Farm Level Irrigation Technology Decisions over Time

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A time-series cross-sectional model of irrigation technology choice is developed for an irrigation district in California's Central Valley to show how changes in the relative price of irrigation water and variations in water supply over time influence the choice of irrigation system. Results indicate changes in crop mix and variations in water supply are at least as important as price in determining the choice of irrigation system.

Key words: irrigation, water policy

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Introduction

Price can play a significant role in promoting conservation of irrigation water, and conservation pricing of water has become a major policy tool for the United States Bureau of Reclamation (USBR, 1997). However, the effects of a price change on irrigation water use are multi-faceted and may not lead to reductions in physical water use. This is due to differences between water application rates at the extensive and intensive margins. Specifically, while increasing the price of irrigation water initially may encourage irrigators to reduce water applications – an intensive margin response – changes at the extensive margin, such as adjustments in acreage levels, crop selection, and irrigation technology, may enforce or counteract initial reductions in water applications.

Chief among potential responses are adjustments in irrigation technology. Irrigation water demand is typically inelastic and not substitutable in production (Nieswiadomy, 1988; Ogg and Gollehon, 1989). Sunding et al. (1997) confirmed the rigidity of irrigation water in agricultural production and showed that irrigators' primary response to water scarcity and drought is taking land out of production, rather than adjustments in water application rates. Given the rigidity of water applications and the importance of fallowing as an irrigator's response to rising water costs, changes in irrigation technology become one of the most important responses by irrigators to rising water prices.

When and how irrigators adopt new irrigation technology has been studied both theoretically and empirically. The primary factors influencing technology adoption decisions are water price and land quality. Caswell and Zilberman (1986) showed theoretically that the adoption decision is affected by well depth (i.e., water price), land quality, and crop type. Cason

and Uhlaner (1991); Wichelns, (1993); Caswell and Zilberman (1985); Green et al. (1996); Negri and Brooks (1990); Nieswiadomy (1988); and Schuck and Green (2001) all support Caswell and Zilberman's theoretical results. Unfortunately, all of this research on irrigation technology adoption focuses on spatial rather than temporal variations in price. This is due largely to the lack of adequate panel data describing irrigation technology choices. As a result, most applied research substitutes time invariant measures of land quality for non-water prices. This leads to irrigation technology choice models that are primarily a function of constant physical attributes rather than relative prices over time. Substitution of field attributes for prices means existing irrigation technology choice models may not adequately capture the extent to which changes in irrigation water price over time leads to extensive margin adjustments in acreage levels and irrigation technology.

The present research extends existing irrigation technology adoption models by developing a model of on-farm irrigation technology choice that recognizes both spatial and temporal variations in water price. The research proceeds by first developing a theoretical model of irrigation technology. This adoption model is conditioned on cropping patterns that are, in turn, conditioned on the relative prices of water and other inputs. The model is applied to time-series cross-sectional data on both irrigation technology choice and acreage allocations for an irrigation district in California's Central Valley.

Background

The amount of water the i-th irrigator applies to the k-th crop is denoted AW_{ik}, which also depends on the type of irrigation system used and the cost of water. For the i-th irrigator, the technical efficiency of their irrigation system (the proportion of applied water which is actually

transmitted to the crop for consumption by the plant) under the j-th type of irrigation system is denoted d_{ij}. If the consumptive water demand of the k-th crop type is EW_k, which relates to AW_{ik} as:

$$(1) \qquad AW_{ijk} = \frac{EW_k}{d_{ij}},$$

which simply shows that the amount of water that must be applied to a crop is the consumptive requirements of the crop inflated by the technical efficiency of the farm's irrigation system.

In the short-run, irrigators will adjust water application rates in response to a change in water price while holding irrigation technology constant. Consequently, the impact of a change in water price on AW_{ik} by differentiating (1) with respect to the price of water r, as follows:

$$(2) \qquad \frac{\partial AW_{ijk}}{\partial r} = \frac{1}{d_{ij}} \frac{\partial EW_k}{\partial r}.$$

Equation 2 shows that the change in water application rates due to a change in surface water price will be the change in the marginal water consumption of the crop weighted by the technical efficiency of the irrigation system. This change in applied water is usually considered to represent water conservation.[1] While (2) shows the marginal reductions in water application rates, it is important to realize that this change hinges on the change in crop consumptive demand known as "water-stressing," which is generally constrained by plant physiology.

