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

Lisa Pfeiffer

NOAA Fisheries, Alaska Fisheries Science Center

Email: lisapfeiffer@gmail.com

C.-Y. Cynthia Lin

Agricultural and Resource Economics, University of California-Davis

Email: cclin@primal.ucdavis.edu

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Abstract

Policies that encourage the use of more efficiency irrigation technology are often viewed as effective, politically feasible methods to reduce the consumptive use of water for agricultural production. Despite their widespread use, these policies have not been subject to empirical evaluation. In this article, we evaluate the effect on groundwater extraction 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. We find that the programs have not had the intended effect; the shift to more efficient irrigation technology has not decreased the amount of water applied to a given crop, and has actually increased groundwater extraction through changing cropping patterns.

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> "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."
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> -William Stanley Jevons, “The Coal Question” (1865)

Agriculture accounts for 99 percent of groundwater withdrawals from the High Plains Aquifer of the Midwestern United States, the largest freshwater aquifer system in the world. The region has experienced a decline in the level of the water table since intensive irrigation became widespread, starting in the 1970s. In parts of southwestern Kansas and in the Texas panhandle, the water table has declined by more than 150 feet. While declines in the water table are expected given rates of extraction that far exceed the recharge to the aquifer, concerns that the aquifer is being depleted too rapidly have become common in public policy and debate. 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, billions of dollars 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. Incentive-based irrigation efficiency cost-share policies 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 the conversion to more efficient irrigation technology (Cooley et al. 2009; Jury and Vaux 2005; Zinn and Canada 2007). However, there have been very few evaluations of these programs, and of those that exist, many raise serious doubts about the effectiveness of the programs in terms of actual reduced consumptive use of water. A debate has emerged between those that believe 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 yield and therefore evapotranspiration 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).

In this article, we empirically investigate the effect of a wide-spread conversion to efficient irrigation technology in Kansas, a state that overlies the High Plains Aquifer, on groundwater extraction. Kansas was chosen for the analysis because of the availability of data; Kansas is a leader worldwide in the collection of data concerning groundwater extraction, water table levels, and policies affecting agriculture. The lessons from the analysis, however, are general and can be applied to agricultural groundwater basins anywhere.

The state of Kansas has been subsidizing a shift towards irrigation systems with higher levels of efficiency, where efficiency is defined as the proportion of total applied irrigation water that is beneficially used by the crop. State and federal agencies have invested considerable resources in equipment cost sharing and technical assistance to farmers since about 1990. Between 1998 and 2005, more than $5.5 million was allocated to farmers through the Irrigation Water Conservation Fund and the

Environmental Quality Incentives Program.[1] Such cost-share programs pay up to 75 percent of the cost of purchasing and installing new or upgraded irrigation technology (NRCS 2004).

Data from western Kansas are used to investigate the effectiveness of subsidized irrigation technology adoption on groundwater extraction. Recently, several studies have pointed out that shifting to more efficient irrigation technology does not necessarily reduce total water use, and that subsidizing the shift can lead to increases in water use (Ward and Pulido-Velazquez 2008; Ahmad, Turral, Masih, Giordano, and Masood 2007; Scheierling, Young, and Cardon 2006; Peterson and Ding 2005; Huffaker and Whittlesey 2003). With the exception of Ahmad, Turral, Masih, Giordano, and Masood (2007), these studies have used a programming model or simulation approach. In contrast, we combine hydrological characteristics of the aquifer with extraction data at the groundwater well level to econometrically model the extraction decisions of farmers. We find that the shift to more efficient irrigation technology has not decreased the amount of water applied to a given crop, and has actually increased groundwater extraction through changing cropping patterns. We also control for the endogeneity of crop choice and irrigation technology choice by using the amount of cost-share money allocated to counties as an instrument for the adoption of efficient dropped nozzle center pivot irrigation systems. Even when the endogeneity is accounted for, more efficient dropped nozzle systems increase groundwater extraction relative to flood and standard center pivot systems.

Background

Irrigation efficiency at the field level is defined as the amount of water beneficially used by the crop (net irrigation) diveded by the amount of water applied (gross irrigation), expressed as a percent, for some time interval (such as an irrigation season or year) (Burt, Clemmens, Strelkoff, Solomon, Bliesner, Hardy, Howell, and Eisenhauer 1997).[2] More efficient irrigation systems generally increase the amount of water that is able to be used beneficially by the crop, thus allowing less water to be applied for a given benefit.

It is important to remember, however, that water conservation occurs only with a decrease in consumptive use of water. In energy economics, the "rebound effect" describes the behavioral response to technology improvements meant to reduce energy use (Greening, Greene, and Difiglio 2000). Increases in efficiency often lower the cost of consumption, thus increasing consumption of that through substitution and income effects. Additional economy-wide production possibility and growth effects may further increase consumption, all of which may result in an increase in use of the resource that that efficiency-enhancing technology was meant to conserve (Jevons 1865; Saunders 1992).

Similarly, increasing irrigation efficiency may not decrease the total consumptive use of water. More efficient irrigation systems typically cause a shift up in the crop production function. However, higher yields necessitate higher rates of evapotranspiration, the water that is consumed by the crop. Irrigators have the incentive to expand irrigated acreage and shift to more water intensive crops due the the decreased marginal cost of application and extra water that may be made available within the quantity allowed given the system of water rights. Additionally, more efficient irrigation technologies can be thought of as "land quality enhancing" (Caswell and Zilberman 1986); they enhance the ability of lower quality soils to provide water and nutrients to crops, reducing the productivity differences between low and high quality land. More efficient irrigation technologies also allow more precise timing of irrigation, and these factors allow the production of higher value crops and/or hybrids that could not be profitably produced on a given plot prior to the investment (Evans and Sadler 2008). These shifting cropping patterns can reduce or negate efficiency savings.

The irrigation technology employed by groundwater users in western Kansas has changed significantly since intensive irrigation development began. Land was converted from flood irrigation systems to center pivot systems. With flood irrigation, water is pumped to one edge of a field, then allowed to run down furrows through the fields between rows of crops and allowed to soak in. Flood irrigation is relatively labor intensive, and necessitates flat land and soils of high quality, uniformity, and with a high water holding capacity. Center pivot systems, on the other hand, are generally self-propelled, can be used on sloped or rolling land, and the quantity of water delivered to the crop can be adjusted to soil and climatic conditions. Lichtenberg (1989) investigates the determinants of the adoption of center pivot irrigation systems in Nebraska; he finds that the adoption of center pivots induced a shift from dryland small grains and hay to irrigated corn. Marginal soils, that prior to center pivots were unsuitable for irrigated agriculture, were brought into irrigated production as a result of this land-quality augmenting technology. Negri and Brooks (1990) find similar results in a national sample. Figure 1 shows the general trends in the change in irrigation technology use in western Kansas in the period 1996 to 2005. From figure 1, it can be seen that the conversion from flood to center pivot systems was well underway by 1996. Rather, most of the change comes 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)) suspend the sprinkler heads just above the canopy of the crop. They further increase the efficiency of water applied to the field by decreasing the amount lost to evaporation and drift, especially in hot and windy climates. Flood irrigation systems are generally assumed to be about 70% efficient, while center pivot and center pivot with dropped nozzle systems are about 85% and 90% efficient, respectively (Perry 2006; NRCS 1997). Thus, increased irrigation efficiency has been touted as an ideal way to decrease total water extraction.

