Crop-specific Irrigation Choices for Major Crops on the West Coast: Water Scarcity and Climatic Determinants

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Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2012 AAEA Annual Meeting, Seattle, Washington, August 12-14, 2012.

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Recent climate change forecasts have aroused growing interest in the influence of climate and water scarcity on agricultural production and irrigation practice. However, it is common in the economic literature to aggregate disparate crops when modeling irrigation choices. That approach confounds the crop-specific effects of climate and water scarcity that govern such choices. This paper addresses the impact of climate and water scarcity on irrigation choices through estimated models of cropland proportion irrigated (PI), and crop-specific irrigation technology choice (TC) and water application rates (AR). This approach is applied to agricultural production data for major crops (orchard/vineyard, vegetable, wheat, alfalfa, hay, and pasture) on the West Coast (California, Oregon, and Washington). Implications for agricultural water policy and how irrigators would respond and adapt to future climate change are discussed.

Keywords: irrigation choices, crop-specific modeling, climate, water scarcity, asset heterogeneity

The West Coast depends on snowpack that is mainly in the Sierra Nevada and Cascade Mountains for a portion of its dry season water supply. Climate warming over the latter half of the 20th century caused snowpack in the Cascade and northern Sierra Nevada Mountains to diminish more rapidly than any other region in the western United States, with some areas having declines in excess of 75% (Mote et al. 2005; Mote 2006). Accelerated snowmelt on the West Coast over the last half century has caused runoff to occur earlier, with increased streamflows during the wet season and decreases in the dry season (Chang et al. 2012; Mayer and Naman 2011). If climate warming proceeds, dry season water scarcity will intensify for two reasons. Firstly, diminished dry season streamflows will reduce available water for diversion (Elsner et al. 2010). Secondly, with greater wet season streamflows, many reservoir ‘rule curves’ will mandate the release of water to hedge against winter flood risk and this will reduce water stored for dry-season uses (Hayhoe et al. 2004).[2]

Several cultural factors will contribute to future water scarcity. Competition for water may intensify from burgeoning urban populations (Kummu et al. 2010) and income growth (Taylor and Young 1995). Interests that seek to increase biological flows for restoration purposes (Burke, Adams, and Wallender 2004) or rectify outstanding Native American water claims (Moore 1989) may heighten competition for water in the future. The Reclamation Reform Act of 1982 replaced the United States Bureau of Reclamation’s (henceforth, “Bureau”) mission of water resource development with an explicit mandate for water resource conservation (Moore 1991). These factors are expected to coalesce with accelerating snowmelt patterns on the West Coast and result in curtailed agricultural water deliveries (Vano et al. 2010) or transfers of agricultural water to higher-value uses (Purkey et al. 2008).

Climate change is also anticipated to impact the productivity and quality of agricultural commodities (Jackson et al. 2011). Adapting irrigation practice is a primary mechanism for irrigated agricultural systems to cope with changing water scarcity and climatic conditions (Howden et al. 2007). Primary adaptations include altering the total amount of irrigated land, adopting water-saving irrigation technologies, and adjusting AR for specific crops.[3,4] Sunding et al. (1997) showed that irrigators' primary response to short-lived water scarcity is to take land out of production. Greater well depth (Caswell and Zilberman 1986) or water price (Moreno and Sunding 2005) has been found to facilitate the adoption of water-saving technologies. Carey and Zilberman (2002) demonstrated theoretically that water scarcity increases the "hurdle rate" needed to induce adoption and farms wait until random events such as drought drive returns significantly above costs before investing in water-saving technologies. Moore et al. (1994) showed that irrigators adjust AR among crops in response to climatic conditions. Given the sensitivity of agricultural production to water scarcity and climate, understanding their influence on irrigation choices is a key contribution to policy evaluation.

Economists have endeavored to explain irrigation choices for the past half-century (Moore and Hedges 1963). The water scarcity and climatic determinants of irrigation choices have been investigated empirically (Schoengold, Sunding, and Moreno 2006) and theoretically (Caswell and Zilberman 1986). The literature has explored how irrigation choices are affected by physical water scarcity, as measured by well depth (Caswell and Zilberman 1986), groundwater saturation thickness (Albrecht 1990), water salinity (Dinar, Campbell, and Zilberman 1992), and whether irrigation water was discontinued long enough to affect yields (Moore et al. 1994).

Some irrigation choice studies model the effects of temperature (e.g., Shoengold, Sunding, and Moreno 2006), precipitation (e.g., Nieswiadomy 1985), or both (e.g., Dinar, Campbell, and Zilberman 1992). Others have used regional approaches to capture the influence of climate on irrigation choices (e.g., Ogg and Gollehon 1989). Dinar, Campbell, and Zilberman (1992) theorized that the irrigation efficiency of particular irrigation technologies is influenced by climate, which was supported by their empirical results.[5] However, the economic literature has not investigated if the effects of climate on irrigation choices are non-linear. Furthermore, the economic literature has failed to explicitly identify how climatic stress factors, such as heat stress and frost damage, affect irrigation choices.

Climate has been demonstrated to have non-linear affects on agricultural yields (Schlenker and Roberts 2008) and crop-choice (Seo and Mendelsohn 2008; Moreno and Sunding 2005). For example, Schlenker and Roberts (2008) demonstrate that yields increase in temperature until about 84°F for corn, 86°F for soybeans, and 90°F for cotton, but temperatures above these thresholds become very harmful. They find that the slope of the decline above the optimum is significantly steeper than the incline below it. Because irrigation choices are often made to adapt to changing climatic and water scarcity conditions

(Howden et al. 2007), it is reasonable to assume that irrigation practices will provide climate adaption services at diminishing rates.

Heat stress can reduce the productivity and quality of all the major West Coast crops. Above-canopy sprinkler irrigation technologies can mitigate heat stress by providing evaporative cooling of crops and their surrounding microclimates (Appendix 1). Evaporative cooling provided by sprinklers has been reported for multiple orchard and vineyard crops, including grape (Pitacco, Giulivo, and Iacono 2000), apple (Iglesias et al. 2002), Navel oranges (Brewer et al. 1977), avocado (Miller, Turrell, and Austin 1963), pear (Lombard, Westigard, and Carpenter 1966), and plum (Gay, Stebbins, and Black 1971). Evaporative cooling by sprinkler irrigation has also been demonstrated for several vegetables, such as potato, bush bean (Hobbs 1973), onions (Wright, Stevens, and Brown 1981), and corn (Cavero et al. 2009). Wheat (Liu and Kang 2006) and alfalfa (Robinson 1970) have benefited from evaporative cooling provided by sprinkler irrigation also.

In the hot and humid southeastern United States, evaporative cooling of pastured dairy cows (and other livestock) is often provided by queuing livestock through shaded environments (e.g., cooling barns, milking parlors, feeding pins, or ventilation tunnels) equipped with sprinklers, fans, swamp coolers, or some combination of these (Kendall et al. 2007; Smith et al. 2006). Cooling cows with sprinkler irrigation in open pasture may be an alternative in the less humid western United States. Outdoor cooling ponds are another method used to alleviate heat stress in pastured dairy cows (Fike et al. 2002). The agronomic literature does not report that certain irrigation technologies are used to mitigate heat stress to hay.

Frost damage can diminish the productivity and quality of fruits, nuts, and vegetables.[6] Crop frost damage can be mitigated by using above-canopy sprinkler irrigation technologies.[7] Sprinkler irrigation has been reported to mitigate frost damage to a wide range of orchard and vineyard crops, including grape, apple (Evans 1999), almond (Micke and Kester 1998), black walnut (Beineke 1978), plum (Lakatos et al. 2010), apricot (Hewett and Hawkins 1968), cherry, and peach (Tsipouridis, Thomidis, and Xatzicharisis 2006). Sprinklers have also been an effective means of mitigating frost damage to many vegetables, such as artichokes, lettuce (Robinson 1971), tomatoes, beans, cucumbers, squash, peppers, peas, broccoli (Kidder and Davis 1956), and potato (Wallis et al. 2011). The ability of sprinkler technologies to mitigate crop frost damage is acknowledged in the TC literature (Negri and Brooks 1990; Moreno and Sunding 2005), but the influence of frost-risk on irrigation choices has never been explicitly tested.

Different crops have different climate susceptibilities and varying thresholds where stress is incurred (Rötter and van de Geijn 1999). Crop-specific modeling offers a means for identifying these susceptibilities and estimating their effect on irrigation choices. There are rare examples where water demand or TC for multiple crops is estimated using crop-specific modeling. The advantage of studies that estimate multiple crop-specific models is that it allows comparison across crops of the factors that influence irrigation choices. Moore, Gollehon, and Carey (1994) and Adusumilli, Rister, and Lacewell (2012) demonstrate that water demand for different crops respond differently to climate. Green and Sunding (1997) show that for different crops land quality and water price do not affect TC in the same manner. Green and Sunding (1997) conclude that the distribution of water policy impacts depends on prior land allocation decisions (i.e., crop choices). This result supports the finding that asset heterogeneity is critical in the study of technology adoption (Bellon and Taylor 1993; Perrin and Winkelmann 1976).

Heterogeneity is a vital component of the threshold model of diffusion (Stoneman and Ireland 1986). An example of asset heterogeneity is the incompatibility between certain irrigation technologies and field types or cropping patterns (Schuck and Green 2001). Most diffusion models of agricultural technologies focus on heterogeneity in farm size (Perrin and Winkelmann 1976) and land quality (Bellon and Taylor 1993; Green and Sunding 1997; Green et al. 1996). However, incompatibility between certain irrigation technologies and cropping patterns can arise from heterogeneity in the climate asset. For example, in regions with susceptibility to late spring or early fall frost events, orchards and vineyards may be incompatible with gravity and drip irrigation technologies because they cannot be used to mitigate frost damage (Evans 1999).

The following section presents the conceptual framework and econometric techniques used for estimating the empirical models. After describing the data, the econometric estimates of the behavioral equations are presented and discussed. We then discuss implications for the design of agricultural water policy and how irrigators would respond and adapt to future climate change. We conclude by summarizing the results, policy implications, and insights for irrigated agriculture under climate change.

Empirical Models

Conceptual Framework

Conceptualize a West Coast agricultural landscape comprised of farms that irrigate at least one of the regions' six major crops. The irrigator is assumed to make irrigation choices that yield the highest perceived profit. Choices made by the irrigator are cropland proportion irrigated (PI), and crop-specific irrigation technology choices (TC) and water application rates (AR). To investigate how climate, water scarcity, and other factors influence irrigation choices, empirical models of PI, TC, and AR are developed. All of the estimation is conducted as single-equation regressions with a similar set of independent variables across equations. These procedures result in 13 estimated equations, one PI equation and six crop-specific equations for both TC and AR. Whether the factors influencing TC or AR differs across crops can be tested statistically through comparisons of behavioral equations across crops.

The profitability of irrigation choices depends on farm-level water scarcity, in both physical and economic terms (Moore, Gollehon, and Carey 1994). Climate is expected to affect irrigation choices (Dinar, Campbell, and Zilberman 1992), as are geographic qualities of the farm (Caswell and Zilberman 1986). For example, Caswell and Zilberman (1986) showed theoretically that water-saving irrigation technologies, or "land quality augmenting technologies", tend to be adopted on poorer quality soils. Institutional arrangements (Moore 1999) and demographic characteristics of the farmer (Khanna 2001) are expected to impact irrigation choices as well. For example, Khanna (2001) found that computer use enhances farmers "innovativeness and technical ability" and increases the likelihood that water-saving technologies will be chosen.

The vector of water scarcity variables affecting irrigation choices is denoted by **S**, and includes variables indicating the price of surface water, well depth, population density, and whether irrigation water was discontinued long enough to affect yields. In addition to the surface water price, two interaction variables are included in **S** to control for the effects of institutional arrangements (Moore 1999) and water supply source on price responsiveness (Green and Sunding 1997). A variable indicating if surface water was only supplied by federal agencies comprises the institutional vector **I**. The vector **D** contains the demographic characteristics of the irrigator. Demographic characteristics denote whether the irrigator is a land owner, whether they have internet access, whether farming is their primary occupation, and their years of experience on the farm.

Climatic factors that affect irrigation choices are represented by the vector **C**. The climatic factors influencing irrigation choices depend on the crop and type of irrigation choice being made. A variable indicating whether the farm is located in a drought region is included in all behavioral equations. Annual maximum temperature, annual precipitation, and their squares are included in all behavioral equations aswell. For the crop-specific TC and AR equations, a variable indicating whether the farm used irrigation to mitigate heat stress is also included in the vector **C**. A variable denoting whether the farm used irrigation to mitigate frost damage is included in the vector **C** for the orchard/vineyard and vegetable TC and AR equations only.

