Just a Drop in the Bucket? Measuring the Relative Importance of Capital Investment and Management Changes on Input Conservation *

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Abstract

Using a panel data set of water use at a disaggregated level, this paper estimates the parameters of an agricultural water demand function. We develop an analytical model which illustrates how producers make decisions on long-term investment and short-term input use, and clarifies the relationship between these choices. From the empirical analysis, we find that including the indirect effects of water price changes on output and technology choices, as well as the direct effect of improved water management leads to a significantly more elastic estimate of water demand than found in previous work. The estimation results provide a direct measurement of the conservation benefits of investment in precision irrigation technology, which can be as high as 35 percent.

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1 Introduction

Allocation of scarce freshwater resources is an issue of great importance in dry regions of the world (Postel 1996, FAO 1997), and the agricultural industry is the dominant user of water in many of these regions. Lacking adequate precipitation during the growing season, agriculture is often dependent on large-scale diversion of surface water and groundwater pumping.[1] In California, for example, even though large urban areas are almost entirely reliant on surface water diversion, agriculture in the state uses nearly 80 percent of developed surface water resources.[2] In fact, considerably more water is used to irrigate hay in the state than is consumed by all the households and businesses in Los Angeles and San Francisco combined.[3] In addition to growing concerns over the quantity of water used by the agricultural industry are other questions about the effect of agricultural water use on water and land quality.

Agriculture affects water quality through several ways. First, irrigated water absorbs chemicals from fertilizer and pesticide applications, polluting downstream water bodies. Runoff water from flood irrigation may convey waste material as well as contribute to soil erosion. Also, irrigation residue

[1] Water sources can be divided into two types (surface water and groundwater), where surface water includes diversions from lakes and rivers, while groundwater includes underground aquifers.

[2] This statistic is available from the Office of Water Use Efficiency in the California Department of Water Resources at http://www.owue.water.ca.gov/agdev/index.cfm.

[3] This is available from the National Agricultural Statistics Service at http://www.usda.gov/nass/pubs/estindx.htm.

may also contribute to waterlogging problems, which occurs when water percolates into soil with insufficient drainage, and builds up over time. As water reaches the root zone of agricultural plants, it requires that land be taken out of agricultural production. Lastly, irrigation may divert water from environmental uses, and thus have a strong impact on environmental quality by providing fewer freshwater resources to fish and wildlife. Economists and other observers have argued that policies to improve the efficiency of water allocation can help alleviate conflicts among competing users and minimize water's role as a limit to growth (Gleick 2000, Easter 2000, Schoengold & Zilberman Forthcoming). Efficiency-enhancing water management strategies can also help reconcile supply and demand imbalances without resorting to costly and environmentally damaging dams and other supply stabilization measures.

This paper develops a model of agricultural water demand based on the role of water in the farm production function. It then presents estimates of the parameters of the model using a unique panel data set from California's San Joaquin Valley. The data contains annual information on crop choice, irrigation technology, water rates, and water use for an 8-year period. A main objective of our analysis is to measure the price elasticity of farm water use, as it provides important information about the effectiveness of using price reforms to manage water demand. Our results support the hypotheses that farmers alter their land allocation choices after a change in water rates and that there is a non-zero elasticity of substitution between management inputs and applied water in the crop production function. Despite the economic and environmental significance of agricultural water use, there have been few empirical studies measuring the parameters of agricultural water demand due to a lack of available data. We also determine how existing investment impacts land use choices, and the effect of land quality characteristics on those choices. Finally, we use our empirical results to estimate the per-acre water use of various crops grown with different irrigation technologies, and to directly measure the reduction in water use under precision irrigation.

There are two different areas of research that are closely related to this work, studies of water demand and of technology adoption. Many previous studies of agricultural water demand rely on simulated data and linear programming techniques (Bontemps & Couture 2002, Hooker & Alexander 1998). Our study decomposes water use by both crop and irrigation technology, something not done in previous econometric studies of water demand (Moore, Gollehan & Carey 1994, Ogg & Gollehon 1989). To our knowledge, this is the first paper to empirically to estimate the water saving capacity of efficient irrigation technology, something which is generally estimated using data from agricultural experiments or from farmers who have professional relationships with academic researchers; not from field level data of farmers facing natural conditions. Much of the work on water demand discusses the importance of land quality characteristics in determining total applied water, however this paper is one of the first to actually estimate the effect of these characteristics using econometric methods. We find evidence that these characteristics (soil permeability, slope, and temperature levels) are significant in determining water demand.

The adoption of new technology in agriculture has been studied most notably with three types of technology - Green Revolution plant varieties, biotechnology, and precision irrigation. Starting with the seminal work of Griliches (1957), many studies have examined the factors that affect the adoption of high-yield varieties (HYV) and the diffusion of those varieties. Many of these studies have focused on understanding the adoption of new varieties or technologies in developing countries (Feder, Just & Zilberman 1985), and in particular in India, as it has been an area with wide adoption of HYV (Foster & Rosenzweig 1995, Foster & Rosenzweig 1996). Studies on the adoption of biotechnology have often focused on the effect of risk on the choice to adopt new technologies, as biologically engineered crops such as Bt cotton or Roundup Ready soybeans may cost more than traditional varieties, but reduce the downside risk from pest infestations or climate variation (Hubbell, Marra & Carlson 2000, Marra, Pardey & Alston 2002). Other studies have focused on the use of the rBST hormone in dairy farming (Barham, Foltz, Jackson-Smith & Moon 2004).

There is a body of literature that looks at the diffusion of precision irrigation technologies, and considers the role of water price in the adoption decision. Previous studies have shown that an increase in water price leads to the adoption of precision (water-conserving) irrigation systems by farmers (Caswell & Zilberman 1985, Caswell & Zilberman 1986, Kanazawa 1992).

This research also shows that the relative profitability of different types of irrigation technologies is conditional on land quality characteristics. However, with the exception of Kanazawa, these papers assume that crop choice is exogenous in the irrigation technology decisions. Other work has shown that these two choices are highly correlated, and should be modeled simultaneously (Lichtenberg 1989, Green, Sunding, Zilberman & Parker 1996, Moreno & Sunding forthcoming).

The demand framework used in this paper reflects the role of water and other factors in agricultural production. An important property of the farm production function is that of jointness (Shumway, Pope & Nash 1984, Mundlak 2003). At any point in time, producers select a production technology given the economic environment, and this choice is made together with the decision about the composition and level of outputs. This notion has important implications for the estimation of farm water demand. Water use per unit of land is determined in part by the choice of outputs since crops vary widely in their water requirements and growth response to irrigation. Water use is also influenced by capital investments in irrigation technologies as traditional technologies result in more runoff and wasted water than modern, precision irrigation systems. The jointness property implies that irrigation technology and output choice (i.e., land allocation among crops) should be modeled simultaneously with the level of water application.

The empirical method we employ allows us to distinguish between short- and long-run elasticities of farm water demand. In addition, these results illustrate how water use is conditioned by capital investments, crop choice, and other factors. Choices of outputs and production technologies are assumed to adjust over time, and thus a water price shock will have long-run effects through its influence on output and technology choice that will be distinct from the short-run effects that incorporate mainly management changes. Further, we employ instrumental variables estimation methods to account for the endogeneity of technology and output choice in the water demand equation, where our instruments include input and output prices, lagged acreage allocations, and land quality variables.

Using the results of the water demand estimation, we are able to measure the reduction in water applications after the adoption of conservation technology. We do so by comparing the estimated water use of the same crop under different irrigation technologies, and test to see if the difference is significant. To date, there is little field evidence of how much applied water is reduced through the use of precision irrigation systems, even though adoption is actively encouraged by governments in the western United States and through federal programs such as the Environmental Quality Incentives Program (EQIP).[4] Our results show that there can be substantial savings from investment in precision irrigation technology, with reductions in water use per acre close to 35 percent in a few instances.

[4]The EQIP program is federally funded through the U.S. Farm Bill, and the 2002 Farm Bill increased the budget of the program over six-fold. The program offers cost-sharing options, where farmers who qualify can have up to 75 % of the cost of installing efficient irrigation systems paid through the program.

The rest of this paper is organized as follows: Section 2 develops the conceptual motivation, while section 3 describes the data and provides some summary statistics. Section 4 explains the procedure used to estimate land allocation and water demand as well as the results of these estimations. Section 5 describes the method used to calculate the conservation potential of precision irrigation technology, and section 6 concludes.

2 Conceptual Model

The motivation for the empirical method used is given by an adaptation of the static model developed in Caswell & Zilberman (1985) to account for investments in irrigation technology and other specialized capital inputs. The importance of existing investment in current crop/irrigation decisions necessitates the use of a dynamic framework in modeling a farmer's decision-making process. The model we develop is consistent with a putty-clay framework, which assumes producers first solve for the profit-maximizing level of variable inputs under each of a finite number of technologies, and then choose the technology that maximizes profits.

We also account for the importance of management decisions into water input demand, and we allow water and management to be substitutes in the agricultural production function. Despite the fact that it is typically assumed there is no substitution between water and other inputs, evidence that the elasticity of substitution between water and labor is non-zero has been shown on occasion (Nieswiadomy 1988). In addition, Wichelns (1991) shows that an increase in the marginal price of water to farmers decreases both the mean and the variance of applied water, even in cases where crop and irrigation technology remain constant. Improved water management can reduce the demand for applied water, as water can be applied at the times which are most beneficial for the crop. For example, a farmer could adjust the timing of water applications so that water is applied for 6-hour intervals each week instead of for 15-hour intervals every two weeks. Improved maintenance of water furrows or drip systems increases the efficiency with which applied water reaches the crops root zone.