As previously noted, however, this does not mean that irrigators will necessarily apply less water to their crops. In fact, figure 2 shows that empirically, there is very little decrease in the average amount of water applied to the five main crops grown in western Kansas as irrigation efficiency increases. Alfalfa acres irrigated with dropped nozzle center pivot systems receive significantly *more* water than those irrigated with flood systems.

In Kansas, water rights are defined by the doctrine of prior appropriation. A landowner is appropriated a quantity of water that they are legally allowed to extract in each year. Each right has a "seniority" associated with it; more senior rights were allocated earlier, beginning in 1945. The quantity authorized for extraction is constant over time, but subject to adjustments, in order of seniority, by the state water authority in times of scarcity (Peck 1995).[3] Because of the way the rights are defined, more efficient irrigation technologies may free up a portion of an irrigator's water right to be used on other parts of a field or pieces of land. Figure 3 shows that the total number of irrigated acres has been relatively constant, but there has been some change in cropping patterns from 1996 through 2005.

The state of Kansas has spent nearly $6 million on incentive programs (cost-sharing, or subsidizing the purchase) to fund the adoption of more efficient irrigation systems. These policies are implemented under the auspices that they will decrease the total consumptive use of groundwater, a key goal of state water managers (Committee 2001), and are in response to declining aquifer levels that are occurring in some portions of the state due to extensive groundwater pumping for irrigation.

However, recent work has suggested that policies of encouraging the adoption of more efficient irrigation technology may not have the intended effect. Lichtenberg (1989) found that the adoption of center pivot irrigation systems in Nebraska induced a shift away from dry-land crops to irrigated corn, and noted that the conversion took place on lower quality, more erosion-prone soils. He also cited investment tax credits as a driver of center pivot adoption. Huffaker and Whittlesey (2003) develop a theoretical framework to compare the water-saving potential of policies that increase the cost of irrigation water versus those that subsidize the conversion to more efficient forms of irrigation. They find that farmers increase irrigated acreage in response to subsidized irrigation technology, resulting in an expansion of water use. Ward and Pulido-Velazquez (2008) do a complete analysis of the effects on yields, acreage, income, and water depletion of a policy that subsidizes the adoption of drip irrigation in New Mexico's Rio Grande Basin. They find that yields and net farm income increase under the subsidy, but water depletions never fall below the base level of no subsidy. If total irrigated acreage is allowed to increase, water depletions increase even more.

Peterson and Ding (2005) come to a slightly different conclusion. Analyzing the corn production system in western Kansas, they find that efficient irrigation technology would reduce overall irrigation water use for corn. However, they neglect to consider changes in cropping patterns or the expansion of irrigated acreage that may result from the subsidy. Additionally, their result that water use reductions would occur under a shift from flood to center pivot systems rely on the assumption that flood systems can irrigate 160 acres, while a center pivot system can generally irrigate only 126 acres. However, the remaining corners are often still irrigated with end-guns and other types of corner systems. Ahmad, Turral, Masih, Giordano, and Masood (2007) note the importance of accounting for the resulting shift from non-irrigated to irrigated crops, and from crops with low water requirements to those with higher water requirements following the adoption of a resource-conserving technology. In the Punjab region of Pakistan, they find an increase in net water use resulting from an increase in farming intensity as measured by irrigation and other input use.

Finally, Ward and Pulido-Velazquez (2008) note that in their analysis, the net economic benefits for the basin increase with an increasing subsidy. However, from a national view (when the taxpayer's cost is included in the total cost of the policy) the net economic benefits are lower under the subsidy than without. The water basin benefits from the subsidy, but the funds for the subsidy are collected from a wider base of taxpayers. This same situation plays out in public policy; for example, Kansas has an incentive to lobby for farm program money and reap the benefits from subsidized irrigation technology without having to shoulder the program's total cost. As subsidized irrigation technology is generally thought of as a good water conservation policy, they have been largely successful in obtaining significant amounts of federal funding.

In contrast to these studies, in this article we present a large-scale empirical analysis of the effects of changing irrigation technology on agricultural producers' behavior. We utilize groundwater extraction data at the individual well and field level, over the years 1996 to 2005, from the Kansas Water Information Management and Analysis System; this is arguably the most extensive, complete, and reliable groundwater use dataset in the world. These data provide empirical significant support for the hypotheses suggested by the data-calibrated models of Ward and Pulido-Velazquez (2008), Huffaker and Whittlesey (2003), and Scheierling, Young, and Cardon (2006), but without imposing the structural framework of a programming model.

Empirical Analysis

In this analysis, we answer two questions. First, do more efficient irrigation technologies reduce groundwater extraction? Holding constant all changes in producer behavior, the engineering relationship says that it must. Producers, however, may expand their irrigated acreage, apply more water to the same crops, or plant more water-intensive crops as a result of the conversion. Second, do subsidies for more efficient irrigation technology reduce water use? We evaluate the recent irrigation efficiency cost-share program in Kansas that attempts to decrease groundwater extraction.

To answer these questions, we model the producer's groundwater pumping decision. The decision of how much irrigation water to pump actually involves several decisions. Moore, Gollehon, and Carey (1994) model it as a three step decision where first, the irrigator decides which crops to plant and second, allocates his total available land between crops. Then, given the crop choice, he decides how much irrigation water to pump. Moore, Gollehon, and Carey (1994) take irrigation technology as given, however. In fact, the choice of irrigation technology and crop choice may be endogenous; producers who wish to plant corn or other water intensive crops may be more likely to install higher efficiency irrigation technologies. On the other hand, it may be producers who are more concerned with conservation who tend to adopt the most efficient technology.

We first model the decision of how much irrigation water to pump as a three step decision given irrigation technology, using as data all plots irrigated with groundwater from the Ogallala Aquifer in western Kansas. This estimation procedure is sufficient to determine if more efficient irrigation technologies are correlated with any change in total groundwater extraction. With this estimation we cannot make claims about causality because the choices of crop mix and irrigation technology are endogenous, but the correlation is interesting nonetheless. It shows general trends in water extraction as irrigation technology changes from flood systems to center pivot and center pivots with dropped nozzle systems.

Second, we analyze the determinants of the adoption of more efficient irrigation technology. This will help us determine how much of the irrigation technology decision is endogenously determined with crop choice, as land quality indicators determine both.

We then aggregate to the county level to establish causality. Dollars allocated to subsidy programs to support the conversion of irrigation systems to more efficient ones, per acre of farmland and by county, are used as an instrument for the percent of irrigators using center pivot dropped nozzle systems.