Geographic conditions that affect irrigation choices are represented by the vector **G**. The variables that constitute **G** will depend on the crop and type of irrigation choice being made. Variables denoting land quality, farm-scale, and whether the farm is only supplied with surface water are included in all estimated equations. Several studies show that the presence of dairy cattle has important implications for water use in pasture operations (Kendall et al. 2007; Fike et al. 2002). Therefore, in the PI and pasture TC and AR equations, a variable indicating whether the farm had dairy cattle is included in the vector **G**. For the crop-specific AR equations, binary variables indicating the primary irrigation technology used for that crop are included in the vector **G**. Conditioning AR on TC controls for the differing irrigation efficiencies of each technology (Hanemann et al. 1987; Negri and Hanchar 1989). We hypothesize that crop-specific TC will be dependent on the TCs of other crops on the farm because some irrigation technologies are mobile, which permits sharing of technologies between crops.[8] A variable denoting the crop diversity of the farm, as measured by the number of major crops irrigated on the farm, is included in the vector **G** for all TC equations to test this hypothesis.

Moore, Gollehon, and Carey (1994) demonstrated that irrigated land allocations for various crops are influenced by climate and water scarcity differently. Thus, PI is conditioned on crop choice by including binary variables in the vector **G** that indicate the crop portfolio of the farm. The crop choice decision simply involves a binary choice for the irrigator on whether to grow a particular crop. The decision depends on water scarcity, climatic, and geographic qualities of the farm, as well as institutional arrangements and demographic characteristics of the farmer. Rather than developing a formal model to be estimated, farm *j*'s choice for crop *k* is stated as:

$$\mathbf{b}_{jk} = f(\mathbf{S}, \mathbf{C}, \mathbf{G}, \mathbf{I}, \mathbf{D}) \tag{1}$$

where $j = 1,\ldots,J$;

k = orchard/vineyard, vegetable, wheat, alfalfa, hay, and pasture, respectively. In equation (1), $\mathbf{b}_{jk}$ is a binary choice variable equal to 1 if farm *j* cultivates crop *k* and equal to 0 else.

PI, TC, and AR for farm *j* and crop *k* (when applicable) are represented by the following equations:

$$\mathbf{PI}_{j} = h(\mathbf{S}, \mathbf{C}, \mathbf{G}, \mathbf{I}, \mathbf{D}); \tag{2}$$

$$\mathbf{TC}_{jk} = m(\mathbf{S}, \mathbf{C}, \mathbf{G}, \mathbf{I}, \mathbf{D}), \tag{3}$$

$$\mathbf{AR}_{jk} = l(\mathbf{S}, \mathbf{C}, \mathbf{G}, \mathbf{I}, \mathbf{D}), \tag{4}$$

Equations (2), (3), and (4) are estimated using agricultural production data for the states of California, Oregon, and Washington. Now that a conceptual framework for the empirical models has been provided, we are prepared to provide a fuller description of the models and econometric estimation techniques.

Econometric Estimation Techniques

PI is the proportion of irrigated acres to cropland acres.[9] There are a non-trivial number of farmers who irrigate all of their cropland, suggesting that the data is censored at 1. Econometric techniques not accounting for this data feature lead to biased and inconsistent parameter estimates (Maddala 1987).

Therefore, a Tobit model is used to estimate PI. Moore, Gollehon, and Carey (1994) used Tobit models to estimate irrigated land allocations among various crops. They termed these land allocations the crop-level "extensive margin" of water demand. PI is the *farm-level extensive proportion* of water demand.

We analyze discrete irrigation technology choices for each of the West Coast's six major crops. Irrigators choose from three types of irrigation technology: gravity, sprinkler, and drip. All three technologies are utilized by substantial numbers of orchard/vineyard and vegetable irrigators. Multinomial logit models are used to estimate TC for orchard/vineyard and vegetable. The vast majority of wheat, alfalfa, hay, and pasture irrigators (99%, 99%, 99%, and 98%, respectively) use either gravity or sprinkler technologies, reducing TC models for these crops to binomial logits. To remove indeterminacy in the TC models, all estimated equations use gravity as the benchmark technology. Multinomial (e.g., Schuck et al. 2005) and binomial logit (e.g., Green and Sunding 1997) have been used extensively to model discrete irrigation technology choices.

Crop-specific AR measures water application rates, the volume (acre-feet) of water applied to separate crops. All observations for AR are positive. AR is assumed to be a linear function of the independent variables (e.g., Moore, Gollehon, and Carey 1994; Ogg and Gollehon 1989). OLS is used to estimate the crop-specific AR models. OLS has been used previously to estimate water demand (Ogg and Gollehon 1989). Crop-specific AR is equivalent to Moore, Gollehon, and Carey's (1994) *crop-level intensive margins* of water demand. The crop-specific AR equations convey how water is allocated among crops in response to water scarcity, climate, and other factors.

The lin-lin functional form is used for all AR models, except for orchard/vineyard, which uses log-lin. There are two reasons why it is appropriate to use the log-lin functional form for the orchard/vineyard AR model. First, orchards tend to use much more water than vineyards (Blaney 1957; USDA 1982). Taking the logarithm of orchard/vineyard AR tightens this variation so that the data more closely resembles that of a homogenous crop. Second, water demand for different crops responds differently to the explanatory variables (Moore, Gollehon, and Carey 1994). This suggests that modeling the same process for different crops may be best achieved through different functional forms.

The price of surface water is assumed to be the marginal price of irrigation water. Irrigators with only access to groundwater were assumed to have a surface water price equal to the county-level mean surface water price. This is assumed to be the surface water price that irrigators would pay in local water markets. There are two variables in every estimated equation which will control for this convention: (1) a variable indicating if the farm only irrigated with surface supplies, and (2) that surface water supply variable interacted with surface water price. Variables that do not vary by farm in the cross-sectional dataset, such as crop prices, are not included in the irrigation choice models since they would be the same for each observation. Price variables with little cross-sectional variation, such as agricultural wage and energy prices, are not included in the irrigation choice models either.

Data

Cross-sectional microdata from USDA's 2008 Farm and Ranch Irrigation Survey (FRIS) and the 2007 Census of Agriculture are the primary data used to estimate the PI, TC, and AR models.[10] There are 1,461 farms in the USDA data for the states of California, Oregon, and Washington that irrigate at least one of the region's six major crops and use either gravity, sprinkler, or drip irrigation technologies. This group will henceforth be denoted as "irrigators". Irrigators represent 86% of all irrigated farms in the tri-state sample. Of the nearly 3 million irrigated acres in the tri-state sample, 80% is cultivated with the region's six major crops.[11]

Farms that solely irrigate with surface water comprise 47% of irrigators (Table 1). 80% of irrigators receive at least some water from surface supplies and 20% solely use groundwater. Farms cultivating only one of the six major crops represent 46% of irrigators, while multicrop production enterprises comprise the remaining 54% (Table 2). The data is evenly distributed across the tri-state study region. California houses 40% of irrigators, while Oregon and Washington house 29% and 31%, respectively.

Mean cropland proportion irrigated is 79% (Table 3). However, PI is negatively skewed, with 46% of irrigators irrigating all of their land. The most water-intensive crop, as measured by mean AR, is alfalfa and wheat is the least water-intensive. Sprinkler irrigation is more frequently used for wheat and alfalfa than for hay and pasture. Table 4 reveals that orchard vineyard and vegetable TC is dominated by drip and sprinkler technologies, respectively.

Secondary data sources are used to create variables that complement the USDA data. Long-term county-level climate data (1971-2000) was obtained from the Western Regional Climate Center. Temperature and precipitation variables were constructed from observation at 669 and 723 weather stations, respectively, across the 111 counties in the tri-state study region. Mean maximum temperature for irrigators in the tri-state study area is about 66°F and mean annual precipitation is approximately 19 inches (Table 1). The tri-state study region occupies a north-south transect spanning 1,500 miles and 17° of latitude, with substantial climatic influences introduced by the coast and Sierra Nevada, Cascade, and Wallowa mountains. The exceptional degree of climatic variation in the tri-state study region is useful for modeling the effects of climate on irrigation choices.

Regions identified by the National Drought Mitigation Center as experiencing severe to extreme drought in at least 10% of years over the last century (1895-1995) were used to denote "drought counties”.[12] Drought counties contain 64% of irrigators. The land quality variable was obtained from the 1997 Natural Resource Inventory. It measures the proportion of county-level cropland in Land Capability Classes (LCC) 1 or 2. LCC 1 and 2 indicate higher-quality cropland with relatively few use restrictions. County-level population density (2007) was assembled from population and land area data at the United States Census Bureau.

Estimation Results

Cropland Proportion Irrigated

Estimated marginal effects and estimation statistics for the Tobit PI model are presented in Table 5. Table 5 reports the number of observations, two statistical tests from the estimation results, and z-statistics to evaluate the performance of the model. Complete estimation results are included in Table A.2.1 (Appendix 2). The PI model has 1,461 observations, 670 (46%) of which are right-censored at PI=1. The McFadden R^2 is calculated as $R^2 = 1\text{-}L_{\Omega}/L_{\Phi}$, where L_{Ω} is the unrestricted maximum log-likelihood and L_{Ψ} is the restricted maximum log-likelihood with all slope coefficients set equal to zero (Maddala 1987). The log-likelihood ratio test is given by $2(L_{\Omega} - L_{\Phi})$ and is distributed as a chi-squared random variable. The log-likelihood ratio test indicates that the model has high statistical significance. More than three-fourths of the marginal effects in Table 5 are significant at the 10% level or better and more than half are significant at the 1% level of better (excluding the intercept).

The statistical results indicate that PI is highly dependent on water scarcity. The results show that for irrigators with federally supplied surface water, PI is responsive to surface water price. The negative effect of discontinued irrigation on PI confirms the finding that irrigators’ respond to short-lived water scarcity by taking land out of production (Sunding et al. 1997). Population density is also negatively associated with PI. There is greater competition for water in more densely populated areas (Kummu et al. 2010), which is more likely to result in curtailed agricultural water deliveries (Burke, Adams, and Wallender 2004) or voluntary transfers of water to higher-value uses (Taylor and Young 1995; Turner and Perry 1997). Therefore, the results suggest that the intense competition for water in more densely populated areas causes PI to decline. Drought is positively related with PI. This supports findings that agricultural water demand is greater under drought conditions (Wheeler 2008).

Results show that the effects of temperature on PI are more profound than the effects of precipitation. Temperature negatively influences PI at a decreasing rate, reaching a minimum at 60°F. In warmer regions that are above the temperature threshold, increasing temperature will increase the already high levels of evapotranspiration and soil desiccation (Dinar and Yaron 1990).[13] In these cases, PI is likely to increase because irrigation will be necessary for satisfying crop water needs. Below the threshold temperature, declining temperature will reduce the already low levels of evapotranspiration and soil desiccation. In these cases, water losses from evapotranspiration will be lower and fixed water supplies can be spread across a larger proportion of land.[14]

Precipitation positively influences PI at a decreasing rate, reaching a maximum at 38 inches of precipitation. Irrigation is used to supplement precipitation (Negri and Brooks1990; Finkel and Nir 1983). If irrigation is supplemental to precipitation, then as precipitation increases in dryer environments that are below the precipitation threshold, fixed water supplies can be spread across more cropland, increasing PI. In wetter environments, irrigation becomes increasingly unnecessary and rain-fed agriculture becomes increasingly feasible, causing PI to decline.

The statistical results show that institutional constraints and geographic factors are the most important determinants of PI. Farms with federal surface water supplies tend to have greater PI. The results also show that irrigators with only a surface water supply tend to have greater PI. Table 6 displays descriptive statistics for surface water prices by institutional provider and physical source. Mean surface water prices for irrigators with federal surface water supplies and for irrigators with only surface supplies were 29% and 42% lower, respectively, than prices for all irrigators. Irrigators typically respond to lower water prices by increasing the quantity of water demanded (Schoengold, Sunding, and Moreno 2006), which explains why these two groups tend to have higher PI. This corroborates findings that federal water suppliers, such as the Bureau, subsidize agricultural water supplies (Moore 1999). For example, the Bureau does not require interest on project cost repayment and since the Reclamation Project Act of 1939, has charged irrigators according to their "ability to pay" for federally provided water.[15] Irrigators with only surface water supplies may have the economies of scale in surface water distribution systems that lead to lower surface water prices.

Results demonstrate that farmer generally increase the extent of irrigation when there is relatively few use restrictions on the land. The variables indicating the crop portfolio of the farm also control for cropland quality and have the expected signs. Higher-value crops that are typically cultivated on higher-quality land are associated with greater PI, while the lowest-value crops are associated with lower PI. Although pasture is negatively related to PI, the presence of dairy cattle is linked to greater PI. According to Dan O'Brien (personal communication), the manager of the Greenberry Irrigation District south of Corvallis, Oregon, pastures with dairy cattle tend to increase the extent of irrigation to increase forage production and to dispose of livestock waste. Farm-scale is negatively related to PI. Because the statistical results evidence that PI is increasing in land quality, this last result suggests that larger farms irrigate the cropland of only the highest quality, causing PI to decline. Operations of smaller farm-scale have less land at their disposal, making this option less feasible.