As mentioned previously, most existing research suggests water price has little impact on crop water demands and that (2) tends to be relatively inelastic. Changes in irrigation efficiency are critical to evaluating irrigators' responses to water price changes. If crop water demands, as measured by EW_k, are nearly constant and irrigators do not cease production, the only means by which reductions in applied water can be achieved is if rising water prices promote adoption of improved irrigation technology, reducing water losses and the costs of production.

To examine the effect of a new irrigation technology, we assumed that EW_k is the same for each irrigation technology and that each irrigation system is being managed as efficiently as possible. If rising water prices promote movement from the k-th irrigation technology to the relatively more efficient l-th irrigation technology, AW_{ik} will decline by the efficiency difference between the two technologies. Denoting the change in applied water as ΔAW_{ik}, water conservation is given by:

$$(3)\ \Delta AW_{ik} = \left(\frac{1}{d_l} - \frac{1}{d_k} \right) * EW_k$$

In this case, water conservation is achieved by improving irrigation technology efficiency, not by water-stressing. This implies that the water conservation effects of a price change are felt primarily through technological change. In this case, analysis of changes in water pricing policy requires determining the degree to which water price encourages adoption of more efficient irrigation technologies.

However, it is important to note that not all irrigation systems are compatible with all crops. Some fields and crops are physically incompatible with certain irrigation systems. This inability to combine certain fields and crops with some irrigation systems limits the choices an irrigator can make and is an example of asset heterogeneity (Bellon and Taylor, 1993; Perrin and Winkelmann, 1976). Asset heterogeneity plays a significant role in irrigation technology choice by limiting the types of systems an irrigator can use (Green et al., 1996).

Crop water consumption is dependent upon crop selection, which is dependent upon the physical characteristics of a field. However, physical field characteristics do not vary over time, and their effects are difficult to capture relative to prices that do vary over time. Consequently, reflecting asset heterogeneity requires including an explanatory variables that adequately reflects

the physical constraints of a field while varying over time. As mentioned previously, fallowing is a primary response by irrigators to water scarcity and rising water costs. Since crop selection will be limited by asset heterogeneity, including acreage can show the effects of asset heterogeneity while still using an explanatory variable that is not constant over time.

This research examines the technology adoption decision for gravity, sprinkler, and drip irrigation systems conditioned on the price of surface water and crop acreage using field-level data from the Arvin-Edison Water Storage District in Kern County, CA. Since the cost-effectiveness of a particular technology also depends upon the relative costs of related inputs, the prices for fuel, manufactured inputs, and fertilizer are also included. Consequently, the adoption function is conditioned on crop selection and the price of other relevant inputs. Use of other inputs and the use of time-series cross-sectional data on crop selection separates this research from previous work.

Empirical Model

Irrigators will choose whichever irrigation system is most profitable for their particular circumstances. The profits of crop production under the *k*-th irrigation technology for the *i*-th irrigator are π_{ij}. Profits under a given technology are a function of vector of crop acreage, *a*, and a vector of input prices, *w*. For a grower to adopt an alternative irrigation system the profits under the *l*-th technology must be at least as great as the *k*-th system:

(4) $\Delta\pi = \pi_{il}(a, w) - \pi_{ik}(a, w) > 0$

Further, for water pricing policy to encourage adoption of a more efficient irrigation system, changes in water price must increase the profit differential between the alternative technologies. Since different crops respond differently to different irrigation systems and because changes I the

price of one input price may promote substitution of other inputs, it is not possible to determine how changes in water price will affect the profit differential theoretically a priori and these effects must be determined empirically.

