Does Efficient Irrigation Technology Lead to Reduced Groundwater Extraction? Empirical Evidence

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Abstract

Encouraging the use of more efficient irrigation technology is often viewed as an effective, politically feasible method to reduce the consumptive use of water for agricultural production. Despite its pervasive recommendation, it is not clear that increasing irrigation efficiency will lead to water conservation in practice. In this article, we evaluate the effect of a widespread conversion from traditional center pivot irrigation systems to higher efficiency dropped-nozzle center pivot systems that has occurred in western Kansas. State and national cost-share programs subsidized the conversion. On average, the intended reduction in groundwater use did not occur; the shift to more efficient irrigation technology has increased groundwater extraction, in part due to shifting crop patterns.

Key words: irrigation efficiency, groundwater, water conservation, agriculture, aquifer, irrigation technology, rebound effect

"It is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth."

-William Stanley Jevons, "The Coal Question" (1865)

Agriculture accounts for 99 percent of groundwater withdrawals from the High Plains Aquifer of the central United States, the largest freshwater aquifer system in the world (Miller and Appel 1997). The region has experienced a decline in the level of the groundwater table since the 1970s, when intensive irrigation became widespread and led to rates of extraction that far exceeded recharge to the aquifer. In parts of southwestern Kansas and in the Texas panhandle, the depth to groundwater has increased by more than 150 feet. Many of the world's most productive agricultural basins depend on groundwater and have experienced similar declines in water table levels. Increasing competition for water from cities and environmental needs, as well as concerns about future climate variability and more frequent droughts, have caused policy makers to declare "water crises" and look for ways to decrease the consumptive use of water. Agriculture, by far the largest user of water, is often targeted.

Irrigated agriculture is often believed to be wasteful. In response, policy makers have called for measures that increase the efficiency of irrigated agriculture. In fact, large sums have been spent on programs to increase irrigation efficiency in agriculture, many of them incentive-based cost-share programs that subsidize the conversion to more efficient irrigation technology. These programs have the advantage of being extremely popular and therefore politically feasible. Numerous state and national governments, international organizations, and scientists have called for additional programs to support conversion to more efficient irrigation technology (Cooley et al. 2009; Jury and Vaux 2005; Zinn and Canada 2007; Johnson et al. 2001; Evans and Sadler 2008). However, there have been very few evaluations of these programs, and of those that exist, many raise serious doubts about the programs' effectiveness in reducing the consumptive use of water. A debate has emerged between those positing that irrigation efficiency enhancement can make significant amounts of water available for other uses (Cooley, Christian-Smith, and Gleick 2009) and those that point out that these policies may have unintended consequences such as increasing total irrigated acreage, increasing evapotranspiration and yields of existing crops, a shift to more water intensive crops, and a reallocation of within-basin water supplies, potentially increasing overall consumptive use (Ward and Pulido-Velazquez 2008; Whittlesey and Huffaker 1995; Ellis et al. 1985).

In this article, we empirically investigate the effect of a wide-spread conversion to efficient irrigation technology on groundwater extraction in Kansas, a state that overlies the High Plains Aquifer. Recently, several studies have shown that shifting to more efficient irrigation technology does not necessarily reduce total water use, and can even lead to increases in water use (Ward and Pulido-Velazquez 2008; Scheierling, Young, and Cardon 2006; Peterson and Ding 2005; Huffaker and Whittlesey 2003; Khanna, Isik, and Zilberman 2002; Hanak, Lund, Dinar, Gray, Howitt, Mount, Moyle, and Thompson 2010). These studies used deterministic programming models or simulation approaches. In contrast, we econometrically evaluate changes in irrigation behavior after conversion from conventional center pivot irrigation systems to a more efficient technology: center pivots with dropped, high efficiency nozzles. We use panel data from over 20,000 groundwater-irrigated fields in western Kansas from 1996 to 2005. We find that as the shift to more efficient dropped nozzle irrigation technology occurred, the amount of groundwater applied to fields in Kansas increased. This was due to increases in water use on both the intensive and extensive margins. On the intensive margin, farmers used more water per acre on irrigated fields. On the extensive margin, farmers irrigated a slightly larger proportion of their fields and were less likely to leave fields fallow or plant non-irrigated crops.

Background

Irrigation efficiency is defined as the proportion of consumed water (also called "consumptive use") that is beneficially used by a crop ("effective water") (Burt et al. 1997):

$$Irrigation\, efficiency = \frac{Effective\, water}{Consumptive\, use\, of\, water}. \tag{1}$$

More efficient irrigation systems increase this proportion, allowing less water to be applied for a given yield. In many watersheds, some portion of the irrigation water applied is available for other uses downstream via runoff, or recharges the aquifer via percolation. In these cases, the "consumptive use of water" is equal to applied water minus this return flow, and the spatial unit of irrigation efficiency must be defined because irrigation efficiency at the basin level would diverge from that at the field level by the amount of water that is reused (Huffaker 2008; Ward and Pulido-Velazquez 2008; Huffaker and Whittlesey 2000). In the portion of the High Plains Aquifer underlying western Kansas, however, recharge to the aquifer by irrigation water that runs off, percolates, or is otherwise not used by the crop but is available for future use is negligible (Miller and Appel 1997). Thus, we can define the consumptive use of irrigation water equal to the amount of water extracted from the aquifer and applied to the field, and define irrigation efficiency as equation 1, at the field level (Peterson and Ding 2005).

The irrigation technology employed by groundwater users in western Kansas has changed significantly since intensive irrigation development began with flood systems in the 1970s. Through the 1980s, land was converted from flood irrigation, which is labor and water intensive and necessitates flat, high quality, uniform land, to center pivot irrigation systems. Center pivots are generally self-propelled and can be used on sloped or rolling land, but require a higher pressure at the pump to operate (Rogers et al. 2008). Figure 1 shows the trend in irrigation technology use in western Kansas from 1996 to 2005, the time period used for our analysis. Center pivot systems were already widespread by 1996. Rather, most of the change came in the conversion from center pivots to center pivots with dropped nozzle packages. Dropped nozzle packages (also called low-pressure nozzles or low energy precision application (LEPA)) are attached to center pivots and suspend the sprinkler heads between about 2 feet above the ground to just above the canopy of the crop. They increase the efficiency of water applied to the field by decreasing the amount lost to evaporation and drift, especially in hot and windy climates, and require less pump pressure to operate (New and Fipps 1990). Irrigation efficiency varies by environmental conditions, but flood irrigation systems (hereafter, "flood") are generally assumed to be 65-75% efficient. Conventional center pivot systems ("center pivot") increase efficiency to 80-90%, and center pivots with LEPA or other types of dropped nozzle systems ("dropped nozzles") are 95-98% efficient (Howell 2003; NRCS 1997).

Between 1998 and 2005, the state of Kansas spent nearly $6 million on incentive programs, such as the Irrigation Water Conservation Fund and the Environmental Quality Incentives Program, to fund the adoption of more efficient irrigation systems. Such programs paid up to 75% of the cost of purchasing and installing new or upgraded irrigation technology, and much of the money was used for conversions to dropped nozzle systems (NRCS 2004). These policies were implemented under the auspices of groundwater conservation, in response to declining aquifer levels occurring in some portions of the state due to extensive groundwater pumping for irrigation (Committee 2001).

However, true water conservation occurs only with a decrease in individual consumptive use. Often overlooked is how changes in irrigation efficiency may change a farmer's profit maximization problem, and could result in behavioral changes that affect individual consumptive use. A limited amount of theoretical research has attempted to determine the conditions under which an increase in irrigation efficiency would result in a decrease in consumptive use. Caswell and Zilberman (1983) focused on how irrigation efficiency improves the "effectiveness" of variable inputs, which are combined with heterogeneous land qualities, for crop production. Land-augmenting technologies such as more efficient irrigation increase the ability of lower quality soils to provide water and nutrients to crops (Caswell and Zilberman 1986). Caswell and Zilberman (1983) show that land quality variation affects the extent of technology adoption. They also show that effective water and yields will always increase when a more efficient irrigation technology is adopted, but the change in actual irrigation application depends on the elasticity of the marginal productivity of water, which can also be interpreted as the elasticity of demand for irrigation water (they are equal at the optimal solution). When demand is inelastic (corresponding to the section of the production function nearing full irrigation, where the marginal yield response is relatively weak), an increase in irrigation efficiency results in a decrease in irrigation. When water demand is elastic (corresponding to a strong marginal yield response), increases in irrigation efficiency will increase irrigation. Huffaker and Whittlesey (2003) developed a similar model incorporating the possibility of return flows.

Empirical estimates of the elasticity of demand for irrigation water are limited, but of those that exist, they suggest that the demand for irrigation water is inelastic (Hendricks and Peterson 2012; Moore et al. 1994; Schoengold et al. 2006; Scheierling et al. 2006), meaning that an increase in irrigation efficiency would reduce groundwater extraction. However, a larger body of research has focused on the development of data-calibrated simulation models to predict the effects of increasing irrigation efficiency on irrigation. Ellis et al. (1985) developed a model to analyze the adoption of limited tillage and dropped nozzles in the high plains region of Texas. They found that because dropped nozzles improve delivery efficiency and reduce the variable cost of irrigation, producers would apply more water per acre to increase yields, plant more water intensive crops, and increase irrigated acreage. However, total water use over the 40 year horizon considered remained essentially constant because in his model, water withdrawals were limited by annual pumping limits. Huffaker and Whittlesey (2000) modeled private investment in a more efficient irrigation technology and its effect on conservation.[1] They found that investment was only cost-effective when consumptive use was below the yield maximizing level with the status quo technology because of some constraint, like a low precipitation year. The investment in irrigation efficiency would be used to increase yields, and consumptive use would increase. Scheierling et al. (2006) incorporated an agronomic simulation model with an economic linear programming model to study the effects of an irrigation efficiency subsidy. They found that consumptive use never decreased as a result of the subsidy; the number of irrigations increased when acreage was fixed, and the number of irrigated acres of the most water intensive crop (corn) increased when acreage was not fixed. Ward and Pulido-Velazquez (2008) analyzed the effect of subsidies for the adoption of drip irrigation in New Mexico's Rio Grande Basin on crop yields, irrigated acreage, income, and total water depletion over a 20 year time horizon. They found that yields and net farm income increased under the subsidy, but total water depletion was always greater than the case with no subsidy for irrigation technology. When total irrigated acreage was allowed to increase in the model, water depletion increased even more. In contrast, Peterson and Ding (2005) found that conversion from flood irrigation to center pivots could reduce overall irrigation water use for corn in Western Kansas. However, they did not consider the possibility of changes in cropping patterns or the expansion of irrigated acreage, and their results relied on the assumption that flood systems can irrigate all 160 acres of a 160 acre field, while center pivots can irrigate only 126 of the 160 acres. In reality, the remaining corners may be irrigated with various types of corner irrigation systems.

