Irrigation Decisions for Major West Coast Crops:

Water Scarcity and Climatic Determinants

Abstract

This article uses the 2007 Farm and Ranch Irrigation Survey database developed by the U.S. Department of Agriculture to assess the impact of water scarcity and climate on irrigation decisions for producers of specialty crops, wheat, and forage crops. We estimate an irrigation management model for major crops in the West Coast (California, Oregon and Washington), which includes a farm-level equation of irrigated share and crop-specific equations of technology adoption and water application rate (orchard/vineyard, vegetable, wheat, alfalfa, hay, and pasture). We find that economic and physical water scarcity, climate, and extreme weather, such as frost, extreme heat and drought, significantly impact producers' irrigation decisions. Producers use sprinkler technologies or additional water applications to mitigate risk of crop damage from extreme weather. Water application rates are least responsive to surface water cost or groundwater well depth for producers of orchard/vineyard. Water supply institutions influence producers' irrigation decisions. Producers who receive water from federal agencies use higher water application rates and are less likely to adopt water-saving irrigation technologies for some crops. Institutional arrangements, including access to distinct water sources (surface or ground) and whether surface water cost is fee based, also affect the responsiveness of water application rates to changes in surface water cost. The analysis provides valuable information about how producers in irrigated agricultural production systems would respond and adapt to water pricing policies and climate change.

Key words: irrigation decisions, water scarcity, climate heterogeneity, extreme weather, water pricing policies

Rising temperatures and shifting precipitation patterns are expected to impact the yield and quality of agricultural commodities in the West Coast (Adams, Wu, and Houston 2001). Damaging frost events are expected to persist in the future (Rigby and Porporato 2008), while extreme heat and drought events are expected to affect larger areas and become more frequent and severe in the West Coast (Jackson et al. 2011). Climate change is also anticipated to accelerate snowmelt in West Coast mountain ranges, which would intensify dry-season water scarcity (Hayhoe et al. 2004).[1] Growth in populations and income and pressure to increase biological streamflows will also intensify water scarcity in the West Coast (Kummu et al. 2010; Burke, Adams, and Wallender 2004).

Agriculture is the largest water user in the United States and accounts for 80-90% of human water consumption in the western United States (U.S. Department of Agriculture 2012). Drought contributes to surface water shortage and groundwater overdraft, which are afflicting the world's most prolific agricultural regions, including the Central Valley of California (Howitt et al. 2014; Famiglietti 2014). Therefore, adapting irrigation management is one of the primary mechanisms for agriculture and society to adapt and respond to changes in water scarcity and climate (Howden 2007). The primary ways to adapt irrigation are to alter the amount of irrigated land, adopt risk-reducing technologies, and adjust water application rates for specific crops. Irrigated agriculture may also respond to climate change by altering land allocations to specific

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[1] Accelerating snowmelt intensifies dry-season water scarcity for two reasons (Hayhoe et al. 2004): (1) dry-season streamflows are diminished, which reduces water available for diversion and increases salt water intrusion to river systems, and (2) wet-season streamflows are increased and therefore reservoir 'rule curves' may mandate the release of water that is stored for dry-season uses to hedge against winter flood risk.

crops (Moore, Gollehon, and Carey 1994), but we do not model that response. Risk-reducing irrigation technologies, including sprinkler and drip, can save water and mitigate crop damage from extreme weather.[2] Given agriculture's sensitivity to water scarcity and climate, providing an understanding of adaptive management in irrigated agricultural production systems is a key contribution to policy evaluation.

In this article we use one of the most complete profiles of irrigation in the United States – the USDA 2007 Farm and Ranch Irrigation Survey (FRIS) – to analyze the effect of water scarcity and climate on producers' irrigation decisions for specialty crops, wheat, and forage crops. The data contains unique information, such as whether the farm used surface water, groundwater, or both, and whether it used irrigation to mitigate crop damage from frost and heat stress. We use the data to estimate an irrigation management model for major crops in the West Coast (California, Oregon and Washington), which includes a farm-level equation of irrigated share and crop-specific equations of technology adoption and water application rate (orchard/vineyard, vegetable, wheat, alfalfa, hay, and pasture). We then use the model to assess the effectiveness of agricultural water pricing policies as a water-saving measure.

This study builds on previous analysis of the effect of water scarcity and climate on irrigation decisions. In a theoretical analysis, Carey and Zilberman (2002) demonstrated that uncertainty in water supplies or prices creates an option value that discourages investment in risk-reducing technologies.[3] Greater well depth (Caswell and Zilberman 1986) and higher water

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[2] Water-saving technologies transmit a higher percentage of applied water to crop consumption compared to gravity technologies (Caswell and Zilberman 1986). Sprinklers affect crop microclimates and can prevent damage from extreme weather (Liu and Kang 2006).

[3] With uncertainty in future water supplies and prices, and the quasi-irreversible nature of an investment in modern technology, the option to delay a sunk investment cost to observe whether prices change can be valuable (Carey and Zilberman 2002).

price (Carey and Zilberman 2002) encourage adoption of risk-reducing technologies. Higher water prices also reduce the demand for water from agriculture (Wheeler et al. 2008).

Other studies found that the effects of water scarcity on irrigation decisions depend on the crop grown. Pfeiffer and Lin (2014) examined the effects of energy prices on irrigated producers' groundwater extraction decision and found that energy prices affect crop selection, acreage allocation, and demand for water. Sunding et al. (2002) showed that irrigators' primary response to curtailed water deliveries is to irrigate less land, particularly for lower-value and water-intensive crops such as pasture, alfalfa, wheat, beans, rice, and feed corn. Green and Sunding (1997) found that for citrus, but not for vineyards, higher water price facilitates adoption of low-pressure irrigation technologies. Green and Sunding's (1997) crop-specific modeling approach allowed them to conclude that for citrus the "biological need of the crop (frost protection) indirectly results in the use of low-pressure irrigation." Adusumilli, Rister, and Lacewell (2011) found that water application rates are responsive to water price for soybeans, but not for corn, wheat, cotton, or sorghum.

It is widely recognized that irrigation efficiency (i.e., the proportion of applied water that is consumed by the crop) is influenced by climate. Dinar and Yaron (1990) showed that drip technologies are often adopted in high temperature regions to offset water loses from high evaporation. Negri and Brooks (1990) found that temperature (growing degree days) is negatively associated with adoption of sprinkler technologies. They provided two reasons for that finding. First, in warmer environments sprinklers can be an inappropriate technology because evaporative losses from the sprinkler spray can approach 15% (Finkel and Nir 1983). Additionally, in cold environments sprinklers can be used for frost protection.

Convincing evidence exists that the effects of temperature and precipitation on irrigation decisions depend on the crop grown. Moore, Gollehon, and Carey (1994) found that water application rates increase with temperature (cooling degree days) for wheat and barley grown in the Pacific Northwest, but decrease for corn. For cotton and sorghum grown in the Texas High Plains, Nieswiadomy (1985) found that water demand is decreasing in precipitation. In contrast, Adusumilli, Rister, and Lacewell (2011) found that water application rates for soybeans grown in the Texas High Plains are increasing in precipitation. Taken together, previous studies suggest that agricultural water demand may have nonlinear relationships with temperature and precipitation because demand depends on the crop and baseline climate conditions.

Our irrigation decision model has several desirable features compared to ones in previous studies. First, our irrigation decision model is crop-specific. Aggregation confounds the crop-specific effects of water scarcity and climate on irrigation decisions (Pfeiffer and Lin 2014; Sunding et al. 2002; Green and Sunding 1997; Moore, Gollehon, and Carey 1994). Second, our irrigation decision model accounts for the influence of climate heterogeneity. Differences in baseline climate conditions impact how irrigators respond to climate changes (Moore, Gollehon, and Carey 1994). Third, our irrigation decision model captures the effect of irrigation on production risk from extreme weather, including drought (Schuck et al. 2005), frost, and extreme heat, and accounts for the fact that different crops are susceptible to different types of extreme weather.[4] Finally, we model important irrigation decisions and their relations to institutions, water scarcity, climate, land characteristics, and producers' demographics. This holistic approach

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[4] Orchards, vineyards, vegetables (Evans 2004), wheat (Liu and Kang 2006) and alfalfa (Robinson 1970) are susceptible to heat stress. Orchards, vineyards (Evans 1999) and vegetables (Wallis et al. 2011) are susceptible to frost damage. Sprinkler irrigation technologies can mitigate damage to these crops from heat stress and frost.

provides valuable insights about how producers in irrigated agricultural production systems would respond and adapt to water pricing policies and climate change.

This article uses arguably the most comprehensive irrigation data to investigate the effects of water scarcity and climate on producers' irrigation decisions for specialty crops, wheat, and forage crops. The analysis leads to several interesting findings. First, water scarcity and climate, especially extreme weather such as frost, extreme heat, and drought, significantly impact producers' irrigation decisions. Producers use sprinkler technologies or additional water applications to mitigate risk of crop damage from extreme weather. Second, institutions influence producers' responses to water scarcity. For example, if producers pay a fee for their surface water or use surface water only, they are more responsive to changes in surface water cost. Paying a fee and using surface water only are both positively correlated with federal supply of surface water. Third, significant changes in well depth would be necessary to cause economically relevant changes in irrigation decisions.