The grower is assumed to maximize expected profits by selecting the irrigation technology with the highest perceived profits, given by:

(5) $\pi_{ik}(a,w) = f_{jk}(a, w) + \varepsilon_{ik}$.

were $f_{ij}(a, w)$ is a deterministic function of crop selection and input prices (including the price of water) and ε_{ij} represents random errors and unmeasured attributes.

Equation 5 can be estimated through a discrete choice model. Estimating a discrete choice model will show the probability of adopting a given technology as a function of cropping patterns and input prices. In particular, if it is assumed that $f_{ik}(a, w)$ takes the form $\beta_k X_i$, where β_k is a vector of parameters associated with the k-th irrigation technology and X_i is a vector of observed crop selections and input prices representing a and w for the i–th irrigator and it is further assumed that the ε_{ik} 's are random independent variables following a Weibull distribution, the distribution of the difference between the ε_{ik} 'sis logistic (Domencich and McFadden, 1975). In that instance, equation 5 reduces to a multinomial logit. In the present research, the model represents the choice between three alternative irrigation systems and is a function of crop selection and input prices over time.

Irrigation technologies fall into three general categories: gravity-based, such as furrow or flood; high-pressure, such as conventional sprinklers and linear move or pivot systems; and low-pressure, such as drip or fan-jets. Low-pressure irrigation systems generally require less water than either high-pressure or gravity-based irrigation systems and are consequently viewed as the most efficient. High-pressure systems are viewed as being the next most efficient technology,

with gravity systems considered the least efficient. However, this ranking does not always hold as a rule. As mentioned previously, not all crops are compatible with all irrigation systems. As a result, for some crops a gravity system can be nearly as efficient as any other system. Additionally, profitability will ultimately determine what type of irrigation system a particular irrigator uses, even if this means adoption of a technically less efficient but lower cost system. Gravity systems are the base irrigation technology. Typically, rising irrigation water prices will prompt movement away from gravity-based irrigation systems toward either high pressure sprinklers or low pressure drip systems.

Since the base technology was generally chosen in a time period outside the current period of analysis, the probability of adopting the base technology is indeterminate. The customary solution to this problem is to normalize the b_0 (the coefficients for gravity irrigation systems) to zero. Under this specification, the probability that the k-th irrigation technology is adopted by the i-th irrigator is given by[2]

$$(6)\quad P_{ik} = \frac{e^{X_i B_k}}{\sum_k e^{X_i B_k}} \; ; k = 1, 2, 3, \ldots, K.$$

The irrigation technology adoption model developed here is applied to the Arvin Edison Water Storage District (Arvin) in Kern County, CA. Arvin is a relatively small and junior irrigation district. Irrigated production began in Arvin at the beginning of the twentieth century, and most of the irrigation water used at that time came from ground water. Heavy dependence on ground water led to significant overdraft of the aquifer. As a result, Arvin was created in 1942 with the express purpose of bringing surface water from the Central Valley Project to Arvin and reducing overdraft of the aquifer.

Arvin manages a conjunctive use system with highly variable water supplies and on-farm

wells are a critical part of Arvin's water management strategies. Since first receiving surface water deliveries in 1966, the District has seen supplies range from a low of 36 thousand acre-feet (kAF) to a high of 376 kAF. The District experiences drought conditions of varying severity 45% of the time.

Arvin is divided up into two different regions, the Surface Water Service Area (SWSA) and the Ground Water Service Area (GWSA). Growers in the SWSA receive water from Arvin through a series of surface water canals. These canals are subdivided into 6 separate pumping zones differentiated by elevation. The price of surface water from Arvin varies with these pumping zones and irrigators receiving water at higher elevations pay a higher price for water. Growers in the GWSA cannot receive deliveries from the District and must rely instead on on-farm wells for irrigation water and are omitted from this study.

Irrigation water price is a major policy tool in Arvin. In response to USBR pricing initiatives, Arvin abandoned a contract-quantity based allocation system in favor of a price based allocation system in 1995, leaving surface water price as their primary control over surface water use. Arvin does still encourage growers to use surface water first and maintain ground water levels by setting the volumetric component of the surface water rate below the pumping cost of growers. However, a key feature of the 1995 contract change was the adoption of drought-contingent pricing as a policy tool. The District defines drought-contingent pricing as a price that rises and falls with imported surface water supplies. Current District plans are to raise or lower the price of surface water by the change in marginal delivery costs attributable to drought (or flood) conditions.