Estimation procedure

The first stages of the groundwater extraction decision involve simultaneous equation models in which the dependent variables (the number of acres planted to each crop) are censored by sample selection. A positive number of acres planted to crop c, for example, is observed only when the farmer chooses to plant crop c. Thus, the sample of crop c-planters is non-random, drawn from a wider population of farmers. Both choices (the decision to plant and the number of acres planted to crop c) must be modeled to avoid sample selection bias. Optimal land allocation on plot i in each time period t, $n*_{ict}$ can be estimated

$$(1) \quad q_{ict} = f(p_{ct}, \mathbf{r_t}, N_{it}, \mathbf{x_{it}}, \mathbf{z_{it-1}}), \, c = alfalfa, \, corn, \, sorghum, \, soy, \, wheat;$$

$$(2)\, n^*_{ict} = f(p_{ct},\, \mathbf{r_t},\, N_{it},\, \mathbf{x_{it}},\, \mathbf{z_{it-1}},\, IMR_c),\, c = alfalfa,\, corn,\, sorghum,\, soy,\, wheat;$$

where $n_{ict}*$ is the number of acres planted to each crop c, and $n_{ict}*$ is observed only when $q_{ict} > 0$, q representing the decision to plant crop c. p_{ct} are crop price futures (for delivery at harvest), $\mathbf{r_t}$ is a vector of variable input prices including the futures prices of natural gas and electricity and the depth to groundwater, N_{it} is the total amount of land owned by the individual who owns plot i, and $\mathbf{x_{it}}$ is a vector of plot-level variables including irrigation technology, average precipitation, and soil quality. $\mathbf{z_{it-1}}$ is a vector of lagged dummy variables indicating if various crops were planted in the previous season to account for crop rotation patterns. The coefficents on the irrigation technology indicator variables are the main coefficients of interest.

The system of equations corresponding to equations 1 and 2 can be estimated using Lee's generalization of Amemiya's two-step estimator to a simultaneous equation model (Lee 1990). Lee (1990) shows that this procedure leads to estimates that are asymptotically more efficient than the Heckman selection model (Heckman 1978). In the first stage, probit regressions corresponding to the crop selection equations 1 are estimated, measuring the effect of the explanatory variables on the decision to grow each crop c. Inverse-Mills ratios (IMR_c) are calculated for each crop.

In the second stage, the inverse-Mills ratios are included as explanatory variables in the acreage allocation equations corresponding to equation 2. They are estimated as a simultaneous system of equations to exploit the information contained in the cross-equation correlations, which is significant assuming a farmer makes joint decisions on how to allocate cropland among his plots.

Finally, water demand is estimated using ordinary least squares.[4]

$$(3) \qquad w_{it} = g(\mathbf{r_t},\, \mathbf{n^*_{ict}},\, \mathbf{x_{it}})$$

This model explains groundwater pumping as a function of those variables that should be included in a producer's marginal pumping decision. The total marginal effect of an exogenous variable, therefore, is the sum of the effect along the intensive margin (from equation 3) and the effects along the extensive margin (from the selectivity-corrected cropland allocation equations 2) (Moore et al. 1994):

$$(4) \qquad \frac{dw}{dx} = \frac{\partial w}{\partial x} + \sum_c \frac{\partial w}{\partial n_c*}\frac{\partial n_c*}{\partial x}$$

where x is some exogenous variable.

The determinants of irrigation technology are analyzed using a binomial logit estimation, following Negri and Brooks (1990). If a and b represent two different irrigation technologies, a producer will adopt technology a if the expected profits are higher under a than under technology b. The probability of choosing technology a is $P_a = F[(\beta_a - \beta_b)'Z > \epsilon_a - \epsilon_b]$, where Z is a vector of variables that affect irrigation technology choice including prices, farm size, variable costs, and soil quality, $(\beta_a - \beta_b)$ is the vector of parameters to be estimated, ϵ_a and ϵ_b are random errors representing unobserved factors that affect the profitability of the two types of irrigation systems, and F is the cumulative distribution function of $(\beta_a - \beta_b)$. If ϵ_a and ϵ_b are assumed to be independent, random, Weibull-distributed variables, then F generates the binomial logit model. For the ith producer, the probability of choosing technology a is $P_{ai} = \frac{exp(\beta'_a Z_i)}{exp(\beta'_b Z_i)+exp(\beta'_a Z_i)}$.

Finally, a series of models similar to 2 and 3 are estimated using aggregated and population-weighted county-level data. The dependent variables (acres to various crops in 2 and acre-feet of water pumped in 3) are divided by the total amount of cropland in the county (both irrigated and non-irrigated), as are the independent variables representing total amounts per county. Other variables, such as soil quality indicators, are county-level averages. Hence, the county-level cropland allocation model is linear.

Dollars allocated to the cost-share program to subsidize the adoption of more efficient irrigation technology per county (divided by total farmed acres) are used as an instrument for the adoption of dropped-nozzle systems to control for the endogeneity of crop choice and irrigation technology choice. The amount of money allocated to the county is assumed to be correlated with the adoption of dropped-nozzle systems, but is assumed not to affect the amount of each crop planted in the county except through its effect on the use of irrigation technology. We instrument only dropped nozzle systems because most of the changes in irrigation technology use between 1996 and 2005 were conversions from standard center pivot to dropped nozzle systems (figure 1). We empirically verify the strength of the instrument in two ways. First, it is included in the estimation of the binomial logit model, a formal model of technology adoption, to show that the program helps to predict the adoption of dropped nozzle center pivot irrigation systems. Second, we report the F-test of the excluded instruments of the two-stage least squares estimation of county-level models 2 and 3. While the exclusion restriction cannot be verified because the model is exactly identified, there is no reason that the amount of money allocated to the cost-share program should affect the number of acres allocated to various crops when the total number of farmed acres in the county are controlled for, except through the adoption of irrigation technology. The full instrumental variables model is estimated using a simultaneous system of equations.

Data

The data used for the analysis are from a variety of sources. Groundwater extraction data, at the individual point of diversion level (usually a single well) is collected from the Water Information Management and Analysis System (WIMAS), supported by the Kansas Water Office. It includes spatially referenced pumping data, and has the farmer, field, irrigation technology, amount pumped, and crops grown identified, as well as other geographic information. There are about 20,000 points of diversion for each of the 10 years from 1996 to 2005.

These data are augmented with hydrological, climate, and price data. Crop price data are a combination of spring futures contracts for September delivery for commodities with futures contracts from the Commodity Research Board (CRB), and average price received for crops without (from the U.S. Department of Agriculture (USDA) Economic Research Service). Crop price ratios are constructed for the estimations, and consist of the crop price divided by an acreage weighted sum of the prices of all crops.[5] Natural gas and electricity prices come from the U.S. Energy Information Administration.

The United States Geological Survey's High Plains Water-Level Monitoring Study maintains a network of nearly 10,000 monitoring wells that are used to estimate yearly water levels. Precipitation data come from the PRISM group.[6] Soil characteristics come from the Web Soil Survey of the USDA Natural Resources Conservation Service. Hydroconductivity and other hydrological information is available from the USGS. Hydrological and climate data were spatially matched to the point of diversion using ArcGIS.