Empirical Model

Consider a West Coast agricultural landscape comprised of farms that grow at least one of the regions' six major crops, including specialty crops (orchard/vineyard and vegetable), wheat, and forage crops (alfalfa, hay, and pasture). Producers are assumed to make irrigation decisions and other production choices to maximize the expected profit, conditional on climate and weather ($\boldsymbol{C}$), water scarcity ($\boldsymbol{S}$), water supply institutions ($\boldsymbol{I}$), land characteristics ($\boldsymbol{L}$), and producer demographics ($\boldsymbol{D}$). To investigate how these factors influence irrigation decisions, we estimate an irrigation management model for major crops in the West Coast (California, Oregon and

Washington), which includes a farm-level equation of share of cropland irrigated (*IS*) and crop-specific equations of technology adoption (*TA*), and water application rate (*AR*):

(1) $$IS_j = h(\boldsymbol{C_j}, \boldsymbol{S_j}, \boldsymbol{I_j}, \boldsymbol{L_j}, \boldsymbol{D_j}),$$

(2) $$TA_{jk} = m(\boldsymbol{C_{jk}}, \boldsymbol{S_{jk}}, \boldsymbol{I_{jk}}, \boldsymbol{L_{jk}}, \boldsymbol{D_{jk}}),$$

(3) $$AR_{jk} = l(\boldsymbol{C_{jk}}, \boldsymbol{S_{jk}}, \boldsymbol{I_{jk}}, \boldsymbol{L_{jk}}, \boldsymbol{D_{jk}}),$$

where $j = 1,\ldots,J$ indexes farms; and k = orchard/vineyard, vegetable, wheat, alfalfa, hay, and pasture, respectively.

Climate and weather conditions affecting irrigation decisions are represented by vector $\boldsymbol{C}$. The variables in $\boldsymbol{C}$ depend on the crop. Based on an extensive review of the economic, agronomic, and environmental engineering literatures related to irrigation, a variable indicating whether irrigation is used to mitigate heat stress is included in the orchard/vineyard, vegetable, wheat, and alfalfa equations and a variable indicating whether irrigation is used to mitigate frost damage is included in the orchard/vineyard and vegetable equations (see footnote 4). A variable indicating whether the farm is located in an arid region with frequent drought is included in all equations, as are variables for annual maximum temperature, annual precipitation, and their squares. The coefficients for the quadratic terms can be interpreted as second-order impacts of climate on the irrigation decision (Schuck and Green 2001).

Economic and physical water scarcity indicators are denoted by vector $\boldsymbol{S}$. We include surface water cost per unit as an economic indicator of water scarcity. Well depth is included as a physical indicator of water scarcity because marginal groundwater pumping cost is a function of well depth and other factors (Caswell and Zilberman 1986). There is greater competition for water in densely populated areas (Kummu et al. 2010), which is more likely to result in curtailed agricultural water deliveries or voluntary transfers of agricultural water to higher-value uses

(Burke, Adams, and Wallender 2004). We include population density to reflect the human demand for water.

Water supply institutions, denoted by vector ***I***, may affect producers' water availability and water costs. One of the variables in ***I*** indicates whether the farm's surface water is only provided by federal agencies, such as the U.S. Bureau of Reclamation and U.S. Army Corps of Engineers. Federal surface water provision is likely an effective indicator of water rights seniority because federal agencies were instrumental in developing irrigated agriculture in the western United States, which is governed by prior appropriations (Moore 1991). The U.S. Bureau of Reclamation (henceforth, "Bureau") is the nation's largest irrigation water supplier. Some producers receiving surface water from the Bureau pay a fee; there is only a fixed charge for water rather than a price per unit of additional supply (i.e., marginal water cost equals zero). Due to the fact that these producers can "apply as much water as they deem necessary," producers set the marginal value product of water equal to the marginal water cost, or zero. In this case, increasing the marginal water price would reduce water use (Moore 1991, pp. 151). In some other cases, the Bureau subsidizes cost per unit of additional supply. The Bureau does not require interest on project cost repayment and it subsidizes agricultural water prices by charging irrigators according to their "ability to pay." The Bureau's interest and ability-to-pay subsidy rates, in tandem, equaled 82% of project costs in 1975 (Moore 1999). Different institutions are used to regulate surface water and groundwater so we include separate variables to indicate whether the farm used surface water only or groundwater only.[5]

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[5] For example, there are not state-wide regulations for groundwater rights in California but there are for surface water. California's Sustainable Groundwater Management Act of 2014 requires groundwater basins to manage using a Groundwater Sustainability Plan, pursuant to criteria developed by the California Department of Water Resources.

We expect that water supply institutions influence producers' responses to water scarcity when making irrigation decisions, and therefore include three interaction terms for institutions and water scarcity. One controls for the effect of paying a fee for surface water on surface water cost responsiveness (Moore 1991). The second controls for the effect of only having a surface water supply on surface water cost responsiveness (Green and Sunding 1997). The third controls for the effect of only having a groundwater supply on well depth responsiveness (Caswell and Zilberman 1986). We expect that increasing water application rates has diminishing marginal benefits because water has diminishing marginal returns on crop yield (Loomis and Young 2014). Thus, if producers increase water application rates as a result of subsidized water cost, their marginal benefit will be lower and their water application rate will be more cost responsive.[6]

Land characteristics are represented by vector ***L***. The variables that constitute ***L*** depend on the crop. A variable indicating whether the farm used irrigation to dispose of livestock waste is included in the *IS* and pasture *TA* and *AR* equations.[7] Variables indicating cropland quality, farm scale, and crop diversity are included in all equations. Some of the irrigation technologies we analyze, particularly sprinkler technologies, are mobile and can be shared between crops. Therefore, we hypothesize that crop-specific *TA* depends on *TA* for other crops grown on the farm. A farm crop diversity variable, measured by the number of major crops grown on the farm, is included in vector ***L*** to test this hypothesis.

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[6] Surface water prices are frequently set administratively rather than in markets, so they serve neither a rationing nor allocative purpose within the district (Moore 1999). However, because price varies across districts, producers' irrigation decisions (especially for a given crop) can be responsive to administratively set prices.

[7] Pasture-based livestock operations often expand irrigation to increase forage production and dispose of livestock waste (Dan O'Brien, manager of Greenberry Irrigation District, Corvallis, Oregon; personal communication).

Vector ***D*** contains the demographic features of the producer. Demographic features include acres of land owned, years of experience operating the current farm, and whether farming is their primary occupation. Producers with more experience are less likely to adopt intensive management practices or to expand production because they are approaching retirement and have developed management solutions using conventional practices (Clawson 1963; Dinar and Yaron 1990). Tenure would increase the extent of irrigation because land ownership increases producers' benefit from investing in irrigation technology (Feder et al. 1985).

Econometric Estimation

The dependent variable of equation (1), *IS*, is the share of irrigated land for the six major crops. Following previous studies using econometric methods for fractional response variables, we specify the regression equation as a fractional logit model (Papke and Wooldridge 1996). To test the robustness of the results to alternative models, we also estimate *IS* using OLS and the log-odds functional form (Pohlman and Leitner 2003).

Adoption of discrete irrigation technologies (gravity, sprinkler, or drip) are analyzed for each of the West Coast's six major crops using equation (2). Multinomial logit models are used to estimate *TA* for orchard/vineyard and vegetable because these crops use all three types of technologies. Binomial logit models are used to estimate *TA* for wheat, alfalfa, hay, and pasture because nearly all producers of these crops use gravity and sprinkler technologies. The logit equations relate the probabilities of adopting certain irrigation technologies to the independent variables and these relations can be compared across crops. Gravity is used as the benchmark technology to remove indeterminacy in the *TA* equations.

The dependent variable of equation (3), *AR*, measures water application rates, which is the volume of water applied per acre for a specific crop (acre-foot). Following Moore, Gollehon, and Carey (1994, pp. 865), we use OLS to estimate *AR*, which is the *crop-level intensive margin of water demand*.

Data

Cross-sectional micro data from USDA's FRIS and Census of Agriculture for production year 2007 are the primary data used to estimate the *IS*, *TA*, and *AR* equations. The FRIS provides observations for about 2,550 farms in the West Coast. About 1,600 of these farms grow at least one of the region's six major crops. We are able to use 1,365 observations to estimate the *IS*, *TA*, and *AR* equations, which represents 53% of the farms in the tri-state FRIS sample and 85% of farms growing at least one of the region's six major crops. The observations we use to estimate the *IS*, *TA*, and *AR* equations are relatively evenly distributed across the West Coast; 40% are in California and 30% are in Oregon and Washington each.

Farms growing only one of the six major crops represent 37% of the observations, while multi-crop production enterprises comprise the remaining 63%. Mean *IS* is 0.81 (table 1) and the mean area used to grow the six major crops is 2,364. The distribution of *IS* is negatively skewed, with 66% of farms irrigating all of their land. There are 1% of farms that do not irrigate any land.[8] As shown in table 1, alfalfa is the most water-intensive crop and pasture is the least, as measured by mean *AR*.[9] Farm scale is positively correlated with growing forage crops (not

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[8] The log-odds of *IS* is undefined if *IS*=0 or *IS*=1. We patch the data for *IS*=0 with a number close to zero (0.01) and we patch the data for *IS*=1 with a number close to one (0.99) so that we can use all the available observations in the OLS (log-odds) estimation of *IS*.