These studies expose what seems to be a disconnect between the theoretical literature, which posits that the demand for irrigation water must be elastic for an increase in irrigation efficiency to result in an increase in consumptive use, and data-calibrated simulations models, which under reasonable assumptions often find that an increase in irrigation efficiency increases consumptive use. Caswell and Zilberman's (1983) and Huffaker and Whittlesey's (2000) models focus on land conversion. They use single crop, single year models that do not allow for the possibility that the technology may affect crop revenue and cost functions as well. Most of these assumptions are unreasonable for a modern Kansan crop production system. The relevant time horizon is longer than one season; the use of crop rotation patterns and fallow cycles is ubiquitous, so over the planning horizon a farmer would likely be irrigating at less-than full irrigation. The long-term demand for irrigation water is likely to be more elastic than the short-term demand (Hendricks and Peterson 2012). In addition, dropped nozzles are known to affect the revenue and cost functions directly. The higher efficiency and directed spray pattern of dropped nozzles aid with the inter-seasonal timing of irrigation, allowing farmers to better fulfill a crop's water requirements during peak water demand days and critical growth stages (New and Fipps 1990; Peterson and Ding 2005). Experimental station research has shown that corn yields under dropped nozzles can be up to 13 percent higher than yields under conventional center pivots, and that the yield benefit is greatest under irrigation deficit situations (such as drought or a case where a farmer's pumping limit is insufficient for full irrigation) (New and Fipps 1990; Howell et al. 1995; Schneider and Howell 1998; O'Brien et al. 2001). Dropped nozzle systems require significantly less pressure than conventional center pivots to operate, which would decrease the energy cost of groundwater extraction and application (Rogers et al. 2008).

These revenue and cost effects can be succinctly incorporated into the basic structure of Caswell and Zilberman's (1983) model. Let $f(x,k)$ denote the revenue earned from from the use of a productive input (x), where x is derived from an input that is acquired (q) and then transformed at some rate (k). Here, q is applied water, $k \in [0,1]$ is irrigation efficiency, and x is effective water. Irrigation efficiency affects the revenue function through the transformation of applied water into effective water, as well as directly, by allowing farmers to better fulfill the crop's water requirements during critical growth stages. The farmer solves the following optimization problem:

$$max_x \left\{ f(x,k) - c(k)q \,:\, x = kq \right\} \tag{2}$$

where $c(k)$ is the marginal cost of water extraction and application. This yields the first order condition:

$$\frac{\partial f(x,k)}{\partial x} = c(k)/k \tag{3}$$

which can also be written as the demand function for effective water:

$$x = X\left(c(k)/k, k\right) = f^{-1}\left(c(k)/k; k\right). \tag{4}$$

Then, denoting $\tilde{c} = c(k)/k$, the price of effective water, and substituting $x = kq$ into equation 4, the demand function for applied water is:

$$q = X\left(c(k)/k, k\right)/k,$$

and the effect of a change in irrigation efficiency on the demand for applied water is:

$$\frac{\partial q}{\partial k} = k^{-1}\left(\frac{\partial X(\tilde{c}, k)}{\partial \tilde{c}} c'(k)k^{-1} - \frac{\partial X(\tilde{c}, k)}{\partial \tilde{c}} c(k)k^{-2} + \frac{\partial X(\tilde{c}, k)}{\partial k} - X(\tilde{c}, k)k^{-1}\right). \tag{5}$$

This implies the following necessary and sufficient condition for increased irrigation efficiency to increase applied water:

$$\frac{\partial q}{\partial k} > 0 \Leftrightarrow \tag{6}$$

$$|\eta_x| > k\left(1 - \frac{\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} c'(k)}{X(\tilde{c}, k)} - \frac{\frac{\partial X(\tilde{c},k)}{\partial k} k}{X(\tilde{c}, k)}\right). \tag{7}$$

Since demand is downward sloping, $\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} < 0$, which means the first fraction on the right-hand-side of the inequality 7 for the elasticity is positive if there is a negative cost effect ($c'(k) < 0$; the higher efficiency technology operates at a lower marginal cost) and the second fraction is positive if there is a positive revenue effect ($\frac{\partial X(\tilde{c},k)}{\partial k} > 0$). In the Results section, we provide back-of-the-envelope calculations for the elasticity of demand, revenue, and cost effects showing that it is plausible for the inequality in equation 7 to hold in western Kansas, thus making our empirical question a theoretically credible one.

Empirical Analysis

In this analysis, we investigate whether the widespread conversion to more efficient irrigation technology (from conventional high pressure standard pivot systems to dropped nozzle center pivots) had the effect of decreasing the total groundwater extracted for irrigation in western Kansas. We focus on the shift from standard center pivots to center pivots with dropped nozzles because it was the change that occurred during the time period for which we have data. We investigate whether farmers adjusted along the intensive margin, by changing the amount of water they applied per acre, or the extensive margin, by changing the proportion of a field that was irrigated or the frequency of fallow cycles.We also investigate changes in crop mix that are likely to affect water application per acre, although they cannot be extrapolated to quantify the effect on total acres planted by crop due to data constraints. We briefly present results for farmers who switched from flood irrigation to center pivots during the time period, mainly to show the effectiveness of the empirical models.

Methods

Total water extraction is equal to the product of the amount of water applied per acre and the number of acres irrigated:

$$W_{it} = b_{it} \cdot A_{it}. \tag{8}$$

We use panel data methods to establish the relationship between increasing irrigation efficiency and total groundwater extraction (W_{it}), and each of its components: applied water per acre (b_{it}) and total acres irrigated (A_{it}). In the reduced form, total water extraction, extraction per acre, and acres irrigated are functions of farmer characteristics, land attributes, environmental variables, economic conditions, and possibly time trends in the dependent variable. Total water extraction is modeled as:

$$W_{it} = c_i + \lambda_t + \mathbf{x_{it}'}\beta + \tau w_{it} + \epsilon_{it}, \tag{9}$$

where $\mathbf{c_i}$ is a vector of individual-level farmer and land attributes that do not vary with time, λ_t is a time effect, and $\mathbf{x_{it}}$ is a matrix of time-varying observable characteristics including precipitation, which is expected to reduce water application, evapotranspiration (a proxy for solar radiation), which is expected to increase irrigation, and the depth to the groundwater table, which increases the cost of pumping. $\mathbf{x_{it}}$ can include crop and energy prices if they vary by individual, otherwise they are absorbed in the time effects. Finally, w_{it} is an indicator variable for the adoption of the efficient irrigation technology; it is equal to 1 for the year in which the new technology was used for the first time, and each year after that. In the results, w_{it} is defined as "pivot to dropped" or "flood to pivot". If a field used all three systems during the time period under study, the observations from the third category are excluded (i.e., observations from when a field was under flood irrigation are excluded from the "center pivot to dropped nozzles" analysis). Our main interest is in the effect of the conversion from center pivots to dropped nozzles, the shift that occurred during the time period under study. The same model describes the conversion to center pivots from flood irrigation systems, but the data is more limited because a large percentage of plots had already been converted by 1996.

Panel data at the field level allows the comparison of water use before and after the adoption of irrigation efficiency enhancing technology while differencing out $\mathbf{c_i}$, the effect of field characteristics such as soil quality and slope, as well as producer characteristics, such as individual preferences over crops and the propensity to over-irrigate or conserve water. Equation 9 is estimated using the within (or fixed effects) estimator:

$$(W_{it} - \bar{W}_i) = (\mathbf{x}_{it} - \bar{\mathbf{x}}_i)'\beta + (w_{it} - \bar{w}_i)'\tau + (\epsilon_{it} - \bar{\epsilon}_i), \tag{10}$$

where $\bar{W}_i$, $\bar{\mathbf{x}}_i$, $\bar{w}_i$ and $\bar{\epsilon}_i$ are individual level means of water extraction, co-variates, a dummy for efficient irrigation technology adoption, and the error term, respectively, and τ is the estimate of the "treatment effect" of the adoption of the more efficient irrigation technology on water extraction. Consistent estimation requires that $\mathbf{x}_{it}$ be uncorrelated with the time-varying component of the error, $\bar{\epsilon}_{it}$.[2] Equation 9 is also estimated with a correlated random trend model, which allows the policy of interest to be correlated with trends in the response variable. Consider $W_{it} = c_i + g_i t + \lambda_t + \tau w_{it} + \mathbf{x'_{it}}\beta + \epsilon_{it}$, where g_i is a trend in the individual-level omitted variable. If (c_i, g_i) is correlated with w_{it}, which would lead to biased estimates with fixed effects, the correlated random trend model can be used. It involves first differencing to obtain:

$$(W_{it} - W_{it-1}) = g_i + \eta_t + (\mathbf{x_{it}} - \mathbf{x_{it-1}})'\beta + (w_{it} - w_{it-1})'\tau + (\epsilon_{it} - \epsilon_{it-1}) \tag{11}$$

for $t = 2, ...T$, where $\eta_t = \lambda_t - \lambda_{t-1}$ is a new set of time effects, and then estimating equation 11 using fixed effects (Wooldridge 2001).