2.1 Optimal Choice of Variable Inputs

In this model, we assume that the choice at a particular location i at time t is independent of the choices at other locations, so to limit notation we remove the location subscript from the following model. We could equivalently define i as an individual farmer, however the use of location as the unit of analysis is closer to our empirical estimation strategy. In addition, the model below is defined for each of the j possible crop and irrigation combinations, but for ease of exposition, we do not use the j subscript in the first stage of the model.

For a particular crop and irrigation pair, we assume that output is given by a constant returns to scale production function, $y = f(e)$, where y denotes the yield per acre, and e the effective water per acre, or water available to the plant.[5] Under each crop/technology pair, the effective water per acre is a function of the applied water per acre (w), land quality conditions (α), weather shocks (X), and management level (m). We also assume that there is a per-acre fixed annual cost (k) associated with each crop and technology pair, where this is the cost of necessary maintenance of the land. To develop the model, we further define the following other variables:

p = output price

p_w = water price

p_m = the price or opportunity cost of management inputs

$h_j(\alpha, Z, m)$ = input use efficiency of water with crop/technology j, land quality conditions α, current weather Z, and management level m. This input use efficiency parameter must be in the (0,1) interval, and is larger for modern irrigation technology than for traditional flood irrigation.

We assume that $e = h(\alpha, Z, m)w$, or that effective water is the product of input use efficiency and applied water. This formulation assumes that input use efficiency and applied water are substitutes in the agricultural production function. We further assume that $h_\alpha > 0$ and $h_m > 0$, where the subscripts denote partial derivatives, for all choices of j, α, Z and m.

Using these variables, we consider the profit maximization problem at a particular time period facing each producer for each crop and irrigation

[5] Applied water is the quantity of water a farmer puts on a field, but due to evaporation and runoff, not all of the applied water is used by the crop. Hence, effective water measures the quantity of water used in crop production. Previous work has shown that models which consider production a function of applied instead of effective inputs overstate the productivity of those inputs (Kim & Schaible 2000).

technology combination (potential land use choice). Equation (1) represents the per-acre profit for land in each crop and technology pair.

$$\max_{w,m} \Pi = pf(h(\alpha, Z, m)w) - p_m m - p_w w - k \tag{1}$$

This maximization results in the following two first order conditions:

$$\frac{\partial \Pi}{\partial w} = pf'h - p_w = 0 \tag{2}$$

$$\frac{\partial \Pi}{\partial m} = pf'wh_m - p_m = 0 \tag{3}$$

Solving these two equations results in the optimal level of each variable input, water and labor. We denote these as $w^*(\alpha, p, p_w, p_m, Z)$ and $m^*(\alpha, p, p_w, p_m, Z)$. Substituting these back into the per-acre profit equation, we have the following expression for the profit earned for a particular crop:

$$\Pi = pf(h(\alpha, Z, m^*)w^*) - p_m m^* - p_w w^* - k \tag{4}$$

The total profit from all crops is just the sum of the profits from each individual crop. Under the assumption of constant returns to scale, each of these is the product of the per-acre profit and the number of acres planted of crop and irrigation technology pair. Denoting the acreage in crop j as a_j, the output price as p_j, and the optimal per-acre inputs as w_j^* and m_j^* gives the following expression for total profits:

$$\sum_{j=1}^{J} \Pi_j = \sum_{j=1}^{J} a_j (p_j f_j (h_j(\alpha, Z, m_j^*) w_j^*) - p_m m_j^* - p_w w_j^* - k_j) \tag{5}$$

Using these results, we model the dynamic problem facing producers, and illustrate how they choose to adjust their acreage allocation after observing a change in relative input and output prices. An important point to note is that in a one-period model with no existing investment, producers will choose the crop and technology pair that earns the highest per-acre profit, and put all of their land in that combination.

2.2 Optimal Choice of Land Allocation in Each Period

We now use the previous results to model the decision facing a producer at a particular time period. To clarify, we use the term 'land allocation' to refer to the joint choice of crop and irrigation technology. This is in contrast to previous work which uses the term to only refer to crop choice. This distinction means that grapes in drip irrigation are considered a different choice than grapes in gravity irrigation. For our purposes, which include modeling water use and demand, it is both logical and necessary to make this distinction.

The dynamic model we develop assumes the following. In each time period, a producer observes relative input and output prices, and decides if they want to keep their existing allocation of acreage between crop/technology choices, or to pay a cost of adjustment to alter those choices. This decision is dependent on both the expected profits in the current period, and the effect of land allocation changes on the present value of profits in future periods. Essentially, this model assumes that a producer ranks possible land use choices by their relative profitability, conditional on input prices, output prices, and land quality. A change in those relative prices will not only change the profitability of each choice, but also the ranking of those choices. As this change is conditional on land quality characteristics, not all producers respond in the same way. For example, we might expect that one producer responds to increased water rates by keeping the same crop but investing in precision irrigation, while another keeps the same irrigation system but alters their choice of crop.

We first consider a producer with existing acreage of $\widehat{A}$ acres in choice 1. After a change in relative prices, the per-period profit of an alternative land use choice (denoted as 2) increases, so that choice 2 earns a greater per-period profit. Denoting $C_i(X)$ as the cost of adjustment of altering X acres of land allocation choice i, we consider the choice of the producer, and if he or she decides to switch from choice 1 to choice 2. Although it may not be symmetric, this cost is both incurred when moving land out of a certain choice, as well as moving land into another choice. If the producer decides to continue to grow crop 1, he earns a profit of $\pi_1 = p_1 y_1 \widehat{A} - p_w w_1^* \widehat{A} - p_m m_1^* \widehat{A} - k_1 \widehat{A}$. If she decides to reallocate the acreage into crop 2, then she earns $\pi_2 = p_2 y_2 \widehat{A} - p_w w_2^* \widehat{A} - p_m m_2^* \widehat{A} - k_2 \widehat{A} - C_1(-\widehat{A}) - C_2(\widehat{A})$. Putting these together, we find that the expected change in profit in the first period from altering land allocation is the following:

$$\Delta\pi = \widehat{A}(p_2y_2 - p_1y_1 - p_w\Delta w - p_m\Delta m - \Delta k) - C_1(-\widehat{A}) - C_2(\widehat{A}) \qquad (6)$$

However, if these prices remain constant after the initial price shock, and the farmer invests in crops or irrigation systems that are durable for many years, the present value of change in expected profits is the following, where r is the relevant interest rate.:

$$\Delta PV(\pi) \approx \frac{\widehat{A}}{r}(p_2y_2 - p_1y_1 - p_w\Delta w - p_m\Delta m - \Delta k) - C_1(-\widehat{A}) - C_2(\widehat{A}) \quad (7)$$

We assume that costs of adjustment are incurred both with investment in a new land allocation and with disinvestment from existing allocation choices. The level of these costs will depend on the crop and technology employed, but with perennial crops such as citrus trees, both of these costs are considerable. From these equations, we see that due to the cost of adjustment in land allocation, a producer will only alter their acreage allocation if the change in expected profits are greater than the costs of that change. Therefore, we expect that marginal price changes will not affect land allocation choices, but that a significant jump in the input price is necessary to alter land allocation.

While we are unable to observe management inputs from our data, the effect of a change in management on water use will be observed from the coefficient on the ratio of water price to the price of management inputs.

Water and management are the only two variable inputs in a particular period, since the capital investment is fixed in the short term.

From this model, we determine that there are at least three possible outcomes after a change in relative input prices. The first possibility is that a producers alters their relative use of management and applied water, substituting increased management inputs for applied water in the production process. The other possibility is that after a change in relative prices, the profitability ranking of the different choices of output will shift, causing a producer to invest in a new crop, irrigation technology, or to alter both decisions. Lastly, it is possible that for high prices of inputs, producers will choose to fallow their land (not grow any crop) for a particular year, in hopes that prices will improve in later years.

3 Data and Summary Statistics

The data used in this analysis come from the Arvin Edison Water Storage District (AEWSD), a utility serving over 130,000 acres and roughly 150 farming operations located 90 miles north of Los Angeles. In 1994, AEWSD began collection of data on technology and output choice at the field level. AEWSD also provided the water price and water delivery data. A water year runs from March until the following February, a time period that parallels the growing season in the district. The district sets the water price at the beginning of each water year, and measures monthly deliveries at each turnout.[6] We aggregate the water delivery data by year and turnout to obtain total water deliveries by section. Combining these data with the land allocation data, it is possible to piece together a fairly complete picture of water use decisions at the micro level.