[9] The share of producers that are non-irrigated (i.e., AR=0) are as follows: orchard/vineyard=1%, vegetable=0%, wheat=5%, alfalfa=1%, hay=4%, and pasture=38%.

shown) and 38% of pasture producers are non-irrigated. *TA* for orchard and vineyard is dominated by drip, *TA* for vegetable, wheat, alfalfa, and pasture is dominated by sprinkler, and *TA* for hay is relatively evenly distributed.

Federal supply of surface water is provided for 29% of producers (table 2), and 50% of producers pay a fee for surface water. Most producers receiving federal supply of surface water also pay a fee (97%). Farms using surface water only comprise 47% of our sample and 21% of farms use groundwater only (table 2). Thus, 79% of farms use some surface water. Federal supply of surface water and using surface water supply only are both positively correlated with paying a fee for surface water, and using groundwater supply only is negatively correlated with paying a fee (table 3). Surface water cost per acre-foot is calculated by dividing the total cost of off-farm supplied water by the amount of off-farm supplied water. Farms using groundwater only have surface water cost equal to the county-level mean, the assumed cost in local water transactions. Farms using surface water only have well depth equal to the county-level mean. If producers can drill groundwater wells, but do not pump water, it is reasonable to assume that well depth is positive and similar to local farms. Producers using surface water supply only pay lower mean surface water cost compared to all producers and to producers paying a fee (table 2). Producers using groundwater only experience lower mean well depth than all producers. The interaction term between surface water cost and surface water supply, as well as the interaction term between well depth and groundwater supply, control for these conventions (see empirical models section). Variables with little cross-sectional variation, such as crop prices, wages and energy prices are excluded from the irrigation decision model.

Variables that complement the USDA data are developed from secondary sources. The latest 30-year PRISM climate normal (1981-2010) is used to calculate average county-level temperature and precipitation. Drought prone counties were identified from long-term data at the National Drought Mitigation Center.[10] Cropland quality was developed from the Natural Resources Conservation Service's 1997 Natural Resources 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. Population density was developed from population and land area data (2007) provided by the U.S. Census Bureau.

Estimation Results

Irrigated Share

The estimation results for the irrigated share equation are presented in table 4. We report estimates from the OLS (log-odds) and fractional logit models. The results are relatively consistent across models. The sign of the coefficients (and marginal effects) for the two models are identical for all variables, except for temperature squared and precipitation, which are not statistically significant. Water supply institutions, climate, land characteristics, and producers' demographics significantly affect IS. As a robustness check, we discuss results which are statistically significant in both models.

Institutional impacts. The results show that federal water supply significantly affects *IS*. Producers with federal water supply have an *IS* that is 14-29% higher than producers that do not receive federal water supply.

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[10] Counties overlapping U.S. Climate Divisions with severe to extreme drought (Palmer Drought Severity Index < -3) in at least 10% of years over the last century (1895-1995) are denoted as "drought prone counties" in the data. Drought prone counties cover southern California, and Oregon and Washington eastward of the Cascade Mountains.

Weather and climate impacts. Our results indicate that *IS* is influenced by extreme weather. We find that *IS* is 14-19% higher if producers use irrigation to mitigate crop damage from frost.

Land characteristics and demographic impacts. The results show that land characteristics have larger effects on *IS* than producers' demographics. We find that *IS* is 23% higher if irrigation is used to dispose of liquid livestock waste. This reflects the fact that pasture-based livestock operations often expand irrigation to increase forage production and to dispose of livestock waste. The effect of cropland quality on *IS* suggests that producers expand irrigation if there are relatively few use restrictions on their cropland. Farm scale is negatively associated with *IS*, which reflects that large farms are more likely to grow non-irrigated pasture. Larger farms experience technological constraints (e.g., water diversion and distribution) which are conducive to less intensive management. Crop diversity is negatively related to *IS*. Specifically, growing one additional crop is correlated to a reduction in *IS* of 4-5%. One explanation for this result is that producers may respond to water scarcity by diversifying their crop portfolio and choosing crops with relatively low water intensity, such as wheat and pasture. We find that farming experience is negatively related to *IS* and tenure is positively related.

Crop-specific Technology Adoption

Estimated marginal effects for *TA* from the binomial and multinomial logit models are reported in tables 4 and 5. Water supply institutions, water scarcity, climate, land characteristics, and demographics are significant determinants of *TA*. The observed *TA* for each crop (table 1) closely matches the predicted probability of choice (tables 5 and 6) and at least two-thirds of the observations are correctly predicted for each crop. Estimated coefficients for the binomial and multinomial logit models are presented in tables A.1 and A.2 in the appendix.

Institutional and water scarcity impacts. Our results show that water scarcity and its effects on *TA* are mediated by institutions. Federal supply of surface water reduces the likelihood of adopting sprinklers by 11% for wheat and pasture. Federal supply, which is an indicator of water rights seniority, could substitute for water-saving irrigation technologies. Producers having only one water source, whether it is surface water or groundwater, are not only more likely to adopt certain irrigation technologies for some crops (direct effect), but also respond to changes in surface water costs differently (indirect effect). For example, orchard/vineyard producers with a surface water supply only are 17% less likely to adopt drip and 13% more likely to adopt gravity as a result of the direct effect of having only one water source. Hay producers with a surface water supply only are 11% less likely to adopt sprinklers as a result of the direct effect. There are at least two explanations for this result: 1) surface water is delivered with low pressure so it is conducive to gravity irrigation, which requires less pressurization than sprinkler and drip (Caswell and Zilberman 1986); and 2) cheap water could substitute for sprinklers because producers with surface water supply only, on average, pay lower surface water cost per unit than all producers and producers paying a fee (table 2). Pasture producers are 41% more likely to adopt sprinklers if they only have groundwater supply.

Surface water cost and well depth modestly encourage adoption of water-saving technologies. The results show that for producers having both groundwater and surface water supply, an increase in well depth by 100 feet is associated with an increase in the likelihood of adopting drip for orchard/vineyard of only 3% and is associated with a decrease in the likelihood of adopting gravity of 2%. An increase in well depth by 100 feet is associated with an increase in the likelihood of adopting sprinklers for hay and pasture of 3% and 2%, respectively. An increase in surface water cost encourages adoption of drip for orchard/vineyard and adoption of sprinklers for vegetable, but the effects are relatively small. For orchard/vineyard producers with a surface water supply only, surface water cost facilitates adoption of sprinklers, but again, the effect is modest. Increasing surface water cost encourages adoption of sprinkler for vegetable producers who pay a price, rather than a fee for their water, but increasing surface water cost has little effect on technology adoption for vegetable producers paying a fee (0.0043-0.0040 = 0.0003).

Weather and climate impacts. Our results highlight the salient influence of extreme weather on *TA*. We find that producers who use irrigation to mitigate frost damage are 14% more likely to adopt sprinklers for vegetables and 9% less likely to adopt gravity for orchard/vineyard than producers who do not use irrigation to mitigate frost damage. If orchard/vineyard producers use irrigation to mitigate heat stress, they are 13% more likely to adopt sprinklers and 16% less likely to adopt drip. The likelihood of adopting sprinklers for alfalfa is 28% higher if irrigation is used to mitigate heat stress. Despite agronomic evidence to the contrary (see footnote 5), we do not find that extreme heat significantly affects vegetable *TA*, although drought and temperature do. We find that producing in an arid region with frequent drought is associated with adoption of water-saving sprinklers for all crops, except for alfalfa. Water-saving technologies can maintain crop yield with lower water application rates, which reduces production risk during water shortage and drought (Schuck et al. 2005). The effects of drought for orchard/vineyard, vegetable, and hay are significant and suggest that producing in a drought region increases the likelihood of adopting sprinklers by 17%, 28% and 21%, respectively. We also find that the likelihood of adopting gravity for vegetable is 19% lower if production is in a drought region.

We find that the impacts of climate changes on *TA* depend on baseline temperature and precipitation levels. The impacts of temperature on sprinkler adoption are qualitatively the same for all crops, but are not significant for orchard/vineyard and alfalfa. The relation between temperature and sprinkler adoption is quadratic with a maximum. The maximum values for vegetable, wheat, hay, and pasture, respectively, are 65°F, 54°F, 62°F and 60°F.[11] These results suggest that, below the temperature thresholds for each crop, higher temperature is associated with higher adoption probabilities for water-saving sprinklers, perhaps because gains from increased irrigation efficiency offset water losses from increasing evaporation. Above the temperature thresholds for each crop, higher temperature is associated with lower adoption probabilities. Under conditions of high heat the evaporative losses from the sprinkler spray can reach 15% and make sprinklers an inappropriate technology (Finkel and Nir 1983). We find that the relation between temperature and gravity adoption for vegetable is quadratic with a minimum of 67°F. These results suggest that temperature has an impact on adoption probabilities for gravity and sprinkler technologies and that these effects depend on the crop and baseline climate conditions.