Finally, while the panel data allows us to control for individual fixed effects, year effects, individual effects that trend over time, and heteroskedasticity and intra-group correlation in the disturbances, if water extraction and irrigation technology choice are simultaneous choices the panel data estimates may be biased (i.e., $E(\tilde{\epsilon}_{it}|\tilde{w}_{it}) \neq 0$ and $cov(\tilde{\epsilon}_{it}, \tilde{w}_{it}) \neq 0$, where $\tilde{\epsilon}_{it}$ and $\tilde{w}_{it}$ are the mean-differenced variables in equation 10). We address the possibility of endogeneity by instrumenting for the conversion to the more efficient technology. As mentioned in the background section, nearly \$6 million was allocated to Kansas counties from 1998 to 2005 to use as cost-share based incentives to increase irrigation efficiency. The amount of money allocated to a county should be correlated with the adoption of the more efficient technology, but is likely not to affect the quantity pumped except through its effect on the use of irrigation technology. We estimated a variety of technology adoption models and find that an important driver of the adoption of dropped nozzle systems was the availability of the irrigation efficiency cost-share funds (results shown in Appendix A). A full fixed effects instrumental variables model is estimated using instrumental variables two stage least squares, where $\mathbf{z_{it}}$ is a vector of time-variant instrumental variables, $\tilde{\mathbf{z}}_{\mathbf{it}}$ is the mean-differenced vector of instrumental variables, and $E(\tilde{\epsilon}_{it}|\tilde{\mathbf{z}}_{\mathbf{it}}) = 0$ or $cov(\tilde{\epsilon}_{it}, \tilde{\mathbf{z}}_{\mathbf{it}}) = 0$ but $cov(\tilde{w}_{it}, \tilde{\mathbf{z}}_{\mathbf{it}}) \neq 0$ (Wooldridge 2001). In our specification, $\mathbf{z_{it}}$ includes cost-share funds allocated to the county as the excluded instrument, as well as precipitation, evapotranspiration, and the depth to groundwater.

We then disaggregate total water extraction into water extraction per acre and acres irrigated. Water extraction per acre, b_{it}, is modeled as:

$$b_{it} = c_i + \lambda_t + \mathbf{x}'_{\mathbf{it}}\beta + \tau w_{it} + \epsilon_{it}, \tag{12}$$

using the same methods and explanatory variables as W_{it}.

The estimation of the number of acres irrigated differs somewhat from that of total extraction and extraction per acre. For a field that has an irrigation system, the main decision a farmer makes is dichotomous: whether or not to irrigate (I_{it}). A farmer will irrigate a field if the expected profit from irrigating, which is a function of expected prices, time-varying characteristics, and individual farmer and field characteristics, $E(\pi_{1it}) = f_1(E(x_{1it}); \beta_1) + c_{1i} + \epsilon_{1it}$, is greater than the expected profit from not irrigating, $E(\pi_{0it}) = f_0(E(x_{0it});\beta_0) + c_{0i} + \epsilon_{0it}$:

$$I_{it} = \begin{cases} 1\, if\, E(\pi^*_{it})>0 \\ 0\, if\, E(\pi^*_{it})\leq 0 \end{cases} . \tag{13}$$

Thus $E(\pi^*_{it})$ is the difference between the outcome and the unobservable counter-factual: the difference in expected profit if the field is irrigated versus if the same field is not irrigated.

Then (although the decision may be simultaneous), a farmer decides how much of a field to irrigate (a_{it}). We observe in the data that often only a portion of the field is irrigated. The farmer may be diversifying his crop portfolio, planting a different crop in the corners of their field, or dedicating his water allocation to a portion of the field. The equation for the proportion of a field irrigated is:

$$a_{it} = \begin{cases} a^*_{it}\, if\, E(\pi^*_{it})>0 \\ 0\quad if\, E(\pi^*_{it})\leq 0 \end{cases} . \tag{14}$$

This type of model is generally estimated as a selection model (Heckman 1978; Cragg 1971). However, in this case the errors are not jointly normally distributed because the panel observations are correlated over time. In fact, we wish to exploit the repeated observations to difference out time-invariant individual field and farmer characteristics. In addition, the decision to not irrigate (fallow a field or plant a non-irrigated crop) is actually a decision between not irrigating and planting a portfolio of alternative crops. Finally, the number of acres irrigated is not the true choice variable; rather, it is the share of a field to be irrigated so a linear model would be mis-specified. Thus, we model the two decisions separately.

Conditional on irrigating, a fractional probit model is used to estimate the share of a field that is irrigated:

$$E(a_{it}|E(\mathbf{x}_{it}), E(\mathbf{p}_{it}), w_{it}, c_{it}) = F(c_i + \lambda_t + \beta\mathbf{E}(\mathbf{x_{it}}) + \tau w_{it}) \tag{15}$$

where $F(.) = \phi(.)$ is the standard normal cdf and $a_{it} \in [0, 1]$ (Papke and Wooldridge 2008, 1993; Wooldridge 2001). Papke and Wooldridge (2008) show that $\phi(.)$ is the preferred estimator when the response variable is not binary and the errors may be serially correlated. Equation 15 fits a population-averaged panel data model for the proportion of a field irrigated, thus incorporating individual time invariant characteristics. $\mathbf{E}(\mathbf{x}_{it})$ are the pre-growing season expectations of the co-variates because the decision occurs before the start of the growing season.

The probability of leaving a field unirrigated (whether through fallowing or planting an non-irrigated crop) is modeled as an alternative in a crop choice model (Antle and Capalbo 2001). A crop choice model is of additional interest because if there was a change in water extraction per acre correlated with the shift to more efficient irrigation technology, it may have occurred because farmers shifted their mix of crops or changed their crop rotation patterns (Castellazzi et al. 2008; Antle and Capalbo 2001). Our ability to test for shifts in crops is limited by data complexities that are described in detail in the following section. Essentially, a field can be multi-cropped, but the proportion of the field planted to each crop is not recorded in the data so we do not know the number of acres planted to a particular crop. Thus, we estimate a qualitative conditional logit model at the individual field level to test the propensity to plant each of the 7 most planted crop groups. An eighth group, "other" captures all other combinations of crops. A final group indicates if a farmer chose to leave the land fallow or plant a non-irrigated crop. Let $p_{ij}, j = 1, ...9$ represent the probability that individual i plants crop j; then p_{ij} can be modeled with a multinomial logit where

$$p_{ij} = \frac{exp(\mathbf{E}(\mathbf{x}_i)'\beta_j + w_i'\tau_j)}{\sum_{j=1}^{10} exp(\mathbf{E}(\mathbf{x}_i)'\beta_j + w_i'\tau_j)}, \ j = 1, ...9. \tag{16}$$

The co-variate matrix $\mathbf{x_i}$ includes indicator variables for whether each crop group was planted in the previous period which assumes a Markovian process of crop rotation (Castellazzi et al. 2008). This captures systematic crop rotation patterns and controls, at least in part, for time-invariant field unobservables that may be correlated with the choice of irrigation system. A two-year lag was included as well, but it did not significantly improve the fit of the model (results not shown). τ estimates the change in the probability of planting each crop after the more efficient irrigation technology is adopted. Planting decisions are assumed to be independent over time after controlling for the previous year's crop (i.e., no individual field fixed effect can be included in the multinomial logit model), but errors are clustered by field to obtain heteroskedasticity- and intra-group correlation-robust standard errors. Several additional models were estimated to confirm that the multinomial logit results were not dependent on the exclusion of fixed effects. Bivariate fixed effects linear probability and logit models estimating the probability of planting corn, planting a water intensive crop (corn, soybeans, or alfalfa), and leaving a field fallow or unirrigated produced robust results and are available in Appendix B.

A change in water use per acre may have also been due to changes in yields. On an individual level, producers may adopt more efficient irrigation technology because they expect an increase in profit, which is likely through increased yields or switching to more valuable crops. Increases in yields may more than justify the additional cost of installing dropped nozzles, and may offset the societal cost (if any) of an increase in groundwater extraction. Unfortunately, we do not have access to data that would allow the investigation of the yield benefits, and it is left for future research.

Data

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), supported by the Kansas Water Office. It includes spatially referenced pumping data, and identifies the farmer, field, irrigation technology, amount pumped, number of acres irrigated, and crops grown for all irrigation wells in Kansas. There are about 20,000 points of diversion utilizing groundwater for each of the 10 years from 1996 to 2005 and summary statistics are provided in table 1.[3] Although there may be more than one point of diversion on what a producer considers a "field", we assume for the analysis that one point of diversion irrigates one field.[4] Thus, the dependent variable for model 9 is simply the total amount of water extracted from each point of diversion. It is divided by the number of acres irrigated to obtain water extraction per irrigated acre, the dependent variable for model 12. The average well irrigates 150 acres. The average total extraction is 170 acre-feet, and the average rate of irrigation is 1.17 acre-feet per acre.

Field size is calculated as the maximum of the number of acres irrigated during 1996-2005. Fields of less than 60 acres or greater than 640 acres are excluded from the analysis.[5] The average field size is 170 acres, and on average 13 percent of fields are left fallow (or planted with a non-irrigated crop). The dependent variable for model 15, the percent of field that is irrigated, is the number of acres irrigated in a given year divided by field size.

The independent variables used in the analyses are from a variety of sources. Precipitation data are from PRISM (Parameter-elevation Regressions on Independent Slopes Model), a model that produces continuous spatial grids of monthly and annual precipitation.[6] ArcGIS is used to match growing season (May-September), pre-growing season (January-April) and annual precipitation to the location of groundwater wells. Average annual precipitation for the region is 22 inches, with an average of 4.4 inches occurring prior to planting in May. Daily evapotranspiration, collected at stations throughout Kansas, was obtained from the Kansas Weather Library, summed over the growing season, and matched to the well data using the station closest to each well. An average of 55 inches of evapotranspiration occurs during the growing season. For models 15 and 16, expected precipitation and expected evapotranspiration are calculated as the average from 1996-2005 at each location.

The United States Geological Survey's High Plains Water-Level Monitoring Study maintains a network of nearly 10,000 monitoring wells. Data from these wells were used to estimate the annual pre-planting depth to groundwater at each point of diversion using ArcGIS.[7] The average depth to groundwater is 121 feet, although it varies widely by region.