The data set includes an 8-year panel (1994-2001) of 117 sections (predetermined, time-invariant blocks of land) in AEWSD. Historically, sections have always been 640 acres due to standard surveying techniques, but AEWSD has redefined several of the sections to include small plots of bordering land. In our data, available cropland per section ranges from 78 to 808 acres, with total production acreage in the surface water service area averaging 44,200 acres in the sample years.[7] Also important is the fact that in 1995, the District enacted a major water rate reform that facilitates identification of the demand function. Like many water authorities, AEWSD prices water according to a two-part tariff. Agricultural producers pay a fixed per-acre fee for access to water, and this fee is paid if the land is left fallow or in production. There is an additional variable fee which is paid per acre-foot of water.[8] In 1995, AEWSD decreased the fixed component and increased the variable one; a change intended to encourage water conservation by in-

[6] A turnout is the endpoint of water deliveries. As a turnout can provide water to multiple fields, and it is difficult to accurately calculate the water use per field.

[7] Minor year to year variations are explained by fallowing.

[8] Agricultural water use is generally measured in acre-feet, where each acre-foot is enough water to cover an acre of land with water at a depth of one foot. An acre-foot is close to 326,000 gallons, or enough to serve 1-2 average households for a year.

creasing its marginal price. By comparing water use before and after the rate reform, we can capture the effects of the price change controlling for factors such as environmental conditions and changes in output prices. Although producers knew the change in price for the 1995 cropping season, the price change was not announced sufficiently ahead of time for their behavior in previous years to reflect an anticipated price change.[9]

Table 1 gives historical water prices to surface water users during the study period. Before 1995, AEWSD assessed a fixed per acre fee of \$136.3, and a variable charge of \$45.3 per acre foot of water delivered. In 1995, the District reduced the fixed fee by over 30 percent to \$94, and increased the variable fee by over 40 percent to \$65.3. In 1999, the variable charge decreased because AEWSD found it was over collecting revenue after the 1995 price change. Water districts in California are run on a non-profit basis, where the board of each district collects fees to cover the necessary costs of procuring water and maintaining the infrastructure, but is constrained to earn zero profits over the long term.

Data on the price of investment into various irrigation technologies is not included since these remained constant over the sample period. In addition, the price of investing into the two widely-use types of water-saving irrigation (sprinkler and drip) are fairly equal.[10] The environmental variables are

[9]We note that even if the price change was anticipated, this would mean that our estimates are biased downward, and if we find a price effect, it is a lower bound.

[10]Verified by personal communication with Blake Sanden, University of California Extension Irrigation Specialist.

chosen to reflect soil and topography characteristics relevant to farming and irrigation. These variables (slope, permeability, number of frost-free days per year, and average temperature) are long run averages and do not change over time, but do vary over section. One concern about using these variables in a statistical analysis is that they may be highly correlated, leading to collinearity problems in a regression analysis. Table 2 shows the correlation between these variables. While they are non-zero, none of the correlations are high enough to merit concern in a regression analysis. Yearly temperature averages for the area were obtained from the Western Regional Climate Center.[11] The use of the two temperature variables addresses two sources of variation in temperatures - cross-sectional variation among microclimates within the District and variation across years.

Table 3 gives a summary of the land allocation over time by percentage, while Table 4 shows the total acreage in each land allocation choice during the study period. In our empirical analysis, we consider only those crop and irrigation technology combinations with a reasonable number of observations. The feasible technology/crop pairs are citrus crops with drip or gravity, grape crops with drip or gravity, deciduous crops with drip, gravity, or sprinkler, truck crops with gravity or sprinkler, and field crops with sprinkler. The main citrus crop in the region is oranges; deciduous crops include mostly almonds, along with some peaches and apples. Truck crops include potatoes, carrots, and onions, while field crops include cotton and

[11]This data is available at www.wrcc.dri.edu/CLIMATEDATA.html

some hay. Interestingly, perennial crop acreage has increased in recent years despite overarching concerns about agricultural water supply reliability. In 1994, perennial crops were planted on 49 percent of total acreage. By 1998, this had increased to 63 percent of total acreage.

3.1 Crop Output Prices

Table 5 summarizes prices for those crops with significant acreage in AEWSD. Most of these data were obtained from the annual Kern County Agricultural Commissioner's Crop Report[12], with the exception of the price of carrots, which was from the U.S. Department of Agriculture. During the study period crop prices exhibit the volatility commonly observed in agricultural output markets. This volatility makes it difficult for a farmer to predict future prices, and may explain why many farmers diversify land allocation. Unlike many agricultural outputs, the crops grown in this region are not traded in futures markets, nor do they benefit from federal price support programs, sources which are often used to estimate expected output prices. In our empirical analysis, we adopt a rational expectations approach, where we hypothesize that farmers accurately predict the output prices they will receive.[13]

[12] This data is available at http://www.co.kern.ca.us/kernag/crp_idx.htm.

[13] In addition to this approach, we also considered the use of a VAR estimation of expected prices. However, we found little evidence that efficiency is gained when using multiple output prices to predict price trends. In fact, the AIK score of the predictions decreased with multiple output prices as explanatory variables, showing that these results added little in terms of explanatory power. In addition, we tried using lagged prices instead of current prices. However, the general results are robust to the choice of method, and we therefore adopt the simpler rational expectations approach.

3.2 Comparison with Groundwater Users

Before developing the econometric model of how input demand changes after a shift in the price of that input, it is informative to compare the trends observed in the sample with trends observed in regions not subject to the change in water rates. AEWSD provides information that is useful for such a comparison. There are two groups of water-users in AEWSD which are mutually exclusive. The district separates agricultural producers into surface water users and groundwater users. This designation is based on the location of the field, and these designations have remained constant over time. While surface water users pay the fees for water shown in Table 1, groundwater users only pay a per-acre fee to the district, but then must incur their own groundwater pumping costs.

While data on total water use is not available for the groundwater users, and we therefore cannot use this data in the estimation of water demand, we can look at the difference in trends between groundwater and surface water users. Considering the fact that there was a discrete jump in the price of water to surface water users, we expect that we might observe a jump in their acreage allocations as well. As the price of water increased, we expect that we might observe a noticeable increase in acreage in irrigation technologies and crops that are relatively more water efficient, and a decrease in more water intensive land use choices. In contrast, we do not expect to observe a jump in acreage totals in the groundwater service area, as there was no single event during the sample period that changed their costs significantly.

Such evidence is presented in Figures 1 - 4. Figures 1 and 2 show the total acreage with citrus crops under drip irrigation in the surface water and groundwater areas, respectively. Figures 3 and 4 show the total acreage in citrus crops under gravity irrigation in the surface water and groundwater areas, respectively. There are a couple of important points to notice in these charts. We observe a jump in acreage in each of the figures depicting surface water acreage, with the drip acreage increasing and the gravity irrigation decreasing. The trend in the groundwater acreage appears to be very different, and despite a consistent increase in groundwater acreage under drip irrigation, the rate of that increase appears to be relatively constant during the study period. This evidence supports the hypothesis that an unexpected increase in water rates to surface water users led to increased investment in drip irrigation systems.

4 Empirical Model

In our econometric analysis we estimate a reduced form model of water demand, explaining water use at a particular location as a function of output and technology choices, relative prices, and other factors such as environmental characteristics. Our estimation strategy assumes that each land allocation choice has a fixed input/output ratio in the short run, and this ratio is a function of environmental conditions and management inputs. We note that our approach is consistent with the commonly used putty-clay production framework, something reflected in the conceptual model presented in section 2. This approach assumes that the durability of physical capital fixes the input/output ratio in the short run, but that the choice of technology will adjust over time to changes in the relative prices of inputs and outputs (Wei 2003, Gilchrist & Williams 2000). Irrigation systems can be modeled using this framework, since they are comprised of pipes, valves, heads, and other types of equipment. The choice of crop can also be viewed as a particular type of capital investment, as all crops require a significant investment in specialized farm equipment and human capital, while perennial crops also require capital investment in plant stock.

One potential problem is the endogeneity of certain explanatory variables, particularly the land allocation variables, as they are functions of both land quality characteristics and water price. In addition, it is likely that there are unobservable variables that affect both the land use choices and the level of water application. Using the regression version of the Hausman test of endogeneity (Hausman 1978) of the land allocation variables, we are able to reject the null hypothesis that all land allocation variables are exogenous with a significance level of 99 %. There are ten land allocation choices we consider, and this test uses a regression analysis to test the null hypothesis that the coefficients on error terms from each of these estimations is zero.[14] Therefore, we use instruments for all of these variables to eliminate any

[14]The estimated F-statistic is 6.38, while the value at the 99 % level with 10 parameters and 936 observations is 2.35.

potential problems with endogeneity. The estimation method chosen is 2SLS, where we estimate the acreage in each crop/technology pair in the first stage, and then use those fitted values to estimate the second stage water demand equation.

4.1 Land Allocation Estimation Possibilities

We note in the analytical model that the relative profitability, and therefore the optimal allocation of land, are influenced by a number of factors including the quality of the land, the existing allocation of land, as well as relative input and output prices. We use these results to inform our estimation equations and the variables employed in those equations. Previous work has often used a discrete choice model to estimate the crop or technology on a particular field, where a field is defined as a contiguous area planted with the same crop and irrigation technology (Green et al. 1996, Moreno & Sunding forthcoming). However, we do not observe water use at the field level, only the total quantity delivered to each section. In addition, for certain years the land allocation data was only available aggregated by section. This requires the development and use of a non-traditional estimation strategy.