The Kansas cost-share program data were compiled by the author from records at the Kansas State Conservation Commission.

Summary statistics for the variables used in the analysis are presented in table 1. The average level of extraction per irrigation well per year is 129 acre-feet. Irrigators (water rights owners) own an average of 7.7 wells, and pump an average of 1195 acre-feet in total. Each water rights owner irrigates an average of 932 acres. Each point of diversion (well) got an average of 21.1 inches of precipitation per year. The average depth from the surface of the ground to the groundwater table is 125 feet. Potential recharge to the Kansas portion of the High Plains Aquifer is low; the average recharge is 1.2 inches. Soil characteristics are assumed to be constant over time. The average slope of the ground surface, as a percent of distance, is 1.1 percent. Other soil characteristics used are saturated hydraulic conductivity, with an average of 20.2 μm/sec, available water capacity (average 0.18 cm/cm), and irrigated capability class, which is a dummy variable equal to 1 if the soil is classified as the best soil for irrigated agriculture with few characteristics that would limit its use. Forty seven percent of plots are in irrigated capability class 1.

Table 1 also includes summaries of county-level variables. An average of 68,828 acre-feet are pumped each year irrigating an average of 76,709 acres. An average of $6,634 were allocated to the irrigation technology cost-share program per county each year. The average number of acres in each irrigation technology type and crop are also reported.

Results

Three sets of results are reported. First, we present the key results of the estimation of the crop choice, cropland allocation, and water demand equations 1, 2, and 3, using plot-level data. We then model the choice of irrigation technology to establish the strength of the instrumental variable. Finally, we aggregate to the county level and estimate the system of equations in 2 and 3, with and without the instrument, to establish a causal link between changes in irrigation technology efficiency and changes in total groundwater extraction.

Crop selection and selectivity-corrected land allocation and total marginal effects

Table 2 shows the condensed results (the irrigation technology variables of interest) of estimation of crop choice (equations 1), selectivity-corrected land allocation (equations 2), and total water demand (equation 3). The full results are available in the supplementary appendix.

Flood irrigation systems are used as the control group. Thus, from the probit model of crop choice in section A, center pivot irrigation systems increase the probability of planting corn, and decrease the probability of planting soybeans, wheat, or sorghum, compared to flood irrigation systems. Center pivots with dropped nozzles have a similar effect.

The estimated coefficients of the selectivity-corrected cropland allocation model represent the effects of the explanatory variables on cropland allocation, given the choice to plant that crop, and are presented in section B. A producer with a center pivot irrigation system would plant 4.8 more acres of alfalfa, 26 more acres of corn, 3.8 more acres of soybeans, 4 more acres of wheat, and about 1 more acre of sorghum compared to a producer with a flood irrigation system. Similarly, a producer with a dropped-nozzle center pivot system would plant 4.5 additional alfalfa acres, 25.6 additional corn acres, 4.3 more acres of soybeans, and 3.2 more acres of wheat. Center pivot and dropped-nozzle center pivots increase the number of acres planted to all the irrigated crops as compared to flood irrigation, and have the largest effect on corn, alfalfa, and soybeans, the most water intensive crops.

Finally, table 2 reports the results from the estimation of equation 3, water use along the intensive margin. Evident from the crop acres planted coefficients in section C of table 2 is that corn and alfalfa are the highest water users, and farmers with more acres of these crops pump more water, followed by soybeans, wheat, and finally sorghum. Then, given crop choice, land allocation, and physical and hydrological variables, section D of table 2 shows that center pivot irrigation systems reduce water extraction by 15.4 acre-feet, as compared to flood irrigation systems. Center pivot systems with dropped nozzles also reduce groundwater extraction, but by only 11 acre-feet. This indicates that while center pivot systems reduce water demand given crop choice, dropped nozzles offer no additional water saving benefits.[7]

The combines results of table 2 indicate that while more efficient irrigation technology may somewhat reduce water extraction given crop choice (at least center pivots compared to flood irrigation systems), there is a significant shift in cropping patterns that takes place. The effects of irrigation technology on total water extraction do not adequately describe the full impact. Changes in irrigation technology can cause changes in crop selection and land allocation decisions (Moore, Gollehon, and Carey 1994; Taylor and Yunez-Naude 2000). Center pivot systems allow the production of water intensive crops and are installed where those crops can be produced. Thus, the impact on crop choice (shifts along the extensive margin), and the total marginal effects calculated using equation 4 must be considered.

The total marginal effects of the main independent variables are reported in table 3. The total marginal effects represent the full effect of the independent variables on water extraction along the intensive and extensive margin, which include the effects on crop choices, cropland allocation, and water extraction. The total marginal effects of center pivot and center pivot dropped-nozzle irrigation systems reported in table

3 are positive, indicating that when crop choices are considered, efficient irrigation technology does not reduce overall water use. It is unlikely that the shift in irrigation technology has resulted in real water savings. In fact, it has significantly increased water use relative to flood irrigation systems. Lichtenberg (1989), Perry (2006), and Ward and Pulido-Velazquez (2008) predicted similar results.

The other variables included in the regressions have the expected total marginal effects; the price of energy, precipitation, land of the highest capability class, and more sloped land all decrease total extraction, and the yearly quantity of water authorized for extraction and rates of aquifer recharge are associated with higher rates of extraction. A 10-year real commodities price forecast is included to account for long term price trends, and the yearly time trend is negative.

The depth to groundwater has a positive total marginal effect, which is not expected because pumping from a larger depth is more expensive. However, considering that commodities prices have had a long-term downward trend, crop price expectations are negative, leading to greater current-period water extraction. This price effect dominates the effect of the increase in marginal extraction cost caused by increases in depth to groundwater, leading to the positive marginal effect we observe. [8]

Irrigation technology

Crop choice and irrigation technology choice can be endogenous decisions, so the estimated effects from table 3 do not represent causal effects. To establish causality, we use an instrumental variables approach. Ideally, we would like to have a completely exogenous policy that affects the propensity to adopt more efficient types of irrigation systems– a natural experiment. No such experiment is available, however, so we use a policy instrument that was designed to encourage the adoption of efficient irrigation technology and control for variables that may have affected the non-uniform application of the policy. The amount of money allocated to each county, per year, for the irrigation technology cost-share program is used as an instrument for the adoption of center pivot dropped nozzle systems. The policy was designed with water conservation in mind, so we control for the size of the agricultural base (the total number of farmed acres in the county) and the average change in the depth to groundwater in the county.