There is a wide variation in irrigation technologies, water prices and crops within the District. The analysis focuses mainly on citrus, deciduous, truck, and vine crops. These are the

standard crop classifications used by the District, and these crops account for over 78% of the irrigated acreage in the District and have significant variation in observed irrigation technologies. Most of the remaining irrigated acreage is made up of cotton. Cotton was omitted since it is irrigated almost exclusively with high-pressure irrigation systems. District employees collected data on irrigation technology, field size, and water price for their annual crop reports. Input prices came from data series maintained by the National Agricultural Statistics Service. This analysis is based on data from the post-1995 contract change water years and relies on field-level irrigation technology and cropping patterns for 1997-2000. Acreage, irrigation technology, and input price data are summarized in Table 1.

To measure the effects of input and water prices on irrigation technology choice over time, a multi-nomial logit model was estimated for each of the four crop categories. The analysis uses four continuous variables: crop acreage in the field, the price of fuel, the price of manufactured inputs, and the price of fertilizer. All input prices are taken from National Agricultural Statistics input price series for California's Central Valley and are expressed as a ratio relative to the price of surface water. Consequently, the effects of water price appear in the adoption model relative to other inputs. Gravity irrigation is the benchmark technology, with high-pressure sprinklers being the next choice, followed by low-pressure drip irrigation systems. Estimation is carried out using the LIMDEP econometrics software, and the results for each crop and each irrigation system are reported in Table 2.

Estimation Results

The multinomial logit results for each crop and each irrigation system are reported in Table 2. The log-likelihood ratio test, given by $2(L\Omega - L\omega)$ and asymptotically distributed as a chi-

squared random variable, is reported since qualitative choice model do not have a single reliable measure of model fit (Maddala, 1987). As the chi-squared statistics show, all of the multinomial logit models are significantly significant and regressions exist. However, examination of the individual slope coefficients shows that relatively few of the individual parameters are statistically significant. This is a sign of multi-collinearity, and is a common problem in time-series models across relatively narrow cross-sections.

While the parameters are not statistically significant, they are unbiased and do provide useful information regarding the role of surface water price in irrigation technology. The coefficients show the relative affect of surface water price on choosing sprinkler or drip irrigation systems choice relative to gravity irrigation for citrus, deciduous, truck and vine crops in the District. It is important to note that relative to the other input prices, the effects of surface water price may increase or decrease the likelihood of adopting a more efficient irrigation system. This suggests that while higher water prices over time may promote adoption of more efficient irrigation systems, changes in the relative prices to technical compliments and substitutes to water may increase or decrease the effects of price. For example, while the price of surface water has a positive effect on the adoption of sprinklers for irrigators growing citrus crops relative to the prices of fuel and manufactured inputs, it has a negative effect relative to the price of fertilizer. As a result, the technology effects of changes in the price of surface water price over time may be increased or decreased by the relative changes in the prices of other inputs.

The coefficients of the multinomial logit models do not directly measure the marginal effects of surface water price on the probability of adopting each irrigation technology. Since the price of surface water is expressed relative to other input prices, the probability of adopting each

irrigation system at alternative water prices are shown for each of the four crop groups in figures 1 through 4.

As the figures show, higher surface water prices generally move irrigators away from gravity systems toward more efficient drip systems. However, the rate at which this transition occurs varies by crop. In particular, while irrigators growing citrus crops appear to move directly from gravity-based irrigation to drip systems at higher water prices, irrigators growing deciduous crops move to both sprinklers and drip systems. For deciduous crops, the transition to drip systems occurs only at relatively higher water prices.

The combination of the mixed effects of surface water price relative to other input prices and the difference in adoption rates across crops suggests that the influence of surface water price on adoption of alternative irrigation systems is not uniform. While the results suggest higher surface water prices over time may promote adoption of more efficient irrigation systems, crop type and the prices of other inputs may increase or decrease these effects. This suggests water pricing policy should account for both other prices and regional crop coverage before adoption of conservation pricing policies.