4.1.1 Estimation of Acreage Totals

There are several possible methods to estimate the acreage in each crop and technology pair. One option is the use of a share model. This type of model estimates the share of total available land in each land allocation choice, instead of the acreage total. However, a share model is a poor choice when the observed shares contain a large number of zeros, as the associated likelihood function of a share model approaches negative infinity as the share approaches zero. As can be seen in Table 6, there are a large number of zeros in the land allocation acreage totals, and therefore we choose not to use a share model for the estimation. To estimate the land allocation variables, we use a modification of a share model. The benefit of the modification we employ is that the predicted values are defined over $[0, \infty)$, and hence can be consistently estimated using a Tobit model. The estimation strategy also imposes an upper bound on the estimated values, guaranteeing that the predicted acreage values are in the range of feasible values. For example, with 50,000 total available acres in the sample area, this strategy imposes the constraint that the predicted acreage totals can never sum to more than 50,000, regardless of the time frame over which we make our predictions.

The data on land allocation acreage totals exhibit a large number of zero observations, or corner solutions. This is not surprising, as when each farmer decides how to allocate his/her land between different crops, he or she might grow several types of crops, but will typically not grow all of the categories we estimate ($J = 10$). In our estimation strategy, we make use of the fact that the entire region is never entirely in agriculture and that there is always some land which is fallowed or used for other purposes. We use this land as an outside option available to farmers. We denote the total acreage in the service area as $\overline{A}$, the total acreage in non-agricultural uses as $A_{non,t}$, the section by i and the time period by t. We also use a_{ijt} to denote the acreage in land allocation choice j at section i in time t. We then use a modification of the shares to calculate the ratio of acreage to non-agricultural land.

$$y_{ijt} = \frac{a_{ijt}}{A_{non,t}} \tag{8}$$

The denominator of this equation is the proportion of land in non-agricultural uses.[15] This ratio is defined over the $[0, \infty)$ range as long as there is some land in non-agricultural uses. Although this outcome is actually the result of corner solutions, instead of censored values, this type of model can be consistently estimated using a Tobit estimation strategy (Wooldrige 2002).

4.2 Stage 1 Estimation Strategy

In the following formulation, we let y_{ijt} denote the ratio of total acreage in crop j at location i to all non-agricultural land at time t, α_i the vector of section specific variables, p_{mt}, p_{wt}, and p_t the management cost, variable water price, and vector of output prices respectively. Letting j denote the crop/technology pair, we estimate J equations of the following form:

$$\begin{aligned} y^*_{ijt} &= \beta_{0j} + \beta'_{1j}\alpha_i + \beta_{2j}p_{mt} + \beta_{3j}p_{wt} + \beta'_{4j}p_t + \beta'_{5j}y_{ijt-1} + \epsilon_{ijt} && (9) \\ \text{Where} & \quad \epsilon_{ijt} \sim \eta(0, \sigma^2_j) \\ y_{ijt} &= \max\{0, y^*_{ijt}\} && (10) \end{aligned}$$

[15]During the study period, this ranges from 10 % to 25 % of the land.

Using this notation, we define β_3 as the Jx1 vector of estimated coefficients, $[\beta_{31}\beta_{32}...\beta_{3J}]'$.

4.2.1 Variables in Stage 1:

Time specific variables: Time specific variables included in the regression include *output prices*, *water price*, and *minimum wage*. For *output prices*, we adopt a rational expectations approach and use current prices as the best indicator of expected future prices. For the *water price*, we use the variable fee, or the marginal price of water to the producers. Interestingly, a change in water price will affect both the numerator and denominator of our dependent variable, as both the acreage allocation and the number of acres left fallow are dependant on the price of water. As the price of water increases, we expect a greater amount of land to be left fallow, which will reduce the dependant variable ratio. However, as seen in the summary statistics, acreage totals in efficient irrigation increase over the study period. The question of if the fallowing effect or the adoption effect is greater needs to be examined empirically.

Location specific variables: The variables specific to each section included in these regressions are *slope*, *soil permeability*, *average section temperature*, and *frost-free days*. As each of these variables affects what type of crop can be grown, and which irrigation systems can be used at a particular location, they also affect the relative profitability of each crop and irrigation system. For example, crops with a low frost tolerance are less likely to be planted in areas with a low number of frost-free days. Precision irrigation systems, such as the use of drip irrigation, are relatively more likely to be adopted on land with a high slope, as the gains in input-use efficiency are greater than on flat land. Since these variables affect the relative profitability of each land use choice, they also will affect the decision to invest or disinvest in those choices after a change in relative prices.

Lagged acreage variables: The *lagged value of acreage* in each crop and technology pair is used as an explanatory variable in the current acreage allocation. This variable is included to measure the effect of adjustment costs and the durable nature of technology and output choices. Obviously, perennial crops are durable since they require an established stand of trees or vines. Other sources of adjustment costs in the cropping decision are that growing a crop takes specific human capital (i.e. knowing how to grow grapes does not imply that one knows how to grow lettuce), and also that the long-term relationship between a farmer and a distributor of a crop influences the price farmers receive for their output (Hueth & Ligon 1999). In addition, we expect to observe some element of crop rotation in the annual crops included in the estimations.[16]

[16]For certain crops grown in the region (such as cotton and carrots), it is beneficial to the soil to have rotation between years.

4.3 Stage 1 Results

The results of the Tobit estimations are presented in Tables 7, 8, and 9. We also find that the coefficient on lagged acreage in the same type of crop and technology as the dependant variable is always positive and significant. This shows that there is some cost of adjusting land allocation each period. We also find that this coefficient is larger in magnitude with permanent crops, reflecting the greater cost of moving land out of these crops, and the fact that the decision to invest in these crops should be seen as long-term investment instead of an annual choice.[17]

Another interesting result comes from the coefficient on the water price variable. This coefficient is negative and significant with all of the estimated equations. We find that when we look at the total acreage (or absolute shares), the coefficient on this variable is positive with precision irrigation. However, when we estimate these results using the modified shares, these are all negative. This result tells us that despite the fact acreage in precision irrigation is positively correlated with water price, the rate of change (which is negative) of fallowed land with increased water prices is greater than the increased use of precision irrigation. This result supports the fact that land allocation is altered at both the intensive and extensive margins.

In Tables 7, 8, and 9, we present both the Tobit estimation results and

[17]We also look at the effect of changes in land allocation between years, which only includes changes in acreage instead of the level of acreage. We find negative coefficients in the lagged acreage of annual crops using this measure, evidence which supports the observations of crop rotation between field and truck crops between years.

the calculated marginal effects. Because of the non-linearity of the Tobit estimation, the marginal effects need to be calculated using the estimation results and the predicted probabilities that a positive value is observed for each land allocation choice. Using Φ to denote the normal CDF and β_j as the estimated coefficients in the jth equation, we use the following formula to calculate the marginal effects:

$$\frac{\partial E[y_{ijt}|X_{ijt}]}{\partial X_{ijt}} = \beta_j \Phi(\frac{\beta_j' X_{ijt}}{\sigma_j}) \tag{11}$$

4.3.1 Calculation of Predicted Land Allocation

These results are easily translated into the predicted acreage totals using the product of the estimated values and the acreage in non-agricultural uses.

$$\widehat{A}_{ijt} = \widehat{y}_{ijt} A_{non,t} \tag{12}$$

These predicted land allocation variables provide the instruments for the actual land allocation in the water demand estimation (Stage 2 of the analysis).

4.4 Stage 2 Estimation

The main equation to be estimated is the water demand equation, where water demand is a function of water price, section specific variables, and time specific variables as shown below.

$$W_{it}^D = q(\alpha_i, X_t, p_{wt}, p_{mt}, \widehat{A_{it}}) \quad (13)$$

Where W_{it}^D is the water used at location i in time period t, X_t are time specific variables, α_i are location specific variables, p_{wt} and p_{mt} are the marginal costs of water and management at time t, and $\widehat{A_{it}}$ is the vector of predicted values for acreage in each crop and irrigation land use choice. The equation we estimate is of total water use in a section with the explanatory variables including acreage in each type of crop and irrigation technology. An alternative option is to estimate the water use per acre with acreage shares included as explanatory variables. We estimated water demand using this specification and found that the water price coefficient is still negative and significant, with a price elasticity close to -0.4. However, this specification does not allow us to examine the conservation benefits of investment in precision irrigation. Therefore, we report the per-section estimates in our results.

4.4.1 Variables in Stage 2

Time dependent variables: *Average yearly temperature* is included in the water demand regression. It is expected to have a positive coefficient, since more water is needed when temperatures are warmer. *Variable water fee* is perhaps the variable of most interest in this study. We expect the coefficient on water price to be negative since farmers will be more careful with water application at a higher water price. While we do not have data and observations on the marginal price paid to labor, we do use the *minimum wage* as a proxy for the price of labor. We do not include prices of other non-water and non-labor farm inputs such as fertilizers and pesticides. While labor in the form of better management can be a substitute for applied water, previous results in both economics and agronomy show that there are very few substitutes for effective water in crop production (see, for example, (Hanks, Gardner & Florian 1969), (Power, Bond, Sellner & Olson 1973)).

The first stage of the estimation includes output prices, which are expected to influence the choice of crop. However, we do not include those variables in the water demand estimation. We expect that while output prices affect the choice of crop, after a particular crop and technology is chosen, output prices will not directly affect the quantity of water demanded by a producer. The only exception to this is if output prices are so low that farmers choose to let a crop die in the field instead of harvesting.

