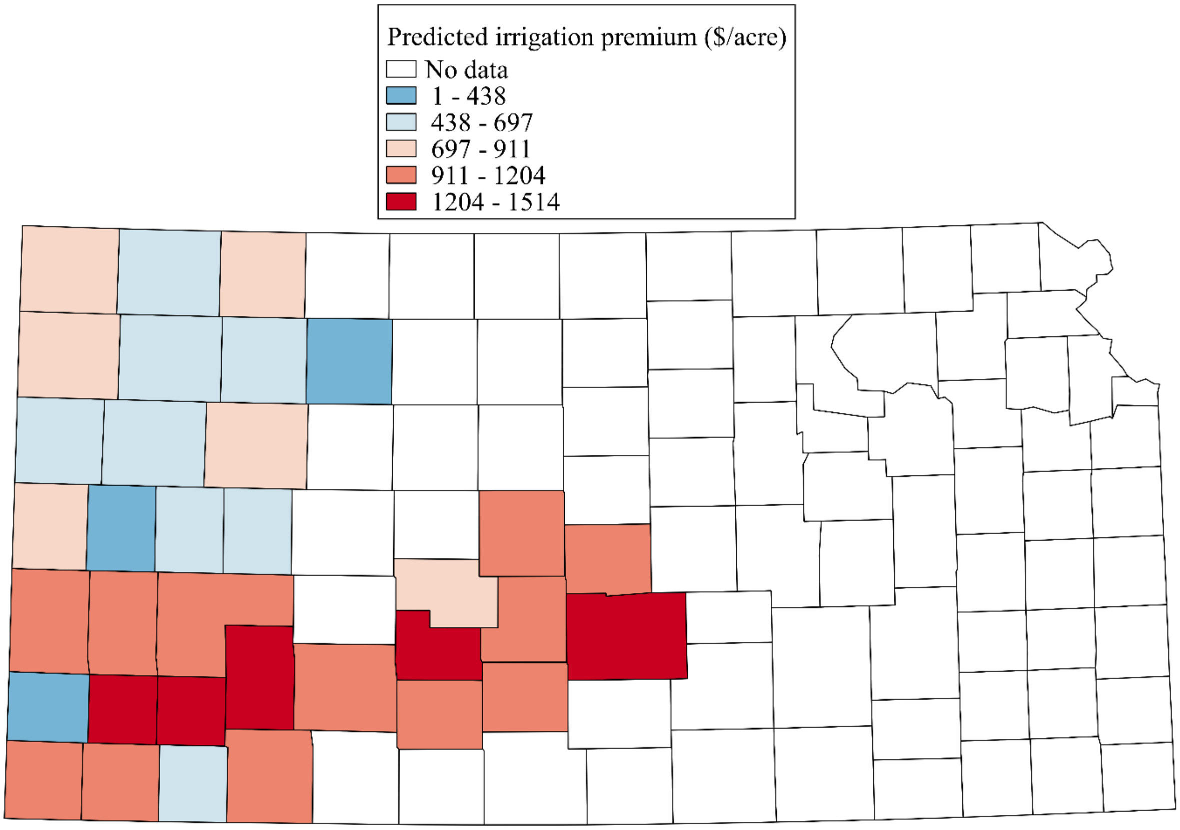

Figure 4. Predicted average irrigation premium by county.