The impacts of precipitation on sprinkler adoption are qualitatively the same for all crops, except for hay. Precipitation does not significantly affect *TA* for orchard/vineyard. The general relation between precipitation and sprinkler adoption is quadratic with a minimum. The minimum values for vegetable, wheat, alfalfa, and pasture, respectively, are 19 inches, 29 inches, 23 inches, and 43 inches. These results suggest that, in dryer environments (below the precipitation thresholds), more precipitation reduces the probability of adopting the water-saving

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[11] Estimated based on the model coefficients reported in Table A2 in the appendix. For example, the maximum values for vegetable equals 3.6927/(2*0.0281)=65.

technology, perhaps due to lower gross irrigation requirements (Finkel and Nir 1983).[12] Crops, especially shallow-rooted ones, are sensitive to water stress caused by heavy and frequent precipitation (Shock, Pereira, and Eldredge 2007). One explanation why producers are more likely to adopt sprinklers in response to increasing precipitation in wetter environments is that precision irrigation delivered by sprinklers can mitigate water stress (Finkel and Nir 1983). This also provides one explanation for why the relation between precipitation and sprinkler adoption for hay, which is often a shallow rooted crop (e.g., Timothy hay), is increasing at an increasing rate under all baseline precipitation conditions.

Land characteristics and demographic impacts. We find that *TA* is more responsive than *IS* and *AR* to land characteristics and demographics. Producers of all crops are more likely to adopt risk-reducing technology if local cropland quality is better. The effects for orchard/vineyard, vegetable, and wheat, are not statistically significant, however. Growing one additional crop increases the likelihood of adopting sprinkler for hay by 10%, which supports our hypothesis that crop-specific *TA* depends on *TA* for other crops grown on the farm.

Finally, we find that younger, less experienced producers with alternate income sources are more likely to adopt new technologies. Producers whose principal occupation is farming are 11% less likely to adopt drip for orchard/vineyard and 20% less likely to adopt sprinklers for vegetable. Producers with more farming experience are more likely to adopt gravity irrigation for all crops, with significant effects for orchard/vineyard and hay. Specifically, ten years of farm experience reduces the probability of adopting sprinklers for orchard/vineyard and hay by 3%.

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[12] Net irrigation water requirement is the quantity of water necessary for crop growth. Gross irrigation water requirement is the quantity of water that must be applied to a crop to satisfy its net irrigation requirement and therefore takes into account water losses from evaporation, transpiration, seepage and other factors.

Crop-specific Water Application Rates

The OLS estimation results for *AR* are reported in table 7. Water supply institutions, water scarcity, climate, and land characteristics are key drivers of *AR*.

Institutional and water scarcity impacts. We find that water scarcity and its effects on *AR* are tied to institutions. The *AR* equation for each crop show a positive relation between *AR* and federal supply of surface water, and the effects are significant for wheat and pasture. Federal supply is linked to an increase in *AR* of 0.29 acre-feet for wheat and 0.31 acre-feet for pasture, or, 15% and 24% of mean *AR* for the two crops (table 1), respectively. Federal supply of surface water is linked to higher *AR* for three reasons: 1) federal supply of surface water is an indicator of water rights seniority; 2) federal suppliers of surface water often charge a fee for water; and 3) federal suppliers of surface water often subsidize project cost and marginal water price.

Producers who have one principal water source only, whether it is surface or groundwater, tend to have lower *AR*. In addition, they respond to changes in surface water costs differently. Specifically, *AR* for orchard/vineyard and hay, respectively, are 0.35 and 0.26 acre-feet lower if producers use a surface water supply only. Pasture *AR* is 0.69 acre-feet lower if there is a groundwater supply only. For wheat, however, we find that surface water supply is tied to an increase in *AR* of 0.44 acre-feet. This “direct effect” is offset by the “indirect effect,” which amounts to a reduction of 0.79 acre-feet (-0.0150*52.5 = -0.79) because wheat producers are more responsive to surface water costs when they have only surface water supply. Thus, the net effect is a reduction of 0.35 acre-feet for wheat producers who have surface water supply only and who face the average surface water cost.

Water application rates are least responsive to surface water cost or groundwater well depth for producers of orchard/vineyard, and institutions influence surface water cost responsiveness. The results show that producers are more responsive to surface water cost if surface water cost per unit (i.e., marginal benefit of surface water) is lower. Surface water cost per unit is 68% lower for producers with surface water supply only than for all producers (table 2). Surface water cost per unit is 42% lower for producers paying a fee than for all producers. For wheat producers with access to surface water and groundwater, higher surface water cost is associated with higher *AR*. One explanation for this is that producers pump more groundwater in response to increasing surface water cost, which increases *AR*. On the other hand, for wheat producers which have a surface water supply only and pay a fee for their water, a ten-dollar increase in surface water cost is associated with a reduction in *AR* of approximately 0.135 acre-feet [10*(0.0048-0.0033-0.0150) = -0.135)], which is 7% of mean *AR* for wheat. An increase in well depth of 100 feet is associated with a reduction in pasture *AR* of 0.06 acre-feet, which is 5% of mean *AR* for pasture.

Weather and climate impacts. The results suggest that extreme weather and climate are important determinants of *AR*. Using irrigation to mitigate frost damage to crops increases mean *AR* for orchard/vineyard by 0.23 acre-feet, which is 9% of mean *AR* for orchard/vineyard. Frost events typically occur during the early morning and can be unpredictable, so the use of irrigation to mitigate frost damage will often not coincide with normally scheduled irrigation events. This is likely to increase the frequency of irrigation and therefore *AR*. Use of irrigation to mitigate heat stress to crops does not significantly affect *AR*. One possible reason for this finding is that normally scheduled irrigation events may closely match irrigation events for relieving heat stress. For example, crop canopy temperature is a crop water stress indicator that has long been used to schedule irrigation applications (Jackson et al. 1981).

We find that *AR* increases for wheat, alfalfa, hay, and pasture if production is in a drought region. The effect for alfalfa, however, is not significant. Drought is associated with an increase in *AR* of 0.35 acre-feet, 0.54 acre feet, and 0.46 acre-feet, respectively, for wheat, hay, and pasture. These results suggest that, conditional on crop choice and irrigation share, producers increase *AR* in arid regions with frequent drought to satisfy gross crop-specific irrigation requirements (see footnote 12). In contrast to this result, *AR* is lower for orchard/vineyard and vegetables produced in a drought region. The orchard/vineyard and vegetable categories include more crop species than other crop categories. Therefore, the results suggest that in arid regions with frequent drought producers may reduce production risk by growing species with lower water-intensity.[13]

We find that *AR* is more sensitive to temperature than to precipitation. The effects of temperature are qualitatively the same for orchard/vineyard, vegetable, and wheat, but are insignificant for wheat. Specifically, there is a quadratic relation between temperature and *AR* for orchard/vineyard and vegetable, which are each minimized at 66°F. The effects of temperature are qualitatively the same for alfalfa, hay, and pasture, but only the effects for pasture are significant. The relation between temperature and *AR* for pasture is maximized at 66°F. This suggests that under extreme temperature conditions (relatively cold or relatively hot) *AR* tends to be lower for forage crops relative to specialty crops and wheat.

The effects of precipitation on *AR* are qualitatively the same for orchard/vineyard, vegetable, and wheat. Specifically, *AR* is decreasing in precipitation for orchard/vineyard, vegetable, and wheat. Vegetable *AR* is decreasing in precipitation at an increasing rate. The

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[13] Most vineyards consume less water than orchards, and most citrus trees (e.g., lemons and oranges) consume less water than many other fruit and nut trees (e.g., walnuts and peaches).

effects of precipitation on *AR* for alfalfa, hay, and pasture are qualitatively the same. There is a quadratic relation between precipitation and *AR* for alfalfa, hay, and pasture, which is maximized at 34 inches, 40 inches, and 49 inches, respectively. Only when precipitation is above the thresholds, will an increase in precipitation lead to lower *AR*.

Land characteristics and demographic impacts. Land characteristics and demographics have some impact on *AR*. Crop diversity negatively affects *AR* for pasture. Specifically, growing one additional crop is associated with a reduction in pasture *AR* of 0.16 acre-feet, which represents 12% of mean *AR* for pasture. We also found significant relation between crop diversity and adoption of sprinklers, including a marginally significant effect for pasture. This suggests that crop diversity, which may encourage sharing irrigation technologies among crops, could reduce *AR* for pasture indirectly through adoption of water-saving sprinklers. Cropland quality significantly affects *AR* for all crops except for alfalfa. Lastly, we find that demographic features of the producer have minor influence on *AR*.

Policy Implications

Heterogeneity in farm size and land quality is well known for reducing the set of production technologies that certain farms can use (Perrin and Winkelmann 1976; Bellon and Taylor 1993). We find that producers of several crops have a propensity to adopt sprinkler technologies that can mitigate damage to crops from frost, extreme heat, and drought. This suggests that heterogeneity in extreme weather reduces the set of production technologies that certain farms can use.

This finding has important policy consequences because water pricing policies are commonly advocated as a means to conserve water by encouraging adoption of water-saving irrigation technologies. Consider a stylized example. Vineyards in Sonoma County, California, and other surrounding counties regularly use sprinklers to mitigate crop frost damage. In this case, water pricing policies would not encourage adoption of the most water-saving technology (drip), but would rather impose costs to producers. In the absence of frost events, the same policies would encourage vineyard irrigators to adopt drip technologies. Hence, our results suggest that the effectiveness of these policies and their distributional impacts are heavily influenced not only by prior land allocation and technological diffusion (Green and Sunding 1997), but also by the spatial distribution of extreme weather. Crop choice could defray these costs, especially for producers of annual crops because crop choice is relatively frequent. This impact of heterogeneity in extreme weather on the effects of water pricing policies has not been clearly identified in the literature.