Demographic characteristics of the irrigator have few effects on PI according to the statistical results. However, farm experience displays a negative effect on PI. Farm experience has a strong positive correlation with the age of the principal farm operator (0.83). Age has a mean value of 57 years, a standard deviation of 12 years, and minimum and maximum values of 20 and 96 years, respectively. Clawson (1963) reported that farmers tend to slowly reduce the extent of farm production as they approach retirement. About one-third of land idled under the Conservation Reserve Program is owned by retired farmers (Hoppe 2001). These findings indicate that land idling is more common for older farmers, explaining the negative effect of farm experience on PI.

Crop-specific Technology Choice

Estimated marginal effects and estimation statistics from the multinomial and binomial logit crop-specific TC models are reported in Table 7 and Table 8, respectively. Complete estimation results for the multinomial and binomial cases are presented in Table A.2.2 and Table A.2.3 (Appendix 2). In Tables 7 and Table 8, we report the number of observations, three statistical tests from the estimation results, and z-statistics to evaluate the performance of the models. Three statistical tests of model performance are provided because none of these measures alone is reliable for describing the performance of a qualitative choice model (Maddala 1987). Table 7 and Table 8 include the probability of choice, the elasticity of the continuous variables, and the percent change in the probability of choice as the discrete variables change from 0 to 1. The estimated marginal effects will allow comparison of choices across crop types and technologies.

Statistical tests indicate that all TC equations perform well. The McFadden R^2 and percentage correctly predicted suggest that the vegetable equation performs better than the orchard vineyard equation, but Wald statistics (Maddala 1987) indicates the opposite. Nonetheless, Wald statistics indicate that the orchard/vineyard and vegetable equations are highly statistically significant. By comparing Table 7and Table 4 it is shown that the multinomial equations correctly predict that orchard/vineyard and vegetable TC are dominated by the choice of drip and sprinkler technologies, respectively. All three test statistics indicate that wheat and alfalfa equations out-perform the hay and pasture equations. Wald statistics indicate that the wheat, alfalfa, and pasture equations have greater statistical significance than the hay equation. Thus, there is some evidence that key variables are omitted from the hay TC equation. The hay equation is statistically significant at the 0.01% level.

Statistical results demonstrate that water scarcity and climate are the most important determinants of TC. The results also clearly exhibit that the effects of water scarcity and climate on TC are crop dependent. In the orchard/vineyard and vegetable equations, the use of irrigation to mitigate frost damage to crops facilitates adoption of sprinklers and abandonment of gravity technologies. The results also show that when orchard/vineyard uses irrigation to mitigate heat stress, they tend to adopt sprinklers and avoid drip technologies. Similarly, the wheat, alfalfa, and pasture equations show that when irrigation is used to mitigate heat stress, sprinklers are more likely to be adopted than gravity technologies. Irrigation technologies are not used to mitigate heat stress to hay according to the statistical results.

The presence of dairy cattle increases the probability of adopting sprinklers in the pasture equation. This suggests that sprinklers are used to relieve heat stress to pastured dairy cattle on the West Coast.[16] However, it is also possible that pasture operations that have dairy cattle also have greater financial resources at their disposal, which makes adoption of the water-saving technology financially feasible. This interpretation is supported by an application of the Theory of Derived Demand which finds that irrigation technology adoption is positively associated with "actual financial control" (Lynne et al. 1995). Actual financial control in the Theory of Derived Demand is expressed by the capital constrained derived demand equation, which is a function of crop price and other factors (Beattie and Taylor 1985).

The effects of temperature on TC support our finding that when irrigation is used to mitigate climate stress, crops are inclined to adopt sprinklers. For orchard/vineyard, higher temperatures promote adoption of gravity technologies at a decreasing rate. This implies that as temperature decreases below the threshold of 75°F, frost occurrence will increase and orchard/vineyard will tend to abandon gravity technologies at an increasing rate. The reasoning for this is that as temperature decreases in colder environments frost occurrence will become more prevalent and orchard/vineyard irrigators will benefit from sprinkler technologies that can mitigate frost damage. In warmer environments that are above the threshold temperature, increasing temperatures also promote abandonment of gravity technologies at an increasing rate. The reason for this process is that as temperature increases in warmer environments, orchard/vineyard irrigators will have an increasing propensity to adopt water-saving technologies such as drip to off-set water losses caused by high levels of evapotranspiration (Dinar and Yaron 1990).

For the binomial TC cases, all sprinkler equations express that temperature facilitates adoption of sprinkler technologies at a decreasing rate. Using wheat as an example, the effect of temperature on the probability of adopting sprinklers reaches a maximum at 57°F. This implies that in relatively cool environments that are below the temperature threshold, increasing temperatures promote adoption of sprinklers to mitigate heat stress. In warmer environments, higher temperatures facilitate abandonment of sprinklers and adoption of gravity technologies. This process is explained by the finding that under conditions of extreme heat, evaporative losses from the sprinkler spray can reach 15%, making sprinklers an inappropriate technology (Finkel and Nir 1983). The statistical results imply similar processes for alfalfa and pasture TC. Hay TC was not found to be influenced by heat stress mitigation. Thus, the hay equation suggests that below a temperature threshold of 64°F, increasing temperatures facilitate adoption of water-saving sprinklers to offset water losses caused by increasing evapotranspiration. Beyond the temperature threshold, high evaporative losses from the sprinkler spray overwhelm the typical water-savings provided by sprinklers, making it an inappropriate technology (Finkel and Nir 1983).

The estimated effects of climatic stress and temperature on TC support a mass of agronomic literature reporting the effectiveness of sprinklers for mitigating frost and heat stress damage to these crops. The finding that irrigation technologies are not used to mitigate heat stress to hay is also in accordance with the agronomic literature. However, vegetable TC is not found to be impacted by heat stress or temperature despite agronomic evidence to the contrary (Appendix 1). Therefore, the estimated results may reflect that there are cool season and warm season vegetables (WSDA 2012; CDFA 2010) that make it difficult to identify how annual temperature affects irrigation choices for vegetable.

There is greater variation among crops in the effect of precipitation on TC than there is for temperature. There are two factors guiding the effects of precipitation on TC. Firstly, in certain situations water availability (i.e., soil moisture) provided by higher precipitation will lessen incentives to adopt water-saving technologies (Koundouri, Nauges, and Tzouvelekas 2006). Secondly, irrigation of crops with greater sensitivity to variation in soil moisture (i.e., water stress) requires systematic scheduling of irrigation to avoid under- and over-irrigation (Shock, Pereira, and Eldredge 2007). Systematic scheduling of irrigation is best provided by sprinkler and particularly drip technologies that provide greater control over the quantity and timing of water applications (Shock, Pereira, and Eldredge 2007; Negri and Brooks 1990; Finkel and Nir 1983). Shallow-rooted crops tend to have greater susceptibility to variation in soil moisture caused by under- and over-irrigation (Shock, Pereira, and Eldredge 2007).

In the hay and pasture equations, precipitation encourages adoption of sprinklers linearly. Timothy hay is a popular West Coast hay variety with shallow root-zone depths that makes it susceptible to water stress from under- and over-irrigation (Fransen 2005). For example, 80% of Timothy roots are found in the top 2 inches of soil, although roots will extend beyond 2 feet (Fransen 2005). Therefore, the hay equation indicates that sprinklers are more likely to be adopted where there are heavier or more frequent precipitation events because sprinklers allow greater control over soil moisture. Greater control over soil moisture helps prevent under- or over-irrigation to shallow-rooted hay crops. A similar process is assumed to govern the response of pasture TC to precipitation.

The wheat equation shows that precipitation discourages adoption of sprinklers at a decreasing rate. This suggests that in dryer environments that are below the threshold level of precipitation (42 inches), higher precipitation increases soil moisture and lessens incentives to adopt the water-saving technology. In wetter environments above the threshold level of precipitation, wheat is more inclined to adopt sprinklers that can systematically manage soil moisture in response to heavier or more frequent precipitation events. One reason why wheat tends to abandon water-saving sprinklers as precipitation increases in dryer environments is that wheat is the least water-intensive crop among all the major West Coast crops (Table 3).

The vegetable equations show that precipitation encourages adoption of gravity and drip, and discourages adoption of sprinkler technologies, all at decreasing rates. The gravity, sprinkler, and drip equations reach their thresholds at approximately 30 inches of precipitation (31, 27, and 28 inches, respectively). There is a wide variety of crops included in the vegetable category, including lettuce, tomato, potato, sweet corn, melons, and “other”. Some vegetables, such as potato (Shock, Pereira, and Eldredge 2007), have shallow root-zone depths that makes them susceptible to water stress from under- and over-irrigation. Delgado et al. (2001) reported that potato root-zone depths are less than 1.5 feet. On the other hand, sweet corn is a relatively deep-rooted vegetable, with root-zone depths exceeding 5 feet (Grimes et al. 1972).

The statistical results from the vegetable equations suggest that for shallow-rooted vegetables, increasing precipitation in dryer areas that are below the temperature threshold will facilitate abandonment of sprinklers and adoption of drip technologies that are most effective for managing soil moisture. For deep-rooted vegetables that are less sensitive to under- and over-irrigation, increasing precipitation in dryer environments will lessen incentives to adopt a water-saving technology (sprinkler) and promote adoption of gravity technologies. The vegetable equations also show that in wetter environments increasing precipitation encourages adoption of only sprinklers. There are three reasons why only sprinklers tend to be adopted as precipitation increases in wetter environments. Firstly, greater water availability (i.e. soil moisture) will lessen incentives for the adoption of drip technologies that provide the greatest water-savings. Secondly, in the wettest environments production conditions will often not be favorable enough to justify adoption of costly drip technologies (Lynne et al. 1995). Thirdly, sprinkler technologies are better equipped than gravity technologies to obviate under- and over-irrigation in environments with more frequent or severe precipitation events.

The estimated marginal effects for orchard/vineyard and alfalfa TC show that they are not influenced by precipitation. One reason for this finding is that orchard/vineyard and alfalfa have very deep root zones, which likely make them less vulnerable to variations in soil moisture caused by under- and over-irrigation. Thus, orchard/vineyard and alfalfa are likely to be less dependent on particular irrigation technologies for the systematic management of soil moisture. Ballantyne (1916) reported that root depths of peach, pear, apple, and grape reached 9-10 feet. Putnam (2001) reported that alfalfa roots are commonly 15 feet or deeper.

Drought is found to have notable affects on TC. Production in a drought region is associated with adoption of sprinklers for all crops, with the effects for vegetable and pasture being significant. These results substantiate previous findings that water-saving technologies tend to be adopted in response to drought conditions (Schuck et al. 2005; Carey and Zilberman 2002). One reason for this finding is that water-saving technologies can maintain output with lower water application rates, reducing the risk of producing in a drought region (Koundouri, Nauges, and Tzouvelekas 2006). It is important to note that drought does not encourage adoption of the most water-saving technology for orchard/vineyard and vegetable (drip). However, this result is only marginally significant in for orchard/vineyard.

Statistical results communicate the importance of economic and physical water scarcity to TC. We find that surface water price facilitates adoption of sprinklers and abandonment of gravity technologies for vegetable. We find that for wheat growers with federal surface water supplies, surface water price encourages adoption of the water-saving technology.[17] The orchard/vineyard equations reveal that if the farm only has surface water supplies, surface water price induces adoption of sprinklers and abandonment of gravity technologies. However, we find the counter intuitive result that when wheat irrigators receive all of their water from surface supplies, surface water price tends to discourage adoption of water-saving sprinklers. Nonetheless, these results generally corroborate previous findings that water price incentivizes adoption of water-saving technologies (Schuck and Green 2001; Green et al. 1996). It is important to note that surface water price does not encourage adoption of the most water-saving technology for orchard/vineyard and vegetable (drip).

Well depth promotes adoption of sprinklers and abandonment of gravity technologies for vegetable, wheat, and hay, according to the statistical results. This supports Caswell and Zilberman's (1986) theoretical result that water-saving technologies are more likely to be adopted at greater well depths. Well depth is positively correlated with pumping cost and therefore the marginal cost of groundwater. However, results also convey that well depth does not encourage adoption of the most water saving technology for vegetable (drip).

Wheat, alfalfa, and pasture equations show that the discontinuance of irrigation water encourages abandonment of sprinklers and adoption of gravity technology. Carey and Zilberman (2002) theoretically demonstrated that water scarcity increases the "hurdle rate" needed to induce adoption and farms wait until random events such as drought drive returns significantly above costs before investing in water-saving technologies.[18] Empirical studies have shown that farms with less groundwater saturation thickness (i.e., groundwater availability) tended to avoid adoption of water-saving technologies (Albrecht 1990; Albrecht and Ladewig). Thus, our empirical results affirm the theoretical conclusion of Carey and Zilberman (2002) that "water supply uncertainty" creates an option value that delays and discourages investment in water-saving technologies. One reason why we find that vegetables tend to abandon sprinklers and adopt gravity technologies as population density increases is that greater competition for water associated with higher population densities (Kummu et al. 2010) may create an option value that delays and discourages investment in water-saving technologies.