Additional Figures

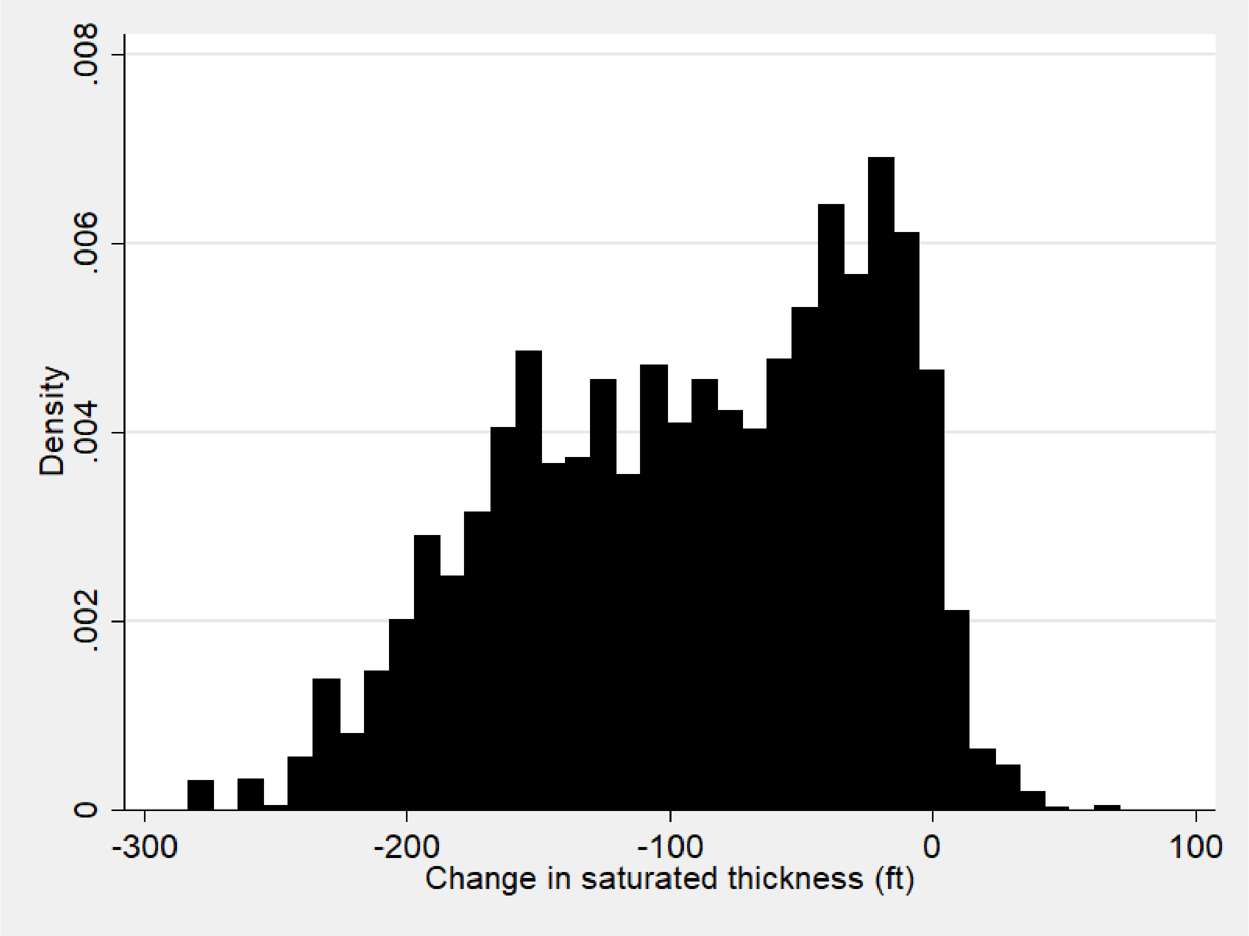

Figure A1. Distribution of aquifer depletion from pre-development to present.