Our results also show that using irrigation for frost protection increases *AR* for orchards and vineyards. Additional use of irrigation water to mitigate crop frost damage can have several detrimental consequences to local water quality. For instance, it can heighten pollutant loading to local aquifers (Wallis et al. 2011) or, as is the case in Sonoma County, increase diversions from local rivers and degrade habitat for species, including Coho Salmon, which is an Endangered Species in the Russian River.[14] Hence, to maintain the productive capacity of orchards and vineyards and to prevent the degradation of local water resources, areas with related challenges should consider policies that incentivize the adoption of alternative frost protection technologies (e.g., wind mixers).

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[14] Irrigators tapping the Russian River and its tributaries in spring to protect crops from frost will have to follow new state rules upheld in the summer of 2014 following a three-year court battle. For more information: http://www.pressdemocrat.com/home/3100985-181/upcoming-frost-season-means-new.

We find that the response of water application rates to water costs depends on water supply institutions and the type of crops grown. Specifically, our results show that water application rates are more responsive to surface water cost if surface water cost per unit (i.e., marginal benefit of surface water) is lower. Surface water cost per unit is relatively low for producers paying a fee for surface water or producers using a surface water supply only, both of which are positively correlated with the federal supply of surface water. Producers also respond to federal supply of surface water by increasing the share of irrigated cropland and the intensive margin of water demand, and by reducing adoption of water-saving sprinklers. Additionally, we find that water application rates are least responsive to surface water cost or groundwater well depth for producers of orchard/vineyard. Lastly, the results suggest that incentive structures which subsidize adoption of water-saving technologies will not necessarily reduce agricultural water use because the water-savings from adoption could be used to expand the irrigated share of cropland.

We also find that significant changes in well depth would be necessary to cause economically relevant changes in irrigation decisions. This highlights the tragedy of the commons (Hardin 1968) that is already afflicting aquifers in the world's most prolific agricultural regions, including the Central Valley of California. Improving groundwater regulation, which California is currently doing under the Sustainable Groundwater Management Act of 2014, would provide a better signal for producers to adopt irrigation practices that conserve groundwater resources.

Conclusion

In this article we used econometric models to analyze irrigation decisions for producers of specialty crops, wheat, and forage crops in the West Coast. We find that economic and physical water scarcity, temperature, precipitation, and extreme weather, such as frost, extreme heat, and drought, significantly impact producers' irrigation decisions. Institutional arrangements, such as federal water supply and fee-based water cost, affect producers' irrigation decisions regarding irrigated acres, irrigation technology adoption, and water application rates. These results suggest that the effectiveness of agricultural water pricing policies for reducing water use depends significantly on water supply institutions, type of crops grown, climate, and risk of extreme weather.

Our results provide valuable information about how producers might respond and adapt to climate variability and change in irrigated agricultural production systems. Producers adopt sprinklers and drip technologies to reduce risk from climate and extreme weather. Sprinklers and drip technologies use water more efficiently than gravity technologies and can affect microclimates, thereby mitigating damage to crops from extreme weather, including frost, extreme heat, and drought. Drought heightens production risk during drought and in subsequent years (Peck and Adams 2010). In response, producers grow crop species that require less water, but producers must apply more water than they would in less arid environments.

We found that irrigation decisions are more responsive to temperature than to precipitation. The impacts of temperature and precipitation on irrigation decisions are nonlinear and have crop-dependent thresholds, above which producers respond very differently to climate changes. These findings suggest that producers' response and adaptation to climate change depends on cropping patterns and temperature and precipitation baselines (Moore, Gollehon, and Carey 1994).

Our results provide useful information for developing effective surface water pricing policies and groundwater regulations. Surface water pricing policies targeted to subsidized producers or producers paying a fee may effectively reduce water application rates for vegetable, wheat, alfalfa, and hay. More stringent groundwater regulations may effectively reduce water application rates for pasture. These results suggest that producers in California may respond to the region's ongoing drought and new groundwater regulations (see footnote 5) by increasing the intensive margin for orchard/vineyard relative to other crops.

This study calls for further crop-specific analysis of irrigation decisions and their relations to water scarcity and climate. Some of the estimated results warrant verification with further studies. For example, there is evidence that orchard and vineyard producers grow species of lower water intensity if production is in an arid region with frequent drought. Thus, it could be appropriate to estimate models with greater crop specificity. Likewise, an empirical study analyzing technology adoption for several vegetables with varying temperature sensitivities could identify whether irrigation is used to mitigate heat stress for some vegetables, but not for others. These examples highlight the importance of incorporating interdisciplinary science (e.g., plant biology) when investigating crop-specific irrigation decisions. Future crop-specific irrigation decision studies would also benefit from panel data with finer land quality variables and daily, seasonal or monthly climate variables that can identify the effects of extreme weather on irrigation decisions. An ideal analysis would adopt a multi-crop production framework that accounts for all potential input and output substitutions. Such an analysis would require more data and improved estimation methods that can estimate mixed structural models simultaneously. Finally, our policy recommendations and conclusions are subject to the caveats that our framework does not include a model for crop choice and that the irrigation decision models were not estimated jointly. Further research could address this limitation by jointly estimating a system of models that includes irrigation and crop choices.

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Table 1. Descriptive Statistics for Dependent Variables

Variable (units)	Mean	Std. Dev.	Min.	Max.
Irrigated Share [0,1]	0.81	0.33	0.00	1.00
Water Application Rates (acre feet)				
Orchard/vineyard	2.46	1.21	0.00	9.60
Vegetable	2.57	1.13	0.00	8.30
Wheat	1.92	1.05	0.00	6.00
Alfalfa	2.82	1.50	0.00	12.00
Hay	2.09	1.43	0.00	8.40
Pasture	1.31	1.35	0.00	7.90
Variable (units)	% Gravity	% Sprinkler	% Drip	
Multinomial Technology Choice (0/1/2)[a]				
Orchard/vineyard	15	31	54	
Vegetable	21	62	17	
Binomial Technology Choice (0/1)[a]				
Wheat	37	63	–	
Alfalfa	37	63	–	
Hay	54	46	–	
Pasture	33	67	–	

[a] The benchmark (0) is gravity technology.

Table 2. Descriptive Statistics for Selected Independent Variables

Variable	Mean	Std. Dev.	Variable Definition (units)
Institutions			
Federal supply[a]	0.29	0.45	off-farm water is supplied by federal agencies (1/0)
Surface water supply	0.47	0.50	surface water is principal water source (1/0), ≥99%
Groundwater supply	0.21	0.41	groundwater is principal water source (1/0), ≥99%
Water Scarcity			
Surface water cost[b]	52.50	209.97	surface water average cost ($/acre foot)
Fee*surface water cost	30.35	189.92	interaction
Surface water supply*surface water cost	16.68	99.52	interaction
Well depth[c]	489.96	393.94	average depth of farm wells (100 feet), weighted by well pump shares
Groundwater supply*well depth	1.04	2.55	interaction
Population density	103.65	254.83	county population density (100 people/mile^2)
Climate			
Frost mitigation	0.15	0.36	irrigation is used to prevent freeze damage (1/0)
Heat mitigation	0.09	0.29	irrigation is used to cool crop canopy or reduce heat stress (1/0)
Drought	0.63	0.48	farm in county overlapping historic drought region (1/0)
Temperature	63.70	7.80	county average daily maximum temperature (°F)
Temperature squared	4,118.30	1,046.66	interaction
Precipitation	21.39	15.70	county average annual precipitation (inches)
Precipitation squared	703.95	1,292.11	interaction
Land Characteristics			
Waste disposal	0.03	0.18	irrigation is used to dispose of liquid livestock waste (1/0)
Cropland quality	0.31	0.16	county cropland in Land Capability Classes 1 or 2 (%)
Farm-scale	4,338.45	27,647.22	crop, pasture and range land (100 acres); potentially irrigated land
Crop diversity	2.04	1.03	number of major crops irrigated on the farm (1/2/3/4/5/6)
Demographic			
Farm experience	25.81	14.30	experience operating the current farm (years)
Farm occupation	0.85	0.36	farming is principal occupation (1/0)
Tenure	3,541.80	32,321.80	land owned (100 acres)

[a] Federal suppliers include the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, Bureau of Indian Affairs, USDA Small Watershed Program and others. [b] Farms only using groundwater have assumed surface water cost equal to the county-level mean. [c] Farms only using surface water have assumed well depth equal to the county-level mean. Note: Crop-specific statistics can be requested from the corresponding author.