Institutional arrangements are found to influence TC. The wheat equation shows that irrigators are less likely to adopt the water-saving technology if their surface water is federally provided. Irrigators with federal surface water supplies have surface water prices that are 29% lower than for all irrigators (Table 6). This corroborates findings that federal water suppliers, such as the Bureau, subsidize agricultural water supplies (Moore 1999; Moore 1991). Subsidization of agricultural water will reduce incentives to adopt water saving technologies. Federal provision of surface water is more common for wheat (43%) than for all other crops (26-38%), providing one reason for the unimportant effects of institutional arrangements on the TCs of all other crops.

Geographic qualities of the farm are found to impact TC. The alfalfa, hay, and pasture equations have a strong propensity to adopt the water-saving technology when land quality is better, according to the statistical results. This contradicts the seminal finding of Caswell and Zilberman (1986) that water-saving technologies, or “land quality augmenting technologies”, tend to be adopted on poorer quality soils. However, in a crop-specific analysis of TC in sugarcane, Shrestha and Gopalakrishnan (1993) find that water-saving technologies (drip) tend to be chosen on higher-quality lands. Because water-saving technologies typically increase crop yields, Shrestha and Gopalakrishnan (1993) argue that TC depends on whether the motivation is for increasing yield or conserving water. Table 9 shows that lower-value crops tend to increase AR as land quality increases, with the effects for hay being significant. Table 9 also shows that higher-value crops tend to decrease AR as land quality rises, with the effects for vegetable being significant. Thus, the statistical results suggest that lower-value crops tend to adopt the water-saving technology and increase AR on higher-quality lands to improve yields. Higher-value crops tend to reduce AR as land quality rises, just as Caswell and Zilberman’s (1986) theoretical results suggest.

Caswell and Zilberman’s (1986) theoretical results indicated that farms with surface water supplies are more likely to adopt gravity technologies. The reasoning for this is that surface water is delivered at lower pressure than groundwater that has to be pumped to the surface. Because surface water is delivered at lower pressure than groundwater, farms with surface water supplies are more inclined to adopt gravity technologies that require very low pressure to distribute water to crops. Our results show that all crops are more likely to adopt gravity technologies when the farm only has a surface water supply. However, none of the estimated effects of surface supply on TC are statistically significant. This suggests that surface water supply may be a much less important determinant of TC when other factors are controlled for, such as the discontinuance of irrigation water, population density, and if surface water is solely from federal suppliers.

We find that TC is affected by farm-scale. The statistical results show that as farm-scale increases, orchard/vineyard is inclined to abandon gravity and vegetables are inclined to adopt drip technologies. These results affirm previous findings that farm scale-economies increase incentives to adopt water-saving technologies (Green and Sunding 1997; Green et al. 1996). Surprisingly, the results indicate that pasture TC has diseconomies in farm-scale. Descriptive statistics of land allocation (Table 10) however, do indicate that farm-scale is most important for orchard/vineyard and vegetable, and least important to pasture.

Crop diversity is found to affect high- and low-value crops differently. Orchard/vineyard and vegetable equations show that greater crop diversity is linked to the adoption of gravity technologies, while the hay equation shows that greater crop diversity is linked to adoption of sprinklers. These results suggest that crop-specific TC will be dependent on the TCs of other crops on the farm. With greater crop diversity, higher-value (lower-value) crops are more likely to adopt gravity (sprinkler) technologies that are more common for lower-value (higher-value) crops on the farm (Table 3, Table 4). These results confirm our hypothesis that sharing of mobile irrigation technologies (e.g., siphon-tubes for gravity irrigation, hand-move sprinklers, side roll sprinklers, linear move sprinklers, and big gun sprinklers) among crops is an important determinant of TC.

Demographic characteristics of the farmer are found to be more important for TC of the highest value crops, but the direction of the effects is consistent across crops. Surprisingly, tenure is not found to affect TC, which disagrees with previous findings (Feder et al. 1988). Orchard/vineyard equations show that sprinklers tend to be abandoned and drip technologies tend to be adopted on farms with internet access. Similarly, the alfalfa equation shows that the likelihood of adopting the water saving technology is positively related to internet access on the farm. These results support the finding that computer use enhances farmers “innovativeness and technical ability”, increasing the likelihood that water-saving technologies will be chosen (Khanna 2001).

We find that occupation and farm experience impact TC, but occupation is only found to influence TC for the highest value crops. When farming is the primary occupation of the farm operator, orchard/vineyard (sprinklers) and vegetable (drip) tend to adopt water-saving technologies. Ervin and Ervin (1982) argued that off-farm income results in less time to “implement and maintain unfamiliar practices”. Several studies of fruit and vegetable producers have found that integrated pest management (IPM) required substantial time for management and that off-farm employment presents a constraint to IPM participation (Fernandez-Cornejo 1996; Fernandez-Cornejo 1998). Dinar, Campbell, and Zilberman (1992) demonstrated that the share or farmland irrigated with water-saving technologies is positively related to the presence of a full-time irrigator on the farm. Our results substantiate previous findings that farm occupation encourages adoption of water-saving technologies because irrigators will have more time to implement and maintain unfamiliar practices associated with water-saving technologies.

The results show that farm experience is a deterrent to the adoption of water-saving technologies. Orchard/vineyard and hay are more likely to adopt gravity technologies as the farm operator’s years of experience on the farm increase. This supports Dinar and Yaron's (1990) finding that an irrigator's years of citrus growing experience was a deterrent to the share of citrus groves adopting water-saving technologies. There are two possible reasons for this relationship. Firstly, a grower with longer experience using a conventional technology is likely to have developed solutions to irrigation problems while applying that technology and is therefore less likely to adopt a modem technology (Stefanou and Saxena 1988). Secondly, experience is usually correlated with the decision maker's age, which in turn is negatively correlated with level of adoption (Dinar and Yaron 1990). In the tri-state FRIS sample, farm experience has a strong positive correlation with the age of the principal farm operator (0.83).

Crop-specific Water Application Rates

Estimation results for the OLS crop-specific AR models are reported in Table 9. To judge the performance of the AR models, we report the number of observations, two statistical tests, and t-statistics in Table 9. Statistical tests indicate that all TC equations perform well. The R^2 (Greene 2008) suggests that the alfalfa equation performs particularly well. The R^2 is relatively low for pasture, suggesting that there may be key variables omitted from this equation. However, F-stats (Greene 2008) indicate that all AR models are highly significant.[19]

Results show that physical and economic water scarcities are integral determinants of AR. Discontinued irrigation is associated with lower AR for all crops, with the effects for wheat, alfalfa, and hay being significant. These results are intuitive. If irrigation water is discontinued long enough to affect yields, some portion of normal irrigation events do not occur. Thus, it is reasonable to expect that the volume of irrigation water applied to each crop (i.e., AR) will decline also. The wheat equation conveys that AR responds positively to surface water price. Among the major West Coast crops, wheat is the least water-intensive (Table 3). Therefore, the statistical results indicate that irrigators respond to higher surface water prices by allocating more water to crops that have a higher value per unit of applied water.

Every estimated AR equation shows that farms with federal surface water supplies are more responsive to surface water price. This effect is only marginally significant in the hay equation. These results are demonstrated by the estimated marginal effects for the interaction between surface water price and federal supply. There are several reasons suggesting that irrigators with federal surface water supplies should actually be less responsive to surface water price. Firstly, the Bureau quantity-rations irrigation water (Moore 1999). Secondly, a common finding of studies investigating the Bureau's quantity-rationing of irrigation water is the sizable difference between water's shadow price and actual price (e.g., Moore 1999; Moore 1991). Thirdly, long term contracts between irrigation districts and the Bureau typically have duration of 40 years (Moore 1991).

The Bureau's constraints on water trading, particularly across irrigation districts (Moore 1991), and the Bureau's ability-to-pay subsidy policy (Moore 1999) may also affect water price responsiveness. Table 6 shows descriptive statistics of surface water price by institutional provider and physical source. There is much less variation in surface water prices for irrigators that only have federal water supplies. Moore (1999) documented the relatively low degree of fluctuation in contract prices under the Bureau's constraints on water trading and ability-to-pay subsidy policy. The Bureau's constraints on water trading and its ability-to-pay subsidy are likely to result in a high negative correlation between surface water price and water use (i.e., AR). For the other groups of irrigators with substantial variation in surface water price, crop-specific AR and surface water price are less likely to be correlated. Therefore, AR for irrigators with federal surface water supplies tends to be more elastic because institutional arrangements regulate irrigators' responsiveness to water price. A similar process is expected to regulate the price responsiveness of PI.

The vegetable and wheat AR equations show that for farms with only surface water supplies, irrigators tend to be more responsive to surface water price. The orchard/vineyard AR equation shows that AR is increasing in surface water price. These results are demonstrated by the estimated marginal effects for the interaction between surface water price and surface supply. These results indicate that farms that only have surface water supplies tend to allocate greater AR to orchard/vineyard and less AR to vegetable and wheat. The reasoning for this process is unclear.

The statistical results demonstrate that climate is a key determinant of AR and that the affects of temperature on AR are more profound than the affects of precipitation. All crop-specific equations show that AR is decreasing in temperature at decreasing rates. However, only the effects for orchard/vineyard, alfalfa, and hay are significant. AR for orchard/vineyard, alfalfa, and, and hay are minimized at 69°F, 49°F, and 63°F, respectively. In warmer regions that are above the respective temperature thresholds, increasing temperature will increase the already high levels of evapotranspiration and soil desiccation (Dinar and Yaron 1990). In these cases, AR is likely to increase because greater water applications will be necessary for satisfying crop water needs. It is unclear why AR is declining in temperature for areas below the threshold level of temperature.

The orchard/vineyard, alfalfa, hay, and pasture equations indicate that AR is increasing in precipitation at a decreasing rate. The effect of precipitation squared on alfalfa AR is only marginally significant. These relationships imply that orchard/vineyard, alfalfa, hay, and pasture AR are maximized at 14, 32, 40, and 40 inches of precipitation, respectively. Irrigation is used to supplement precipitation (Negri and Brooks1990; Finkel and Nir 1983). In wetter environments that are above the respective precipitation thresholds, a greater proportion of crop water needs are satisfied by precipitation. This is likely to cause a greater proportion of water allotments to be unused or transferred to higher-value uses, causing AR to decline. It is unclear why AR is increasing in precipitation for areas below the threshold level of precipitation.

Results show that producing in a drought region tends to decrease AR for orchard/vineyard. The wheat and hay equations show that producing in a drought region is related to greater AR. Among the West Coast's six major crops, Orchard/vineyard is one of the most water-intensive and wheat and hay are among the least water-intensive crops (Table 3). Drought areas are typified by greater aridity and soil desiccation (Keyantash and Dracup 2002). Therefore, our findings suggest that when farms produce in drought regions they will respond to the higher levels of aridity and soil desiccation by allocating less water to water-intensive crops and more water to crops of lower water-intensity.

The orchard/vineyard equation shows that if the farm uses irrigation to mitigate frost damage AR increases. The use of irrigation to mitigate frost damage does not necessarily coincide with typical irrigation schedules. Therefore, using irrigation to mitigate frost damage is likely to increase the frequency of irrigation. Increased irrigation frequency is likely to cause the volume of applied water (i.e., AR) to increase. The use of irrigation to mitigate heat stress is not found to affect AR. One reason for this finding is that normal irrigation schedules may closely match the irrigation schedules for relieving heat stress to crops. For example, crop canopy temperature is a crop water stress indicator that has long been used to schedule irrigation applications (Jackson et al. 1981).

Institutional arrangements and geographic qualities of the farm decidedly influence AR. All crop equations show a positive relation between federal water provision and AR, with the effects for orchard/vineyard, wheat, alfalfa, and pasture being significant. This confirms reports that federal water suppliers, such as the Bureau, subsidize agricultural water supplies (Moore 1999, Moore 1991). The results show that if a farm has only surface water supplies they are inclined to decrease AR for orchard/vineyard and increase AR for wheat. Farms with only surface water supplies do not have substitute water supply sources and typically have fixed water allotments. Therefore, the statistical results suggest that when there are few substitute sources of irrigation water and (surface) water allotments are fixed, irrigators will tend to allocate more water to less water-intensive crops such as wheat, and less water to crops of greater water-intensity such as orchard/vineyard.

Farm-scale has a positive effect on AR for all crops, with the effects for orchard/vineyard and alfalfa being significant. This result supports previous findings that economies of farm-scale increase the crop-specific water demand (Moore, Gollehon, and Carey 1994). The effects of land quality on AR were previously discussed in conjunction with the effects of land quality on TC. We concluded that the statistical results suggest that lower-value crops tend to choose the water-saving technology and increase AR on higher-quality lands to improve yields. Higher-value crops tend to reduce AR as land quality rises, just as Caswell and Zilberman's (1986) theoretical results suggest. These findings are further supported by the estimated effects of TC on AR.

By conditioning AR on TC we find that adoption of sprinkler technologies reduces AR for the higher-value crops, but does not for the lower-value crops. The adoption of drip irrigation technologies is found to result in lower AR also, as demonstrated by the orchard/vineyard and vegetable equations. These results support the finding that sprinkler and drip irrigation technologies provide greater irrigation efficiencies and allow water-savings relative to gravity technologies (Hanemann et al. 1987; Negri and Hanchar 1989). However, this result is also consistent with our finding that lower-value crops tend to choose sprinklers and increase AR (on higher-quality lands) to improve yields. The effects of TC on AR are also consistent with our finding that higher value-crops tend to adopt water-saving technologies (on higher-quality land) to save water, as opposed to motivations for increasing yield.