The WIMAS does not report yields, and in many cases, the data containing the crop planted on the field cannot be used to calculate the acreage planted to each crop. The data reporter is asked to code the crops that were planted in a field, but not the proportion of the field planted to each crop. For example, a field planted in half corn and half wheat would look the same in the data as a field planted in corn with wheat planted in the center pivot corners. Ideally, we would like to study the relationship between the use of more efficient irrigation and crop acreage decisions. However, this would involve potentially inaccurate assumptions about the proportion of crops planted to each multi-cropped field. Instead we estimate a qualitative crop choice model where the choices include the five most often planted monocrops (corn, alfalfa, wheat, soybeans, and sorghum), as well as the most often planted crop combinations. These include corn and soybeans, corn and wheat, and an "other" category that includes all other crop combinations. Thirty-six percent of western Kansas farmers plant [monocropped] corn, 8 percent plant alfalfa, 6 percent plant soybeans, and 4 percent plant wheat. The other crops and combinations are shown in table 1, as well as the proportions by the five groundwater management districts in western Kansas.

The Kansas cost-share program data used for the instrumental variable were compiled by the authors from hard-copy records at the Kansas State Conservation Commission, and include the dollar amount spent on center pivot irrigation efficiency upgrades via the federally-funded Irrigation Water Conservation Fund and Environmental Quality Incentives Program cost share programs, by county.

Results

Table 2 shows that total groundwater extraction has increased on average as a result of conversions from center pivots to dropped nozzles. The results from the fixed effects, correlated random trend (CRT), and instrumental variables (IV) regressions are robust. The estimates range from 3.6 (IV-FE) to 5.0 (CRT estimated via difference equations) acre-feet per irrigation unit (field); this amounts to about a 3 percent increase over the average total annual extraction using standard center pivots. This implies that rather than conserving groundwater, farmers used their efficiency "savings" to expand irrigated acreage or apply more water per acre. All of the time-varying co-variates have the expected signs; irrigation decreases with precipitation, increases with evapotranspiration, and decreases with the depth to groundwater. All four methods eliminate the effects of individual time-invariant characteristics and determinants of behavior that do not vary cross-sectionally, such as crop and energy prices. The IV estimate controls for the possibility of endogeneity of the choice of irrigation system. The first stage of the pooled two stage least squares is shown in table 3, along with the instrumental variables estimation diagnostics. The instrument passes the under-identification test and the weak-instrument robust-inference test, and its first-stage F-statistic is considerably greater than 10.

The increase in total water extraction could have occurred because farmers adjusted at the extensive margin, the intensive margin, or both. Conditional on deciding to irrigate, the adoption of dropped nozzles was associated with a 1 percent increase in the average percentage of a field that is irrigated (table 4). This represents a small (likely economically insignificant) adjustment along the extensive margin.

Column 1 of table 5 shows the results for the probability of fallowing a field or planting a non-irrigated crop from the crop choice model specified in equation 16. This is another type of adjustment along the extensive margin; if fields are left unirrigated less often, more land is in irrigated production each year.The coefficients indicate the effect of the independent variables on the latent propensity of each outcome, and are presented as risk ratios relative to the base category of planting wheat. The average predicted probabilities of each result are shown at the bottom of the table. A farmer's relative probability of leaving a field fallow (versus planting irrigated wheat) after switching to dropped nozzles is 0.29 times their probability of leaving a field fallow when using center pivot irrigation. More generally, a switch from center pivot to dropped nozzles is expected to decrease the probability of leaving a field fallow, compared to the probability of planting wheat (because the relative risk ratio$<$1). The marginal effect at the means of the independent variables (MEM) and the average marginal effects (AME) of a switch from center pivots to dropped nozzles are calculated and shown at the bottom of the table. The probability of leaving a field fallow decreases by 0.11 for a farmer with average values of the independent variables after the adoption of dropped nozzles. The magnitude of the AME is slightly smaller, 0.06 on average.

Farmers may also make adjustment along the intensive margin by applying more water per acre to irrigated fields (model 12, results in table 6). Applied water per acre increased on average by 0.03 to 0.05 acre-feet per acre with the adoption of dropped nozzles, a 2.5 percent increase from the average application rate with standard center pivots. The effect is robust across model specifications.

This increase in water applied per acre may have occurred because farmers adjusted their mix of crops toward more water intensive crops or varieties, or because yield increased. While the data to conduct an analysis of yields of the varieties planted is not available, the marginal effects in table 5 show that farmers did change their crop mix after the adoption of dropped nozzle irrigation. In particular, they were more likely to plant alfalfa, corn, and soybeans. While the data does not allow us to determine if quantitatively more total acres of the more water intensive crops were planted, table 5 shows that qualitatively, a farmer was more likely to plant relatively water intensive crops (monocropped corn, alfalfa, and soybeans) on a given field after the adoption of dropped nozzles.

These results suggest that the long-run demand for groundwater, taking into account the revenue and cost effects described in the Background section, is elastic in western Kansas. We utilize the demand elasticity estimated by Hendricks and Peterson (2012), along with estimates of the change in marginal costs of pumping and marginal revenue to calculate back-of-the-envelope estimates for comparing the short-run demand elasticity with the cost and revenue effects in equation 7. If, under reasonable assumptions, $|\eta_x| > k\left(1 - \frac{\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}}c'(k)}{X(\tilde{c},k)} - \frac{\frac{\partial X(\tilde{c},k)}{\partial k}k}{X(\tilde{c},k)}\right)$, then our empirical findings are plausible. Hendricks and Peterson (2012) estimated a demand elasticity of -0.113, but in order to make their estimate independent of the choice of irrigation technology, assumed a necessary operating pressure of zero. The actual operating pressure required by an irrigation system depends on the specifics of the system; a conventional center pivot system would require an operating pressure of approximately 70 psi (Rogers et al. 2008). Assuming 70 psi would increase the Hendricks and Peterson (2012) elasticity of demand estimate to -0.585. The conversion to a dropped nozzle LEPA system would decrease the average pressure required from approximately 70 to 10 psi, cutting the marginal cost of extraction in half. Thus, the first fraction on the right-hand-side of inequality 7 would be approximately 0.282. Finally, yields are expected to increase due to the ability to more precisely match the crop's water requirements to delivery. The change in revenue may vary widely depending on the crop, prices, precipitation, and the degree of water deficit, but based on experimental station research we assume the average to be 5 percent. Plugging these estimates into equation 7, with k=0.85, yields $|\eta_x|$ =0.585 and $k\left(1 - \frac{\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}}c'(k)}{X(\tilde{c},k)} - \frac{\frac{\partial X(\tilde{c},k)}{\partial k}k}{X(\tilde{c},k)}\right)$ =0.564. Thus, under reasonable assumptions, the conversion from conventional center pivot irrigation to dropped nozzle center pivot irrigation could plausibly increase the extraction of groundwater in western Kansas. The details of the calculations and the sensitivity of these estimates are discussed in Appendix C.

In 1972, five groundwater management districts were created in Kansas to decentralize the administration of groundwater policy and information to facilitate responsiveness to local issues (shown in figure 2) (Sophocleous 2012). Within each district, the soil quality, aquifer characteristics, and farming practices are similar. However, small differences between groundwater managment districts may correspond to variation in the potential cost and revenue effects of a change in irrigation efficiency, and may have resulted in differences in the effect of the shift to dropped nozzles on groundwater extraction. For example, the depth to groundwater is the largest in groundwater management districts 1, 3, and 4 (table 1), which would correspond to a more negative cost effect (the conversion to dropped nozzles would cause a larger decrease in the marginal cost of extraction). The percentage of fields left fallow was the highest in district 1. The proportion of a field irrigated and the percentage of acres in monocropped corn or alfalfa were also the lowest in district 1. This could correspond to a weak revenue effect; if district 1 has characteristics that make it a relatively poor place to grow the most water intensive crops or where crop rotations and fallow cycles are necessary, the potential revenue benefit from conversion may be smaller.

Table 7 presents the main results for total water extracted (equation 9), water extraction per acre (equation 12), the share of a field irrigated (equation 15), and the probability of a fallow/non-irrigated cycle by groundwater management district. The estimated change in total groundwater use and irrigation per acre are significantly different from zero only in districts 3 and 4. A decrease in the probability of leaving a field fallow or planting a non-irrigated crop was associated with the conversion to dropped nozzles in all five irrigation districts, but the effect was the greatest in groundwater management districts 1 and 2. The average proportion of a field irrigated increased with the transition to dropped nozzles in districts 2 and 3. Together, these results corroborate expectations based on the potential cost and revenue effects of the change in irrigation efficiency: groundwater extraction is more likely to increase when the cost and revenue benefits are larger. Adjustment along the extensive margin, including leaving fields fallow or unirrigated less often and irrigating a slightly larger proportion of a field, still occurred in the least irrigation intensive areas even if it did not result in a net change in groundwater extraction.

Finally, in tables 8-9 the results for total water use and water application per acre for plots that were converted from flood irrigation to center pivots during 1996-2005 are shown. The results are strikingly different from the results for the switch from center pivots to dropped nozzles (tables 2 and 6), but corroborate previous literature that focused on the conversion from flood to center pivot irrigation in western Kansas (Peterson and Ding 2005; Hendricks and Peterson 2012). On average, the conversion from flood to center pivot irrigation is associated with a reduction in total water extracted of 10 to 14 acre-feet, and a reduction in water use per acre of about 0.04 acre-feet per acre (although only the result from CRT estimated via fixed effects is significant). These results are also consistent with the theoretical implications of equation 7; a conversion from flood irrigation to a conventional center pivot system would generally involve an increase in the operating pressure necessary to run the system, increasing (rather than decreasing) the marginal cost of applied water.[8]

Conclusions

The depletion of groundwater in the High Plains Aquifer has become an important topic of policy in western Kansas, as it has in agricultural basins around the world. Crop and livestock systems often form the base of the economy in these regions and depend almost exclusively on the availability of irrigation water. In some areas, the economic systems that depend on the water are not sustainable because recharge to the aquifer is very small– a tiny fraction of annual extraction. In order to make the water last longer, policy has focused on reducing rates of extraction. One of the most popular and politically feasibly programs involves encouraging the adoption of more efficient irrigation technology for agricultural production.