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Drought	0.63	0.48	farm in county overlapping historic drought region (1/0)
Temperature	63.70	7.80	county average daily maximum temperature (°F)
Temperature squared	4,118.30	1,046.66	interaction
Precipitation	21.39	15.70	county average annual precipitation (inches)
Precipitation squared	703.95	1,292.11	interaction
Land Characteristics			
Waste disposal	0.03	0.18	irrigation is used to dispose of liquid livestock waste (1/0)
Cropland quality	0.31	0.16	county cropland in Land Capability Classes 1 or 2 (%)
Farm-scale	4,338.45	27,647.22	crop, pasture and range land (acres); potentially irrigated land
Crop diversity	2.04	1.03	number of major crops irrigated on the farm (1/2/3/4/5/6)
Demographic			
Farm experience	25.81	14.30	experience operating the current farm (years)
Farm occupation	0.85	0.36	farming is principal occupation (1/0)
Tenure	3,541.80	32,321.80	land owned (acres)

[a] Federal suppliers include the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, Bureau of Indian Affairs, USDA Small Watershed Program and others. [b] Farms only using groundwater have assumed surface water cost equal to the county-level mean. [c] Farms only using surface water have assumed well depth equal to the county-level mean. Note: Crop-specific statistics can be requested from the corresponding author.

Table 3. Pearson Correlation Coefficients for Water Supply Institutions

	Federal surface water supply	Surface water supply only	Groundwater supply only
Fee for surface water	0.6111	0.2734	-0.5067
	(<0.0001)	(<0.0001)	(<0.0001)

Note: The p-value is in parenthesis.

Table 4. Estimation Results for the Irrigated Share Equation

Variable	OLS, Log-odds		Fractional Logit Model	
	Parameter Estimate	Marginal Effect	Parameter Estimate	Marginal Effect
Intercept	-29.7557* (16.6728)		-3.5098 (9.9233)	
Institutions				
Federal supply	1.8825*** (0.3681)	0.2894*** (0.0566)	0.9059*** (0.2322)	0.1392*** (0.0357)
Surface water supply	-0.1473 (0.3688)	-0.0226 (0.0567)	-0.2172 (0.2104)	-0.0334 (0.0323)
Groundwater supply	0.3676 (0.6702)	0.0565 (0.1030)	0.1396 (0.3633)	0.0215 (0.0558)
Water Scarcity				
Surface water cost	0.0006 (0.0016)	9.95E-5 (0.0002)	0.0030 (0.0027)	0.0005 (0.0004)
Fee*surface water cost	-0.0010 (0.0018)	-0.0001 (0.0003)	-0.0034 (0.0027)	-0.0005 (0.0004)
Surface water supply*surface water cost	0.0013 (0.0017)	0.0002 (0.0003)	0.0005 (0.0011)	7.19E-5 (0.0002)
Well depth	0.0008 (0.0005)	0.0001 (7.92E-5)	0.0007** (0.0003)	0.0001** (5.32E-5)
Groundwater supply*well depth	-0.0008 (0.0011)	-0.0001 (0.0002)	-0.0008 (0.0006)	-0.0001 (9.50E-5)
Population density	-0.0909 (0.0802)	-0.0140 (0.0123)	-0.0672* (0.0390)	-0.0103* (0.0060)
Climate				
Frost mitigation	1.2635*** (0.4449)	0.1942*** (0.0684)	0.8962** (0.3561)	0.1378** (0.0547)
Heat mitigation	1.1902** (0.5419)	0.1830** (0.0833)	0.4739 (0.4068)	0.0728 (0.0625)
Drought	1.2189** (0.5120)	0.1874** (0.0787)	0.4401 (0.2822)	0.0676 (0.0434)
Temperature	0.7694 (0.4981)	0.1183 (0.0766)	0.0464 (0.3046)	0.0071 (0.0468)
Temperature squared	-0.004 (0.0038)	-0.0006 (0.0006)	0.0004 (0.0024)	6.55E-5 (0.0004)
Precipitation	0.0644 (0.0415)	0.0099 (0.0064)	-0.0008 (0.0224)	-0.0001 (0.0034)
Precipitation squared	-0.0008* (0.0005)	-0.0001 (0.0001)	-4.13E-6 (0.0002)	-6.35E-7 (3.72E-5)
Land Characteristics				

Waste disposal	1.4926*	0.2294*	1.5131*	0.2326*
	(0.8515)	(0.1309)	(0.7948)	(0.1222)
Cropland quality	6.4848***	0.9968***	2.3581***	0.3625***
	(1.0099)	(0.1552)	(0.5810)	(0.0893)
Farm-scale	-0.0002***	-2.42E-5***	-0.0002***	-2.46E-5***
	(2.98E-5)	(4.57E-6)	(2.50E-5)	(3.84E-6)
Crop diversity	-0.3147**	-0.0484**	-0.2516***	-0.0387***
	(0.1553)	(0.0239)	(0.0883)	(0.0136)
Demographic				
Farm experience	-0.0345***	-0.0053***	-0.0110*	-0.0017*
	(0.0105)	(0.0016)	(0.0057)	(0.0009)
Farm occupation	0.6967*	0.1071*	0.3406	0.0524
	(0.4182)	(0.0643)	(0.2248)	(0.0346)
Tenure	0.0001***	2.10E-5***	0.0001***	1.25E-5***
	(2.98E-5)	(4.59E-6)	(2.40E-5)	(3.69E-6)
	Observations	1,365	Observations	1,365
	R-squared	0.21	AIC	1021.00
	F-value (df)	15.63 (1,341)	AICC	1021.80
	P-value	<0.0001	BIC	1146.20

*, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. The asymptotic standard error is in parenthesis. Marginal effects are calculated at the means of the data.

Table 5. Marginal Effects on the Probability of Adopting Sprinkler Technology, Binomial Logit Models[a]

	Marginal Effect and standard error			
Variable	Wheat	Alfalfa	Hay	Pasture
Institutions				
Federal supply	[-0.1086]**	[0.0287]	[0.0648]	[-0.1062]*
	(0.0559)	(0.0364)	(0.0588)	(0.0552)
Surface water supply	[-0.0589]	[-0.0519]	[-0.1121]*	[0.0494]
	(0.0589)	(0.0401)	(0.0635)	(0.0514)
Groundwater supply	[0.2144]	[0.1505]	[0.2282]	[0.4118]***
	(0.1555)	(0.0948)	(0.1406)	(0.1256)
Water Scarcity				
Surface water cost	-0.0005	-0.0002	-0.0004	0.0004
	(0.0007)	(0.0003)	(0.0005)	(0.0006)
Fee*surface water cost	0.0011	0.0001	-0.0009	0.0014
	(0.0009)	(0.0004)	(0.0012)	(0.0010)
Surface water supply*surface water cost	-0.0027*	0.0004	0.0006	-0.0009
	(0.0016)	(0.0009)	(0.0013)	(0.0011)
Well depth	0.0001	0.0001	0.0003**	0.0002**
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Groundwater supply*well depth	-0.0001	-0.0001	-3.98E-6	-0.0003
	(0.0002)	(0.0002)	(0.0003)	(0.0002)
Population density	0.0030	0.0181	-0.0001	0.0042
	(0.0188)	(0.0144)	(0.0179)	(0.0088)
Climate				
Heat mitigation	[0.1062]	[0.2783]**	–	–
	(0.0764)	(0.1214)		
Drought	[0.0945]	[-0.0951]*	[0.2089]**	[0.0102]
	(0.0647)	(0.0535)	(0.0944)	(0.0670)
Temperature	0.1849**	0.0672	0.4204***	0.2977***
	(0.0897)	(0.0735)	(0.1435)	(0.1061)
Temperature squared	-0.0017**	-0.0008	-0.0034***	-0.0025***
	(0.0007)	(0.0006)	(0.0011)	(0.0008)
Precipitation	-0.0288**	-0.0186*	-0.0041	-0.0258***
	(0.0117)	(0.0105)	(0.0074)	(0.0079)
Precipitation squared	0.0005**	0.0004*	0.0002*	0.0003***
	(0.0002)	(0.0002)	(0.0001)	(0.0001)
Land Characteristics				
Waste disposal	–	–	–	[0.2615]
				(0.1607)
Cropland quality	0.1370	0.4919**	0.6685***	0.8053***

	(0.1458)	(0.2017)	(0.2248)	(0.2150)
Farm-scale	2.66E-6	4.86E-7	-6.99E-7	-4.28E-6
	(7.07E-6)	(2.89E-6)	(2.80E-6)	(3.34E-6)
Crop diversity	0.0170	-0.0008	0.0960***	0.0353
	(0.0188)	(0.0155)	(0.0336)	(0.0220)
Demographic				
Farm experience	-0.0012	-0.0014	-0.0033**	-0.0007
	(0.0013)	(0.0010)	(0.0016)	(0.0012)
Farm occupation	[-0.0459]	[0.0295]	[-0.1060]	[-0.0038]
	(0.0694)	(0.0448)	(0.0672)	(0.0490)
Tenure	-1.62E-6	-6.77E-7	4.15E-7	4.02E-6
	(6.02E-6)	(2.91E-6)	(2.82E-6)	(3.34E-6)
Probability of choice	0.67	0.66	0.45	0.66
Estimation statistics				
Observations	457	591	376	526
Correct prediction	83%	86%	77%	69%

[a] The benchmark is gravity technology. Note: The percentage change in technology adoption as the discrete variable changes from 0 to 1 is in brackets. *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. The standard error is in parenthesis.