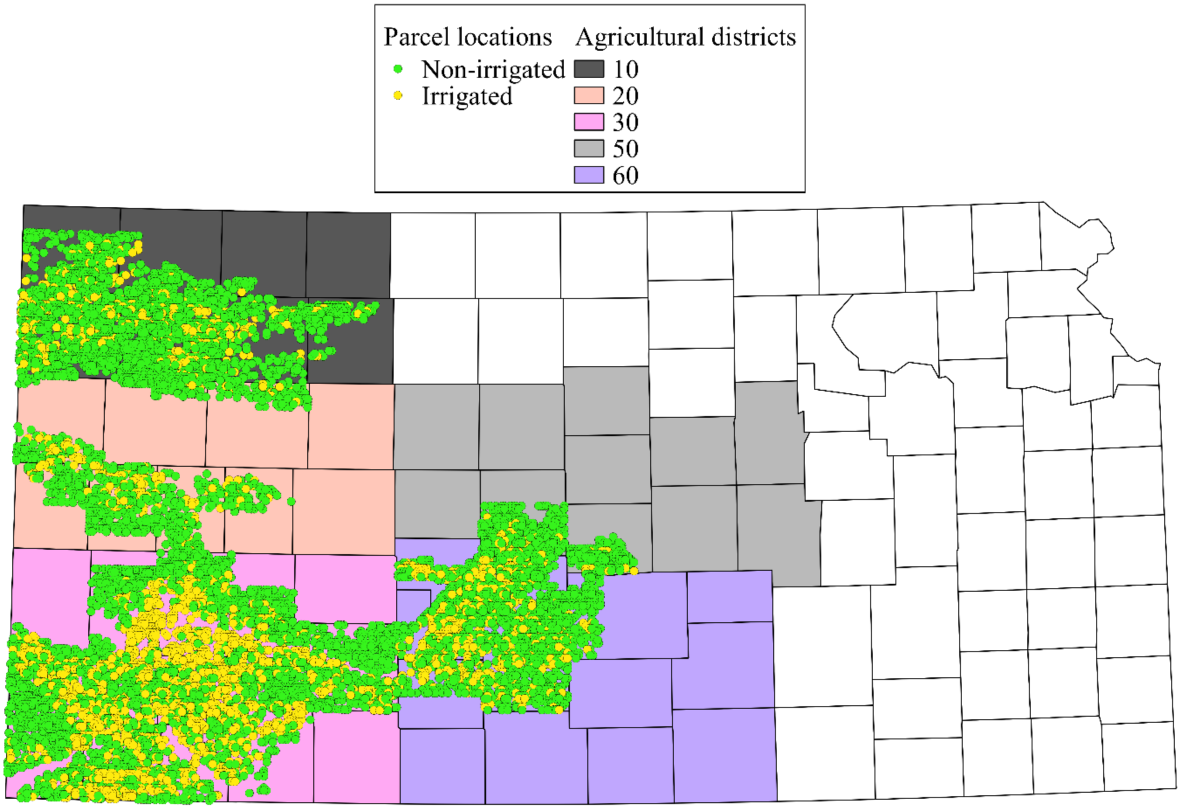

Figure A2. Location of Kansas agricultural districts.