Conclusions

The effects of surface water price on the adoption of alternative irrigation systems over time vary relative to the prices of other inputs. Additionally, surface water price influences each crop type differently. Previous research, notably Green et al. (1996) and Schuck and Green (2001), observed that the effectiveness of surface water price varied over space. The current research suggests that the effectiveness of surface water price as a conservation tool will also vary over time, particularly when the prices of other inputs are varying. Since the possibility exists for

limited technical substitution across inputs, the mixed effects of surface water price on adoption of alternative irrigation systems relative to other prices suggests that surface water price is an effective policy tool, but which by no means is flawless.

Table 1: Crop Acreage in Arvin Edison Water Storage District and Percentage of Each Crop under Three Types of Irrigation

	Average Acres:	Average Field Size:	% in Gravity/Furrow	% in Sprinkler	% in Drip
Citrus	9990	61	7.36%	0.31%	92.33%
Deciduous	5369	58	34.24%	18.75%	47.01%
Truck	13134	58	15.81%	80.15%	4.03%
Vineyard	11127	69	35.81%	0.78%	63.41%
All Crops	50705				

Average Prices		Units
Pfuel	16.83	$/ac
Pmanuf	102.63	$/ac
Pfert	28.35	$/ac
Water	57.93	$/af

Table 2: Multinomial Logit Results for Irrigation System Adoption

CROP:	SYSTEM:	*Sprinkler*		*Drip*	
		Coefficient	t-ratio	Coefficient	t-ratio
Citrus	Constant	-3.37	-0.60167	-3.5614	-3.09502
	Acres	-0.00264	-0.24095	-0.00122	-0.54723
	ps/pfuel	2.8909	0.361042	0.274747	0.253694
	ps/pmanuf	7.0195	0.136455	-18.6918	-1.58488
	ps/pfert	-6.82883	-0.63516	7.65536	3.62639
		chi-squared = 38.28	d. of f.	8	
		n = 652			
Decidous	Constant	-3.49361	-2.78473	-5.84841	-5.47219
	Acres	0.000741	0.288991	0.001453	0.696323
	ps/pfuel	1.58435	1.406265	-0.92188	-0.99912
	ps/pmanuf	-13.4909	-1.08471	4.01303	0.39237
	ps/pfert	2.55001	1.152807	3.58416	2.038413
		chi-squared = 45.44	d. of f.	8	
		n = 368			
Truck	Constant	0.12212	0.203527	-2.8253	-2.34632
	Acres	0.004579	1.843559	0.002584	0.538556
	ps/pfuel	0.059006	0.094676	-0.81998	-0.64438
	ps/pmanuf	1.69673	0.23792	-0.52613	-0.03369
	ps/pfert	0.04049	0.034073	2.14321	0.828007
		chi-squared = 14.28	d. of f.	8	
		n=917			
Vineyard	Constant	-9.40641	-2.92892	0.470585	0.828848
	Acres	-0.00743	-0.85136	-0.00544	-4.01241
	ps/pfuel	-5.42746	-1.45444	0.732397	1.195739
	ps/pmanuf	41.4786	1.00304	-13.4691	-1.92513
	ps/pfert	0.555436	0.093363	2.7746	2.312608
		chi-squared = 32.61	d. of f.	8	
		n=645			

Figure 1: Probability of Drip Irrigation Adoption for Citrus Crops in California's Central Valley at Alternative Water Prices