Statistical results indicate that demographic characteristics of the farmer rarely influence AR. Internet access is found to be positively associated with AR for all crops, with the effects for orchard/vineyard, vegetable, and alfalfa being significant. It is unlikely that the "innovativeness and technical ability" associated with computer use (Khanna 2001) or internet access affects AR per se. It is more likely that internet access captures irrigators' "actual financial control" over the adoption of irrigation technologies (Lynne et al. 1995). Therefore, the results suggest that irrigators with internet access will also tend to have greater financial resources which result in a greater willingness to pay for irrigation water.

Policy Implications

The most important policy implications that we find involve asset heterogeneity and the distributional effects of agricultural policy. Several of our findings provide valuable information about how irrigators would respond and adapt to future climate change. Our findings also lead us to some commonly advocated revisions to federal water subsidy policies. We have also identified some key differences between the irrigation choices of higher- and lower-value crops. Identifying these differences sheds further light on the distributional consequences of agricultural policy. Many of our findings are crop-specific and will have a high degree of policy relevance to irrigation districts or other agricultural jurisdictions that cultivate some of the West Coast's major crops. Furthermore, our data has an incredible degree of variation in water scarcity and climatic factors, making our findings applicable to other Mediterranean climates in the world.

Water pricing policies are commonly advocated as a means to conserve water by facilitating adoption of water-saving irrigation technologies (Peterson and Ding 2005). We found that specific crops have a proclivity for certain irrigation technologies that can mitigate particular climatic stressors. Our results indicate that in areas where frost occurrence is regular, water pricing policies will often not induce orchards, vineyards, and vegetable farms to adopt the most water-saving technology (drip) because they will have a propensity for sprinklers that can mitigate frost damage. In this case, water pricing policies will not encourage water conservation by technology adoption for orchards, vineyards, and vegetable farms, and will impose pure costs to these producers. Thus, with asset heterogeneity, the distribution of water policy impacts depends on prior land allocation decisions such as crop choices (Green and Sunding 1997). These findings have high policy relevance for diverse agricultural landscapes such as the West Coast where the distributional impacts of policy can be complex.

We found that irrigation for frost protection tends to increase AR for orchards and vineyards. Using sprinklers for frost protection of vineyards has recently been a highly publicized and contentious issue in Sonoma County, California.[20] In Sonoma County, vineyards have been diverting water from the Russian River to acquire water for frost protection. Environmental groups are concerned that these diversions are harming salmon and steelhead habitat, the latter being a threatened species. Sonoma County legislators have, thus far, sided with grape growers by scaling back rules regulating how they can use Russian River water for frost protection. Policies that incentivize the adoption of alternative frost protection technologies (e.g., wind mixers and chemical applications) could help ensure that irrigators have the ability to mitigate frost damage, while reducing competition for streamflows. Sonoma County legislators and others facing similar issues should evaluate this option while considering the inherent tradeoffs between energy, chemical pollution, and water use implied by the alternative technologies.

Our findings evidenced when orchards, vineyards, wheat, alfalfa, and pastured dairy cattle are exposed to heat stress, water pricing policies will likely encourage adoption of the water-saving technology for wheat, alfalfa, and pasture because sprinklers can mitigate heat stress to these crops. However, water pricing policies will not encourage adoption of the most water-saving technology for orchards and vineyards (drip) because these crops have a propensity for sprinklers that can mitigate heat stress. This indicates, once again, that water pricing policies will not encourage water conservation by technology adoption for orchards and vineyards, and will subject these producers to pure costs.

We showed that the inclination for orchard, vineyard, and vegetable irrigators to use sprinklers for frost protection overwhelms other factors that incentivize the adoption of drip technologies. For orchards and vineyards, the proclivity to use sprinklers for mitigating heat stress contributes to this effect. For example, surface water price, well depth, and production in a drought region promoted the adoption of sprinklers, but not drip technologies for vegetable. This corroborates the finding that asset heterogeneity limits options available to farmers and reduces the set of production technologies that a farm can use (Bellon and Taylor 1993; Perrin and Winkelmann 1976). This finding reiterates that asset heterogeneity affects the distributional consequences of water pricing policy.

Several of our results provide valuable information about how irrigators would respond and adapt to future climate change. The discontinuance of irrigation water is expected to become more frequent and severe with climate change (Vano et al. 2010). Our results indicated that for several crops the discontinuance of irrigation water (i.e., water supply uncertainty) creates an option value that delays and discourages adoption of water-saving technologies. The discontinuance of irrigation water was also shown to reduce water demand at the farm-level extensive proportion (i.e, PI) and crop-level intensive margin (i.e., AR).

We thoroughly investigated the effects of temperature and precipitation on irrigation choices. The effects of temperature on irrigation choices were more profound than the effects of precipitation. For TC and AR, temperature and precipitation were often each found to have consistent effects across crops. For example, all crop-specific equations showed that AR decreased at a decreasing rate with temperature. However, in other cases, we demonstrated that the effects of climate on irrigation choices are crop-dependent. This case was demonstrated by the effects of precipitation on TC, for example.

We found that irrigators respond to higher water prices by increasing the intensive margin of water demand for the least water-intensive crops. Likewise, we found that when a farm has few substitute sources of water (i.e., surface water supply only) or produces in a drought region, irrigators respond by increasing (decreasing) the intensive margin of water demand for crops of lower water-intensity (higher water-intensity). These findings indicate that under conditions of water scarcity or drought, farms will allocate water to crops with the greatest value per unit of applied water. We also showed that if production occurs in a drought region, several crops are inclined to adopt water-saving sprinkler technologies. These findings provide insights into the likely adaptation responses of irrigators that face changing water scarcity and climatic conditions.

Federal water provision was found to have important influences on TC, but its influences on water demand at the farm-level extensive proportion and crop-level intensive margin were more salient. These influences reflect subsidy policies and constraints on water trading from federal water providers such as the Bureau (Moore 1999; Moore 1991). The Bureau is, by far, the nation’s largest agricultural water provider. Since the Reclamation Reform Act of 1982 the Bureau has had an explicit mandate for water resource conservation. To achieve this mandate, the Bureau’s policy of charging irrigators for water based on their “ability to pay” could be revised to more closely reflect long-run production cost. Creating opportunities for increased water trading of Bureau provided water could also reduce inefficiencies in federal water provision. Opportunities for expanded trading of federally provided water will, of course, be dependent on mechanisms that limit third-party effects from water redistribution.

We now review key differences we have identified between the irrigation choices of higher-value and lower-value crops. We found strong evidence that for lower-value crops, irrigators tend to respond to higher quality land by choosing sprinklers and increasing the intensive margin of water demand. By contrast, higher-value crops tend to reduce the intensive margin of water demand as land quality rises. Furthermore, we found that adoption of water-saving technologies only reduces the intensive margin of water demand for higher-value crops. These results indicate that when lower-value crops are cultivated on higher-quality land, irrigators will take measures to increase yield. On the other hand, irrigators of high-value crops will respond to higher land quality by taking measures to conserve water and reduce cost. These findings suggest that the merit of water pricing policies intending to conserve water by facilitating adoption of water-saving technologies will be dependent on the distributions of land quality and cropping patterns in the relevant policy region.

Conclusion

This paper addressed irrigation choices with a particular focus on their water scarcity and climatic determinants. This was accomplished through estimated models of land proportion irrigated, and crop-specific irrigation technology choice and water application rates. This approach was applied to agricultural production data for major crops on the West Coast. The statistical results indicated that irrigation choices are highly dependent on water scarcity and climate. Institutional arrangements, geographic qualities of the farm, and demographic characteristics of the farmer also exhibited important influences on irrigation choices.

Federal water provision had salient effects on all three components of irrigation choice and evidenced the effects of subsidized water supplies and constrained water trading on these choices. The effects of climate on irrigation choices were often found to be crop-dependent and non-linear. The effects of temperature on irrigation choices were found to be more profound than the effects of precipitation. We argued that heat stress and frost-risk are dominating factors for the TCs of several crops. This argument supported the finding that asset heterogeneity has crucial implications for the distributional effects of agricultural policy (Schuck and Green 2001; Green and Sunding 1997; Green et al. 1996). Other implications related to the distributional effects of agricultural water policies and how irrigators would respond and adapt to future climate change were discussed.

Different crops have different climate susceptibilities and varying thresholds where stress is incurred. Crop-specific modeling offers a means for identifying these susceptibilities and estimating their effect on irrigation choices. The advantage of studies that estimate multiple crop-specific models is that it allows comparison across crops of the factors that influence irrigation choices. Therefore, estimating multiple crop-specific models can provide information about the distributional impacts of agricultural policy and climate change. This advantage is particularly important for the diverse agricultural landscape of the West Coast where the distributional impacts of policy can be complex. By using crop-specific equations, quadratic climate variables, and a large study region, we resolved many inconsistent findings regarding the determinants of irrigation choices.

This study establishes a research agenda for crop-specific analysis of irrigation choices. Some of our results warrant verification with further studies. For example, the effects of precipitation on vegetable TC should be verified by a crop-specific study including vegetables with varying root-zone depths (i.e., sensitivity to water stress from under- and over-irrigation). We found preliminary evidence that sprinkler technologies are used to mitigate heat stress to pastured dairy cattle, which warrants further investigation. Future crop-specific irrigation choice studies would benefit from panel microdata with improved land quality variables, and seasonal or monthly climate variables that are better able to identify the effects of climate stress (e.g., heat stress and frost damage) on irrigation choices.

Footnotes

[1] We thank Chris Mertz, Director of the USDA National Agricultural Statistic Service's Oregon Field Office, for providing access to the USDA data used in this paper.

[2] Rule curves coordinate the operation of reservoirs under various water conditions. Different types of rule curves depict different operating objectives. The Hydro System Seasonal Regulation (HYSSR) program is used extensively to guide reservoir operation for the Columbia River System in the Pacific North West. For a definition of rule curves used by HYSSR, visit http://www.nwd-wc.usace.army.mil/PB/HYSSRM/RULECURV.pdf.

[3] Water-saving irrigation technologies transmit a higher percentage of applied water to crop consumption, reducing water losses and allowing irrigators to maintain output at reduced application rates (Peterson and Ding 2005). Drip technologies typically provide the greatest water savings, followed by sprinklers, and then by gravity technologies (Hanemann et al. 1987; Negri and Hanchar 1989).

[4] Irrigated agricultural systems also respond to change by altering the amount of land allocated to different crops (Moore et al. 1994), but that response is not modeled in the current paper.

[5] Dinar, Campbell, and Zilberman (1992) established a theoretical relation stating that effective irrigation is a function of applied water, the irrigation technology, water quality, and climate. Effective irrigation is the amount of water consumed by the crop. However, by including applied water in the functional definition of effective water, they convert it into an efficiency measure.

[6] In orchards and vineyards, late spring frosts can damage young buds and hinder productivity, while early fall frosts can damage ripening fruit and product quality (Jones 2005). Many spring- and fall-grown vegetables are vulnerable to frost damage as well (Dukes et al. 2012).

[7] Above-canopy sprinkler irrigation can simultaneously coat an entire crop with water. Under freezing conditions sprinkled water freezes across the entire crop. This process prevents the freezing of plant tissue by exploiting the release of latent heat which follows the freezing of water, keeping plant tissue at 32°F (Ozaki 1963). Most plant tissues freeze at temperatures below 32°F (Dukes et al. 2012). Sprinkler irrigation can also provide evaporative cooling of orchards which can delay bloom timing and help sensitive plant blossoms obviate damage from late spring frost events (Lakatos et al. 2010).

[10] In this paper, twenty-three different irrigation methods are grouped into three types of irrigation technology: gravity, sprinkler, and drip. Some of the gravity (e.g., siphon-tube) and sprinkler (e.g., hand-move, side roll, linear move, and big gun) technologies are mobile.

[11] Cropland excludes acres of developed farmland and woodland. Therefore, cropland only includes farmland with the potential of being irrigated.

[12] The 2008 FRIS samples respondents to the 2007 Census of Agriculture.

[13] Crops comprising the remaining 14% of irrigated farms and 20% of irrigated acreage in the tri-state FRIS sample are: cotton, sugar beets, rice, corn for grain or seed, corn for silage or greenchop, barley, soybean, dry edible beans, other small grains, and "other".