Section specific variables: *Average slope* is expected to have a positive coefficient. A greater slope increases the amount of water that runs off the land, resulting in a lower amount of applied water reaching the roots of the plant. *Average permeability* is also expected to have a positive coefficient. Permeability refers to how easily water moves through the soil. With a high permeability, water will quickly move away from the root zone of the plant, and increase requirement for applied water. *Average section temperature* measures the long run average temperature at the section. This measures variability within the sample at each point in time. A higher average temperature should increase water use, for the same reasons as average yearly use.

Fitted land allocation variables: The variables are the fitted values of acreage in each of the land allocation variables. The expected sign on all of these variables is positive, since a greater quantity of land in production requires more applied water. However, one can develop interesting hypotheses about the relative magnitudes of these coefficients. We expect that the coefficient on a particular crop in drip irrigation is smaller than the coefficient on the same crop in gravity irrigation. These relationships have often been tested using experimental data, but farmers are exposed to conditions that don't mimic the idealized conditions of a field test experiment.

4.4.2 Specification Issues in Stage 2

The estimation of the water demand equation uses panel data which raises several potential issues. One potential problem is heteroscedasticity. If the variation in errors is due to unobserved characteristics at the section level, another possible method is to use either fixed or random effects. Random effects models assume that the error term can be divided into the 'true' error and another term unique to a specific group in the sample. However, for random effects to be valid, the error terms must be uncorrelated with the explanatory variables. A test of our data shows that this assumption does not hold. Fixed effects allow correlation between the error terms and the explanatory variables, but it limits the choice of variables. Because a fixed effects model examines the differences within a group over time, the impact of individual specific variables (such as land quality characteristics) that remain constant cannot be identified.

There are two reasons that we decide against the use of a fixed effects regression. First, the data contains many of the micro variables that determine crop and irrigation choice at a section level. Since these are some of the factors that would be included and not identifiable in a fixed effects regression, we would be unable to observe the importance of these characteristics. The second reason to not use fixed effects is the lack of a direct link between a section and a single landowner. If a section was owned by a single individual, there could also be individual characteristics that influence behavior. However, multiple farmers can own land in the same section, and a single farmer can own land in multiple sections. Also, land could have been sold during the period from one farmer to another, something we have no information on. For these reasons, attempting to use fixed effects to account for individual variation is inaccurate. We do use clustering at the section level in our estimates. This allows correlation between observations from the same section without specifying the form of that correlation. It does assume that observations are independent across sections.

As the demand estimation uses predicted values of land acreage instead of actual values, the error terms and the standard errors from the second stage regression are biased. We therefore use bootstrapping to obtain consistent estimates of the standard errors from the econometric results.

The choice of a functional form for the estimation equation is important. Previous work on residential water demand has generally used linear, log-log, or log-linear functional forms (Hanemann 1998). Information on the crop production function informs the decision of the appropriate functional form. Other research has shown that a quadratic production function provides a good fit for observed yields and water input levels in agriculture. A quadratic production function implies that we estimate a linear input-demand function. In addition, in contrast to a Cobb-Douglas production function, which assumes a constant elasticity, a quadratic production function allows the elasticity to differ depending on the price observed.

Using these results, we estimate the following model:

$$W_{it}^{D} = \gamma_0 + \gamma_1 X_t + \gamma_2 \alpha + \gamma_3' \widehat{A_{it}} + \gamma_4 p_{wt} + \gamma_5 p_{mt} + \epsilon_{it} \tag{14}$$

The results of the water demand estimation are in table 6. For comparison, we present the results of the OLS estimation and the IV estimation with robust standard errors. The results are very similar across econometric specifications. At a qualitative level, the estimation results invite a couple of observations. One regards the difference in the coefficients on precision (drip or sprinkler) and traditional (gravity) irrigation methods. This comparison provides direct evidence that even under non-experimental conditions, there is a reduction in water use achieved by the adoption of modern irrigation systems. To our knowledge, this is the first time such a benefit from investment in agricultural water conservation technology has been demonstrated and measured under field conditions. Another interesting result is the importance of water price in the second-stage water use equation - this coefficient is negative and significant. This finding demonstrates that marginal price can influence farm water demand - even controlling for other factors such as output choice and capital investments in production technology. The significance of water price in this equation suggests that better management alone can result in a significant amount of conservation, and can do so in the short run. We discuss both these points in more detail below.

4.5 Direct and Indirect Water Price Elasticity

The estimation method chosen accounts for the potential endogeneity of investment in perennial crops and efficient irrigation. One benefit of this approach is that the microeconomic response to changes in water price can be decomposed into direct and indirect effects, where the latter include changes in capital investment and land allocation. Using the notation from equations 9 and 14, we calculate the following formula for the change in water use with respect to the price of water. To calculate these effects, we use the marginal effects from the Tobit estimations. As the Tobit estimations are non-linear by design, the marginal effects differ from the coefficients in the acreage estimations.

$$\frac{\partial W_{it}^D}{\partial p_{wt}} = \underbrace{\gamma_4}_{\text{direct effect of management}} + \underbrace{A_{non,t}\gamma_3'\beta_3\Phi(\frac{\beta' X_{ijt}}{\sigma_j})}_{\text{indirect effect of land use changes}} \quad (15)$$

Converting this to an elasticity measure at mean values gives the following:

$$\epsilon_p = \frac{\partial \overline{W}^D}{\partial \overline{p_w}} \frac{\overline{p_w}}{\overline{W}^D} = \underbrace{\gamma_4 \frac{\overline{p_w}}{\overline{W}^D}}_{\text{direct price elasticity}} + \underbrace{A_{non,t}\gamma_3'\beta_3\Phi(\frac{\beta' X_{ijt}}{\sigma_j})\frac{\overline{p_w}}{\overline{W}^D}}_{\text{indirect price elasticity}} \quad (16)$$

Table 11 presents the estimated demand elasticities from each econometric specification. The direct elasticities are all negative and significantly different from zero for the average section in our sample, providing evidence of improved water management and conservation at higher water prices. The indirect elasticity is negative, although not as significant as the direct elasticity, implying that a change in the price of water induces water-conserving changes in crop and technology choices. It should also be noted that the indirect effects or water price are greater than the direct effects. Much of this result is due to the fallowing of land, and the estimated indirect elasticity holding acreage constant (but allowing changes in land allocation) is approximately 50% of the value found including fallowing.[18] This pattern is explained by the fact that, while the price of water has been shown to be a

[18] This indirect elasticity, which is calculated holding land acreage constant but allowing substitution between crops and irrigation systems is approximately -0.25.

significant determinant of adoption of conservation technology in agriculture, it is by no means the only determinant (Green et al. 1996). Other factors such as weed control, a desire to save on labor costs, or a need to apply fertilizers precisely through the irrigation system can all spur investment in precision irrigation systems. Similarly, the price of water has been shown to have only a relatively small influence on crop choice since the price of water is often a small share of the cost of production (Moore et al. 1994).

The calculated total own-price elasticity of water use is in the range [-0.912, -0.221]. This finding implies that agricultural water demand is somewhat more elastic with respect to the price of water than indicated by previous studies. Accordingly, one implication of our research is that water rate changes can have a larger effect on water allocation than previously assumed. It is also worth noting that our panel only includes 7 years of data after the major rate change (inclusive of 1995). Given the durability of capital investments in irrigation systems, which can have a useful life of ten years or more, and plant stock, which can last up to forty years for some trees and vines, we would expect that the indirect effects may be larger when measured over a longer time period.

5 Water Savings from Investment in Precision Technology

An interesting and useful result of this analysis is that it allows measurement of the water savings resulting from investment in precision irrigation technology. By comparing the coefficients of the same crop under different irrigation technologies in the water demand estimation, we can estimate the reduction in water application per acre from a change in technology. The results of the tests on the water saving capacity of precision irrigation are presented in Table 12. With the exception of the difference between water use by deciduous crops in gravity and in sprinkler irrigation, the water conservation potential of all pairwise comparisons is significantly different from zero In some cases, adoption of precision technology can cut water use per acre by an average rate of 35 %.

Another important result is that precision technology results in different amounts of conservation when used on different crops. For example, the water savings capacity of drip irrigation compared to gravity is much greater in citrus crops than in grapes. Therefore, the gain in moving from gravity to drip in citrus is very high. In grapes, drip irrigation still uses less water then gravity, but the difference is much smaller. This comparison provides at least a partial explanation for the fact that there are many more acres in the grapes/gravity pair than in citrus/gravity. The differential gains of the switch to efficient technology make sense from an agronomic or physical point of view as well. With citrus crops, the trees are planted far away from each other, leaving a lot of land between the trees where water is not used by the plant. Applying water directly to the root zone, as is the case with drip irrigation, will accordingly result in more water savings. Grapevines are planted much closer to each other, resulting in less wasted water from gravity applied irrigation water.