Jevons (1865) postulated that the invention of a technology that enhances the use efficiency of a natural resource does not necessarily lead to a reduction in consumption of that resource. This idea, now referred to as "Jevons' Paradox" or "the rebound effect" in the energy economics literature, describes the behavioral response of increasing [energy] consumption as gains in the efficiency of consumption reduce the per unit price. The increase in consumption of energy services may fully or partially offset the energy savings impact of the increase in efficiency. Empirically, there is evidence of the rebound effect in vehicle use, space heating and cooling, and lighting (Greene, Kahn, and Gibson 1999; Greening, Greene, and Difiglio 2000; Hertwich 2005), but the estimated magnitude of the effect is small to moderate (5%-65% of savings due to increased efficiency). Although the rebound effect has not been previously explicitly discussed in relation to increases in irrigation efficiency, the idea is similar. More efficient irrigation technology generally increases the "effectiveness" of a unit of water, but it also changes a farmer's profit maximization problem and can lead to changes in yields, crop choices, crop rotation patterns, or expand irrigated acreage.

We find that increases in irrigation efficiency brought about by a voluntary shift from center pivot systems to center pivot systems with dropped (high efficiency) nozzles in western Kansas from 1995 to 2005 was correlated with *increases* in groundwater extraction. This is a rebound effect of over 100 percent. The effects that we estimate represent the net change in applied water, which include both the effect of increased efficiency and any movement along the demand function for irrigation in response to lower per-unit prices and higher productivity. Our results indicate that farmers adjusted the extensive margin: fields were left fallow (or unirrigated) less often, and when they were irrigated, a larger percentage was irrigated. Farmers adjusted at the intensive margin as well: dropped nozzles were associated with an increase in applied water per acre of approximately 2.5 percent; these changes were driven by farmers in the most irrigation intensive areas of aquifer. Changes in crop mix are an important part of the story; farmers were more likely to plant corn, alfalfa, and soybeans, which are relatively water intensive crops. Previous theoretical and deterministic research has dealt with the dynamic nature of crop rotation patterns and farmers' planning horizons in a very simplified manner, if at all; our results indicate that empirically, changes in crop rotation patterns (including fallow cycles) were an essential component of the behavioral response to the investment in higher irrigation efficiency. Yields undoubtedly increased as well due to the increase in irrigation efficiency, but individual-level yield data were not available to us.

It should be noted that farmers in western Kansas are extremely conservation minded, and that much of the conversion from flood irrigation to center pivots, and then from center pivots to dropped nozzle center pivot systems, was driven he desire to reduce water losses from runoff, evaporation, and drift, as well as by reductions in well capacity due to falling water tables. These results thus underscore the importance of considering the full effect of conversion. while increased irrigation efficiency is likely to be individually welfare-enhancing through increased yields, the ability to plant more valuable crops, decreases in the cost of irrigation water, and consistency with conservation ideals, individual adjustments at the margins may negate conservation goals. If conservation is truly the goal, policies designed to increase irrigation efficiency must be examined critically, with attention paid to behavioral responses. To achieve conservation, increases in irrigation efficiency must be accompanied by corresponding decreases in the quantity of water that a user is allowed to extract, either through a decrease in the legal water right, a tax on water extraction, the regulation of crop and fallow cycles, or through other measures. Any type of regulation, however, necessitates clear property rights and effective systems of reporting and enforcement, institutions that are scarce in the real world of groundwater management.

Notes

[1]The focus of Huffaker and Whittlesey (2000) model was on the importance of accounting for return flows in a basin model, but they included a case without return flows.

[2]Equation 9 is also estimated using first-difference estimations, which are consistent even if the errors are serially correlated although the first year of data is lost (results not shown). Random effects are not appropriate because we believe the individual effect to be correlated with the choice of irrigation technology.

[3]The number of observations in the table of summary statistics is not directly comparable to the number of observations in the regression results tables because the regressions include observations where extraction is zero, while the summary statistics (for total extraction, extraction/acre, and acres irrigated) do not. In addition, N=237430 in the regression tables because the regressions utilize data from before and after a change in irrigation technology but exclude observations from the third category of technology (i.e., for a shift from center pivot to dropped nozzles, observations when a field used flood irrigation are excluded).

[4]Additionally, in some cases, more than one well (a "battery of wells") irrigates what we consider a single field. In this case we aggregate the water extracted from the battery of wells and georeference it to the centroid of the battery.

[5]Hendricks and Peterson (2012) make a similar assumption, although we include fields from 275-640 acres, which they exclude. Our results are robust to either assumption.

[6]PRISM (Parameter-elevation Regressions on Independent Slopes Model) data sets are the USDA's official source of climate data. http://www.prism.oregonstate.edu/

[7]The depths at each point of diversion were interpolated from monitoring well data using the kriging method of geostatisitcal interpolation. A variable search radius with a minimum of 12 data points and an exponential model of the empirical semivariogram (the relationship between variance and distance) was determined to be the most efficient predictor of the water table depth (using the tools available in ArcGIS). Alternative predictions resulting from variations in the radius or semivariogram model chosen resulted in no detectable differences in the final regression results.

[8]The results for the transition from flood to center pivot systems should be interpreted with caution because our dataset does not include the time period when most of the conversions from flood to center pivots occurred. Thus, there may be a selection bias: the last fields converted to center pivots were likely the ones with the smallest expected net benefit from conversion, and differences in the behavior of irrigators on these plots and the first plots to be converted may be significant. This type of selection bias is less likely to be present for the estimation of the effect of the transition from standard center pivots to dropped nozzles because our sample includes a majority of the adopters.

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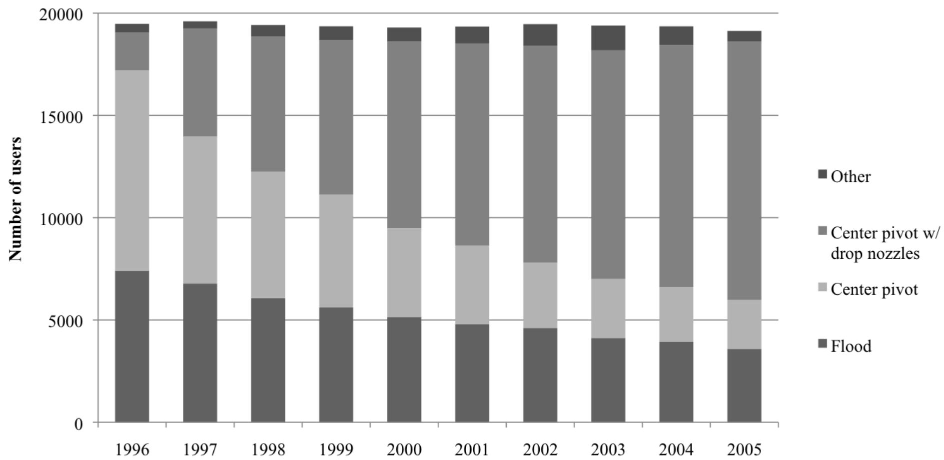

Figure 1: Irrigation technology used in western Kansas by groundwater users, 1996-2005. Source: WIMAS data

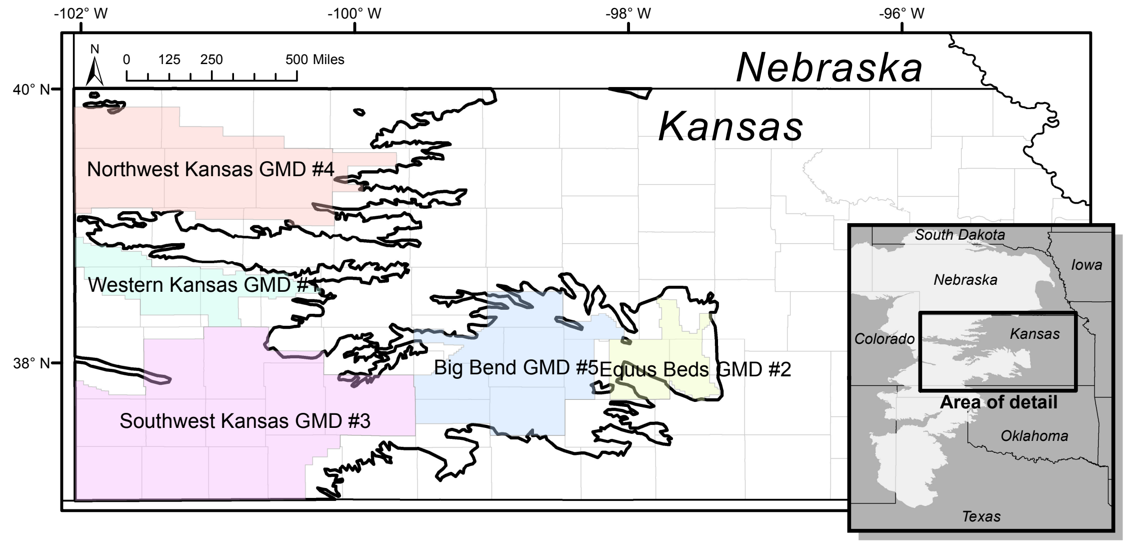

Figure 2: The High Plains Aquifer, the area of study, and the 5 groundwater management districts in western Kansas.