First, however, we model technology adoption and establish that cost-share funds are, in fact, a good predictor of dropped nozzle adoption. Part A of table 4 presents the marginal effects from logit regressions of the adoption of any type of center pivot over flood irrigation (column 1), and dropped nozzle systems over standard center pivots (column 2). These results support previous findings from the irrigation technology adoption literature and indicate that center pivot systems are land quality augmenting. More steeply sloped parcels are more likely to adopt in all three specifications, and parcels with an irrigated capability class equal to one (the best quality soils) are less likely to adopt. Parcels with a higher available water capacity are less likely to adopt center pivot systems (vs. flood), but more likely to adopt dropped nozzles. Larger farms with larger groundwater extraction permits are also more likely to adopt. Dollars allocated to the cost-share program in the county is also a significant predictor of adoption. Section B of table 4 presents the results of a fixed effects logit. These regressions measure the effect of a change in the independent variables on the probability of adoption for a given individual.[9] The fixed effects model controls for individual level unobservables. For a given individual, an increase of $1000 allocated to their county for the cost-share program (roughly 15 percent of the mean allocation) would increase their probability of adopting dropped nozzles on their center pivot systems by 0.01.

Instrumental variables estimation

In tables 5-6, we aggregate to the county level in order to use cost-share program dollars as an instrument for the adoption of dropped nozzle systems. We observe the cost-share program allocation only at the county level. The dependent variables, the other county aggregated variables, and the instrument are divided by the total number of farmed acres in the county to control for county size and agricultural base. The number of acres under standard center pivot irrigation is dropped; thus, the coefficients on the percent of acres irrigated using the various technologies are in relation to standard center pivot technology.[10]

Sections A and B of table 5 show the non-instrumented county-level regressions. The results are similar to those found using individual level data. For example, if the percent of acres being irrigated by flood systems were to increase by 1 percent, the percent of acres planted to corn would increase by 0.41 percent. A 1 percent increase in the acres irrigated by center pivots with dropped nozzles is associated with a 0.75 percent increase in the percent of acres planted to corn, relative to standard center pivots. Along the intensive margin, flood irrigation is associated with an increase in pumping by 0.61 percent more than center pivots, and dropped nozzle systems increase pumping by 0.48 percent more than standard center pivots.

Sections C and D of table 5 use the instrumental variable. The coefficient on the instrumented percent of acres irrigated with center pivot dropped nozzle systems becomes insignificant in the wheat regression, and significantly negative in the alfalfa regression. While an increase in the percent of acres irrigated by center pivots with dropped nozzles is associated with an increase in the percent of acres planted to alfalfa and wheat, there is no evidence of a causal relationship. On the other hand, the coefficient on the instrumented percent of acres irrigated with center pivot dropped nozzle systems in the corn and soybeans regressions are larger than in the non-IV regressions. This means that the relationship between center pivots with dropped nozzles and the acres planted to corn and soybeans *is* causal and the endogeneity of the adoption of dropped-nozzle systems creates a downward bias in the non-IV estimates. An exogenous increase in center pivot dropped nozzle irrigation systems would cause an increase in acres planted to corn and soybeans. The percent of parcels with dropped nozzles also increases the amount pumped given cropland allocation, compared to flood and standard center pivot systems.

The total marginal effects, reported for both models in table 6, show that a one percent change in the percent of acres irrigated with center pivot dropped nozzle systems (an increase of about 3300 acres in dropped nozzle irrigation) would result 1.7 percent increase in the water extracted per farmed acre relative to an equivalent increase in standard center pivots. This would amount to an increase in pumping of about 8800 acre-feet, for the average county. This indicates that a policy of subsidizing more "efficient" irrigation technology actually increased total groundwater extraction in western Kansas.

Conclusions

William Stanley Jevons postulated in 1865 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 (Jevons 1865). This idea, now referred to as "Jevons' Paradox", "the rebound effect", or "take-back" 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 of energy services. 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 very similar. More efficient irrigation technology generally increases the "effectiveness" of a unit of water, but the water "saved" can be used to increase yields, shift to more water intensive crops, or expand irrigated acreage.

We find that increases in irrigation efficiency in western Kansas from 1995 to 2005 have led to increases in groundwater extraction, a rebound effect of over 100%. Our results indicate that center pivot systems with dropped (high efficiency) nozzles do not reduce groundwater extraction, given crop choice, compared to standard center pivot systems. They have had the additional consequence of leading to a shift in cropping patterns, towards higher yielding and more water intensive crops. This result is robust across levels of data aggregation (individual to county-level) and controlling for the endogenous choices of crops and irrigation technology. We find that a 1% increase in the percentage of acres irrigated with dropped nozzle center pivot systems leads to a 1.7% increase in the amount of water extracted per farmed acre, relative to an increase in standard center pivot technology.

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 make the water last longer, however, policy has focused on reducing rates of extraction.

We show that the measures taken by the state of Kansas to reduce groundwater extraction have been ineffective. In fact, the subsidized shift toward more efficient irrigation systems has had the unintended consequence of increasing water extraction through a shift in cropping patterns. This result has been predicted elsewhere, and in fact has been realized by water conservation authorities in Kansas who have worked to put an end to the program. The lesson seems to have remained unlearned, however, as EQIP funding for irrigation efficiency continues to increase, and many continue to recommend the subsidization of efficient irrigation technology as a method to reduce the consumptive use of water.

As Ward and Pulido-Velazquez (2008) point out, accurate accounting and measuring of water use is rarely done, and long-term water availability measures such as groundwater table levels are rarely available. In fact, precise definitions of water rights and enforcement of those rights are uncommon in most of the world. Addressing these problems is the first step in effective water management. The state of Kansas is world-wide leader with their system of measurement, reporting, and enforcement; its example and empirical lessons should not be ignored.

Notes

[1] Personal communication the Kansas State Conservation Commission, March 24, 2009.

[2] Technically, the demoninator of irrigation efficiency is total water applied minus the change in storage. Storage is the amount of water held in the root zone. Irrigation efficiency can also be defined at the farm, district, project, or basin level. These measures consider the gross and net irrigation for the entire level under analysis, allowing for runoff to be used by those downstream.

[3] Reductions in the quantity authorized for extraction of junior rights holders has never been ordered, however.

[4] Because there are a number of users that decide not to pump in a given year, modeling this choice with a selection model may be appropriate. However, the estimated effects are very similar to OLS, so only the OLS results are presented.

[5] The weights used are the average proportion of irrigated acres planted to each crop over the 1996 to 2005 time period.

[6] PRISM (Parameter-elevation Regressions on Independent Slopes Model) data sets are recognized world-wide as the highest-quality spatial climate data sets currently available. http://www.prism.oregonstate.edu/

[7] Any water savings resulting from net efficiency increases may be used for purposes such as corner irrigation, for example. If we instead use center pivot systems as the control group, center pivots with dropped nozzles are not significantly different from standard center pivots in terms of total water use.

[8] See the discussion in chapter 2.5.3 of Pfeiffer (2009) for further exploration of this issue.

[9] The fixed effects logit can only be used with time-varying regressors, and only those plots that underwent a change from one category of irrigation technology to another can be included.

[10] We could include all the irrigation technology variables in the regression, and the estimated coefficients would be in relation to non-irrigated land. However, because most of the changes come from plots being switched from standard center pivot to center pivot dropped nozzle systems, and we have only one instrument available (positively correlated with dropped nozzle systems and negatively correlated with standard center pivot systems, because irrigators are switching between the two), we use standard center pivot as the reference group and instrument for dropped nozzles. We can do this because the other two groups, flood and other/not reported, are relatively constant.