[14] The National Drought Mitigation Center identifies United States Climate Divisions (Guttman and Quayle 1995) that experienced severe to extreme drought typified by a Palmer Drought Severity Index of < -3 in at least 10% of years from 1895-1995. These regions generally occupy southern California, and Oregon and Washington eastward of the Cascade Mountains. Counties that overlapped these drought regions were identified as "drought counties" in the data. This approach resulted in slight over identification of drought area. In California, the majority of Kern, San Luis Obispo, and Mono Counties are over identified. In Oregon, a small portion of Deschutes and larger portions of Klamath and Lake Counties are over identified. In Washington, portions of Klickitat, Yakima, Kittitas, Chelan, and Okanogan counties are over identified. The over identified areas in Oregon are not of great concern because there is a long history of agricultural drought in eastern Oregon (Gray and Plath 1957) and the Klamath Basin (Burke, Adams, and Wallender 2004). The over identified areas in Washington are the eastern slopes of the Cascades, where there is assumed to be a small number of observations in the USDA data. Similarly, in California, the Sierra Nevada Mountains dominate Mono County and so there is assumed to be a small number of observations in the USDA data for that county. The USDA data indicates that there are no observations in San Luis Obispo County. Therefore, we are confident that the drought counties we have identified are satisfactory for denoting drought prone regions on the West Coast.

[15] Evapotranspiration is the sum of evaporation and plant transpiration. Evaporation accounts for the movement of water to the air from sources such as the soil. Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapor through stomata in its leaves. All else equal, evapotranspiration is increasing in temperature (Brown and Rosenberg 1973).

[16] Surface water has been treated as a fixed allocatable input to agricultural production because institutional constraints fix surface water supplies to irrigators (Moore 1999). Fixed input models for land and surface water inputs are found to be superior to variable input models (Moore and Dinar 1995).

[17] The Bureau's ability-to-pay subsidy completely divorced water prices from long run production cost and established profitability of irrigated farms as the basis for water pricing. The Bureau uses farm budget studies for the area in question and various crops and grades of land to estimate irrigators' ability-to-pay for water. The Bureau's interest and ability-to-pay subsidy rates, in tandem, equaled 82% of Bureau project costs in 1975 (Moore 1999).

[18] In the pasture TC equation, interacting the dairy cattle and heat stress variables would explicitly identify if sprinkler technologies are used to mitigate heat stress to dairy cattle. However, because the dairy cattle and heat stress variables are both binary, interacting them causes multicollinearity when an intercept is included in model.

[19] Federal provision of surface water is more common for wheat (43%) than for all other crops (26-38%), which helps to explain why other crops are less affected by this institutional arrangement.

[20] According to Carey and Zilberman (2002), the uncertainty of future water supplies and prices and the quasi-irreversible nature of an investment in modern technology, the option to delay investment can be valuable. By waiting to invest, a farm can observe whether water prices increase or decrease before committing to a sunk investment cost.

[21] While interpreting the estimated coefficients for AR, keep in mind that orchard/vineyard is specified as a log-lin model, while all other AR equations are in lin-lin form.

[22] To find several newspaper articles from The Press Democrat that discuss the conflict in Sonoma County, California between grape growers and environmental interests visit: http://www.pressdemocrat.com/article/20120417/articles/120419546.

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Table 1. Descriptive Information for Selected Independent Variables

Variable	Mean	Std. Dev.	Variable Definition (units)
Water Scarcity			
Surface water price[a]	52.95	206.49	Average surface water price for the farm ($/acre-foot)
Well depth[b]	364.34	323.73	Average depth to well bottom for all farm wells (feet)
Discontinued irrigation[c]	0.17	0.37	Farm discontinued irrigation long enough to affect yields (0,1)
Population density	1.02	2.24	County population density (100 people/square mile)
Climate			
Drought region	0.64	0.48	Farm in county overlapping historic drought region (0,1)
Frost mitigation	0.15	0.36	Farm uses irrigation to mitigate frost damage (0,1)
Heat stress mitigation	0.09	0.29	Farm uses irrigation to mitigate heat-stress (0,1)
Temperature	66.40	7.42	County average annual maximum temperature (°F)
Precipitation	19.23	14.21	County average annual precipitation (inches)
Geographic			
Surface supply	0.47	0.50	Farm receives all (>99%) water from surface sources (0,1)
Land quality	0.31	0.16	County cropland in LCC 1 or 2 (proportion)
Farm-scale	4.35	27.83	Cropland, excluding developed land and woodland (1000 acres)
Crop diversity	1.88	0.99	Number of major crops irrigated on the farm (1-6)
Orchard/vineyard	0.33	0.47	Farm irrigates orchard or vineyard (0,1)
Vegetable	0.26	0.44	Farm irrigates vegetable (0,1)
Wheat	0.33	0.47	Farm irrigates wheat (0,1)
Alfalfa	0.43	0.50	Farm irrigates alfalfa (0,1)
Hay	0.28	0.45	Farm irrigates hay (0,1)
Pasture	0.25	0.43	Farm irrigates pasture (0,1)
Dairy cattle	0.07	0.25	Farm has dairy cattle (0,1)
Institutional			
Federal supply[d]	0.29	0.46	Farm receives all surface water from federal suppliers (0,1)
Demographic			
Tenure	0.35	0.48	Principal operator fully owns farm operation (0,1)
Internet	0.83	0.38	Farm has high speed internet access (0,1)
Farm occupation	0.82	0.38	Farming is the principal operator's primary occupation (0,1)
Farm experience	25.81	14.26	Time principal operator has operated the farm (years)

[a] Missing observations for farms solely using groundwater are replaced by the county-level mean surface water price.

[b] Descriptive statistics for well depth are only for irrigators using groundwater. Farms without access to groundwater have well depth equal to zero.

[c] FRIS provides several reasons why farms may discontinue irrigation long enough to affect yields: (1) shortage of surface water, (2) shortage of groundwater, (3) irrigation equipment failure, (4) energy price increases or shortage, (5) poor water quality, (6) loss of water rights due to voluntary transfers, (7) cost of purchased water, or (8) other. All of these reasons, with the exception of (3) and possibly (8), relate to the physical or economic scarcity of quality irrigation water. It is unlikely that a farmer would discontinue the use of irrigation water willfully for a long enough period to affect yields. This suggests that the discontinuance of irrigation water is an exogenous factor to irrigation choices. Moore, Gollehon, and Carey (1994) also use FRIS and this variable in their investigation of multicrop production relationships in irrigated agriculture.

[d] Federal suppliers include the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, Bureau of Indian Affairs, USDA, and "other". The U.S. Bureau of Reclamation is, by far, the nation's largest irrigation water supplier in terms of land area served and volume of water delivered.

Table 2. Percent of Irrigators by Number of Major Crops Grown

Number of Major Crops Grown	Percent of Irrigators
1	46
2	30
3	17
4	6
5	1
6	0

Table 3. Descriptive Statistics for Selected Dependent Variables

Variable (units)	Mean	Std. Dev.	Min.	Max.
Proportion Irrigated (proportion)	0.79	0.32	9.09E−5	1.00
Binomial Technology Choice (0/1)[a,b]				
Wheat	0.61	0.49	0	1
Alfalfa	0.63	0.48	0	1
Hay	0.44	0.50	0	1
Pasture	0.47	0.50	0	1
Water Application Rates (acre-feet)[c]				
Orchard/vineyard	2.46	1.06	0.10	6.70
Vegetable	2.53	1.01	0.10	6.70
Wheat	2.01	0.97	0.10	6.00
Alfalfa	2.84	1.48	0.10	12.00
Hay	2.17	1.38	0.10	8.40
Pasture	2.10	1.12	0.10	7.90

[a] The base case (0) are gravity technologies.

[b] Binomial TC variables also enter the AR models as independent variables.

Table 4. Descriptive Statistics for Multinomial TC Dependent Variables

	% Gravity	% Sprinkler	% Drip
Orchard/vineyard	15	30	55
Vegetable	21	62	17

Note: Binary variables indicating whether orchard/vineyard or vegetable chose gravity, sprinkler, or drip, respectively, is also included as independent variables in the corresponding AR equations.

Table 5. Tobit Marginal Effects and Estimation Statistics for PI

Variable	dF/dx	z-stat.
Surface water price	−1.3E−5	−0.65
Surface water price × Federal supply	−0.0004**	−2.38
Surface water price × Surface supply	−0.0001	−1.36
Well depth	1.4E−5	0.81
Discontinued irrigation	[−0.0262]***	−2.56
Population density	−0.0067***	−3.43
Drought region	[0.0272]*	1.91
Temperature	−0.0241**	−2.20
Temperature squared	0.0002***	2.73
Precipitation	0.0030**	2.51
Precipitation squared	−3.9E−5***	−2.64
Federal supply	[0.0747]***	6.53
Surface supply	[0.0171]*	1.66
Land quality	0.1472***	5.45
Farm-scale	−0.0008***	−6.56
Orchard/vineyard[a]	[0.0587]***	5.54
Vegetable	[0.0569]***	5.62
Wheat	[0.0237]**	2.49
Hay	[−0.0350]***	−3.77
Pasture	[−0.0269]***	−2.81
Dairy cattle	[0.0720]***	4.31
Tenure	[0.0077]	0.89
Internet	[−0.0119]	−1.09
Farm occupation	[−0.0053]	−0.47
Farm experience	−0.0013***	−4.88
Intercept	0.8845**	2.24
Estimation statistics		
Observations		1,461
Uncensored observations		791
Right-censored observations at PI=1		670
McFadden R^2		0.23
LR chi^2 (df=25)		478.60

Note: Terms in brackets are the percent change in PI as the discrete variable changes from 0 to 1.
Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.
[a] Alfalfa is the base case crop choice; it has been excluded to eliminate indeterminacy in the model.

Table 6. Descriptive Statistics of Surface Water Prices by Provider and Source

Provider and Source	Mean	Std. Dev.	Min.	Max.
Non-federal surface supply	30.51	141.80	0	3600.00
Federal surface supply	37.53	44.43	0	384.62
All irrigators[a]	52.95	206.29	0	4891.59

Note: All surface water prices are expressed in dollars ($).
[a] All irrigators include irrigators with non-federal surface supplies, federal surface supplies, federal and non-federal surface supplies, and irrigators only with access to groundwater. Irrigators with only access to groundwater are assumed to have a surface water price equal to the county-level mean surface water price.

Table 7. Elasticities, Probabilities, and Estimation Statistics from Multinomial Logits of Orchard/vineyard and Vegetable TC

	Orchard/vineyard			Vegetable		
	Gravity	Sprinkler	Drip	Gravity	Sprinkler	Drip
Variable	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx
Surface water price	3.5E−5	−0.0007	0.0007	−0.0021**	0.0020**	4.7E−5
	(0.99)	(−1.55)	(1.57)	(−2.03)	(2.10)	(0.24)
Surface water price × Federal supply	−0.0003	−0.0008	0.0011	0.0011	−0.0009	−0.0001
	(−1.02)	(−0.82)	(1.17)	(0.94)	(−0.83)	(−0.40)
Surface water price × Surface supply	−0.0007**	0.0010**	−0.0004	1.2E−5	−0.0005	0.0005
	(−2.04)	(2.24)	(−0.74)	(0.01)	(−0.40)	(1.08)
Well depth	−2.7E−5	−0.0001	0.0001	−0.0002*	0.0002*	−1.5E−5
	(−0.86)	(−0.70)	(0.94)	(−1.85)	(1.85)	(−0.36)
Discontinued irrigation	[0.0403]	[−0.0533]	[0.0130]	[0.1095]	[−0.1477]	[0.0382]
	(1.28)	(−0.76)	(0.18)	(1.30)	(−1.57)	(0.91)
Population density	−0.0006	−0.0014	0.0019	0.0647*	−0.0808*	0.0160
	(−0.25)	(−0.18)	0.24	(1.91)	(−1.92)	(1.03)
Drought region	[−0.0215]	[0.1211]	[−0.0996]	[−0.1029]	[0.1805]*	[−0.0776]
	(−1.02)	(1.47)	(−1.21)	(−1.27)	(1.81)	(−1.51)
Frost mitigation	[−0.0376]**	[0.0904]*	[−0.0528]	[−0.1385]***	[0.1818]***	[−0.0433]
	(−2.23)	(1.66)	(−0.95)	(−3.76)	(4.14)	(−1.54)
Heat stress mitigation	[0.0156]	[0.1627]**	[−0.1783]***	[0.0639]	[−0.0594]	[−0.0045]
	(0.65)	(2.41)	(−2.56)	(0.82)	(−0.72)	(−0.14)
Temperature	0.0902*	−0.0724	−0.0178	−0.0656	0.0342	0.0313
	(1.95)	(−0.65)	(−0.15)	(−0.80)	(0.36)	(0.68)
Temperature squared	−0.0006*	0.0004	0.0002	0.0006	−0.0004	−0.0002
	(−1.90)	(0.51)	(0.24)	(1.00)	(−0.62)	(−0.51)
Precipitation	0.0068	0.0061	−0.0129	0.0247***	−0.0378***	0.0131**
	(1.58)	(0.80)	(−1.58)	(3.00)	(−3.55)	(2.47)
Precipitation squared	−0.0001	−2.4E−5	0.0001	−0.0004***	0.0007***	−0.0003***
	(−1.46)	(−0.23)	(1.23)	(−4.18)	(5.09)	(−3.15)
Federal supply	[−0.0079]	[0.0303]	[−0.0224]	[0.1094]	[−0.1001]	[−0.0093]
	(−0.35)	(0.40)	(−0.29)	(1.41)	(−1.19)	(−0.27)
Surface supply	[0.0535]	[0.0453]	[−0.0988]	[0.0476]	[−0.0480]	[0.0004]
	(1.63)	(0.64)	(−1.36)	(0.66)	(−0.57)	(0.01)
Land quality	−0.0400	0.1817	−0.1417	0.1384	−0.1735	0.0351
	(−0.73)	(0.86)	(−0.67)	(0.63)	(−0.68)	(0.34)
Farm-scale	−0.0097***	−0.0092	0.0189	−0.0059	0.0024	0.0035*
	(−3.65)	(−0.65)	(1.32)	(−1.38)	(0.52)	(1.66)
Crop diversity	0.0132*	0.0140	−0.0271	0.0350*	−0.0082	−0.0268
	(1.71)	(0.60)	(−1.11)	(1.91)	(−0.32)	(−1.48)
Tenure	[0.0064]	[0.0610]	[−0.0674]	[−0.0143]	[−0.0633]	[0.0776]
	(0.42)	(1.19)	(−1.29)	(−0.28)	(−0.85)	(1.50)
Internet	[−0.0330]	[−0.2104]**	[0.2434]***	[−0.1062]	[0.1053]	[0.0009]
	(−1.06)	(−2.09)	(2.59)	(−0.97)	(0.86)	(0.02)
Farm occupation	[0.0223]	[0.0994]**	[−0.1217]**	[0.0783]	[−0.1290]**	[0.0507]*
	(1.41)	(2.04)	(−2.40)	(1.46)	(−1.99)	(1.66)
Farm experience	0.0014**	0.0004	−0.0018	0.0016	−0.0023	0.0007
	(2.37)	(0.23)	(−1.02)	(1.01)	(−1.16)	(0.73)
Probability of choice	0.04	0.25	0.71	0.15	0.78	0.07
Estimation statistics						
Observations		485			386	
McFadden R^2		0.26			0.36	
Wald chi^2 (df=44)		175.96			154.19	
Correct prediction		66%			76%	