Table 1: Summary statistics

	N	Mean	Std. Dev.	Min.	Max.
Total extraction (AF)	175923†	174.61	121.4	0.0	1988.6
Flood irrigation	46260	154.58	155.4	0.0	1988.6
Center pivot	34894	161.73	112.8	0.0	1102.0
Dropped nozzle	80979	174.03	117.8	0.0	1491.5
Extraction/acre (AF/ac)	175923	1.16	0.5	0.0	5.0
Flood irrigation	46260	0.98	0.6	0.0	5.0
Center pivot	34894	1.08	0.6	0.0	4.8
Dropped nozzle	80979	1.15	0.6	0.0	4.8
Acres irrigated	175923	153.16	85.1	1.0	640.0
Flood irrigation	46260	156.19	108.2	1.0	640.0
Center pivot	34894	151.85	72.3	1.0	640.0
Dropped nozzle	80979	155.87	78.6	1.0	640.0
Proportion of irrigable acres irrigated	175923	0.87	0.2	0.0	1.0
Flood irrigation	46260	0.78	0.2	0.0	1.0
Center pivot	34894	0.91	0.2	0.0	1.0
Dropped nozzle	80979	0.89	0.2	0.0	1.0
Annual precipitation (in)	219722‡	21.71	5.4	9.3	41.7
Pre-season precipitation (in)	219722	4.39	2.4	0.0	15.3
Percent of farmers planting:					
alfalfa	8.20				
corn	36.58				
sorghum	2.08				
soy	6.21				
wheat	3.22				
other (including combinations)	31.76				
soy and corn	3.59				
corn and wheat	8.38				
By Goundwater Management District:	1	2	3	4	5
Total extraction (AF)	125.8	101.8	226.5	141.9	130.5
Extraction/acre (AF/ac)	1.03	0.91	1.30	1.14	1.05
Acres irrigated	130.1	113.3	187.2	128.0	124.3
Proportion of irrigable acres irrigated	0.79	0.93	0.89	0.87	0.95
Percentage of fields left fallow	31.7	18.8	23.7	14.0	14.4
Depth to groundwater (ft)	138.4	25.1	161.3	130.2	29.0
Annual precipitation (in)	19.2	33.0	20.0	18.9	26.1
Percent of farmers planting:					
alfalfa	1.45	1.32	13.75	5.80	9.29
corn	25.59	28.89	29.27	50.18	41.10
soy	0.85	23.49	2.25	4.35	14.75
wheat	3.53	1.36	4.35	4.48	2.36
N	23027	11361	86352	35384	33972

†N=176051 refers to plots with positive irrigation in a given year. Minima for total extraction and extraction/acre are small positive numbers that round to zero. ‡N=219722 refers to all plots and all years with sufficient data quality to be included in the dataset.

Table 2: Fixed effects and difference regressions for the effect of conversions from center pivot to dropped nozzle irrigation on total extracted water (af)

	(1)	(2)	(3)	(4)
	Fixed effects Year dummies	CRT (FE)	CRT (Difference)	IV-FE
Pivot to dropped	3.948***	4.795***	5.071***	3.600*
	(0.761)	(1.005)	(1.387)	(1.677)
Annual precipitation (in)	-2.307***	-2.714***	-3.169***	0.037
	(0.065)	(0.071)	(0.080)	(1.200)
Summer evapotranspiration (in)	0.314***	0.806***	1.300***	3.901*
	(0.068)	(0.098)	(0.123)	(1.554)
Depth to groundwater (ft)	-0.308***	0.062	0.026	-0.189*
	(0.032)	(0.040)	(0.052)	(0.080)
Year dummies	included	included	included	included
Constant	202.373***	9.475***		
	(5.748)	(0.630)		
N	173512	151750	131043	131791
R^2	0.78	0.10	0.10	

Notes: Standard errors in parentheses. Significance codes: * p<0.05, ** p<0.01, *** p<0.001. "CRT" is correlated random trend. "IV-FE" is fixed effects instrumental variables. The first stage if the IV-FE model is reported in table 3.

Table 3: First stage of the fixed effects instrumental variables model

	First stage IV Adoption of dropped nozzles
County cost-share (thousands of $)	0.0003*
	(0.000)
Annual average precipitation (in)	-0.0070***
	(0.000)
Summer average evapotranspiration (in)	-0.0094***
	(0.001)
Depth to groundwater (ft)	-0.0002
	(0.000)
Year dummies	included
N	131791
R^2	0.325
First-stage F-statistic	1374.5
Under-identification test (Kleibergen-Paap rk LM P-value)	0.0137*
Weak-instrument robust-inference test (Anderson-Rubin Wald P-value)	0.000***

Notes: Standard errors in parentheses. Significance codes: * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 4: Fractional probit model of the proportion of a field irrigated, conditional on the decision to irrigate

	Fixed effects year dummies	dy/dx
Pivot to dropped	0.053***	0.010
	(0.008)	
Annual average precipitation (in)	0.050***	0.009
	(0.004)	
Jan-Mar precipitation (in)	0.002	0.000
	(0.002)	
Summer average	-0.074***	-.013
evapotranspiration (in)	(0.008)	
Depth to groundwater (ft)	0.001***	0.000
	(0.000)	
Field size (acres)	-0.002***	-0.001
	(0.000)	
Year dummies	included	
Constant	4.564***	
	(0.460)	
N	134929	

Notes: Standard errors in parentheses. Significance codes: * p<0.05, ** p<0.01, *** p<0.001.

Table 6: Fixed effects and difference regressions for the effect of conversions from center pivot to dropped nozzle irrigation on marginal application rates (af/ac)

	(1)	(2)	(3)	(4)
	Fixed effects Year dummies	CRT (FE)	CRT (Difference)	IV-FE
Pivot to dropped	0.027***	0.042***	0.049***	0.026*
	(0.005)	(0.006)	(0.009)	(1.149)
Annual precipitation (in)	-0.017***	-0.021***	-0.024***	0.000
	(0.000)	(0.000)	(0.001)	(0.008)
Summer evapotranspiration (in)	0.001**	0.000	0.002*	0.026*
	(0.001)	(0.001)	(0.001)	(0.011)
Depth to groundwater (ft)	-0.002***	0.000	0.000	-0.002**
	(0.000)	(0.000)	(0.000)	(0.001)
Year dummies	included	included	included	included
Constant	1.452***	0.064***		
	(0.037)	(0.005)		
N	173512	151750	131043	131791
R^2	0.51	0.15	0.16	

Notes: Standard errors in parentheses. Significance codes: * p<0.05, ** p<0.01, *** p<0.001. "CRT" is correlated random trend. "IV-FE" is fixed effects instumental variables. The first stage if the IV-FE model is reported in table 3.

Table 5: Multinomial logit model of the effect of conversions from center pivot to dropped nozzle irrigation on crop choice

	(1) fallow/ non-irrigated	(2) alfalfa	(3) corn	(4) sorghum	(5) soy	(6) wheat	(7) other	(8) corn, soy	(9) corn, wheat
Pivot to dropped	0.293***	1.078	1.026	0.966	1.120**		0.917**	0.937	0.857***
	(0.015)	(0.054)	(0.041)	(0.064)	(0.052)		(0.037)	(0.055)	(0.041)
Annual average precipitation (in)	1.056***	0.970*	1.192***	1.197***	1.343***		1.111***	1.463***	1.001
	(0.015)	(0.017)	(0.016)	(0.025)	(0.020)		(0.016)	(0.027)	(0.016)
Jan-Mar precipitation (in)	1.015	1.029	0.980	0.988	1.016		1.013	0.952**	0.988
	(0.018)	(0.021)	(0.015)	(0.025)	(0.017)		(0.016)	(0.021)	(0.019)
Summer average evapotranspiration (in)	0.846***	0.865***	1.045*	1.111**	1.095***		1.004	1.740***	1.002
	(0.023)	(0.027)	(0.025)	(0.048)	(0.032)		(0.025)	(0.095)	(0.030)
Depth to groundwater (ft)	1.002***	0.998***	1.003***	1.000	0.998***		1.000	1.001	1.000
	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)		(0.000)	(0.001)	(0.001)
Field size (acres)	1.002***	1.000	1.002***	1.002***	0.998***		1.006***	1.005***	1.007***
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)		(0.000)	(0.000)	(0.000)
Year dummies	included	included	included	included	included		included	included	included
Lagged crop group dummy variables	included	included	included	included	included		included	included	included
Average probabilities	0.208	0.065	0.291	0.017	0.050	0.026	0.240	0.029	0.076
MEM of "Pivot to dropped"	**-0.113*** **	**0.024*** **	**0.087*** **	**0.001**	**0.012*** **	**0.005*** **	**0.007**	**-0.002** **	**-0.006*** **
AME of "Pivot to dropped"	**-0.057*** **	**0.009*** **	**0.026*** **	**0.001* **	**0.010*** **	**0.005*** **	**0.007*** **	**0.000**	**0.000**

Notes: N=151,944. Pseudo R^2=0.455. Coefficients are presented as relative risk ratios. Robust standard errors in parentheses. MEM is the marginal effect at the means of the independent variables, and AME is the average marginal effect. Significance codes: * p<0.05, ** p<0.01, *** p<0.001.

Table 7: Effect of conversions from center pivot to dropped nozzle irrigation on total water extraction, water application per acre, the dichotomous decision to irrigate, and the proportion of a field irrigated, by groundwater management district (GMD)

	GMD 1†	GMD 2	GMD 3	GMD 4	GMD 5
Total irrigation	0.512	-0.661	6.421**	7.678***	1.847
	(8.553)	(2.544)	(1.964)	(2.218)	(1.334)
Irrigation/acre	0.029	-0.009	0.047***	0.063***	0.015
	(0.066)	(0.021)	(0.011)	(0.015)	(0.011)
Proportion to irrigate	0.013	0.015*	0.007*	0.009*	0.003
	(0.012)	(0.007)	(0.003)	(0.004)	(0.003)
Probability of fallow	-0.103***	-0.140***	-0.086***	-0.049***	-0.068***
(AME from multinomial logit)	(0.013)	(0.011)	(0.003)	(0.004)	(0.004)
N	14228	8155	67868	29963	29447

Notes: Standard errors in parentheses. AME is average marginal effect. Significance codes: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. †Sorghum was cultivated in so few fields in district 1 that the variance matrix of the multinomial logit was singular. Thus, sorghum was included in the "other" category for the estimation of the multinomial logit for district 1.