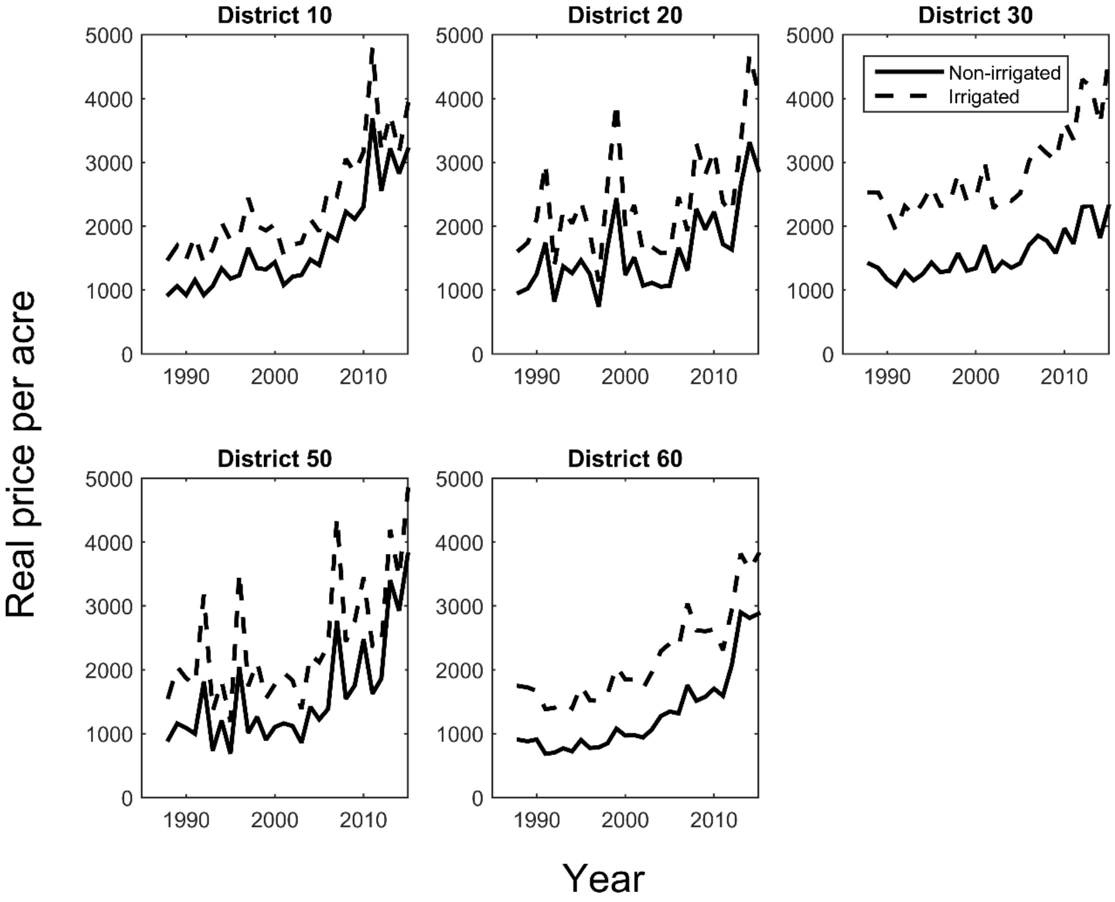

Figure A3. Real price per acre for dryland (non-irrigated) and irrigated parcels by agricultural district over time.