Note: Terms in brackets are the percent change in the probability of adoption as the discrete variable changes from 0 to 1.

Note: Terms in parathesis are z-statistics.

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table 8. Elasticities, Probabilities, and Estimation Statistics from Binomial Logits of Wheat, Alfalfa, Hay, and Pasture TC

	Wheat	Alfalfa	Hay	Pasture
	Sprinkler	Sprinkler	Sprinkler	Sprinkler
Variable	dy/dx	dy/dx	dy/dx	dy/dx
Surface water price	0.0009	4.0E−5	0.0001	0.0011
	(1.06)	(0.36)	(0.39)	(1.17)
Surface water price × Federal supply	0.0035*	0.0011	3.7E−5	−0.0013
	(1.95)	(0.40)	(0.03)	(−0.77)
Surface water price × Surface supply	−0.0059**	−0.0004	0.0001	0.0003
	(−1.97)	(−0.18)	(0.12)	(0.22)
Well depth	0.0003*	0.0001	0.0003*	4.4E−5
	(1.90)	(0.43)	(1.69)	(0.24)
Discontinued irrigation	[−0.1609]*	[−0.1590]**	[−0.0425]	[−0.1470]*
	(−1.89)	(−2.05)	(−1.31)	(−1.86)
Population density	0.0002	0.0177	0.0075	−0.0294
	(0.01)	(0.43)	(0.82)	(−0.96)
Drought region	[0.0853]	[0.0961]	[0.0813]	[0.2415]*
	(0.73)	(0.84)	(1.07)	(1.80)
Heat stress mitigation	[0.2354]**	[0.5027]***	[0.1131]	[0.3830]***
	(2.05)	(4.39)	(0.86)	(2.86)
Temperature	0.4760**	0.5009*	0.5101***	1.6184***
	(2.55)	(1.83)	(4.65)	(7.59)
Temperature squared	−0.0042***	−0.0045**	−0.0040***	−0.0126***
	(−2.98)	(−2.16)	(−4.86)	(−7.62)
Precipitation	−0.0420***	0.0062	0.0099**	0.0251**
	(−3.12)	(0.48)	(2.14)	(1.93)
Precipitation squared	0.0005***	3.2E−5	−0.0001	−0.0002
	(2.79)	(0.15)	(−0.88)	(−0.94)
Federal supply	[−0.3228]***	[0.0351]	[0.0238]	[0.0462]
	(−3.34)	(0.32)	(0.52)	(0.48)
Surface supply	[−0.1008]	[−0.1726]	[−0.0395]	[−0.1249]
	(−0.75)	(−1.62)	(−0.88)	(−1.25)
Land quality	−0.0444	0.9281***	0.4242***	2.3672***
	(−0.14)	(3.61)	(3.47)	(6.29)
Farm-scale	−0.0006	−0.0004	−0.0003	−0.0102*
	(−0.21)	(−0.77)	(−1.15)	(−1.69)
Crop diversity	0.0272	−0.0231	0.0597**	−0.0241
	(0.76)	(−0.70)	(2.23)	(−0.66)
Dairy cattle	—	—	—	[0.2926]*
				(1.88)
Tenure	[0.0654]	[−0.0469]	[0.0215]	[0.0148]
	(0.72)	(−0.67)	(0.71)	(0.20)
Internet	[0.1271]	[0.1430]*	[−0.0255]	[−0.0509]
	(1.33)	(1.95)	(−0.56)	(−0.50)
Farm occupation	[−0.0773]	[0.0400]	[−0.0498]	[0.0061]
	(−0.54)	(0.37)	(−0.82)	(0.06)
Farm experience	−0.0009	−0.0032	−0.0020*	−0.0029
	(−0.33)	(−1.41)	(−1.83)	(−1.16)
Probability of choice	0.47	0.47	0.13	0.43
Estimation statistics				
Observations	501	651	416	356
McFadden R^2	0.47	0.52	0.32	0.37
Wald chi^2 (df)	115.14 (21)	133.07 (21)	54.88 (21)	96.20 (22)
Correct prediction	86%	88%	79%	79%

Note: Terms in brackets are the percent change in the probability of adoption as the discrete variable changes from 0 to 1.

Note: Terms in parenthesis are z-statistics.

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Note: Gravity systems are the base case technology for all TC models.

Table 9. OLS Estimation Results for Orchard/vineyard, Vegetable, Wheat, Alfalfa, Hay, and Pasture AR

	Orchard / vineyard[a]	Vegetable	Wheat	Alfalfa	Hay	Pasture
Variable	Coef.	Coef.	Coef.	Coef.	Coef.	Coef.
Surface water price	−0.0001	0.0004	0.0043***	−0.0001	−0.0007	0.0027
	(−0.77)	(0.30)	(3.71)	(−1.08)	(−0.58)	(1.40)
Surface water price × Federal supply	−0.0015**	−0.0041**	−0.0109***	−0.0168***	−0.0106	−0.0096**
	(−2.18)	(−2.23)	(−4.68)	(−3.97)	(−1.40)	(−2.37)
Surface water price × Surface supply	0.0002**	−0.0064***	−0.0121***	−0.0045	0.0056	−0.0015
	(2.06)	(−2.73)	(−3.63)	(−1.14)	(0.68)	(−0.34)
Well depth	0.0001	−0.0001	0.0001	−0.0002	3.0E−5	−0.0002
	(0.76)	(−0.39)	(0.90)	(−1.02)	(0.12)	(−0.88)
Discontinued irrigation	−0.0679	−0.0056	−0.2568***	−0.2328**	−0.2251*	−0.2020
	(−1.00)	(−0.04)	(−3.11)	(−2.22)	(−1.78)	(−1.41)
Population density	−0.0002	0.0333	−0.0260	−0.0013	−0.0535	0.0261
	(−0.03)	(0.78)	(−0.63)	(−0.02)	(−1.24)	(0.49)
Drought region	−0.2324**	−0.1051	0.4569***	0.1706	0.4579*	0.1934
	(−2.56)	(−0.72)	(3.31)	(1.09)	(1.88)	(0.63)
Frost mitigation	0.1108*	0.0138	—	—	—	—
	(1.87)	(0.12)				
Heat stress mitigation	0.0522	−0.1237	−0.0964	0.0214	0.0446	−0.0638
	(0.73)	(−0.88)	(−0.85)	(0.16)	(0.21)	(−0.22)
Temperature	−0.3190***	−0.1913	−0.1452	−0.2813**	−0.6591***	−0.2713
	(−3.40)	(−1.23)	(−1.21)	(−2.19)	(−4.07)	(−0.74)
Temperature squared	0.0023***	0.0016	0.0012	0.0029***	0.0052***	0.0024
	(3.54)	(1.41)	(1.41)	(3.25)	(4.67)	(0.85)
Precipitation	−0.0075	−0.0128	−0.0175	0.0256*	0.0319**	0.0397*
	(−0.69)	(−0.89)	(−1.20)	(1.65)	(2.11)	(1.94)
Precipitation squared	−0.0003*	−0.0002	0.0002	−0.0004	−0.0004***	−0.0005**
	(−1.74)	(−1.02)	(0.84)	(−1.53)	(−2.77)	(−2.36)
Federal supply	0.1964***	0.2041	0.5235***	0.5142***	0.1434	0.3115*
	(2.68)	(1.54)	(4.47)	(3.51)	(0.73)	(1.93)
Surface supply	−0.1353*	−0.0017	0.4728***	−0.1349	−0.1177	−0.0207
	(−1.83)	(−0.01)	(3.77)	(−0.96)	(−0.66)	(−0.13)
Land quality	−0.0001	−0.8367**	−0.3793	0.4454	1.2975***	0.4824
	(0.00)	(−2.25)	(−1.29)	(1.53)	(3.17)	(0.88)
Farm-scale	0.0005***	0.0004	0.0004	0.0010**	0.0001	0.0006
	(3.46)	(1.46)	(0.11)	(2.26)	(0.29)	(0.28)
Dairy cattle	—	—	—	—	—	−0.0436
						(−0.25)
Sprinkler TC[b]	−0.1758**	−0.5384***	−0.3289***	0.0518	0.0993	0.0767
	(−1.80)	(−3.66)	(−3.15)	(0.41)	(0.80)	(0.50)
Drip TC	−0.1248**	−0.3929**	—	—	—	—
	(−1.73)	(−2.55)				
Tenure	0.0208	0.1402	0.1071	−0.0517	0.0569	−0.1284
	(0.40)	(1.28)	(1.24)	(−0.57)	(0.48)	(−0.98)
Internet	0.0648*	0.3153**	0.0183	0.2056**	0.1209	0.2072
	(0.69)	(2.05)	(0.17)	(2.02)	(0.90)	(1.36)
Farm occupation	0.1424	0.0200	0.2502	0.1274	0.2643	0.1631
	(1.86)	(0.13)	(1.48)	(0.78)	(1.36)	(1.03)
Farm experience	4.4E−5	0.0039	0.0019	0.0035	0.0027	0.0027
	(0.02)	(1.14)	(0.65)	(1.20)	(0.68)	(0.68)
Intercept	11.8083***	8.9746	6.0122	7.8078*	21.276***	8.3570
	(3.49)	(1.64)	(1.38)	(1.66)	(3.56)	(0.69)
Observations	483	384	501	651	416	356
R^2	0.24	0.44	0.36	0.52	0.37	0.14
F-stat. (df)	4.87 (459)	9.70 (360)	10.85 (479)	20.99 (629)	8.18 (394)	3.42 (333)

Note: Terms in parenthesis are t-statistics.

Note: All AR equations are estimated with robust standard errors.

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

[a] The dependent variable for Orchard/vineyard AR is in logged form.

[b] Gravity systems are the base case TC in all AR models; it has been excluded to remove an indeterminacy in the model.

Table 10. Descriptive Statistics of Farm-Scale and Land Allocation

Variable	Mean	Std. Dev.
Farm	5,028	32,867
Cropland[a]	4,349	27,827
Irrigated[a]	1,792	4,032
Irrigated, by crop type		
Orchard/vineyard	1,073	2,486
Vegetable	1,315	2,578
Wheat	615	1,251
Alfalfa	675	1,072
Hay	560	1,178
Pasture	555	1,363

Note: All land allocation values are measured in acres.
Note: All land allocation values are rounded to the nearest integer.
[a]Cropland and irrigated land exclude woodland and developed farmland.

Appendix 1

Evaporative Cooling and Sprinkler Irrigation Technologies

Evaporative cooling occurs when evaporation of a liquid into the surrounding air cools an object in contact with it (Wright, Stevens, and Brown 1981). Above-canopy sprinkler irrigation systems can simultaneously coat an entire crop with water. Thus, under hot conditions, sprinkler technologies can provide evaporative cooling to an entire crop and its surrounding microclimate.