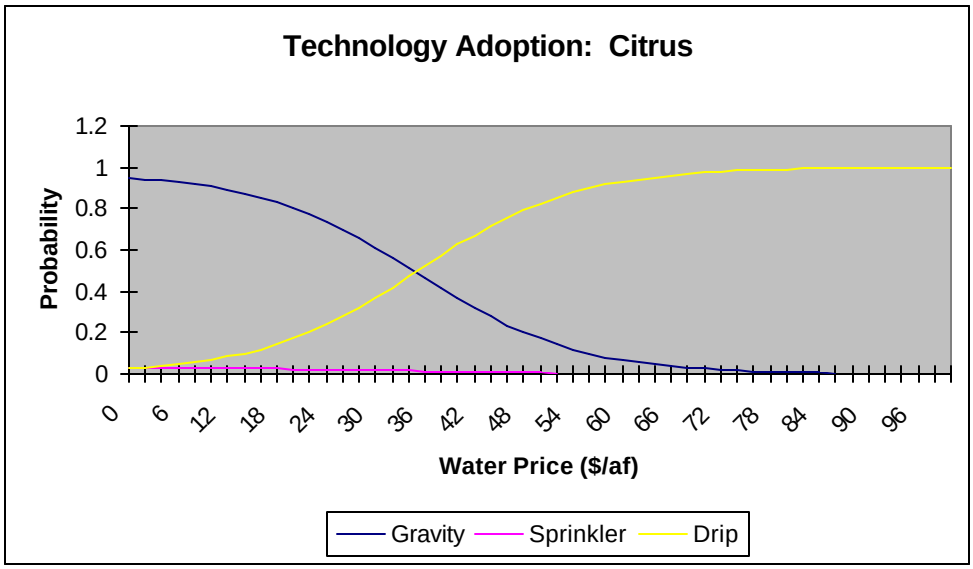


Figure 2: Probability of Drip Irrigation Adoption for Deciduous Crops in California's Central Valley at Alternative Water Prices

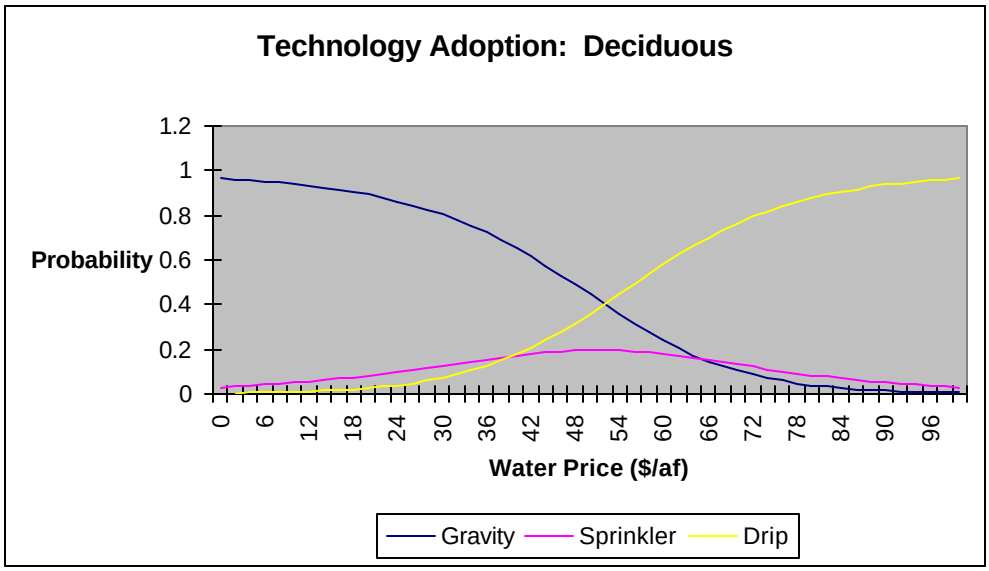


Figure 3: Probability of Drip Irrigation Adoption for Truck Crops in California's Central Valley at Alternative Water Prices