In Table 13 we compare the estimated water use of each type of crop with the recommended levels from the University of California's Cost and Return Studies. There are a couple of interesting observations that we see from these results. The first is that the estimated per-acre water use with our study is in a similar range to the recommended levels. However, despite being in a similar range, our estimates are consistently higher than the levels in the Cost and Return Studies. There are several reasons that we might expect this to be true. The first reason is that water is used for purposes other than irrigation (such as frost protection), and these uses will be predicted in our estimation, as we have no way to separate the water applied for irrigation and the water applied for frost protection. Another reason is that the Cost and Return Study estimates are for a larger region than our sample, and regional differences are important in determining water use. Lastly, the difference might in fact be real, and reflect the difference in the farmers surveyed for the Cost and Return Studies and an 'average' farmer. In general, the recommendations from these studies are found by surveying farmers with established relationships with Agricultural Extension researchers, and these farmers might not be representative of an 'average' farmer. Anecdotal evidence suggests that they may be 'better than average' farmers, and therefore have lower levels of water use than we observe in our sample.

6 Conclusions

Agriculture producers use the majority of water in the western United States and in many arid regions of the world. As a result of rapid population growth and increasing concern about the environmental effects of surface water diversions, agricultural interests are under increasing pressure to conserve water. Financial incentives, whether embodied in water trading opportunities or increased water rates, are widely touted by economists as an effective means of reallocating water supplies and encouraging conservation in agriculture. On the other hand, it is sometimes postulated that the price of water delivered to farmers is so highly subsidized that there is no significant demand response to modest price changes (Garrido 2003, Jones 2003). Missing from this important policy debate are sound estimates of the price elasticity of farm water demand.

Using a unique data set along with an estimation methodology that reflects the role of water in the production function, we are able to answer this and several other important questions about farm water use. The estimated own-price elasticity of agricultural water demand is in the range [-0.912, -0.221]. Of this total elasticity, the indirect effects of water price on output and technology choices account for roughly 60 percent of the total, while direct effects make up the balance. This finding suggests that more active management has a large influence on water use, although the indirect effects of land use change are also significant.

Another important finding concerns the conservation benefits of adoption of precision irrigation technology. Comparing coefficients in the demand equation, the savings from switching from, say, gravity irrigation to drip is measured directly. For some crops, the water savings from investment in modern technology is large - in the range of 35 percent per acre. For others, the savings are not nearly as great. These findings provide a window on the performance of programs designed to stimulate investment in modern irrigation technologies and suggest that expectations of water savings be conditioned on land allocation among crops.

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Table 1: Summary of Water Prices (in Dollars), 1994 - 2001

Year	Fixed Cost	Variable Cost
1994	136.3	45.3
1995	94.0	65.3
1996	94.0	65.3
1997	94.0	65.3
1998	80.0	64.8
1999	80.0	50.8
2000	80.0	50.8
2001	58.0	50.8

Fixed costs are paid per acre, while variable costs are paid per acre-foot.

Table 2: Correlation Between Land Quality Variables

	Slope	Permeability	Frost-free Days	Temperature
Slope	1.0000			
Permeability	0.0810	1.0000		
Frost-free Days	-0.3403	-0.0584	1.0000	
Temperature	-0.2462	0.2681	0.6515	1.0000

Table 3: Land Allocation Percentages over Time by Crop & Technology

Crop Type	Irrigation Type	1994	1995	1996	1997	1998	1999	2000	2001
Citrus	Drip	16.9	16.8	16.4	20.9	22.0	22.4	22.0	22.3
	Gravity	1.9	2.0	2.2	2.3	2.4	0.9	1.4	1.3
Grape	Drip	9.3	9.3	9.4	12.0	12.8	18.5	15.6	15.8
	Gravity	10.1	11.6	10.9	12.6	12.4	8.0	9.6	10.2
Deciduous	Drip	3.8	3.8	4.5	6.8	7.4	5.3	5.6	6.0
	Gravity	2.9	2.6	3.6	3.5	3.8	4.1	4.2	4.6
	Sprinkler	4.5	4.6	1.9	2.6	2.1	3.1	1.8	1.9
Truck	Gravity	4.0	3.2	0.0	3.7	3.5	3.8	4.2	2.3
	Sprinkler	27.3	24.8	29.7	12.4	16.6	17.0	16.0	16.7
Field	Sprinkler	18.3	19.7	21.3	21.5	16.2	16.3	17.4	17.6
All Perennial Crops	Drip	30.0	29.9	30.3	39.7	42.2	46.2	43.2	44.2
	Gravity	14.9	16.2	16.7	18.4	18.6	12.9	15.2	16.2
	Sprinkler	4.5	4.6	1.9	2.9	2.4	3.1	2.2	2.2
All Annual Crops	Gravity	4.4	4.2	0.0	4.1	3.6	3.8	4.4	2.3
	Sprinkler	45.5	44.5	51.0	33.9	32.8	33.3	33.4	34.3

Table 4: Land Allocation Acreage Totals over Time by Crop & Technology

Crop Type	Irrigation Type	1994	1995	1996	1997	1998	1999	2000	2001
Citrus	Drip	7,784	7,619	7,837	8,723	8,998	9,399	9,554	9,732
	Gravity	871	904	1,046	976	976	369	588	588
Grape	Drip	4,273	4,249	4,506	5,031	5,245	7,764	6,795	6,894
	Gravity	4,670	5,273	5,222	5,248	5,065	3,338	4,186	4,449
Deciduous	Drip	1,769	1,716	2,147	2,856	3,043	2,200	2,425	2,634
	Gravity	1,323	1,191	1,719	1,453	1,556	1,712	1,822	2,020
	Sprinkler	2,061	2,082	934	1,103	864	1,284	772	813
Truck	Gravity	1,827	1,434		1,534	1,438	1,601	1,819	989
	Sprinkler	12,567	11,271	14,212	5,186	6,793	7,115	6,963	7,255
Field	Sprinkler	8,406	8,939	10,197	9,007	6,629	6,815	7,540	7,685
All Perennial Crops	Drip	13,826	13,584	14,490	16,610	17,286	19,363	18,774	19,260
	Gravity	6,864	7,368	7,987	7,677	7,597	5,419	6,596	7,057
	Sprinkler	2,061	2,082	934	1,229	990	1,284	940	962
All Annual Crops	Gravity	2,035	1,926		1,694	1,476	1,601	1,916	989
	Sprinkler	20,973	20,210	24,409	14,193	13,422	13,930	14,503	14,940

Table 5: Summary of Crop Output Prices (in Dollars), 1994 - 2001

Crop	1994	1995	1996	1997	1998	1999	2000	2001	Mean
Onions	147	267	288	244	239	177	231	280	231
Carrots	12.9	16.7	13.4	12.9	12.0	16.8	13.1	17.4	14.1
Potatoes	6.9	8.9	5.1	6.7	6.9	6.9	5.4	10.7	7.3
Cotton	243	216	216	226	285	305	210	214	240
Grapes	1186	1225	1384	1150	1250	1210	1110	1150	1196
Oranges	437	443	370	429	455	685	410	512	460
Almonds	2598	5000	4065	3060	3200	1710	2040	1780	3035

Price information on onions, cotton, grapes, oranges, and almonds were obtained from the Kern County Agricultural Commissioner's Report and are in dollars per ton.
Price information on carrots and potatoes were obtained from USDA, and are in dollars per container weight.