Sensitivity of Major West Coast Crops to Heat Stress

High heat can lead to fruit sunburn damage (i.e., “sunscald”) in numerous orchard and vineyard crops. Sunburn has been reported to damage apple (Racskó et al. 2010), pomegranate (Melgarejo 2004), pear (Wand et al., 2005), orange (Ketchie and Ballard 1968), plum (Maxie and Claypool 1956), peach (Moore and Rogers 1943) avocado (Schroeder and Kay 1961), persimmon (George et al. 1997), and grape (Rhoads1924). Heat stress in apple can cause diminished firmness, color, and size (Iglesias et al. 2002). Heat stress can cause premature abscission (i.e., fruit falling from tree) of Navel oranges (Brewer et al. 1977). For grape, prolonged periods with temperatures exceeding 30°C can induce premature véraison (i.e. transition from grape growth to ripening), grape abscission, enzyme inactivation, and less flavor development (Mullins, Bouquet, and Williams 1992).

Excessive heat can cause sunburn damage to an array of vegetables as well. Sunburn damage has been reported for tomato (Kedar and Retig 1967), peppers, cucumber (Rabinowitch, Ben-David, and Friedmann 1986), cabbage (Ramsey, Winant, and Link 1938), onion, and bean (Ramsey and Wiant 1941).

The optimal temperature range for potato is 59-68°F, with an upper threshold of 77°F (Rötter and van de Geijn 1999). Productivity and quality of potato is impacted by heat stress in three important ways. First, higher temperatures accelerate leaf senescence (i.e., biological aging), effectively reducing growing season length and therefore yield (Timlin et al. 2006). Second, higher temperatures impede translocation of carbohydrates from plant tissue to tubers, resulting in reduced tuber-bulking (Timlin et al. 2006). Third, high temperatures during tuberization can contribute to lower tuber quality (Alva et al. 2002).

Wheat is vulnerable to either long periods above their upper limit of optimal temperature (73°F) or short periods of heat-shock, such as a few days with maxima of over 90°F (Skylas et al. 2002; Rötter and van de Geijn 1999). High heat accelerates wheat senescence, which effectively reduces growing season length and therefore yields (Ferris et al. 1998). Excessive heat can impede grain-fill by reducing leaf and ear photosynthesis (Ferris et al. 1998). High temperature can cause grain shriveling, negatively impacting grain quality (Ortiz et al. 2008). Elevated temperatures during grain-filling progressively reduce milling and bread-making quality by reductions in dough strength (Jacobsen, Jensen, and Liu 2012).

Vough and Marten (1971) demonstrated that alfalfa yield can be negatively impacted at temperatures as low as 81°F. At temperatures of 104°F alfalfa may cease production of "heat-shock proteins" that protect cells and organisms from severe damage and enable survival (Königshofer and Lechner 2002).

There is a paucity of literature documenting the vulnerability of hay to heat stress. However, the literature does report the effects of heat stress on other cereals and grasses. This footnote already described how the productivity and quality of wheat are adversely affected by heat stress. Xu and Zhou (2006) demonstrated that the effects of high temperature on a perennial grass, *Leymus chinensis*, included decreased plant biomass, leaf green area, and photosynthetic rate, and that these effects may be exacerbated by severe water stress. Heat stress can cause changes in various metabolic processes of turfgrass, such as protein degradation and inhibition of synthesis of normal cellular proteins (DiMascio and Danneberger 1990). Protein degradation has been linked to accelerated leaf senescence in wheat, which effectively reduces growing season length and therefore yields (Al-Khatib and Paulsen 1984).

Dairy cows are extremely sensitive to heat stress because of their large body size and high metabolic rate (Nienaber and Hahn 2007). Pastured dairy cows have greater activity level and less shelter from solar radiation relative to non-pastured dairy cows, resulting in greater heat load (Fike et al. 2002). The effects of elevated temperatures on dairy cows are compounded by low wind and high humidity (West 2003). Characteristic symptoms of heat stress in dairy cows include an increased respiratory rate, and decreased activity and feed intake (West 2003). Thus, heat stress can decrease breeding efficiency (Thompson 1973) and milk production (Igono and Johnson 1990). The symptoms of heat stress are exacerbated for more productive dairy cows (Igono and Johnson 1990). Annual economic losses due to heat stress alone for the United States dairy industry have been estimated at $900 million (Collier, Dahl, and VanBaale 2006).

Appendix 2

PI and TC Estimation Results

Table A.2.1. Tobit Estimation Results for PI

Variable	Coef.	t-stat.
Surface water price	−3.9E−5	−0.65
Surface water price × Federal supply	−0.0011**	−2.38
Surface water price × Surface supply	−0.0002	−1.36
Well depth	4.1E−5	0.81
Discontinued irrigation	−0.0767**	−2.50
Population density	−0.0200***	−3.43
Drought region	0.0809*	1.89
Temperature	−0.0724**	−2.20
Temperature squared	0.0006***	2.73
Precipitation	0.0089**	2.51
Precipitation squared	−0.0001***	−2.64
Federal supply	0.2359***	6.85
Surface supply	0.0515*	1.66
Land quality	0.4428***	5.45
Farm-scale	−0.0024***	−6.56
Orchard/vineyard[a]	0.1826***	5.73
Vegetable	0.1792***	5.89
Wheat	0.0722**	2.52
Hay	−0.1030***	−3.69
Pasture	−0.0792***	−2.75
Dairy cattle	0.2439***	4.85
Tenure	0.0233	0.89
Internet	−0.0362	−1.10
Farm occupation	−0.0160	−0.47
Farm experience	−0.0040***	−4.88
Intercept	2.6600	2.24
Observations		1,461
Uncensored observations		791
Right-censored observations at PI=1		670
McFadden R^2		0.23
LR chi^2 (df=25)		478.60

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

[a] Alfalfa is the base case crop choice; it has been excluded to eliminate indeterminacy in the model.

Table A.2.2. Estimation Results from Multinomial Logits of Orchard/vineyard and Vegetable TC

	Orchard/vineyard		Vegetable	
	Sprinkler	Drip	Sprinkler	Drip
Variable	Coef.	Coef.	Coef.	Coef.
Surface water price	−0.0037	0.0002	0.0167**	0.0148*
	(−1.34)	(0.60)	(2.07)	(1.77)
Surface water price × Federal supply	0.0040	0.0086	−0.0085	−0.0094
	(0.53)	(1.32)	(−0.94)	(−0.94)
Surface water price × Surface supply	0.0190**	0.0143**	−0.0007	0.0068
	(2.55)	(2.02)	(−0.07)	(0.68)
Well depth	0.0002	0.0007	0.0015*	0.0011
	(0.30)	(1.16)	(1.94)	(1.17)
Discontinued irrigation	−0.9146*	−0.6618	−0.7965	−0.1144
	(−1.70)	(−1.54)	(−1.57)	(−0.21)
Population density	0.0067	0.0149	−0.5386**	−0.1974
	(0.11)	(0.28)	(−2.09)	(−0.97)
Drought region	0.9595	0.3278	0.8823	−0.3533
	(1.61)	(0.71)	(1.50)	(−0.62)
Frost mitigation	1.2314***	0.8020**	1.6294***	0.5610
	(2.86)	(2.07)	(3.37)	(0.74)
Heat stress mitigation	0.2442	−0.5877	−0.4504	−0.4413
	(0.49)	(−1.21)	(−0.91)	(−0.66)
Temperature	−2.2604**	−1.9928**	0.4848	0.9069
	(−2.08)	(−1.97)	(0.75)	(1.10)
Temperature squared	0.0151**	0.0137*	−0.0043	−0.0062
	(1.97)	(1.92)	(−0.98)	(−1.08)
Precipitation	−0.1234	−0.1662*	−0.2141***	0.0294
	(−1.35)	(−1.92)	(−3.25)	(0.25)
Precipitation squared	0.0026	0.0029	0.0038***	−0.0015
	(1.43)	(1.63)	(4.39)	(−0.57)
Federal supply	0.2980	0.1467	−0.8107	−0.8223
	(0.47)	(0.26)	(−1.47)	(−1.17)
Surface supply	−0.7885	−1.1120**	−0.3758	−0.3087
	(−1.38)	(−2.25)	(−0.68)	(−0.39)
Land quality	1.6076	0.6723	−1.1522	−0.4095
	(1.03)	(0.55)	(−0.65)	(−0.21)
Farm-scale	0.1751	0.2390***	0.0426	0.0910**
	(1.55)	(2.61)	(1.15)	(2.35)
Crop diversity	−0.2309	−0.3258**	−0.2457	−0.6332***
	(−1.35)	(−2.11)	(−1.62)	(−2.67)
Tenure	0.1053	−0.2359	0.0164	0.9498*
	(0.26)	(−0.66)	(0.04)	(1.86)
Internet	−0.0825	0.9846**	0.7009	0.5714
	(−0.16)	(2.28)	(1.14)	(0.86)
Farm occupation	−0.1170	−0.7451*	−0.8576	0.4955
	(−0.23)	(−1.69)	(−1.25)	(0.58)
Farm experience	−0.0294**	−0.0336***	−0.0139	−0.0005
	(−2.34)	(−3.37)	(−1.05)	(−0.03)
Intercept	85.5117	75.6822**	−8.5771	−32.7877
	(2.24)	(2.12)	(−0.37)	(−1.13)
Observations	485		386	
McFadden R^2	0.26		0.36	
Wald chi^2 (df=44)	175.96		154.19	
Correct prediction	66%		76%	

Note: Terms in parathesis are z-statistics.
Note: All TC equations are estimated with robust standard errors.
Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.
Note: Gravity systems are the base case technology for all TC models.

Table A.2.3. Estimation Results from Binomial Logits of Wheat, Alfalfa, Hay, and Pasture TC

	Wheat	Alfalfa	Hay	Pasture
	Sprinkler	Sprinkler	Sprinkler	Sprinkler
Variable	Coef.	Coef.	Coef.	Coef.
Surface water price	0.0036	0.0002	0.0011	0.0043
	(1.07)	(0.36)	(0.39)	(1.17)
Surface water price × Federal supply	0.0142*	0.0045	0.0003	−0.0052
	(1.94)	(0.40)	(0.03)	(−0.77)
Surface water price × Surface supply	−0.0237**	−0.0017	0.0012	0.0014
	(−1.97)	(−0.18)	(0.12)	(0.22)
Well depth	0.0013*	0.0005	0.0025**	0.0002
	(1.87)	(0.44)	(2.49)	(0.24)
Discontinued irrigation	−0.6709*	−0.6588*	−0.4164	−0.6232*
	(−1.73)	(−1.89)	(−1.19)	(−1.77)
Population density	0.0008	0.0710	0.0670	−0.1199
	(0.01)	(0.43)	(0.72)	(−0.96)
Drought region	0.3467	0.3899	0.8399	1.0607
	(0.72)	(0.83)	(1.26)	(1.62)
Heat stress mitigation	0.9752*	2.7958***	0.7911	1.7149**
	(1.89)	(3.04)	(1.15)	(2.13)
Temperature	1.9131**	2.0113*	4.5764***	6.5971***
	(2.44)	(1.76)	(3.86)	(7.82)
Temperature squared	−0.0168***	−0.0179**	−0.0361***	−0.0513***
	(−2.84)	(−2.07)	(−3.83)	(−7.85)
Precipitation	−0.1687***	0.0249	0.0891*	0.1021*
	(−3.24)	(0.48)	(1.64)	(1.93)
Precipitation squared	0.0019***	0.0001	−0.0005	−0.0006
	(2.86)	(0.15)	(−0.72)	(−0.94)
Federal supply	−1.3539***	0.1408	0.2074	0.1875
	(−3.09)	(0.32)	(0.55)	(0.48)
Surface supply	−0.4062	−0.6999	−0.3473	−0.5082
	(−0.75)	(−1.58)	(−0.91)	(−1.24)
Land quality	−0.1784	3.7266***	3.8051***	9.6493***
	(−0.14)	(3.64)	(2.73)	(6.54)
Farm-scale	−0.0024	−0.0018	−0.0025	−0.0416*
	(−0.21)	(−0.77)	(−1.23)	(−1.67)
Crop number	0.1094	−0.0929	0.5359***	−0.0982
	(0.75)	(−0.70)	(3.77)	(−0.66)
Dairy cattle	—	—	—	1.2235*
				(1.66)
Tenure	0.2621	−0.1890	0.1896	0.0603
	(0.72)	(−0.67)	(0.73)	(0.20)
Internet	0.5264	0.5926*	−0.2166	−0.2060
	(1.27)	(1.88)	(−0.63)	(−0.51)
Farm occupation	−0.3096	0.1613	−0.4006	0.0248
	(−0.53)	(0.37)	(−1.06)	(0.06)
Farm experience	−0.0036	−0.0128	−0.0183**	−0.0119
	(−0.33)	(−1.41)	(−2.02)	(−1.16)
Intercept	−50.0355*	−55.4408	−147.7990	−214.8678***
	(−1.88)	(−1.46)	(−3.87)	(−7.68)
Observations	501	651	416	356
McFadden R^2	0.47	0.52	0.32	0.37
Wald chi^2 (df=21)	115.14	133.07	54.88 (21)	96.20 (22)
Correct prediction	86%	88%	79%	79%

Note: Terms in parenthesis are z-statistics.

Note: All TC equations are estimated with robust standard errors.

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Note: Gravity systems are the base case technology for all TC models.