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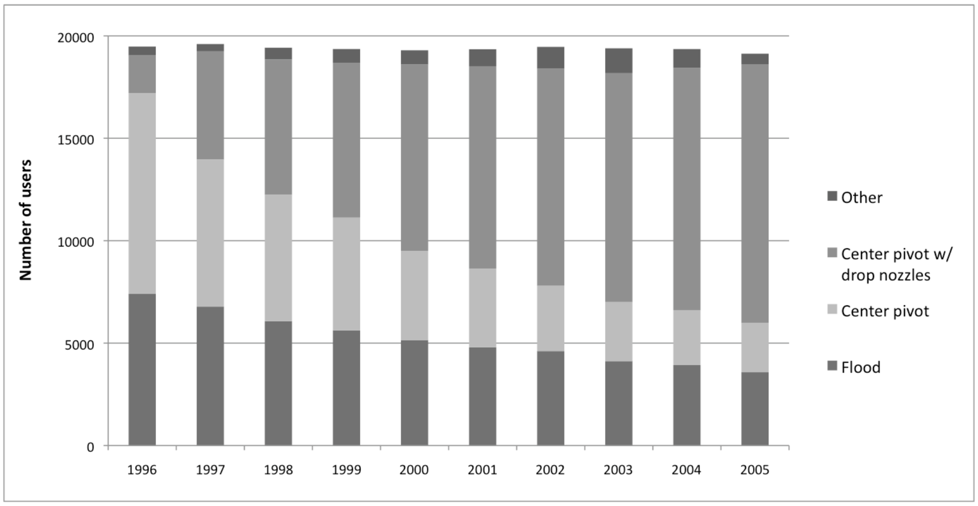
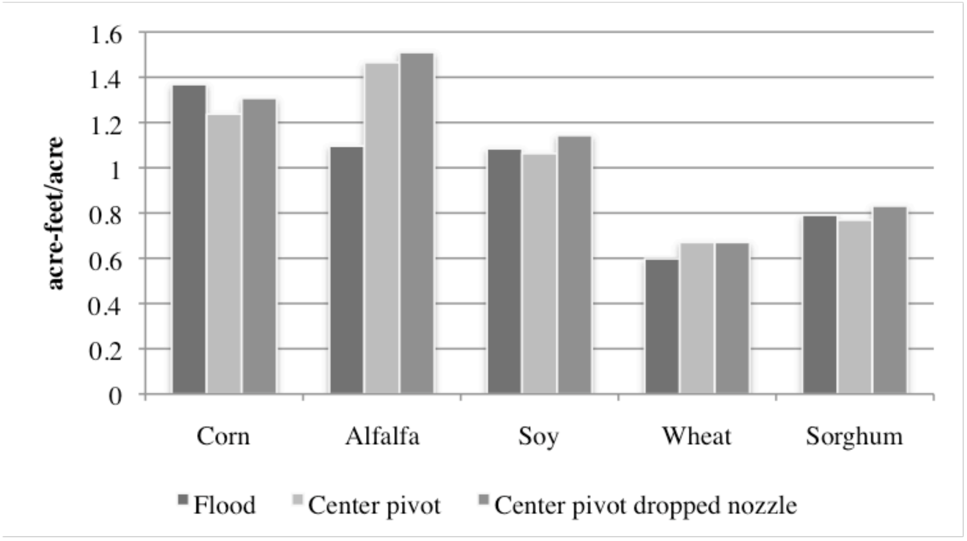


Figure 1: Irrigation technology used in western Kansas by groundwater users, 1996-2005. Source: WIMAS data



Note: Average applied water per acre was calculated using only those parcels that were planted entirely with one crop. N=67270 (corn), 15410 (alfalfa), 11821 (soy), 6250 (wheat), and 4615 (sorghum).

Figure 2: Average applied water, by crop and irrigation system. Source: WIMAS data