Table 6. Marginal Effects on the Probability of Adopting Alternative Irrigation Technologies, Multinomial Logit Models[a]

	Marginal Effect and standard error					
	Orchard/vineyard			Vegetable		
Variable	Gravity	Sprinkler	Drip	Gravity	Sprinkler	Drip
Institutions						
Federal supply	[-0.0719]	[-0.0315]	[0.1034]	[0.0962]	[-0.0527]	[-0.0435]
	(0.0512)	(0.0507)	(0.0662)	(0.0650)	(0.0619)	(0.0519)
Surface water supply	[0.1266]*	[0.0446]	[-0.1712]**	[0.1195]	[-0.1042]	[-0.0152]
	(0.0676)	(0.0606)	(0.0799)	(0.0818)	(0.0825)	(0.0669)
Groundwater supply	[-0.0404]	[-0.0338]	[0.0742]	[-0.0467]	[0.0757]	[-0.0290]
	(0.0686)	(0.0839)	(0.1025)	(0.1733)	(0.1537)	(0.1166)
Water Scarcity						
Surface water cost	9.06E-6	-0.0007	0.0007*	-0.0051	0.0043*	0.0008
	(0.0002)	(0.0004)	(0.0004)	(0.0032)	(0.0025)	(0.0016)
Fee*surface water cost	0.0002	-0.0001	-0.0001	0.0047	-0.0040*	-0.0007
	(0.0002)	(0.0005)	(0.0004)	(0.0031)	(0.0024)	(0.0015)
Surface water supply*surface water cost	-0.0014	0.0012*	0.0001	-0.0012	0.0005	0.0008
	(0.0009)	(0.0007)	(0.0010)	(0.0012)	(0.0011)	(0.0008)
Well depth	-0.0002*	-0.0001	0.0003**	-6.7E-5	3.78E-5	2.95E-5
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(7.41E-5)	(0.0001)
Groundwater supply*well depth	0.0002	4.14E-5	-0.0002	4.60E-5	-6.58E-5	1.97E-5
	(0.0001)	(0.0001)	(0.0001)	(0.0003)	(0.0003)	(0.0002)
Population density	0.0016	-0.0031	0.0015	0.0694*	-0.0870**	0.0177
	(0.0054)	(0.0099)	(0.0107)	(0.0384)	(0.0435)	(0.0286)
Climate						
Frost mitigation	[-0.0921]*	[0.0762]	[0.0159]	[-0.1144]	[0.1444]*	[-0.0300]
	(0.0512)	(0.0477)	(0.0624)	(0.0822)	(0.0844)	(0.0660)
Heat mitigation	[0.0348]	[0.1251]**	[-0.1599]**	[0.0469]	[-0.0274]	[-0.0195]
	(0.0527)	(0.0600)	(0.0754)	(0.0701)	(0.0738)	(0.0677)
Drought	[-0.0961]	[0.1733]**	[-0.0772]	[-0.1902]*	[0.2833]**	[-0.0931]
	(0.0645)	(0.0826)	(0.0967)	(0.1097)	(0.1297)	(0.0939)
Temperature	0.1139	0.0191	-0.1329	-0.3065**	0.3383**	-0.0318
	(0.0947)	(0.0688)	(0.1027)	(0.1314)	(0.1522)	(0.0991)
Temperature squared	-0.0008	-0.0002	0.0010	0.0023**	-0.0026**	0.0003
	(0.0007)	(0.0005)	(0.0008)	(0.0010)	(0.0012)	(0.0008)
Precipitation	0.0156	-0.0022	-0.0134	0.0209	-0.0311**	0.0102
	(0.0102)	(0.0067)	(0.0102)	(0.0148)	(0.0155)	(0.0121)
Precipitation squared	-0.0003	0.0001	0.0002	-0.0006	0.0008**	-0.0002
	(0.0002)	(0.0001)	(0.0001)	(0.0003)	(0.0004)	(0.0003)
Land Characteristics						
Cropland quality	-0.1382	0.1317	0.0066	-0.1056	0.0855	0.0200

	(0.1470)	(0.1796)	(0.2190)	(0.1710)	(0.1862)	(0.1703)
Farm-scale	-1.77E-5	9.85E-6	7.90E-5	-7.95E-6	1.11E-6	6.85E-6
	(1.41E-5)	(1.12E-5)	(1.51E-5)	(9.78E-6)	(8.56E-6)	(7.15E-6)
Crop diversity	0.02607	-0.0198	-0.0063	0.0161	0.0219	-0.0381
	(0.0196)	(0.0206)	(0.0263)	(0.0229)	(0.0261)	(0.0253)
Demographic						
Farm experience	0.0029*	-0.0002	-0.0027	0.0004	-0.0013	0.0009
	(0.0015)	(0.0014)	(0.0019)	(0.0016)	(0.0018)	(0.0015)
Farm occupation	[0.0546]	[0.0626]	[-0.1172]*	[0.1279]	[-0.2043]*	[0.0764]
	(0.0478)	(0.0534)	(0.0656)	(0.1107)	(0.1167)	(0.0938)
Tenure	-1.16E-5	-1.38E-5	2.55E-5	-8.37E-6	4.88E-6	3.49E-6
	(1.67E-5)	(1.35E-5)	(1.79E-5)	(1.40E-5)	(1.01E-5)	(8.13E-6)
Probability of choice	0.16	0.32	0.52	0.21	0.62	0.17
Estimation statistics						
Observations		486			361	
Correct prediction		68%			77%	

[a]The benchmark is gravity technology. Note: The percentage change in technology adoption as the discrete variable changes from 0 to 1 is in brackets. *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. The standard error is in parenthesis.

Table 7. OLS Estimation Results for the Water Application Rate Equations

Variable	Parameter Estimate and standard error					
	Orchard / vineyard	Vegetable	Wheat	Alfalfa	Hay	Pasture
Intercept	28.0421***	16.6402***	7.5462	-5.6532	-4.1511	-18.7635**
	(5.4013)	(6.21028)	(4.9718)	(5.5885)	(7.778)	(8.1762)
Institutions						
Federal supply	0.1166	0.0163	0.2947***	0.0975	0.2263	0.3050**
	(0.1252)	(0.1075)	(0.0997)	(0.1122)	(0.1484)	(0.1461)
Surface water supply	-0.3506***	0.0596	0.4440***	0.1101	-0.2568*	-0.0655
	(0.1293)	(0.1253)	(0.1205)	(0.1172)	(0.1529)	(0.1458)
Groundwater supply	-0.2176	-0.1619	-0.3233	0.1604	-0.1902	-0.6945***
	(0.2115)	(0.2172)	(0.2263)	(0.2253)	(0.3331)	(0.2645)
Water Scarcity						
Surface water cost	0.0003	-0.0041***	0.0048***	0.0015*	0.0006	-0.0003
	(0.0003)	(0.0015)	(0.0016)	(0.0009)	(0.0015)	(0.0007)
Fee*surface water cost	-0.0005	0.0029*	-0.0033*	-0.0017*	-0.0090***	-0.0004
	(0.0004)	(0.0016)	(0.0020)	(0.0009)	(0.0026)	(0.0008)
Surface water supply*surface water cost	3.51E-5	-0.0078***	-0.0150***	-0.0106***	0.0037	-0.0014
	(0.0003)	(0.0019)	(0.0034)	(0.0029)	(0.0031)	(0.0021)
Well depth	-3.89E-5	-0.0002	-0.0001	-0.0001	3.58E-5	-0.0006**
	(0.0002)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0002)
Groundwater supply*well depth	-0.0003	0.0002	0.0001	-0.0004	0.0003	0.0003
	(0.0004)	(0.0003)	(0.0002)	(0.0004)	(0.0006)	(0.0004)
Population density	-0.0075	0.1020*	-0.0482	0.0141	-0.0244	-0.0013
	(0.0185)	(0.0545)	(0.0395)	(0.0420)	(0.0454)	(0.0289)
Climate						
Frost mitigation	0.2257**	-0.1504	–	–	–	–
	(0.1119)	(0.1262)				
Heat mitigation	0.0323	-0.0703	-0.1473	0.0047	–	–
	(0.1410)	(0.1417)	(0.1347)	(0.1667)		
Drought	-0.5877***	-0.3999**	0.3461***	0.2013	0.5379***	0.4609**
	(0.1686)	(0.1717)	(0.1381)	(0.1416)	(0.2043)	(0.2111)
Temperature	-0.7300***	-0.3935**	-0.1852	0.1348	0.1357	0.5701**
	(0.1589)	(0.1799)	(0.1479)	(0.1683)	(0.2346)	(0.2526)
Temperature squared	0.0055***	0.0030**	0.0015	-0.0002	-0.0010	-0.0043**
	(0.0012)	(0.0013)	(0.0011)	(0.0012)	(0.0018)	(0.0019)
Precipitation	-0.0329**	-0.0160	-0.0115	0.0338***	0.0479***	0.07762***
	(0.0155)	(0.0139)	(0.0120)	(0.0134)	(0.0167)	(0.0162)
Precipitation squared	-0.0002	-0.0003**	-0.0001	-0.0005***	-0.0006***	-0.0008***
	(0.0002)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0002)
Land Characteristics						

Waste disposal	–	–	–	–	–	-0.4136
						(0.3971)
Cropland quality	-0.9434**	-1.2314***	-0.5426*	0.2698	1.9280***	1.5348***
	(0.4373)	(0.3849)	(0.3177)	(0.3037)	(0.4208)	(0.4107)
Farm-scale	-1.16E-5	4.98E-6	-8.37E-6	4.78E-6	-5.31E-6	1.29E-5
	(2.74E-5)	(1.24E-5)	(1.11E-5)	(6.72E-5)	(8.01E-6)	(7.89E-6)
Crop diversity	-0.0458	-0.0352	-0.0219	0.0380	-0.0452	-0.1568***
	(0.0510)	(0.0422)	(0.0405)	(0.0452)	(0.0632)	(0.0618)
Demographic						
Farm experience	0.0012	0.0060*	0.0026	0.0032	0.0014	0.0008
	(0.0035)	(0.0035)	(0.0029)	(0.0030)	(0.0040)	(0.0038)
Farm occupation	0.2046	0.1160	0.1080	0.0693	0.2826	0.1604
	(0.1299)	(0.1743)	(0.1573)	(0.1472)	(0.1751)	(0.1502)
Tenure	1.25E-5	-4.54E-6	6.88E-6	-3.93E-6	5.37E-6	-1.38E-5*
	(2.73E-5)	(1.23E-5)	(1.10E-5)	(6.74E-6)	(8.05E-6)	(7.95E-6)
Observations	486	361	457	591	376	526
R-squared	0.20	0.33	0.26	0.33	0.16	0.13
F-value (df)	5.36 (463)	7.49 (338)	7.42 (435)	13.10 (569)	3.27 (355)	3.68 (504)
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Note: *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. The standard error is in parenthesis.