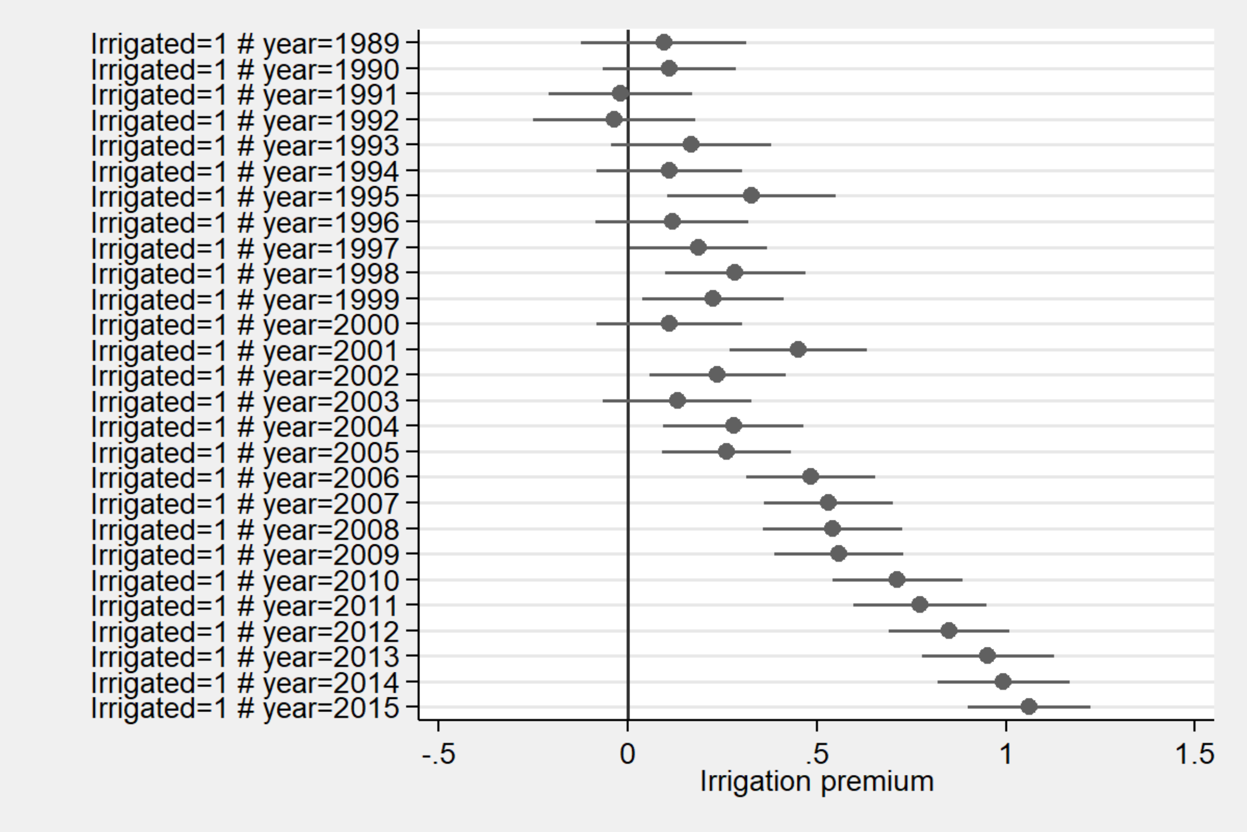

Figure A4. Percentage irrigation premium by year.

Note: Controls for township.

Note: Estimates are given additively to the statistically significant baseline year of 1988 (0.31).