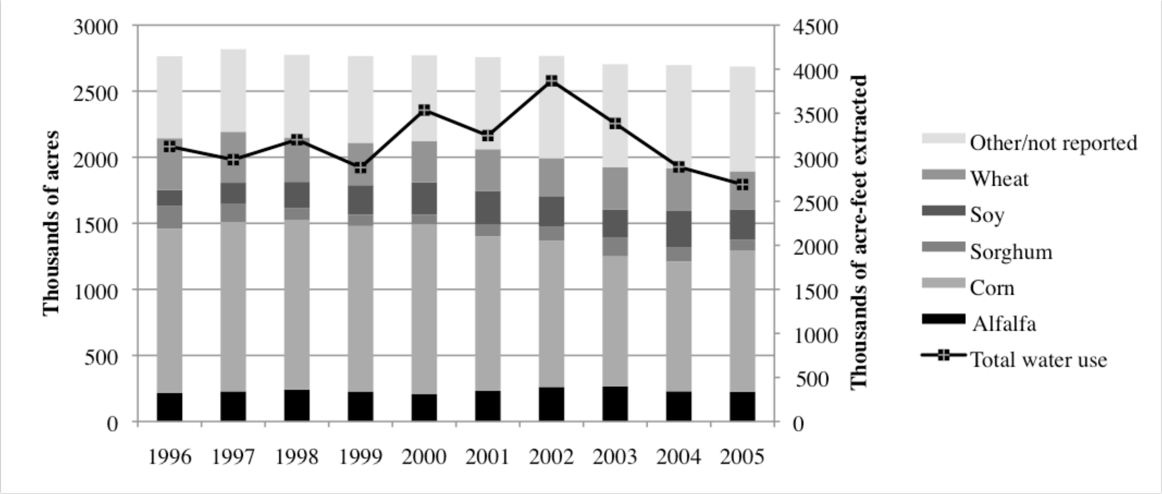


Figure 3: Irrigated acres and total water use, 1996-2005. Source: WIMAS data

Table 1: Summary Statistics, 1996-2005

Individual-year level variables	N	Mean	Std Dev
Acre-feet pumped, single well	183962	129.10	129.10
Acre-feet pumped, single water rights owner	183962	1195.25	1195.25
Acres planted on irrigable land, single well	183962	150.52	150.52
Acres planted on irrigable land, water rights owner	183962	931.88	931.88
Depth to groundwater (ft)	183962	124.67	124.67
Precipitation (in)	183962	21.15	5.27
Individual level variables			
Recharge (in)	20139	1.23	1.14
Hydroconductivity (ft/day)	20139	66.3	75.7
Slope (% of distance)	20139	1.09	0.92
Saturated Hydraulic Conductivity (um/sec)	20139	20.19	25.45
Irrigated Capability Class 1	20139	0.47	0.50
Available water capacity (cm/cm)	20139	0.18	0.03
Year level variables			
Price of energy (cents/1000 btu)	10	0.92	0.45
Corn price (cents/bu)[†]	10	256.46	32.22
Wheat price (cents/bu)[†]	10	353.80	47.13
Soybeans price (cents/bu)[†]	10	595.35	117.09
Alfalfa price ($/ton, yearly average)	10	81.23	9.51
Sorghum price (cents/bu, Sept. average)	10	684.84	183.84
County-year level variables			
Appropriated quantity of groundwater	460	123520.90	121051.20
Acre-feet pumped	460	68827.62	72017.22
Acres irrigated	460	76709.12	73349.21
Farmed acres (dryland and irrigated)	460	528663.00	108619.10
Irrigation technology cost-share program ($)	460	6633.54	9447.14
Acres in flood irrigation	460	16373.60	23066.81
Acres in center pivot	460	15317.24	18543.11
Acres in center pivot dropped nozzle	460	28348.80	30208.27
Acers in other/not reported irrigation systems	460	1750.91	2283.99
Irrigated acres not irrigated	460	14918.58	17666.27
Acres in irrigated alfalfa	460	5030.96	9222.68
Acres in irrigated corn	460	25188.79	23693.44
Acres in irrigated soy	460	4574.58	5029.34
Acres in irrigated sorghum	460	2368.27	2501.29
Acres in irrigated wheat	460	7121.30	9430.47

[†] Prices are January through March average of futures contract for September delivery.

Table 2: Effect of Irrigaiton Technology on Crop Selection, Cropland Allocation, and Total Water Extraction

		Alfalfa	Corn	Soy	Wheat	Sorghum
A.	**Probit crop selection**					
	Flood irrigation	control group				
	Center pivot	-0.029	0.078***	-0.072***	-0.055***	-0.426***
	Center pivot, dropped nozzles	-0.057***	0.089***	0.010	-0.101***	-0.503***
B.	**Selectivity-corrected cropland allocation**					
	Flood irrigation	control group				
	Center pivot	4.808***	26.093***	3.808***	4.090***	0.806***
	Center pivot, dropped nozzles	4.489***	25.656***	4.349***	3.182***	-0.177
	OLS Total water extraction					
C.	Crop acres planted coefficients	0.527***	0.558***	0.420***	0.166***	0.122***
D.	Flood irrigation	control group				
	Center pivot	-15.438***				
	Center pivot, dropped nozzles	-11.069***				

Note: * p<0.05, ** p<0.01, *** p<0.001. N=155096. Full tables are available from the authors.

Table 3: Total Marginal Effects on Groundwater Extraction, Individual Level

Variable	
Center pivot irrigation system	4.034
Center pivot dropped-nozzle irrigation system	7.962
Other/not reported irrigation system	-8.508
Acres in CRP and land conservation programs (thousands)	0.012
Depth to groundwater (ft)	0.433
Energy price (cents/1000 btu)	-25.441
Precipitation (in)	-4.252
Slope (% of distance)	-0.783
Irrigated capability class=1	-15.248
Quantity authorized for extraction (AF)	0.122
Recharge (in)	7.596
10 year price forecast	-1.844
Year	-18.707

Table 4: Determinants of Irrigation Technology, Marginal Effects from Logit and Fixed Effects Logit

	Center pivot, standard or dropped nozzles (vs. flood)	Dropped nozzles (vs. standard center pivot)
A. Marginal Effects from Logit		
Corn price/price ratio	0.469***	3.079***
10 year price forecast†	0.001*	0.002***
Farm size (100s of acres)	0.001***	0.001***
Depth to groundwater (ft)	0.000***	0.000*
Natural gas futures price (cents/1000btu)	0.002	0.002
Avg yearly precipitation (in), 1971-2000	0.044***	0.015***
Slope (% of distance)	0.025***	0.011***
Irrigated Capability Class=1	-0.122***	-0.055***
Available water capacity	-3.184***	0.180***
Quantity authorized for extraction	0.0002	0.0004
Recharge (in)	-0.095***	-0.040***
Time trend (year)	0.001	0.077***
Dollars allocated to county for cost share program (1000s)	0.0016***	0.0004***
N	179081	135077
B. Fixed Effects Logit		
Corn price/price ratio	5.059***	21.056***
10 year price forecast	0.025***	0.034***
Depth to groundwater (ft)	0.018	-0.054***
Natural gas futures contract (cents/1000btu)	0.046***	0.039***
Time trend (year)	0.479***	0.753***
Dollars allocated to county for cost share program (1000s)	-0.003***	0.010***
N	70534	89594

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. †10 year price forecast is of the real, acreage weighted price of commodities, cents/bu.

Table 5: Condensed County-Level Cropland Allocation and Total Water Extraction Regressions[†]

	Alfalfa	Corn	Soy	Wheat	Sorghum
A. **County-level cropland allocation (no IV)**					
Acres flood	0.070**	0.408***	0.071***	0.166***	0.024***
Acres center pivot	control				
Acres center pivot dropped nozzles	0.003	0.756***	0.156***	0.119***	0.006
Acres other or not reported	0.486***	-0.498	0.199*	-0.176	0.167***
Acres not irrigated	-0.151***	-0.241***	-0.105***	0.137***	-0.004
B. OLS Total water extraction (no IV)					
Crop acres planted coefficients	1.0763***	1.0236***	-0.1943	0.4504*	0.4259
Flood	0.6108***				
Center pivot	control				
Center pivot, dropped nozzles	0.4827***				
Other/not reported	3.232***				
Not irrigated	-0.0183				

	Alfalfa	Corn	Soy	Wheat	Sorghum
C. County-level cropland allocation (with IV)					
Acres flood	-0.081	0.709***	0.168***	0.080**	0.003
Acres center pivot	control				
Acres center pivot dropped nozzles	-0.321***	1.403***	0.365***	-0.066	-0.039
Acres other or not reported	0.587***	-0.756*	0.137	-0.106	0.192***
Acres not irrigated	-0.228***	-0.086	-0.055*	0.093***	-0.014
D. OLS Total water extraction (with IV)					
Crop acres planted coefficients	0.701***	0.592**	-0.843*	0.212	-0.019
Flood	1.185***				
Center pivot	control				
Center pivot, dropped nozzles	1.540***				
Other/not reported	3.253***				
Not irrigated	-0.098				

Note: [†]Dependent variable in sections A and C is the number of acres planted to crop c, normalized by the number of farmed acres in the county. Dependent variable in B and D is the number of acre-feet of water extracted, normalized by the number of farmed acres in the county. Acres under irrigation systems and all other variables (that are not shown) are normalized by the number of farmed acres in the county. * $p<0.05$, ** $p<0.01$, *** $p<0.001$. N=405. Full tables are available from the authors.