Appendix: Parameter Estimates for Irrigation Technology Adoption Models

Table A.1. Estimation Results for Adopting Sprinkler Technology, Binomial Logit Models[a]

	Parameter Estimate and standard error			
Variable	Wheat	Alfalfa	Hay	Pasture
Intercept	37.4540**	10.2781	82.0566***	50.0914***
	(18.1984)	(22.0827)	(20.9711)	(16.5296)
Institutions				
Federal supply	-0.8827***	0.2794	0.3938	-0.5982**
	(0.3522)	(0.3385)	(0.3427)	(0.2895)
Surface water supply	-0.4786	-0.5055	-0.6810**	0.2784
	(0.4406)	(0.3476)	(0.3498)	(0.2836)
Groundwater supply	1.7424	1.4669*	1.3860*	2.3204***
	(1.1190)	(0.7696)	(0.7848)	(0.5787)
Water Scarcity				
Surface water cost	-0.0039	-0.0019	-0.0024	0.0023
	(0.0051)	(0.0028)	(0.0031)	(0.0035)
Fee*surface water cost	0.0091	0.0010	-0.0057	0.0078
	(0.0065)	(0.0040)	(0.0072)	(0.0055)
Surface water supply*surface water cost	-0.0222**	0.0036	0.0038	-0.0048
	(0.0107)	(0.0088)	(0.0077)	(0.0059)
Well depth	0.0009**	0.0007	0.0016**	0.0013***
	(0.0005)	(0.0006)	(0.0007)	(0.0005)
Groundwater supply*well depth	-0.0004	-0.0011	-2.40E-5	-0.0016
	(0.0018)	(0.0015)	(0.0016)	(0.0011)
Population density	0.0246	0.1768	-0.0003	0.0234
	(0.1526)	(0.1247)	(0.1090)	(0.0491)
Climate				
Heat mitigation	0.8628	2.7122***	–	–
	(0.5510)	(0.7497)		
Drought	0.7676*	0.9309**	1.2689***	0.0576
	(0.4562)	(0.4143)	(0.4858)	(0.3764)
Temperature	1.5026***	0.6548	2.5533***	1.6771***
	(0.5418)	(0.6686)	(0.6374)	(0.5125)
Temperature squared	-0.0136***	-0.0078	-0.0205***	-0.0138***
	(0.0041)	(0.0051)	(0.0049)	(0.0040)
Precipitation	-0.2340***	-0.1812**	-0.0249	-0.1452***
	(0.0603)	(0.0820)	(0.0444)	(0.0360)
Precipitation squared	0.0038***	0.0043***	0.0012**	0.0019***
	(0.0011)	(0.0017)	(0.0006)	(0.0005)
Land Characteristics				
Waste disposal	–	–	–	1.4736*

				(0.8588)
Cropland quality	1.1135	4.7936***	4.0605***	4.5372***
	(1.1219)	(1.1592)	(1.0126)	(0.9176)
Farm-scale	2.00E-5	4.73E-6	-4.25E-6	-2.40E-5
	(5.10E-5)	(1.90E-5)	(1.50E-5)	(1.60E-5)
Crop diversity	0.1385	-0.0078	0.5832***	0.1990*
	(0.1451)	(0.1501)	(0.1532)	(0.1175)
Demographic				
Farm experience	-0.0101	-0.0140	-0.0203**	-0.0040
	(0.0101)	(0.0089)	(0.0090)	(0.0071)
Farm occupation	-0.3731	0.2870	-0.6441*	-0.0214
	(0.5484)	(0.4231)	(0.3767)	(0.2758)
Tenure	-1.38E-5	-6.602E-6	2.52E-06	2.00E-5
	(4.30E-5)	(2.00E-5)	(1.50E-5)	(1.60E-5)
Observations	457	591	376	526
Likelihood Ratio Chi-squared (df)	224.8451 (21)	357.2362 (21)	143.1608 (20)	124.5663 (21)
P-value	<0.0001	<0.0001	<0.0001	<0.0001

[a]The benchmark is gravity technology. Note: *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. The standard error is in parenthesis.

Table A.2. Estimation Results for Adopting Alternative Irrigation Technologies, Multinomial Logit Models[a]

	Parameter Estimate and standard error			
	Orchard/vineyard		Vegetable	
Variable	Sprinkler	Drip	Sprinkler	Drip
Intercept	31.4367	43.2469	-116.6000***	-63.9348**
	(28.4752)	(27.0725)	(30.6209)	(31.8541)
Institutions				
Federal supply	0.4417	0.8058*	-0.9118*	-1.0139*
	(0.4716)	(0.4299)	(0.4753)	(0.5542)
Surface water supply	-0.8329	-1.3973***	-1.3118**	-0.9512
	(0.5403)	(0.4902)	(0.5928)	(0.7293)
Groundwater supply	0.1666	0.4847	0.6737	0.0942
	(0.7618)	(0.6553)	(1.6377)	(1.6968)
Water Scarcity				
Surface water cost	-0.0038	0.0014	0.0555***	0.0422**
	(0.0030)	(0.0013)	(0.0209)	(0.0208)
Fee*surface water cost	-0.0017	-0.0016	-0.0514***	-0.0381*
	(0.0034)	(0.0013)	(0.0204)	(0.0202)
Surface water supply*surface water cost	0.0177**	0.0117*	0.0107	0.0147
	(0.0077)	(0.0069)	(0.0096)	(0.0093)
Well depth	0.0010	0.0020***	0.0006	0.0007
	(0.0008)	(0.0008)	(0.0006)	(0.0007)
Groundwater supply*well depth	-0.0011	-0.0018	-0.0006	-0.0002
	(0.0014)	(0.0013)	(0.00304)	(0.0032)
Population density	-0.0291	-0.0106	-0.8844***	-0.3424
	(0.0726)	(0.0521)	(0.2621)	(0.2299)
Climate				
Frost mitigation	1.1580***	0.8019**	1.4623***	0.5578
	(0.4100)	(0.3718)	(0.5941)	(0.6999)
Heat mitigation	0.3443	-0.6069	-0.4522	-0.4803
	(0.5183)	(0.5018)	(0.6074)	(0.7739)
Drought	1.6848***	0.6518	2.6309***	0.5841
	(0.5939)	(0.5056)	(0.7384)	(0.7844)
Temperature	-0.8556	-1.2149	3.6927***	1.8786**
	(0.8515)	(0.8114)	(0.8942)	(0.9292)
Temperature squared	0.0059	0.0090	-0.0281***	-0.0136**
	(0.0064)	(0.0061)	(0.0066)	(0.0068)
Precipitation	-0.1416*	-0.1568**	-0.2885***	-0.0638
	(0.0848)	(0.0813)	(0.1034)	(0.1173)
Precipitation squared	0.0034**	0.0031**	0.0079***	0.0029

	(0.0015)	(0.0015)	(0.0024)	(0.0027)
Land Characteristics				
Cropland quality	1.8255	1.1696	1.1286	0.8927
	(1.5624)	(1.3447)	(1.5088)	(1.9227)
Farm-scale	0.0002*	0.0002	0.0100	0.0110
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Crop diversity	-0.3187*	-0.2305	-0.0107	-0.4138*
	(0.1850)	(0.1652)	(0.1921)	(0.2264)
Demographic				
Farm experience	-0.0254**	-0.0295***	-0.0089	0.0046
	(0.0120)	(0.0104)	(0.0146)	(0.0161)
Farm occupation	-0.1392	-0.6884	-1.832**	-0.2829
	(0.4813)	(0.4223)	(0.8390)	(0.9911)
Tenure	2.70E-5	0.0001	8.10E-5	8.16E-5
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Observations	486		361	
Likelihood Ratio Chi-squared (df)	244.9673 (44)		274.1008 (44)	
P-value	<0.0001		<0.0001	

[a] The benchmark is gravity technology. Note: *, ** and *** denote significance at the 10%, 5% and 1% levels, respectively. The standard error is in parenthesis.