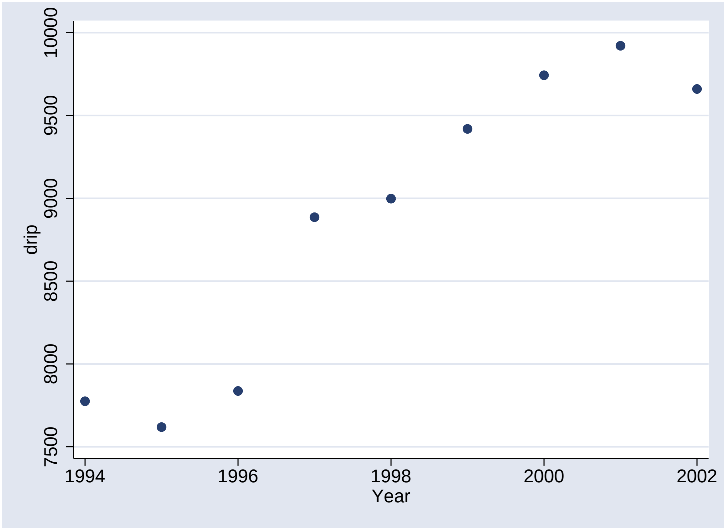

Figure 1: Acreage in Drip Irrigation and Citrus: Surface Water Users

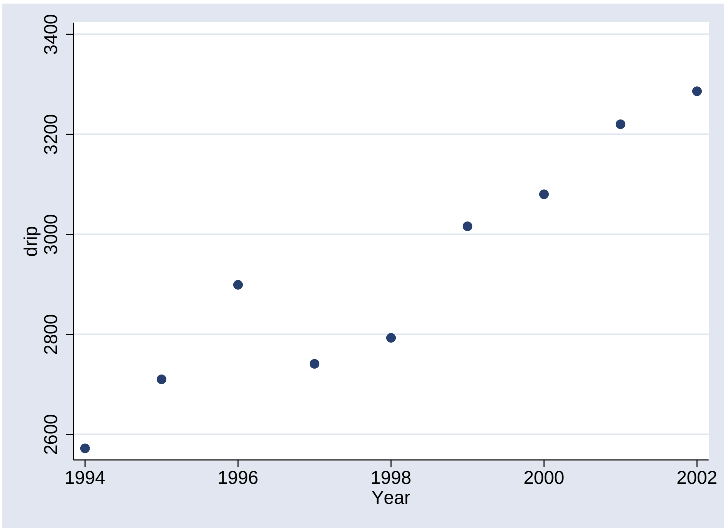

Figure 2: Acreage in Drip Irrigation and Citrus: Groundwater Users

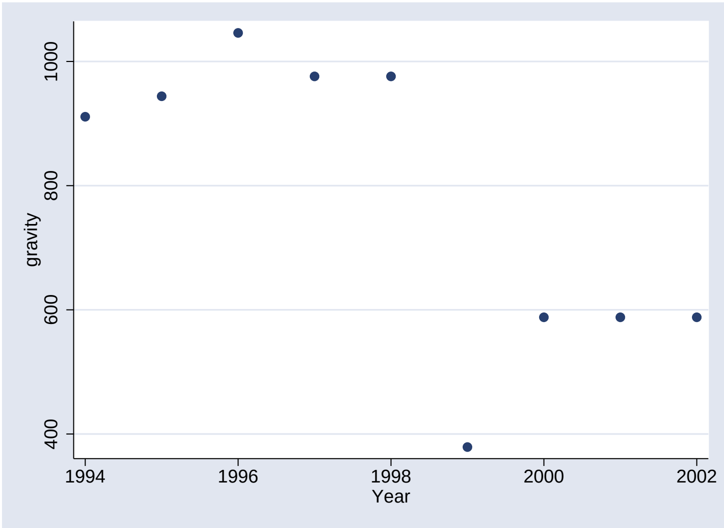

Figure 3: Acreage in Gravity Irrigation and Citrus: Surface Water Users

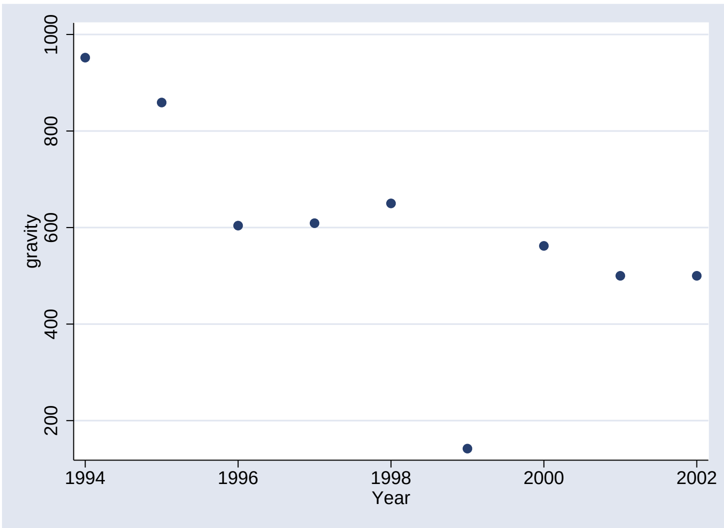

Figure 4: Acreage in Gravity Irrigation and Citrus: Groundwater Users

Table 6: Comparison of Zero and Non-Zero Acreage Totals

Crop Type	Irrigation Type	Number of Zero Observations	Number of Non-Zero Observations
Citrus	Drip	70	47
	Gravity	114	3
Grape	Drip	74	43
	Gravity	88	29
Deciduous	Drip	94	23
	Gravity	104	13
	Sprinkler	105	12
Truck	Gravity	108	9
	Sprinkler	65	52
Field	Sprinkler	67	50

These numbers are from 2001, however they are representative of the other years in the survey.

Table 7: Tobit Estimation Results - Dependent Variables are the Ratios of Acreage in Each Crop and Technology Pair to Non-agricultural Land (x 1000)

	Citrus Drip (1)	Citrus Drip (2)	Citrus Gravity (1)	Citrus Gravity (2)	Grape Drip (1)	Grape Drip (2)	Grape Gravity (1)	Grape Gravity (2)
Water Price	*** -1.61 (0.23)	-0.61	** -1.93 (0.60)	-0.09	*** -1.25 (0.22)	-0.39	*** -1.54 (0.28)	-0.40
Minimum Wage	*** 17.77 (3.90)	6.70	** 24.03 (9.92)	1.13	*** 13.67 (3.79)	4.29	*** 16.22 (4.78)	4.19
Slope	*** 1.53 (0.37)	0.58	1.12 (0.96)	0.05	* 0.68 (0.39)	0.21	** -2.01 (0.82)	-0.52
Soil Permeability	-0.05 (0.16)	-0.02	* -1.31 (0.82)	-0.06	0.21 (0.16)	0.07	0.10 (0.23)	0.03
Frost-free Days	** -0.12 (0.05)	-0.05	* -0.26 (0.14)	-0.01	* 0.13 (0.08)	0.04	*** 0.36 (0.14)	0.09
Section Temperature	0.79 (0.61)	0.30	* 2.96 (1.57)	0.14	* -1.11 (0.69)	-0.35	** -2.63 (1.08)	-0.68
Orange Price Index	** -0.07 (0.03)	-0.02	* -0.12 (0.08)	-0.01	0.02 (0.02)	0.01	*** -0.13 (0.04)	-0.03
Grape Price Index	*** 0.88 (0.10)	0.33	*** 0.85 (0.25)	0.04	*** 0.67 (0.10)	0.21	*** 0.63 (0.12)	0.16
Almond Price Index	*** 0.34 (0.08)	0.13	*** 0.54 (0.20)	0.03	*** 0.26 (0.08)	0.08	*** 0.39 (0.10)	0.10
Annual Price Index	0.02 (0.07)	0.01	-0.03 (0.19)	0.00	-0.02 (0.06)	-0.01	0.10 (0.08)	0.02
Citrus/Drip Lagged Ratio	*** 1179 (34.9)	445	* -218 (133.6)	-10.2	41.3 (38.0)	13.0	-16.4 (56.2)	-4.2
Citrus/Gravity Lagged Ratio	-8.15 (131)	-3.07	*** 2049 (206)	96.4	* -256 (155)	-80.3	*** 446 (142)	115
Grape/Drip Lagged Ratio	67.1 (47.4)	25.3	58.8 (110)	2.76	*** 1386 (45.3)	435	101 (66.4)	26.0
Grape/Gravity Lagged Ratio	26.9 (55.5)	10.1	** -619 (299)	-29.1	*** 132 (47.2)	41.4	*** 1285 (51.1)	332
Decid./Drip Lagged Ratio	66.1 (73.0)	24.9	-167 (296)	-7.84	28.6 (66.3)	8.97	10.8 (81.4)	2.78
Decid./Gravity Lagged Ratio	** -297 (139)	-112	** 399 (165)	18.8	48.3 (80.1)	15.2	94.0 (87.9)	24.3
Decid./Sprinkler Lagged Ratio	-209 (132)	-78.9	-302 (358)	-14.2	44.2 (73.1)	13.9	* -358 (206)	-92.5
Truck/Sprinkler Lagged Ratio	* 64.0 (37.7)	24.2	1.08 (80.7)	0.05	*** -131 (48.0)	-41.1	** -116 (48.6)	-30.0
Truck/Gravity Lagged Ratio	** -334 (165)	-126	-754 (876)	-35.4	-192 (138)	-60.2	*** -801 (265)	-207
Field/Sprinkler Lagged Ratio	-151 (55.9)	-56.9	-238 (176)	-11.2	** 110 (43.7)	34.4	-68.7 (54.6)	-17.8
Constant	*** -140 (36.1)		*** -258 (97.5)		* -65.3 (37.3)		-23.5 (53.6)	
Censored Obs.	598		891		658		698	
Uncensored Obs.	338		45		278		238	
Chi-sq Value	*** 1054.3		*** 258.39		*** 809.87		*** 695.17	

Numbers in parentheses are standard errors. The first column (1) in each pair are the coefficients from the Tobit regression, and the second column (2) are the estimated marginal effects.

Table 8: Tobit Estimation Results - Dependent Variables are the Ratios of Acreage in Each Crop and Technology Pair to Non-agricultural Land (x 1000)