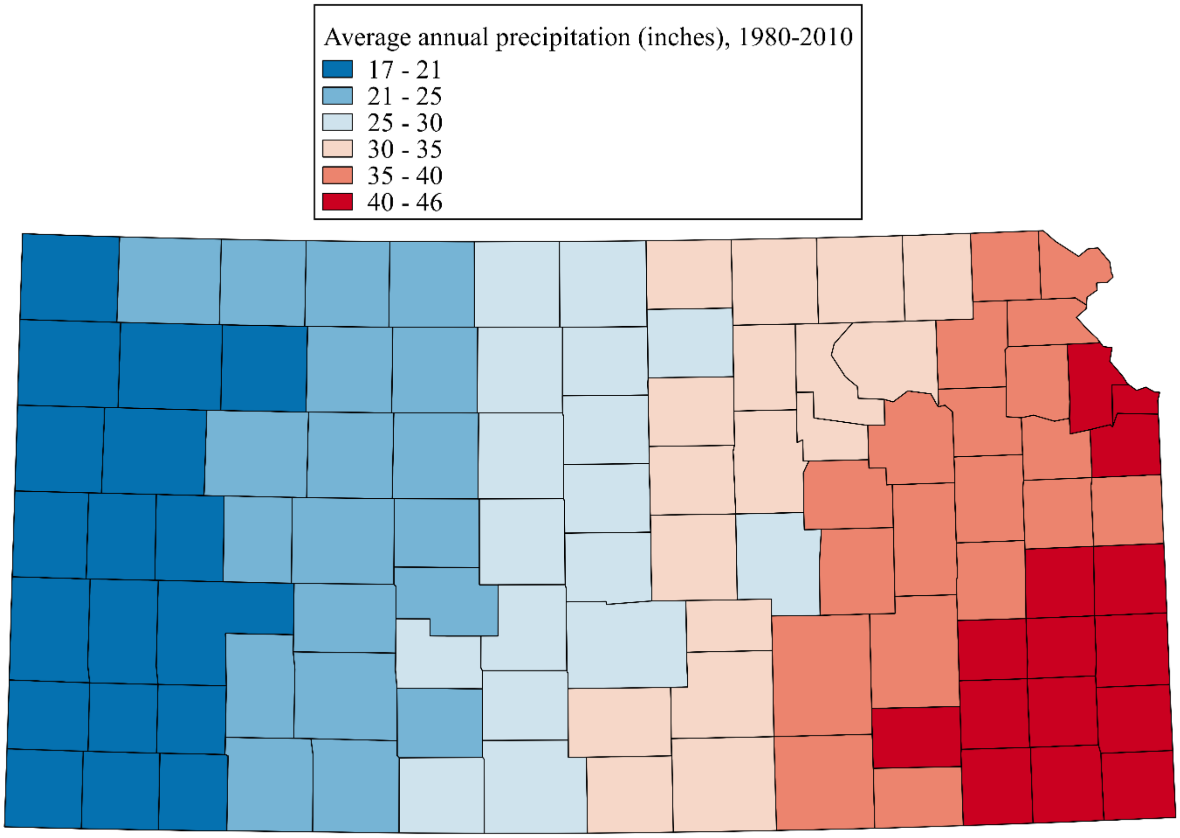

Figure A5. Average annual county precipitation from 1980-2010.

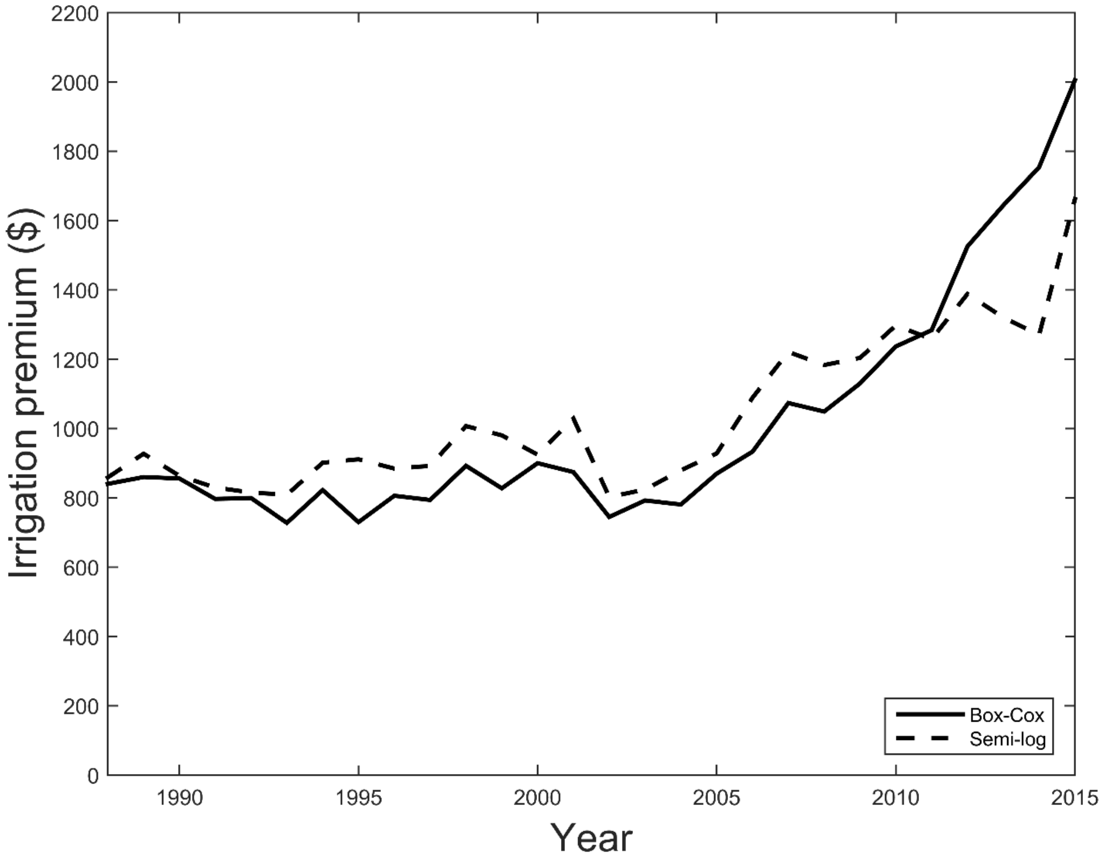

Figure A6. Estimated irrigation premium ($/acre) by year for Box-Cox and semi-log models.

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