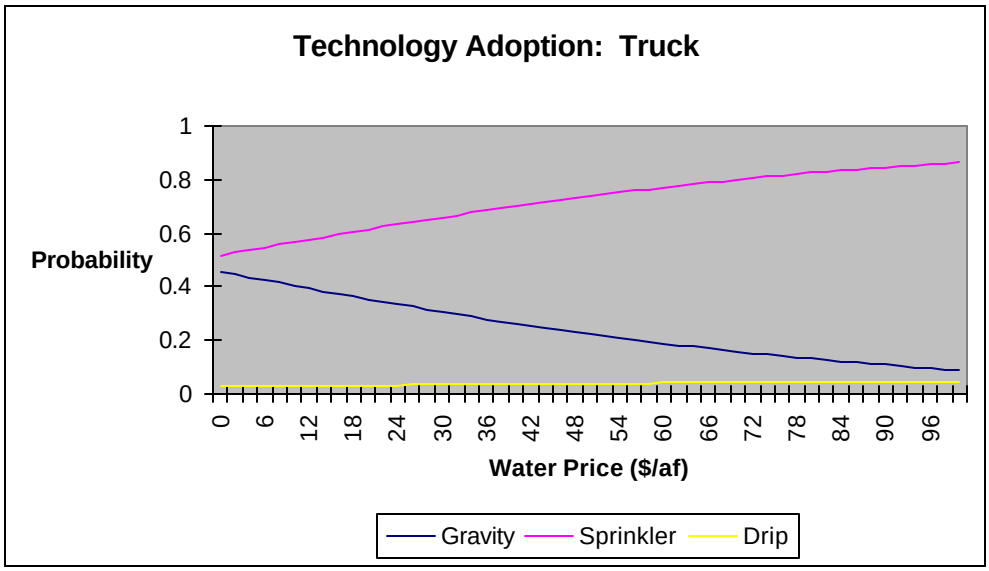
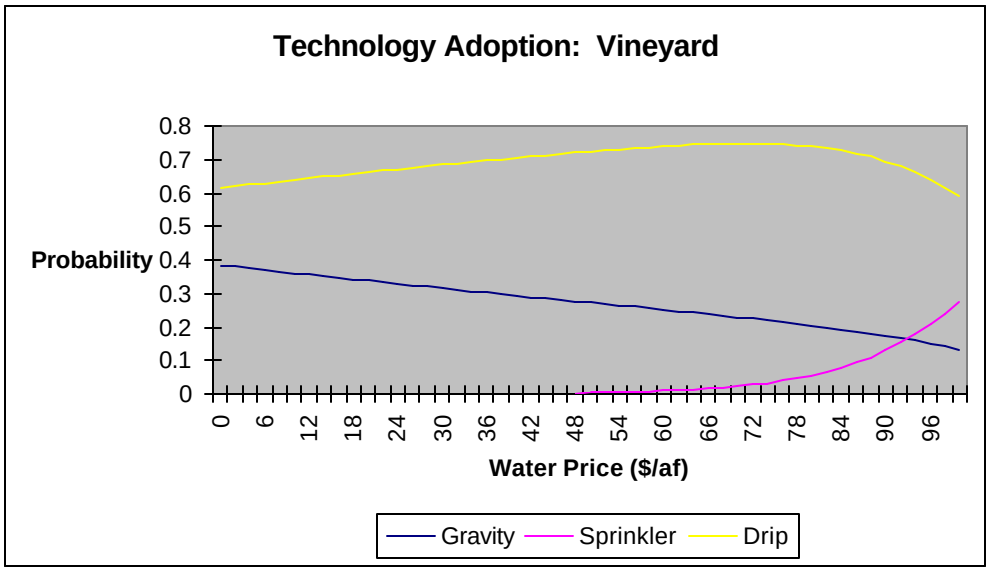


Figure 4: Probability of Drip Irrigation Adoption for Vineyards in California's Central Valley at Alternative Water Prices



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[1] It is important to distinguish between on-farm conservation and basin-wide conservation. For a basin, reductions in on-farm water applications may not lead to basin-wide conservation, particularly if other irrigators rely on return flows for their irrigation water. See Huffaker et al. (1998) or Green and Hamilton (2000) for a more detailed discussion.

[2]. Amemiya and Nold (1975) showed that this specification of the logit is efficient only if all relevant parameters are included in the X matrix. Omission of a critical variable from the X matrix leads to estimates of *b* that are inefficient. Amemiya and Nold suggest using a panel data set to correct for specification error. Existing research does not follow this recommendation and this problem is the motivation for this research.