Table 8: Fixed effects and difference regressions for the effect of conversions from flood irrigation to center pivots on total extracted water (af)

	(1)	(2)	(3)
	Fixed effects	CRT (FE)	CRT (Difference)
Flood to pivot	-9.767***	-12.526***	-13.797***
	(2.463)	(3.075)	(4.075)
Yearly precipitation (in)	-1.965***	-1.194***	-1.141***
	(0.167)	(0.181)	(0.225)
Summer evapotranspiration (in)	1.384***	2.833***	4.016***
	(0.159)	(0.205)	(0.260)
Depth to groundwater (ft)	-0.772***	0.065	0.036
	(0.078)	(0.093)	(0.107)
Year dummies	included	included	included
Constant	251.700***	-9.765***	
	(15.565)	(1.546)	
N	50811	43129	36212
R^2	0.78	0.12	0.13

Notes: Standard errors in parentheses. Significance codes: * p<0.05, ** p<0.01, *** p<0.001. "CRT" is correlated random trend.

Table 9: Fixed effects and difference regressions for the effect of conversions from flood irrigation to center pivots on marginal application rates (af/ac)

	(1)	(2)	(3)
	Fixed effects	CRT (FE)	CRT (Difference)
Flood to pivot	-0.025	-0.044*	-0.039
	(0.014)	(0.019)	(0.025)
Yearly precipitation (in)	-0.014***	-0.011***	-0.011***
	(0.001)	(0.001)	(0.002)
Summer evapotranspiration (in)	0.006***	0.009***	0.014***
	(0.001)	(0.002)	(0.002)
Depth to groundwater (ft)	-0.003***	0.001**	0.001*
	(0.000)	(0.000)	(0.001)
Year dummies	included	included	included
Constant	1.488***	-0.057***	
	(0.101)	(0.013)	
N	50811	43129	36212
R^2	0.49	0.12	0.11

Notes: Standard errors in parentheses. Significance codes: * p<0.05, ** p<0.01, *** p<0.001. "CRT" is correlated random trend.

Appendix A: Irrigation technology adoption

Potential for endogeneity-induced bias exists in models 9 and 12 if the choice of irrigation technology and the amount of irrigation water to pump are simultaneous decisions. For example, if the estimates of τ are driven by farmers who anticipate increasing their water usage by converting to the more efficient irrigation technology, the estimates may be biased. In this appendix, we estimate several common technology adoption models for the conversion to dropped nozzle irrigation systems to provide evidence that a main driver of conversion was the availability of cost-share based incentives to increase irrigation efficiency that were offered by different counties at different times, rather than an anticipated increase in water usage, and therefore that our results are not driven by endogenous adoption.

Econometric studies of irrigation technology adoption have focused on the effect of water cost, labor cost, climate, and the characteristics of the field, including soil quality, slope, and water holding capacity, affect conversion rates (Negri and Brooks 1990; Green et al. 1996; Carey and Zilberman 2002; Schaible et al. 1991; Koundouri et al. 2006; Lichtenberg 1989; Moreno and Sunding 2005). Several deterministic programming-type models have focused on the effect of subsidies for irrigation technology adoption (Scheierling et al. 2006; Ward and Pulido-Velazquez 2008). Cost-share-type subsidies are a common instrument for accelerating the adoption of more efficient irrigation technology under the auspices of water conservation (Cooley et al. 2009; Jury and Vaux 2005; Zinn and Canada 2007; Johnson et al. 2001; Evans and Sadler 2008). However, research specific to the conversion to LEPA or other types of dropped nozzle systems from conventional center pivot irrigation systems, to our knowledge, has not been done.

As mentioned in the Background section, nearly $6 million was allocated to Kansas counties from 1998 to 2005 to use as cost-share based incentives to increase irrigation efficiency. The program paid up to 75 percent of the cost of purchasing and installing new or upgraded irrigation technology, and much of the money was used for conversions to dropped nozzle systems (NRCS 2004).

The technology adoption models for the conversion from conventional center pivots to dropped nozzle center pivot irrigation systems that we estimate include linear probability, logit, probit, and survival (parametric exponential) models. The primary explanatory variable of interest is the amount of money allocated to each county in each year for cost-share based incentives to increase irrigation efficiency. We also include as explanatory variables field, soil, and aquifer characteristics, climate variables, and characteristics of the water right (year of appropriation and annual limit). The linear probability, logit, and probit models include year fixed effects.

The results are presented in table A1. The results show that the availability of cost-share funds in the county increased the probability of conversion to dropped nozzles. As expected, field and climate characteristics also affected the probability of conversion. Prices were not included because we have used year fixed effects, which are highly significant.

The results show that an important driver of adoption was the availability of cost-share based incentives to increase irrigation efficiency that were offered by different counties at different times. Endogenous adoption that may bias our results on the effects of the adoption of efficient irrigation technology on water use is therefore less of a concern.

To further adress the possibility of endogeneity, we use this result that the availability of cost-share based incentives is an important driver of adoption to motivate the use of county-level cost share funds availability as an instrument for the conversion to dropped nozzles. A fixed effects instrumental variables model is estimated as a variation of models 9 and 12 and included in the main body of the paper.

Appendix B: Bivariate fixed effects crop selection models

Because the estimation of multinomial logit crop choice model (model 16, results in table 5) does not allow the inclusion of fixed effects, we estimated several variations of bivariate crop selection models in which we are able to include fixed effects. These models show that the results of the multinomial logit are qualitatively similar to models that account for endogeneity by including fixed effects. We estimate linear probability and fixed effects logit models for the probability of planting corn; the probability of planting either corn, alfalfa, or soybeans (all water intensive crops); and the probability of fallowing/not irrigating a field.

The results are presented in table B1. Consistent with our multinomial logit results, the results from the bivariate fixed effects models show that the conversion from traditional center pivot irrigation systems to higher efficiency dropped-nozzle center pivot systems has increased the probability of planting corn; increased the probability of planting corn, alfalfa or soybeans (all water intensive crops); and decreased the probability of leaving a field fallow or unirrigated.

Appendix C: Groundwater demand elasticity, cost effect, and revenue effect calculations

The model presented in the Background section implies the following necessary and sufficient condition for improved irrigation efficiency k to increase applied water use q:

$$\frac{\partial q}{\partial k} > 0 \Leftrightarrow |\eta_x| > k\left(1 - \frac{\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} c'(k)}{X(\tilde{c},k)} - \frac{\frac{\partial X(\tilde{c},k)}{\partial k} k}{X(\tilde{c},k)}\right)$$

In this appendix, we detail the calculations used to show that it is plausible that the inequality for the elasticity in equation 7 holds in western Kansas, thus making our empirical results showing that groundwater extraction increased due to the shift toward more efficient irrigation technology theoretically credible.

Elasticity of the demand for groundwater

The most relevant empirical estimation of the elasticity of demand for irrigation groundwater in western Kansas is from Hendricks and Peterson (2012), who use the same basic dataset used in this study. Their estimate, however, relies on an important assumption that is inadequately detailed in their paper. The full formula for pumping cost is $\theta \cdot P_{ng} \cdot (H + 2.31 \cdot PSI)$, where θ is the amount of natural gas required to lift one acre-inch of water one foot, P_{ng} is the price of natural gas, H is the distance in feet that the water must be lifted (the depth of the water table), and 2.31 is a conversion factor (Rogers and Mahbub 2006). However, Hendricks and Peterson (2012) omitted the $2.31 \cdot PSI$ component because actual PSI depends on the irrigation system, any adjustment that may occur to the irrigation system in their demand elasticity estimate. In doing so, they assumed $PSI = 0$. The cost of pumping water to the surface without any irrigation system ($PSI = 0$) is not the correct cost, especially if irrigation technology is fixed in the short term (changing irrigation technology is a significant investment and is generally not done during a growing season). The correct cost would incorporate the pressure needed at the pump, which varies by irrigation system. A fuel cost calculator developed by Kansas State Research and Extension was used to estimate the pumping cost per acre-inch as a function of PSI, using the data in table 1, for $P_{ng} = \$5/Mcf$ and $P_{ng} = \$6/Mcf$ (http://www.ksre.ksu.edu/mil/FuelCost.htm). Figure C1 shows the results. High impact conventional center pivot irrigation systems require 55-80 PSI (Rogers et al. 2008). Assuming $PSI = 70$, the elasticity of the demand for groundwater estimated by Hendricks and Peterson (2012) would increase in absolute value from 0.113 to 0.577 for a conventional center pivot system.

Cost effect

To estimate the cost effect (the first fraction on the right hand side of the inequality in equation 1), we need to approximate $c'(k)$. LEPA irrigation systems require a pressure of 5-15 PSI (Rogers et al. 2008). Thus, if we assume that the transition from a center pivot system to a dropped nozzle system would decrease average PSI required from 70 to 10 PSI, the cost/acre-in of pumping would be halved (assuming \$5/mcf gas). If the P_{ng} is higher, the decrease in total pumping cost would be larger (figure C1). Using Hendricks and Peterson (2012) estimates for X' and mean water extraction/acre from table 1, we calculate the cost effect to be approximately -1.95*(-2/13.6)=0.287.

Revenue effect

To estimate the revenue effect (the second fraction on the right hand side of the inequality in equation 7), we need to calculate $\frac{\partial X}{\partial k}$, the change in effective water resulting from a change in efficiency. The best measurement for this would be the change in evapotranspiration resulting from a change in efficiency, but evapotranspiration is difficult to measure. However, differences in evapotranspiration will result in differences in yield. Yield affects farmers' revenue, so it is likely the most relevant, measurable parameter. Estimates of the change in yield due to a conversion from center pivots to dropped nozzles from experimental fields range from 0 to 13 percent, with even greater benefits occurring in water-deficit conditions (New and Fipps 1990; Howell et al. 1995; Williams et al. 1996; Schneider and Howell 1998; O'Brien et al. 2001).