	Deciduous Drip (1)	Deciduous Drip (2)	Deciduous Gravity (1)	Deciduous Gravity (2)	Deciduous Sprinkler (1)	Deciduous Sprinkler (2)
Water Price	*** -1.82 (0.42)	-0.27	*** -1.55 (0.42)	-0.17	-0.62 (0.38)	-0.06
Minimum Wage	*** 27.99 (7.15)	4.19	** 17.78 (6.96)	1.93	3.20 (6.73)	0.31
Slope	0.51 (0.67)	0.08	** -3.99 (1.64)	-0.43	-0.58 (1.00)	-0.06
Soil Permeability	** 0.75 (0.31)	0.11	-0.41 (0.43)	-0.04	** 0.83 (0.33)	0.08
Frost-free Days	* 0.25 (0.15)	0.04	** 0.53 (0.25)	0.06	0.09 (0.20)	0.01
Section Temperature	*** -3.53 (1.32)	-1.33	-0.37 (1.94)	-0.04	2.86 (1.82)	0.28
Orange Price Index	* -0.09 (0.05)	-0.01	-0.06 (0.05)	-0.01	0.04 (0.05)	0.00
Grape Price Index	*** 0.85 (0.19)	0.13	*** 0.79 (0.18)	0.09	0.00 (0.18)	0.00
Almond Price Index	*** 0.41 (0.14)	0.06	*** 0.40 (0.14)	0.04	0.15 (0.13)	0.01
Annual Price Index	0.02 (0.11)	0.00	0.06 (0.11)	0.01	-0.01 (0.12)	0.00
Citrus/Drip Lagged Ratio	*** 226 (66.4)	33.8	5.8 (96.9)	0.6	*** -477.9 (162)	-46.0
Citrus/Gravity Lagged Ratio	119.7 (232.7)	17.9	*** 723.5 (233.6)	78.4	-385.6 (448.4)	-37.2
Grapes/Drip Lagged Ratio	*** 328.0 (77.0)	49.1	-143.7 (116.4)	-15.6	62.4 (84.7)	6.0
Grapes/Gravity Lagged Ratio	*** 227.8 (79.9)	34.1	141.5 (65.8)	15.3	*** -746.0 (247.1)	-71.9
Decid./Drip Lagged Ratio	*** 1454.2 (85.9)	217.6	*** 256.4 (77.0)	27.8	54.6 (105.5)	5.3
Decid./Gravity Lagged Ratio	*** 392.2 (132.7)	58.7	*** 1583.5 (106.7)	171.6	*** 367.2 (136.8)	35.4
Decid./Sprinkler Lagged Ratio	*** 745.0 (100.2)	111.5	46.8 (126.3)	5.1	*** 1313.5 (100.0)	126.6
Truck/Sprinkler Lagged Ratio	*** 243.8 (66.3)	36.5	-99.5 (72.0)	-10.8	11.8 (66.5)	1.1
Truck/Gravity Lagged Ratio	-64.2 (245.4)	-9.6	-82.1 (171.8)	-8.9	-323.0 (240.6)	-31.1
Field/Sprinkler Lagged Ratio	-26.4 (84.8)	-3.9	-102.1 (84.8)	-11.1	** 133.3 (65.9)	12.8
Constant	-22.4 (68.4)		** -245.9 (106.5)		** -219.6 (104.6)	
Censored Obs. Uncensored Obs.	790 146		831 105		838 98	
Chi-sq Value	*** 373.2		*** 353.19		*** 280.8	

Numbers in parentheses are standard errors. The first column (1) in each pair are the coefficients from the Tobit regression, and the second column (2) are the estimated marginal effects.

Table 9: Tobit Estimation Results - Dependent Variables are the Ratios of Acreage in Each Crop and Technology Pair to Non-agricultural Land (x 1000)

	Truck Sprinkler (1)	Truck Sprinkler (2)	Truck Gravity (1)	Truck Gravity (2)	Field Sprinkler (1)	Field Sprinkler (2)
Water Price	*** -4.140 (0.325)	-1.846	*** -0.399 (0.150)	-0.040	*** -2.024 (0.281)	-0.843
Minimum Wage	*** -45.1 (2.97)	-20.1	** 6.59 (2.90)	0.659	*** -23.2 (2.73)	-9.68
Slope	-0.767 (0.74)	-0.342	-1.273 (1.65)	-0.127	*** -2.729 (0.849)	-1.136
Soil Permeability	0.243 (0.274)	0.108	*** -2.363 (0.727)	-0.236	** 0.695 (0.276)	0.290
Frost-free Days	-0.002 (0.116)	-0.001	9.525 (8.499)	0.953	*** 0.485 (0.148)	0.202
Section Temperature	-0.002 (1.180)	-0.001	-4.569 (3.182)	-0.457	*** -5.866 (1.348)	-2.443
Potato Price Index	*** 0.323 (0.103)	0.144			0.031 (0.099)	0.013
Carrot Price Index	*** -1.071 (0.159)	-0.478			** -0.367 (0.148)	-0.153
Onion Price Index	*** 1.375 (0.105)	0.613			*** 0.676 (0.095)	0.281
Cotton Price Index	*** 1.852 (0.164)	0.826			*** 0.812 (0.144)	0.338
Annual Price Index			** -0.260 (0.132)	-0.026		
Permanent Price Index	*** 1.429 (0.240)	0.637	-0.194 (0.126)	-0.019	*** 0.497 (0.225)	0.207
Citrus/Drip Lagged Ratio	*** -309.8 (80.8)	-138.1			** -406.4 (94.9)	-169.2
Citrus/Gravity Lagged Ratio	89.0 (198.8)	39.7			-667.0 (286.0)	-277.8
Grape/Drip Lagged Ratio	54.9 (71.0)	24.5			*** 133.9 73.0	55.8
Grape/Gravity Lagged Ratio	*** -372.3 (91.5)	-166.0			-336.4 (86.1)	-140.1
Decid./Drip Lagged Ratio	174.2 (94.7)	77.7			45.5 (90.3)	19.0
Decid./Sprinkler Lagged Ratio	-56.5 (124.3)	-25.2			22.6 (107.9)	9.4
Decid./Gravity Lagged Ratio	174.2 (129.5)	77.7			*** 219.5 (122.7)	91.4
Truck/Sprinkler Lagged Ratio	*** 954.7 (50.3)	425.6	*** 292.1 (69.8)	29.2	*** 323.8 (47.9)	134.8
Truck/Gravity Lagged Ratio	*** 659.3 (126.1)	294.0	*** 1199.5 (145.2)	120.0	*** 455.4 (124.9)	189.7
Field/Sprinkler Lagged Ratio	*** 432.3 (54.0)	192.7	*** 205.1 (67.2)	20.5	*** 829.5 (52.6)	345.5
Constant	54.9 (60.9)		-2311.4 (2300.9)		290.5 (66.9)	
Censored Obs. Uncensored Obs.	507 429		843 93		542 394	
Chi-sq Value	*** 700.39		*** 241.1		*** 610.9	

Numbers in parentheses are standard errors. The first column (1) in each pair are the coefficients from the Tobit regression, and the second column (2) are the estimated marginal effects.

Table 10: Water Demand Estimation Results (Dependent Variable is Total Water Use at Each Section)

	OLS	IV
Water Price	** -4.19	*** -7.22
	(1.89)	(2.43)
Minimum Wage	*** 134.23	30.58
	(46.75)	(78.57)
Slope	1.94	42.90
	(14.67)	(44.40)
Permeability	*** 22.70	*** 25.93
	(5.59)	(8.36)
Section Temperature	** -37.23	** -58.57
	(17.16)	(71.42)
Annual Temperature	*** 48.27	*** 34.41
	(14.05)	(17.72)
Citrus Drip	*** 1.66	*** 1.29
	(0.14)	(0.26)
Citrus Gravity	*** 3.09	1.89
	(0.45)	(9.56)
Grape Drip	*** 1.30	*** 0.88
	(0.17)	(0.24)
Grape Gravity	*** 1.95	1.13
	(0.18)	(0.98)
Deciduous Drip	*** 2.34	1.62
	(0.23)	(1.38)
Deciduous Gravity	*** 2.83	** 2.63
	(0.30)	(1.11)
Deciduous Sprinkler	*** 2.50	2.67
	(0.34)	(5.87)
Truck Sprinkler	*** 1.25	*** 1.28
	(0.15)	(0.39)
Truck Gravity	*** 2.08	0.97
	(0.47)	(4.17)
Field Sprinkler	*** 1.95	*** 1.75
	(0.28)	(0.48)
Constant	-790.7	2170.94
	(1513.0)	(1572.1)
Number of obs.	936	936
R-sq	0.435	0.357

Numbers in parentheses are standard errors. Both sets are clustered by section, and the robust IV standard errors are calculated using bootstrapping.

Table 11: Estimated Direct and Indirect Water Demand Elasticities

	Direct Elasticity	Indirect Elasticity	Total Elasticity
OLS Estimation	** -0.221	0	** -0.221
	(0.090)		(0.090)
IV	*** -0.381	-0.542	-0.912
	(0.103)	(1.71)	(1.65)

Numbers in parentheses are the bootstrapped standard errors of the estimates.

Table 12: Water Saving Capacity of Precision Irrigation

		Citrus	Grape	Deciduous	Truck
OLS	Gravity - Drip	*** 1.42	** 0.65	0.49	na
		(0.48)	(0.27)	(0.71)	na
	Gravity - Sprinkler	na	na	0.33	*** 0.83
		na	na	(0.47)	(0.32)
IV	Gravity - Drip	0.61	0.25	1.01	na
		(12.7)	(0.82)	(0.85)	na
	Gravity - Sprinkler	na	na	-0.04	-0.31
		na	na	(4.04)	(3.78)

Numbers in parentheses are the bootstrapped standard errors of the estimates.

Table 13: Comparison of Water Use per Acre Estimates with Cost and Return Studies (University of California)

OLS	Citrus	Grape	Deciduous	Truck		Field
Drip	3.70	3.33	4.38	na		na
Gravity	5.12	3.98	4.86	4.12		na
Sprinkler	na	na	4.54	3.28		3.99
IV	Citrus	Grape	Deciduous	Truck		Field
Drip	3.91	3.51	4.26	na		na
Gravity	4.52	3.75	4.39	3.61		na
Sprinkler	na	na	5.30	3.92		4.38
Cost and Return Studies	Oranges	Grapes	Almonds	Tomatoes	Potatoes	Cotton
Drip	2.50	2.00	4.30	na	na	na
Gravity	na	3.50	5.10	3.00	na	3.00
Sprinkler	na	na	na	2.50	4.00	na