Table 6: County-Level Total Marginal Effects, With and Without Instrumented Endogenous Variable

	No IV	IV
Flood irrigation systems	1.149	1.423
Center pivot irrigation system	control	
Center pivot dropped nozzle irrigation system	1.323	1.823
Other/not reported irrigation	2.804	3.076
Not irrigated	-0.293	-0.242

Table 7: Probit Results for Crop Selection

	(1) Alfalfa	(2) Corn	(3) Soybeans	(4) Wheat	(5) Sorghum	(6) Non-irrigated
Crop price/price ratio	2.389***	2.262***	0.106	-0.970***	0.458***	2.191***
Acres planted on irrigable land	-0.001***	-0.002***	-0.001***	0.000*	-0.001***	-0.003***
Depth to groundwater (ft)	-0.002***	0.001***	-0.003***	0.001**	-0.001***	-0.002***
Fut. price of natural gas, cents/1000 btu	0.131	0.114*	-0.472***	0.627***	-0.075	-0.212**
Depth to groundwater*Energy price	-0.001	-0.001***	0.004***	-0.002***	0.001*	0.003***
Avg yearly precipitation (in), 1971-2000	-0.065***	0.014***	0.094***	-0.046***	0.016***	-0.041***
Slope (% of distance)	0.114***	-0.003	-0.060***	-0.014*	0.029***	-0.016**
Irrigated Capability Class	-0.202***	-0.039***	0.024*	0.080***	0.112***	0.071***
Available water capacity (cm/cm)	-2.711***	3.576***	1.663***	1.792***	1.514***	2.904***
Quantity authorized for extraction	-0.000***	-0.000	-0.000**	-0.000**	-0.000	-0.001***
Recharge (in)	0.042***	-0.051***	0.013*	-0.010	-0.008	0.061***
Flood irrigation system	control					
Center pivot irrigation system	-0.029	0.078***	-0.072***	-0.055***	-0.426***	
Center pivot dropped-nozzle irrigation	-0.057***	0.089***	0.010	-0.101***	-0.503***	
Other/not reported irrigation system	0.205***	-0.697***	-0.209***	-0.274***	-0.460***	
10 year price forecast†	0.015***	0.023***	-0.003	-0.003*	-0.006***	0.007***
Land conservation programs (1000s acres)	-0.001*	-0.002***	-0.004***	0.002***	0.001***	0.001**
Acres planted to alfalfa, t-1	0.019***	-0.004***	-0.004***	-0.002***	-0.002***	-0.004***
Acres planted to corn, t-1	-0.003***	0.010***	0.002***	-0.001***	-0.002***	-0.005***
Acres planted to soybeans, t-1	-0.003***	0.008***	0.006***	0.002***	0.002***	-0.006***
Acres planted to wheat, t-1	0.001***	0.002***	0.002***	0.013***	0.004***	0.000
Acres planted to sorghum, t-1	-0.001***	0.001***	0.003***	0.003***	0.013***	-0.001***
Acres not irrigated	0.001***	0.001***	0.000	0.001***	0.001***	0.014***
Year	0.143***	0.204***	-0.008	-0.048**	-0.060**	0.084***
Constant	-290.032***	-417.698***	13.046	96.538**	118.269**	-172.295***
Psuedo r^2	0.484	0.223	0.171	0.249	0.194	0.527

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. N=155096. †10 year price forecast is of the real, acreage weighted price of commodities, cents/bu.

Table 8: Selectivity-Corrected Estimates of Acres Allocated to Crops

	(1) Alfalfa	(2) Corn	(3) Soybeans	(4) Wheat	(5) Sorghum	(6) Non-irrigated
Acres planted on irrigable land	0.030***	0.220***	0.023***	0.115***	0.031***	0.201***
Crop price/price ratio	209.058***	0.579	5.362***	-138.146***	28.167***	100.773***
Depth to groundwater (ft)	-0.154***	-0.010**	-0.021***	0.020***	-0.019***	0.034***
Fut. price of natural gas, c/1000 btu	2.587***	1.783	-2.059**	45.698***	0.760	15.584***
Avg yearly precip. (in), 1971-2000	-4.648***	-0.483***	2.490***	-4.551***	1.223***	-2.538***
Slope (% of distance)	7.793***	-0.355*	-1.337***	-0.667***	1.779***	-2.092***
Irrigated Capability Class	-16.235***	1.271***	0.502**	4.627***	7.541***	5.582***
Available water capacity (cm/cm)	-414.218***	-43.699***	0.897	145.238***	138.552***	149.332***
Quantity authorized for extraction	0.000	-0.001	0.000	0.031***	0.010***	-0.066***
Flood irrigation system	control group					
Center pivot irrigation system	4.808***	26.093***	3.808***	4.090***	0.806***	
Center pivot dropped-nozzle system	4.489***	25.656***	4.349***	3.182***	-0.177	
Other/not reported irrigation system	-3.957***	2.731**	2.096***	0.328	-0.247	
Recharge (in)	2.725***	1.697***	0.553***	-2.558***	-1.113***	4.176***
10 year price forecast†	1.023***	-0.387***	-0.208***	-0.819***	-0.615***	0.595***
Land conservation programs (1000s acres)	-0.019***	0.002	-0.038***	0.228***	0.042***	0.091***
Year	9.410***	-3.632***	-1.360***	-10.420***	-6.352***	6.663***
Mills' ratio	97.298***	-76.876***	14.518***	153.614***	66.440***	65.823***
Acres planted to alfalfa, t-1	250.948***	8.219***	-6.136***	-21.528***	-4.368***	-0.088
Acres planted to corn, t-1	-27.983***	-8.530***	16.360***	16.241***	-7.072***	-18.279***
Acres planted to soybeans, t-1	-20.425***	-19.236***	26.480***	38.021***	17.837***	-5.414***
Acres planted to wheat, t-1	3.713***	-15.267***	-0.167	237.843***	27.560***	0.694
Acres planted to sorghum, t-1	-14.522***	-1.364*	10.218***	37.398***	116.071***	22.236***
Acres not irrigated	-25.153***	39.154***	-5.508***	-45.943***	-12.207***	243.779***
Constant	-19184.0***	7470.9***	2684.5**	20920.1***	12606.5***	-13706.7***
r^2	0.509	0.361	0.122	0.345	0.150	0.552

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. N=155096. †10 year price forecast is of the real, acreage weighted price of commodities, cents/bu.

Supplementary Appendix

Table 9: Ordinary Least Squares Regression of Total Water Extraction

	Acre-feet extracted
Acres planted to alfalfa	0.527***
Acres planted to corn	0.558***
Acres planted to soybeans	0.420***
Acres planted to wheat	0.166***
Acres planted to sorghum	0.122***
Acres not irrigated	-0.381***
Depth to groundwater (ft)	0.544***
Energy Price	-7.070***
Depth to groundwater*Energy Price	-0.211***
Yearly precipitation (in)	-1.871***
Slope (% of distance)	-4.077***
Irrigated Capability Class	-8.443***
Available water capacity (cm/cm)	-384.02***
Quantity authorized for extraction	0.116***
Not irrigated	-62.820***
Flood	control group
Center pivot irrigation system	-15.438***
Center pivot dropped nozzles	-11.069***
Other/not reported irrigation system	-8.826***
Recharge (in)	5.476***
10 year price forecast[†]	-1.929***
Land conservation programs (1000s acres)	-0.007
Year	-19.199***
Constant	39098.1***
r^2	0.528

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. N=155096. [†]10 year price forecast is of the real, acreage weighted price of commodities, cents/bu.