In table C1 and figure C2, we present some sensitivity analyses of these back-of-the-envelope calculations. Irrigation efficiency of a conventional center pivot system is assumed to be 0.85. The first section of the table allows the estimate of $\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}}$ to vary around the parameter estimated by Hendricks and Peterson (2012). The second section of the table allows $c'(k)$ to vary. The final section of the table allows the revenue effect to vary around a conservative estimate of 5 percent. Figure C2 charts the results. In each case, $|\eta_x|$ is greater than $k\,(1 - cost\,effect - revenue\,effect)$ for a portion of the range of the sensitivity analysis. Clearly, there may be cases where the inequality does not hold, meaning that the increase in irrigation efficiency would be more likely to decrease groundwater extraction. However, for much of the range of parameters calibrated to the conditions in western Kansas, it is plausible that an increase in irrigation efficiency would increase groundwater extraction.

Table A1: Dropped nozzle irrigation system adoption models

	Linear probability	Logit	Probit	Survival (exponential)
County cost-share (thousands of $)	0.002***	0.006***	0.004***	0.012***
	(0.000)	(0.001)	(0.000)	(0.001)
Depth to groundwater (ft)	0.000***	0.001***	0.001***	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Field size (ac)	-0.000***	-0.001***	-0.001***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Slope (% of distance)	-0.013***	-0.066***	-0.040***	0.017
	(0.002)	(0.009)	(0.005)	(0.016)
Saturated Hydraulic Conductivity (um/sec)	0.002***	0.009***	0.006***	0.010***
	(0.000)	(0.000)	(0.000)	(0.001)
Irrigated Capability Class (1=highest class, 0=all others)	-0.065***	-0.318***	-0.193***	-0.247***
	(0.003)	(0.016)	(0.009)	(0.031)
Available water capacity (cm/cm)	0.127	0.513	0.346	1.351*
	(0.075)	(0.367)	(0.224)	(0.686)
Avg yearly precipitation (in) 1971-2000	0.016***	0.077***	0.047***	0.062***
	(0.001)	(0.004)	(0.002)	(0.006)
Average evapotranspiration (in)	0.009***	0.050***	0.032***	0.052***
	(0.002)	(0.010)	(0.006)	(0.010)
Irrigation quantity authorized to extract (hundreds of AF)	0.015***	0.074***	0.045***	0.020**
	(0.001)	(0.004)	(0.002)	(0.007)
Year of prior appropriation (date of permit)	0.000*	0.001	0.001*	-0.008***
	(0.000)	(0.001)	(0.000)	(0.001)
Year fixed effects	included	included	included	
Year				0.412***
				(0.003)
Constant	-1.539***	-12.719***	-7.360***	-819.344***
	(0.319)	(1.550)	(0.950)	(7.130)
Observations	132413	132413	132413	126411
R^2	0.13	0.12	0.12	

Notes: Standard errors in parentheses. Significance codes: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. R^2 is pseudo R^2 for logit and probit models.

Table C1: Sensitivity analysis of elasticity estimates

$\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}}$	$X(\tilde{c},k)$	$c(k)$	$\lvert\eta_x\rvert$	$c'(k)$	$\frac{\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} c'(k)}{X(\tilde{c},k)}$	$\frac{\frac{\partial X(\tilde{c},k)}{\partial k} k}{X(\tilde{c},k)}$	$k\left(1 - \frac{\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} c'(k)}{X(\tilde{c},k)} - \frac{\frac{\partial X(\tilde{c},k)}{\partial k} k}{X(\tilde{c},k)}\right)$
-2.35	13.6	4.08	0.705	-2	0.346	0.05	0.514
-2.15	13.6	4.08	0.645	-2	0.316	0.05	0.539
-1.95	13.6	4.08	0.585	-2	0.287	0.05	0.564
-1.75	13.6	4.08	0.525	-2	0.257	0.05	0.589
-1.55	13.6	4.08	0.465	-2	0.228	0.05	0.614
-1.95	13.6	4.08	0.585	-1	0.143	0.05	0.686
-1.95	13.6	4.08	0.585	-1.5	0.215	0.05	0.625
-1.95	13.6	4.08	0.585	-2	0.287	0.05	0.564
-1.95	13.6	4.08	0.585	-2.5	0.358	0.05	0.503
-1.95	13.6	4.08	0.585	-3	0.430	0.05	0.442
-1.95	13.6	4.08	0.585	-2	0.287	0	0.606
-1.95	13.6	4.08	0.585	-2	0.287	0.025	0.585
-1.95	13.6	4.08	0.585	-2	0.287	0.05	0.564
-1.95	13.6	4.08	0.585	-2	0.287	0.075	0.543
-1.95	13.6	4.08	0.585	-2	0.287	0.10	0.521

Note: k=0.85.

Table B1: Fixed effects bivariate crop selection models for the probability of planting corn; the probability of planting either corn, alfalfa, or soybeans (all irrigation intensive crops); and the probability of fallowing/not irrigating the field

	Corn FE Linear prob	Corn FE logit	Corn+alfalfa+soy FE Linear prob	Corn+alfalfa+soy FE logit	Fallow FE Linear prob	Fallow FE logit
Pivot to dropped	0.018***	0.154***	0.034***	0.270***	-0.010***	-0.370***
	(0.005)	(0.032)	(0.005)	(0.035)	(0.002)	(0.065)
Spring precipitation (in)	-0.006***	-0.037***	-0.001	0.003	0.001	0.022
	(0.001)	(0.008)	(0.001)	(0.009)	(0.000)	(0.016)
Depth to groundwater (ft)	-0.001**	-0.010***	-0.000	-0.003	0.000***	0.012***
	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)	(0.003)
Corn planted in t-1	0.248***	1.715***	-0.132***	-0.988***	-0.002	-0.053
	(0.007)	(0.053)	(0.007)	(0.049)	(0.003)	(0.098)
Sorghum planted in t-1	0.199***	1.610***	-0.179***	-1.041***	0.011	0.297*
	(0.013)	(0.090)	(0.013)	(0.076)	(0.007)	(0.143)
Soy planted in t-1	0.420***	2.682***	-0.210***	-1.541***	0.000	0.090
	(0.010)	(0.060)	(0.008)	(0.057)	(0.003)	(0.128)
Wheat planted in t-1	0.141***	1.337***	-0.275***	-1.552***	0.012*	0.324**
	(0.010)	(0.072)	(0.010)	(0.060)	(0.005)	(0.117)
Other planted in t-1	0.136***	1.303***	-0.282***	-1.577***	-0.004	-0.022
	(0.007)	(0.057)	(0.007)	(0.048)	(0.003)	(0.098)
Corn, soy planted in t-1	0.091***	0.990***	-0.352***	-2.059***	-0.003	-0.018
	(0.012)	(0.079)	(0.012)	(0.073)	(0.004)	(0.198)
Corn, wheat planted in t-1	0.086***	0.849***	-0.327***	-1.974***	-0.012**	-0.191
	(0.009)	(0.071)	(0.009)	(0.064)	(0.004)	(0.120)
Fallow in t-1	0.168***	1.495***	0.065***	0.816***	0.168***	0.906***
	(0.010)	(0.075)	(0.005)	(0.045)	(0.008)	(0.090)
Year fixed effects	included	included	included	included	included	included
Constant	0.283***		0.802***		0.132***	
	(0.028)		(0.027)		(0.012)	
N	120902	76925	123025	72570	153840	24401

Notes: Standard errors in parentheses. Significance codes: * p<0.05, ** p<0.01, *** p<0.001. Estimates for corn and corn, alfalfa, and soybeans are conditional on irrigating.

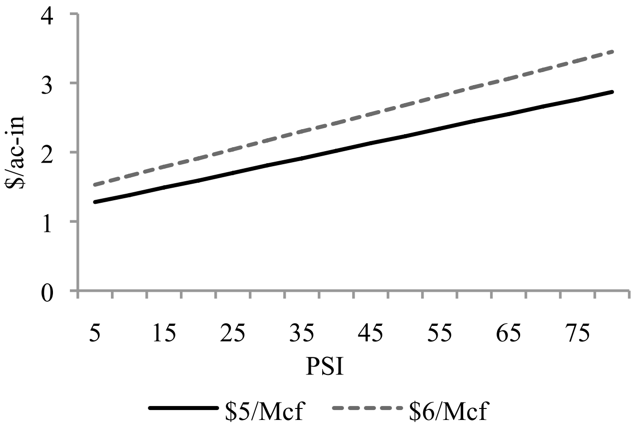

Figure C1: Price of water application as a function of the pressure required to run irrigation system (PSI) and energy price

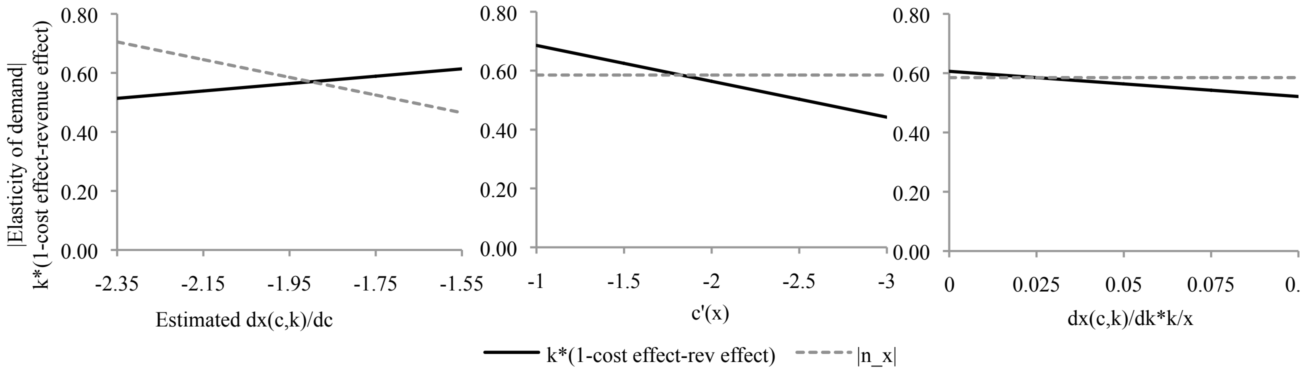

Figure C2: Sensitivity analysis of elasticity estimates